BIOMEDICAL JOURNAL 44 (2021) S25–S36

Available online at www.sciencedirect.com

ScienceDirect

Biomedical Journal

journal homepage: www.elsevier.com/locate/bj

Original Article

Exposure to PM2.5 and PM10 and COVID-19 infection rates and mortality: A one-year observational study in Poland

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ARTICLE INFO

Article history:
Received 30 June 2021
Accepted 12 November 2021
Available online 19 November 2021

Keywords:
SARS-CoV-2
Air pollution
Population density
Polish society

ABSTRACT

Background: Atmospheric contamination, especially particulate matter (PM), can be associated viral infections connected with respiratory failure. Literature data indicates that intensity of SARS-CoV-2 infections worldwide can be associated with PM pollution levels.
Objectives: The aim of the study was to examine the relationship between atmospheric contamination, measured as PM2.5 and PM10 levels, and the number of COVID-19 cases and related deaths in Poland in a one-year observation study.
Methods: Number and geographical distribution of COVID-19 incidents and related deaths, as well as PM2.5 and PM10 exposure levels in Poland were obtained from publicly accessible databases. Average monthly values of these parameters for individual provinces were calculated. Multiple regression analysis was performed for the period between March 2020 and February 2021, taking into account average monthly exposure to PM2.5 and PM10, monthly COVID-19 incidence and mortality rates per 100,000 inhabitants and the population density across Polish provinces.
Results: Only December 2020 the number of new infections was significantly related to the three analyzed factors: PM2.5, population density and the number of laboratory COVID-19 tests ($R^2 = 0.882$). For COVID-19 mortality, a model with all three significant factors: PM10, population density and number of tests was obtained as significant only in November 2020 ($R^2 = 0.468$).
Conclusion: The distribution of COVID-19 incidents across Poland was independent from annual levels of particulate matter concentration in provinces. Exposure to PM2.5 and PM10 was associated with COVID-19 incidence and mortality in different provinces only in certain months. Other cofactors such as population density and the number of performed COVID-19 tests also corresponded with both COVID-19-related infections and deaths only in certain months. Particulate matter should not be treated as the sole determinant of the

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Peer review under responsibility of Chang Gung University.
https://doi.org/10.1016/j.bj.2021.11.006

spread and severity of the COVID-19 pandemic but its importance in the incidence of infectious diseases should not be forgotten.

At a glance commentary

Scientific background on the subject

During the SARS-Cov-2 pandemic, scientists are trying to identify the factors that may facilitate the development of the disease. Environmental pollution is indicated as one of the important factors of COVID-19 spread and severity but literature date derived only from the short-time observation.

What this study adds to the field

Our annual observation did not revealed the direct relationship between such air pollution as PM2.5 and PM10 and the incidence and mortality of COVID-19 but such connection was obsered only in certain months in different provinces. Other cofactors such as population density and the number of performer COVID-19 tests are probably important.

Airborne particulate matter (PM) is considered to be one of the most frequent and important components of air pollution [1]. Long-term exposure to atmospheric pollution such as PM is linked to an increased prevalence of respiratory diseases and mortality [2]. PM is a heterogeneous mixture of solid and liquid, organic and inorganic material suspended in air. It is usually grouped by diameter: ultrafine PM (PM0.1, <0.1 mm), fine PM (PM2.5, <2.5 mm) and coarse PM (PM10, <10 mm). PM2.5 is considered a major health risk factor, causing millions of deaths related to cerebrovascular disease, chronic obstructive pulmonary disease, ischemic heart disease and lung cancer every year [3]. Both PM2.5 and PM10 are associated with an increased rate of respiratory diseases and hospitalization for chronic lung disease and pneumonia [2,3]. In recent years, Poland has recorded the highest annual average concentration of particulate matter PM10 and PM2.5 particles in Europe. The report published by the World Health Organization (WHO) showed that 33 out of 50 cities with the highest concentration of PM2.5 in European Union (UE) are located in Poland [4]. Additionally, a link between atmospheric contamination and an increased transmission rate of viral pathogens such as influenza has been found [5,6]. Actually, it is indicated that an increased particulate matter exposure can influence Severe acute respiratory syndrome coronavirus (SARS-CoV) fatality [7]. The pathogenic agent behind the coronavirus disease 19 (COVID-19) is a novel coronavirus, named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [8]. Illnesses caused by coronaviruses differ in severity, with some causing only common cold symptoms and others – like SARS-CoV and MERS coronavirus – holding responsibility for dangerous outbreaks of pneumonia [9]. While most patients diagnosed with COVID-19 present only mild symptoms, including fever and cough, approximately a quarter of hospitalized patients require intensive care due to a rapid onset of respiratory complications [10,11]. It remains unclear what the exact predisposing factors contributing to increased severity in some patients may be, but an excessive inflammatory response is pointed to as a possible cause [12].

The outbreak of the coronavirus disease in 2019 has been declared as a global pandemic in March 2020 by the WHO, posing new and dynamic challenges for the health care system globally. During the course of the pandemic, attention was gradually paid to other factors that could facilitate the spread of the virus and be associated with the increase in the number of new cases. Setti et al. [13] were the first to suggest that SARS-CoV-2 RNA can be presented on outdoor PM, which may enhance the persistence of the virus in the atmosphere, while a study by Pluchino et al. [14] identified PM10 concentration as an important factor in a priori epidemic risk analysis that could help understand the inhomogeneous spread of COVID-19 in Italy during the first wave of COVID-19 pandemic. Although an increased incidence of COVID-19 associated with ambient air pollutants remains largely unknown, SARS-CoV-2 showed stability in ambient aerosols in laboratory environment, which may be a factor in COVID-19 transmission [15]. Table 1 summarizes the results of recent publications on the relationship between the incidence of COVID-19 and air quality in various regions of the world.

In addition to the information presented in the table above, on the various direction and intensity of the potential relationship between air pollution and COVID-19 spread, lockdowns and restrictions on social activity may have different effects depending on the economic and demographic situation of individual countries.

Available studies conducted across Europe focused mainly on short-term exposure to particulate matter – results from England [16] and Italy [17] suggest a link between the spread of the SARS-CoV-2 virus and PM levels. Therefore the aim of the study was to determine the one-year association between changes in PM pollution levels, especially PM2.5 and PM10, and the number of new SARS-CoV-2 infections and mortality in Poland in relation to population density and the number of COVID-19 tests performed in different provinces. Because each province has a different population density and different mean concentrations of PM, thus each province was examined separately with taking into account monthly averages of PM2.5 and PM10 concentration. This approach takes into account the geographic and demographic differentiation of Polish population. To the best of our knowledge, a long-term observational study of this kind has not been yet conducted and published for Poland.

Table 1 An up-to-date review of the literature on the relationship between air pollution exposure and the incidence of COVID-19 infection and death.

Author (year)	Study area	Study period	Key conclusions
Gupta et al. (2021)	9 cities across Asia	July 2020	Long-time exposure to high levels of PM2.5 was significantly correlated with present COVID-19 mortality per unit reported cases ($p < 0.05$) compared to PM10, with non-significant correlation ($p = 0.118$).
Bherwani et al. (2020)	4 cities (Delhi, London, Paris, WUhan)	March–April 2020	Due to lockdown, a reduction in air pollution-related morbidity was seen in Delhi in 2020. Lockdown affected cities differently, indicating other factors like geographic location, seasonality and meteorological parameters played a role.
Guatam (2020)	selected South Asian and European countries	March 2020	A significant reduction in the level of NO_2 was observed in Asian and European countries due to COVID-19 lockdowns.
Ambade et al. (2021)	Jamshedpur city, Jharkhand, India	March–May 2020	Reduction in air pollutants emission was observed during lockdown. Primary sources of polycyclic aromatic hydrocarbons included biomass, coal burning, and vehicle emission on normal days, while emission from biomass and coal burning was a significant contributor to PAHs during lockdown.
Gautam et al. (2021)	India	January–August 2020	A link was found between air pollution, COVID-19 confirmed cases, and meteorological factors and it may have a potential impact on the transmission of the virus and the high rate of infection and mortality.
Levi et al. (2021)	279 cities and towns, Israel	March 2020–January 2021	Statistically significant nationwide association was observed between population chronic exposure to five main air pollutants in Israeli cities and towns and COVID-19 morbidity rates during two of the three morbidity waves experienced in Israel.
Valdes et al. (2020)	188 communes, Chile	2020	Long-time exposure to PM2.5 and PM10 was significantly associated with a higher risk of COVID-19 incidence, but no statistically significant relationship was found between exposure to air pollutants and COVID-19 related mortality.
Bianconi et al. (2020)	110 Italian provinces	March 2020	Exposure to PM2.5 and PM10 was found to be associated with COVID-19 cases and deaths.
Hutter et al. (2020)	Vienna, Austria	February–April 2020	Chronic exposure to increased levels of NO_2 and PM10 was associated with COVID-19 incidence and mortality. NO_2 was an independent risk factor for both incidence and mortality.
Paez-Osuna et al. (2021)	Sinaloa, Northwest Mexico	February 2020–April 2021	Communes characterized by high PM2.5 levels and population density had a higher COVID-19 mortality rate. High COVID-19 mortality rates of the rural municipalities could be associated with dust events.
Kiser et al. (2021)	Reno, Nevada, USA	May–October 2020	During periods of elevated PM2.5 from wildfires an increase in the SARS-CoV-2 test positivity rate was observed.

Material and methods

Epidemiological data collection

The analysis was based on daily reported COVID-19 incidents and COVID-19 related deaths collected at the epidemiological documentation system of the Ministry of Health between March 2020 and February 2021 [18]. The first diagnosis of COVID-19 in Poland was reported on 4 March 2020. The first fatality was attributed to COVID-19 in Poland on 12 March 2020. New infections were reported with the date of first diagnosis or death, age, gender and the province of residence between 4 March 2020 and 18 November 2020. The data provided by the Ministry of Health websites did not contain any patient identifiers and was therefore completely anonymous. After 18 November 2020 only the date of first diagnosis or death and district of residence were published. The number of COVID-19 tests performed was included in the study database for a shorter time, as the Ministry of Health has published these data only from May 2020 onwards.

Demographic data collection

Population numbers for each province as well as population density were extracted from Statistics Poland annual population data sets [19]. Poland, with a total population of 38,411,148 as of 31 December 2019, consists of 16 provinces and the population density in each of them is shown in Fig. 1.

Air pollution data sources

The Chief Inspectorate of Environmental Protection (*pol. Główny Inspektorat Ochrony Środowiska*; GIOŚ) website was used to obtain the daily levels of PM2.5 and PM10 [20] between March 2020 and February 2021. Data on PM2.5 and PM10 concentrations was available for all 16 provinces, with 155 stations measuring daily levels of PM10 and 57 stations recording levels of PM2.5. Two periods were considered: March 2020 to September 2020, to evaluate the first wave of pandemic, and October 2020 to February 2021 to analyze pollutant levels during the second wave of COVID-19 pandemic in Poland. The average concentrations for the periods under review were calculated based on daily mean values of PM2.5 and PM10 concentrations registered by The Chief Inspectorate of Environmental Protection sites. Monthly population exposure to PM2.5 and PM10 between March 2020 and February 2021 were calculated based on the collected data.

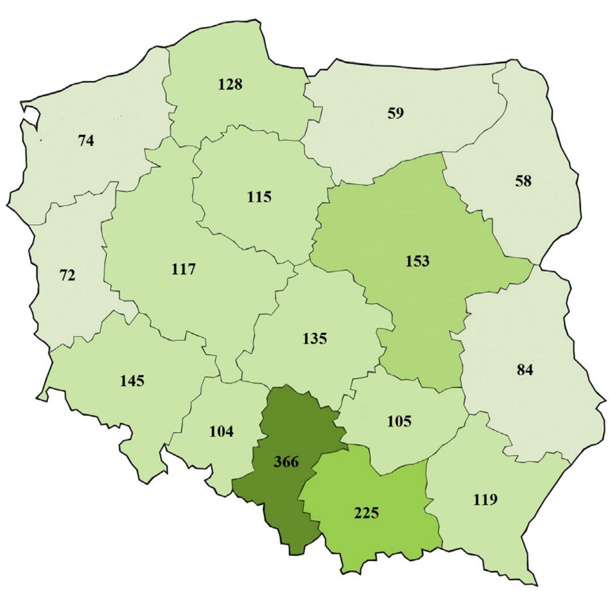

Fig. 1 Map of Poland provinces with color-coded indication of population density (person per km^2).

Statistical analysis

Infection and mortality rates and performed COVID-19 laboratory tests were analyzed per 100 thousands inhabitants for each month and province. Population exposure to PM2.5 and PM10 were included as a monthly average value for each province. Population density in each of Poland provinces was also taken into account. The Shapiro–Wilk test was used to evaluate the normality of the residuals of these variables. As the data were not normally distributed, a logarithmic transformation was performed, resulting in a normalization of the data distribution. Monthly average air pollution concentration: PM2.5 or PM10 in each province in the time period of interest was assumed to be the independent factor; population density as well as the number of performed COVID-19 tests were included in the model as possible confounders. Firstly, a linear regression model was used to examine the association between PM2.5 or PM10 levels and COVID-19 incidence rates in all study observations. Multiple linear regression analyses were performed to test whether the exposure to PM2.5 or PM10 was associated with either COVID-19 incidence proportions across provinces or COVID-19-specific death rates. Variables with a significant crude association with COVID-19 endpoints were included as covariates in the multivariable regression analyses. The created models were fitted by stepwise procedure and only significant independent variables were selected for the final model. The results of multiple regression were presented as standardized correlation coefficients (β) for the successive analyzed independent variables and a comparison coefficient for the entire model proving the fit of the model. Standardized coefficients for individual independent variables can be compared with each other and ranked in terms of their importance for the model. A positive value of the coefficient indicates an increase in the value of the dependent variable with an increase in the value of the independent variable, while a negative beta value indicates an inverse relationship. Statistical significance was set at $p < 0.05$. The data were processed using the Statistica package version 13.1 PL (StatSoft, Poland).

Results

Among the 16 provinces the highest annual values of PM2.5 were observed for Silesian, Lesser Poland and Lodz provinces with average levels of air pollution at 23.04, 22.10 and 21.18 μg/m^3 respectively [Table 2]. The same was true for mean annual PM10 concentration with Silesian province levels reaching

32.8 μg/m^3, Lesser Poland – 31.4 μg/m^3, and Lodz province – 29.3 μg/m^3, were also the highest. At the same time Silesian and Lesser Poland provinces were characterized by the highest population density. Lowest mean annual values of PM2.5 were captured in Pomeranian province (12.86 μg/m^3), while West Pomeranian province was characterized by lowest mean annual values of PM10 pollution (20.6 μg/m^3). No clear link has been found between population density, which characterizes every province, and the annual average of PM2.5 and PM10 values – Kuyavian-Pomeranian and Warmian-Masurian provinces recorded the highest annual average numbers of cases and deaths related to COVID-19 while their annual PM2.5 and PM10 levels could be placed on the lower side of the pollution scale [Table 2].

In the next step, the annual changes of PM2.5 and PM10 were presented across the analyzed months in Fig.2 respectively (the numbers from 0 to 12 indicate the subsequent months from March 2020 to February 2021). The U-shaped range of changes indicates that from May to October 2020 air pollution levels regarding PM2.5 and PM10 were the lowest, while a significant increase can be observed from October 2020 onwards, which is also true for the highest levels of PM10. A seasonal change in air pollution level can be observed.

There was no clear linear dependence between the number of new COVID-19 cases and the observed average monthly PM2.5 and PM10 concentration [Fig. 3]. Two distinctive time periods can be observed regarding new COVID-19 cases per 100 thousand people: first one between March 2020 and September 2020, characterized by less than 200 new monthly cases per 100 thousand people and another one between October 2020 and February 2021, when more than 200 new monthly cases per 100 thousand people were observed. These two phases coincide with the first and definitely more intense second wave of COVID-19 pandemic in Poland.

The simultaneous comparison of the number of COVID-19 cases and deaths in relation to the number of tests performed is presented in Fig. 4. The number of new COVID-19 infections and mortality rate was rising throughout the entire study period, with a distinctive increase in new cases and deaths in November 2020. At the same time the number of tests performed remained more or less constant. This might have a potential impact on the number of new cases and deaths reported, as the percentage value of positive test results was rising throughout the study period.

Due to the non-linear change in the number of cases and deaths caused by the first and second wave of the pandemic as well as the variability of PM2.5 and PM10 values throughout the year, further analyzes were carried out separately for each month of the studied period. They consisted of checking whether there was a relationship between the number of new cases and deaths in individual provinces. Variables such as PM2.5 and PM10 concentrations, population density and the number of tests performed were considered.

The three dimensional relation of: new COVID-19 cases, PM2.5/PM0 average monthly concentration and subsequent month/population density are presented in Fig. 5. The analysis of panels A and B of Fig. 5 indicates a clear increase in the number of cases in each month, especially from October 2020 onwards, which is essentially independent from the average concentrations of PM2.5 and PM10 over the entire study period. On the other hand, panels C and D indicate that the number of new cases was lower when PM2.5 and PM10 exposure was the lowest and independent from the population density of a given province.

An analogous analysis was carried out regarding the number of COVID-19 related deaths and showed similar results, indicating similar connections [Supplementary material, Fig. S1A–D].

Due to the non-linear change in the number of cases and deaths caused by the first and second wave of the pandemic as well as the variability of PM2.5 and PM10 values throughout the year, multiple regression analysis was carried out separately for each month of the studied period. Such factors as the concentration of PM2.5 and PM10, population density and the number of tests performed were examined as independent factors that may be related to the number of new COVID-19 cases or the number of deaths in patients with confirmed COVID-19 infection.

Table 2 Characteristics of the study population.

Province	Population number (N)	Density (N/km^2)	Annual average number of cases per 100 thousand	Annual average number of deaths per 100 thousand	Annual average of PM2.5 [μg/m^3]	Annual average of PM10 [μg/m^3]
Lower Silesian	2,900,163	145	320.6	7.9	15.45	23.9
Silesian	4,517,635	366	350.5	8.6	23.04	32.8
Kuyavian-Pomeranian	2,072,373	115	479.6	11.3	15.43	24.7
Lublin	2,108,270	84	330.2	11.4	19.07	23.4
Lubusz	1,001,159	72	364.8	9.6	13.53	21.2
Mazovian	5,423,168	153	335.9	8.5	17.29	26.0
Lesser Poland	3,410,901	225	312.2	8.2	22.10	31.4
Opole	982,626	104	371.3	11.4	18.61	25.8
Podlaskie	1,178,353	58	335.5	9.6	20.72	24.6
Subcarpathian	2,127,164	119	297.1	9.7	15.24	23.0
Pomeranian	2,343,928	128	428.7	9.8	12.86	21.4
Lodz	2,454,779	135	363.7	10.4		21.18
Holy Cross	1,233,961	105	286.3	8.7		19.39
Warmian-Masurian	1,422,737	59	479.7	11.4		14.15
Greater Poland	3,498,733	117	402.6	10.6		21.04
West Pomeranian	1,696,193	74	428.8	9.2		13.01

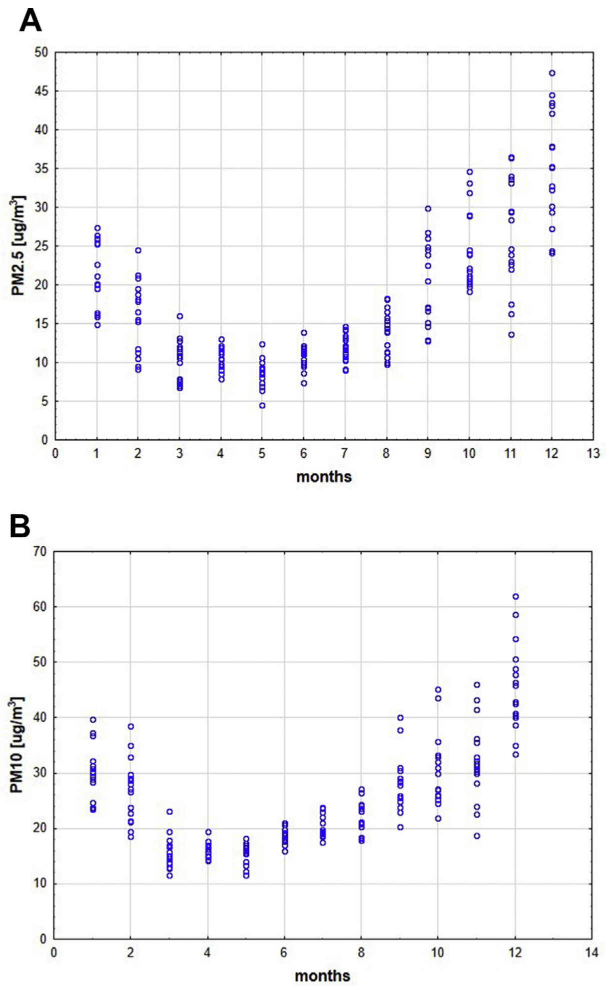

Fig. 2 Changes in average monthly PM2.5 (A) and PM10 (B) levels between March 2020 and February 2021.

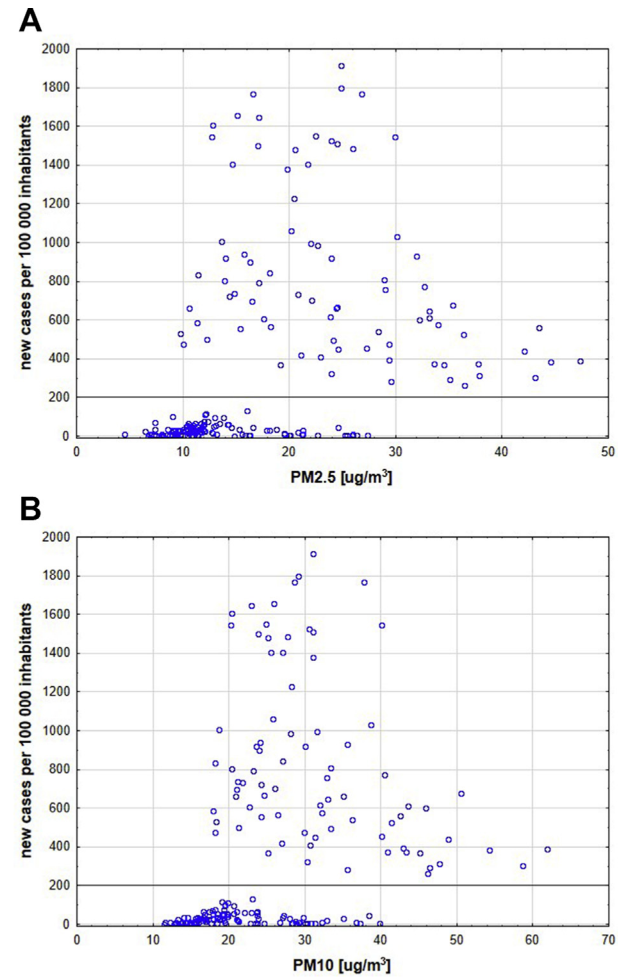

Fig. 3 Illustration of Covid-19 cases versus PM2.5 (A) and PM10 (B) in every month and all 16 provinces.

The analysis of the best fitted monthly models presented in Table 3 shows that the number of cases is related to the analyzed variables only in selected months. The positive correlation between the concentration of PM2.5 and the number of cases was visible only for two months at the beginning of summer (May, June), followed by a link between population density and the number of infections (July, August), and at the end of the study period it was the number of tests performed which had a correlation with new COVID-19 cases (January, February). Only for December 2020 the model including all three dependent variables showed a strong link ($R^2 = 0.882$). However, a negative correlation of COVID-19 cases with population density was observed for this month, compared to July and August. The analysis taking into account PM10 showed a positive connection with this parameter in May (similar to PM2.5). On the other hand, for July and August, the most important variable was population density, and for the last three months of the analysis – between December 2020 and February 2021 – it was the number of tests performed. Between September and November 2020 none of the three variables were associated with the number of new SARS-CoV-2 infections.

As shown in Table 4 the best fitted models considering PM2.5 as a predictor of COVID-19 related deaths indicated a weak positive correlation between the number of deaths and tests performed in January 2021. In the models taking into account PM10, the variable of population density as an independent single positive predictor appeared irregularly in April and August 2020 and along the variable of number of tests performed in the last month of observation. However, in this case, opposite directions of correlation were shown for the analyzed factors, and so mortality was lower for more populated provinces and higher for provinces where more tests were performed per 100,000 inhabitants. The variable of number of tests was shown as an independent predictor of COVID-19-related mortality in January 2021 (the same observation was made for the PM2.5 model in the same month). On the other hand, in November, all three analyzed dependent variables turned out to be significant for the prediction of the number of COVID-19-related deaths. PM10 concentration was a positive predictor, while population density and COVID-19 test number turned out to be negative predictors. However, the degree of fit of the models was only mediocre ($R^2 = 0.468$).

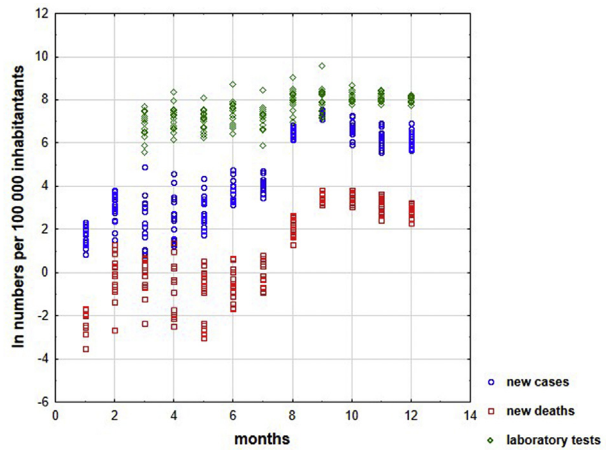

Fig. 4 Monthly logarithmic numbers of new COVID-19 cases, COVID-19 related mortality and tests performed in each province.

Discussion

Respiratory failure, heart disease, stroke and lung cancer are some of the wide range of diseases that may be accelerated by air pollution [21–23]. Exposure to air pollution is strongly associated with local transmission of respiratory infections, as many studies have proved [24–28]. When it comes to COVID-19, infection rates and mortality depend highly on human contact [29]. Nonetheless, other key players such as genetics [30] or environmental factors [31,32] cannot be ruled out in studying the prevalence of the disease. PM2.5 and PM10 were the first to spark our interest regarding the possible link between air pollution and COVID-19. It was hypothesized that particulate matter can create preconditions for the development of COVID-19, resulting in high infection and mortality rates [14].

Our study demonstrated positive associations of PM2.5 and PM10 with COVID-19 infection rates in some months, but not throughout our observation period. However, other factors such as the number of COVID-19 tests performed and population density of certain provinces were linked to increased risk of COVID-19 infection too. Our analysis showed no associations between the annual average number of cases and deaths per 100 thousand inhabitants and the population density of different geographical regions. Silesian and Lesser Poland provinces recorded the highest exposure to air pollution in 2020, but neither was subject to the most new COVID-19 cases and deaths when taking into account its annual averages. As other cofactors such as sex, age, smoking and

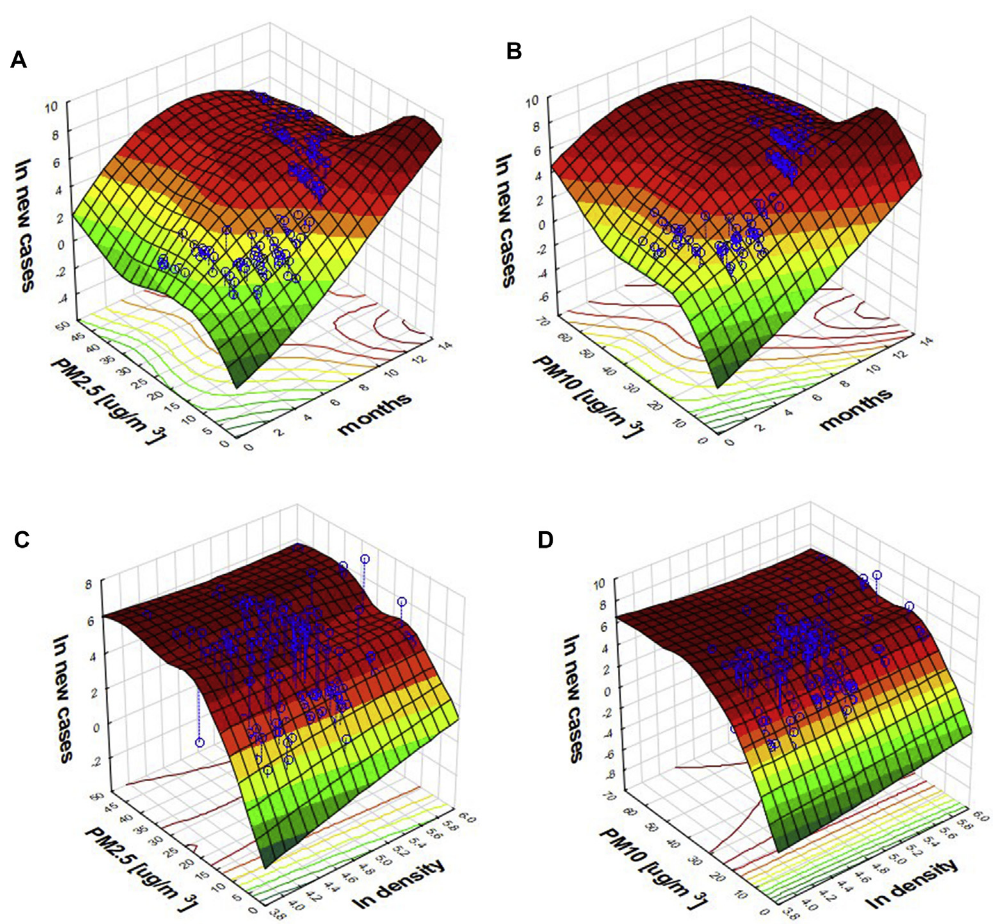

Fig. 5 The number of COVID-19 cases between March 2020 and February 2021 in relation to PM2.5 (A), PM10 (B), as well as the number of COVID-19 cases in relation to population density and PM2.5 (C) and PM10 (D).

Table 3 Adjusted associations between PM2.5 or PM10 and COVID-19 incidence in all provinces every month of observation.

Month	Model I				Model II			
	PM2.5 β; p	Population density β; p	Tests numbers β; p	R^2	PM10 β; p	Population density β; p	Tests numbers β; p	R^2
March 2020	–	–	nd	–	–	–	nd	–
April 2020	–	–	nd	–	–	–	nd	–
May 2020	0.802; <0.001	–	–	0.618	0.799; <0.001	–	–	0.612
June 2020	0.750; <0.001	–	–	0.531	–	–	–	–
July 2020	–	0.684; 0.003	–	0.429	–	0.684; 0.003	–	0.429
August 2020	–	0.771; <0.001	–	0.565	–	0.771; <0.001	–	0.565
September 2020	–	–	–	–	–	–	–	–
October 2020	–	–	–	–	–	–	–	–
November 2020	–	–	–	–	–	–	–	–
December 2020	0.290; 0.026	−0.344; 0.008	0.919; <0.001	0.882	–	–	0.905; <0.001	0.806
January 2021	–	–	0.857; <0.001	0.715	–	–	0.857; <0.001	0.715
February 2021	–	–	0.783; <0.001	0.585	–	–	0.782; <0.001	0.585

For independent significant variables adjusted standardized β, p and R^2 for model are given; '–' indicates that this variable was rejected from the model in step-wise procedure; nd: no data available.

population density may affect potential risk for higher morbidity and mortality of COVID-19, caution has to be taken when translating high values of air pollution levels into an easily applied measure of vulnerability [33,34]. Only one study conducted by Bochenek et al. discussed the impact of meteorological conditions on the dynamics of the COVID-19 pandemic in Poland [35]. In this study the authors revealed that maximum temperature, sunshine duration, relative humidity and variability of mean daily temperature were some of the potential agents influencing new COVID-19 cases in Poland between April and October 2020. An increase in temperature and sunlight duration decreased the number of new cases according to the study, while high humidity caused an increase in COVID-19 cases, with approximately 10–14 days time lag between meteorological parameters and epidemiological statistics. However, this analysis only covers the summer period and did not include the sudden spike in pollution that occurred during the second wave of the pandemic in Poland.

As uncovered by the linear regression in our study, neither PM10 nor PM2.5 was found to have a strong relation to the number of infections or deaths in different provinces – the number of new cases of SARS-CoV-2 infections and COVID-19 related deaths was generally independent from air pollution levels. Though a rapid increase of cases can be observed during the first and second wave of pandemic, it does not seem to be related to the exposure to particulate matter. It can be observed though that while high levels of PM2.5 and PM10 could not be linked to a higher number of infections and mortality, analysis of the data available proved that lower levels of air pollutants corresponded with fewer new cases. This association was not related to population density in provinces which was shown in Fig. 4. A study by Bianconi et al. [17] showed a significant relationship between PM exposure and COVID-19 incidence and cause-specific death rate in Italy in a one month observation in March 2020. Similar results were reported in Vienna [36], where it was found that the daily hazard for both incidence and death from COVID-19 was about

Table 4 Adjusted associations between PM2.5 or PM10 and COVID-19 mortality in all provinces every month of observation.

Month	Model I				Model II			
	PM2.5 β; p	Population density β; p	Test numbers β; p	R^2	PM10 β; p	Population density β; p	Test numbers β; p	R^2
March 2020	–	–	nd	–	–	–	nd	–
April 2020	–	–	nd	–	–	0.663; 0.007	nd	0.396
May 2020	–	–	–	–	–	–	–	–
June 2020	–	–	–	–	–	–	–	–
July 2020	–	–	–	–	–	–	–	–
August 2020	–	–	–	–	–	0.605; 0.013	–	0.321
September 2020	–	–	–	–	–	–	–	–
October 2020	–	–	–	–	–	–	–	–
November 2020	–	–	–	–	0.950; 0.005	−0.709; 0.025	−0.552; 0.014	0.468
December 2020	–	–	–	–	–	–	–	–
January 2021	–	–	0.758; <0.001	0.545	–	–	0.758; <0.001	0.545
February 2021	–	–	–	–	–	−0.440; 0.039	0.484; 0.026	0.527

For independent significant variables adjusted standardized β, p and R^2 for model are given; '–' indicates that this variable was rejected from the model in step-wise procedure; nd – no data available.

40% higher if PM10 was above 20 μg/m^3 between 28 February and 21 April 2021. In a study conducted between March and May 2020 in Buenos Aires [37] exposure to air pollution was significantly correlated with an increased risk of becoming infected and dying from COVID-19. Meanwhile our study revealed that a separate analysis of each month between March 2020 and February 2021 showed that air pollution level did impact infection rates in some of them, in particular May and June 2020 for PM2.5 and May 2020 for PM10. The highest correlation coefficient of the analyzed model was observed in December 2020 ($R^2 = 0.882$) when all three tested factors – PM2.5 level, population density and number of COVID-19 tests performed – had an impact on COVID-19 incidence.

Though significant correlations were not found for particulate matter levels and COVID-19 causes throughout the entire year, close monitoring of air pollution and local level protection measures are crucial when considering PM10 and PM2.5 values for risk stratification. PM10 was highlighted by Setti et al. [13] as a significant variable that can be considered an independent early indicator of epidemic recurrence. Recent studies suggest a link between exposure to air pollution and COVID-19-related mortality, while pointing out that these relationships are significantly influenced by differences between geographic areas, specifically in population density, which is associated with both increased COVID-19 dissemination and air pollution levels [38,32]. One USA study showed that even a small increase in long-term exposure to PM2.5 leads to a large increase in the mortality rate for COVID-19 [39].

As respiratory infections are spread by direct transmission from person to person – such as touching an infected person – respiratory droplets can be deposited directly on a person in close proximity to the infected patient. However, the liquid content of the droplets can evaporate, some of the droplets becoming so small that they are able to travel in the air and carry pathogens over the distance of tens of meters. Multiple studies showed that airborne transmission participates in the spread of different respiratory pathogens like parainfluenza viruses [40], rhinoviruses [41], adenoviruses [42] and human coronaviruses, including SARS-CoV-2 [43,44]. Whether the pathogen can be transmitted further depends on a wide scale of variables such as temperature, humidity, and solar radiation [45]. As revealed by Coccia [46] the accelerated transmission dynamics of the SARS-CoV-2 virus had a significant association with highly polluted cities and was linked in recent studies mainly to the mechanism of airborne viral infectivity rather than "human-to-human transmission". In addition to serving as a transmission medium, exposure to air pollution itself can impact the patient's response to infection. As of today, the mechanism of said impact remains a matter of debate. It is hypothesized that particulate matter pollution disrupts host defenses via innate and cell-mediated immune response. Pulmonary oxidative stress, which can be caused by environmentally persistent free radicals associated with PM, may lead to local immunosuppression and the exacerbation of influenza in mice [47]. Particulate matter can also activate inflammatory signaling cascades, change macrophage morphology [48] and alter the expression of multiple genes in lung tissue [49]. The angiotensin-converting enzyme 2 (ACE2) receptor present on the cells can be overexpressed following exposure to PM2.5. Therefore, PM might increase the probability of SARS-CoV-2 infection, as ACE2 is the key receptor mediating virus entry [50]. Research conducted by Chen et al. [51] compared changes between PM2.5 levels before and during the quarantine period in China, showing improved air quality and suggesting that lockdown helped avoid NO_2-related and PM2.5-related deaths. In the analyses of PM2.5 and PM10 in our study, we observed that during the summer, when PM levels are low compared to winter months, a decrease in the number of COVID-19 related infections and deaths could be noticed.

In our study, exploring the association between PM2.5 and PM10 and the rise of COVID-19-related cases and deaths in Poland, three main trends emerged. First, we have observed that the distribution of COVID-19 cases across Poland was independent from annual levels of particulate matter in provinces. Second, province-stratified exposure to PM2.5 and PM10 was associated with COVID-19 incidence proportion only in certain months. Third, other cofactors such as population density and the number of COVID-19 tests performed also corresponded with both COVID-19-related infections and deaths only in certain months.

Some authors suggest increased exposure to indoor air pollution during lockdown periods. Fireplaces, kitchens, furniture, wall insulation, and personal care products are indicated as sources of indoor pollution [52,53]. The variability of seasons in a temperate climate is another factor that must be taken into account when interpreting a potential relationship between the severity of the COVID-19 pandemic and the level of air pollution. In some countries, such as Poland, the concentration of PM2.5 and PM10 is associated with the seasons and the need to heat apartments and houses during autumn and winter. Simultaneously, lower temperatures tend to push interpersonal contacts indoors. Currently, there is a huge body of research describing the relationship between COVID-19 and environmental factors, in particular air quality. However, they do not always take into account the numerous factors that determine the content of air pollutants associated with the change in lifestyle caused by the introduced lockdowns of varying intensity and duration [54–57]. Therefore, it is important to consider the level of air pollution in real time, as in this study, and not to rely on archival data like some authors have done [17].

Several differential factors might have contributed to the seasonal nature of PM2.5 and PM10 association with COVID-19 infection rates, including weather, humidity, urbanization level and various prevention methods introduced at the time by Polish authorities. Local strategies aimed at diagnosing the viral infection, including quarantine of people suspected of close contact with COVID-19 infected patients, might be an important factor when assessing the association between the number of COVID-19 tests performed and infection rates. Guidelines for COVID-19 testing and diagnosis changed throughout our study period as well as the way new cases, mortality and tests were reported by official channels to the public.

To date, several studies showed the association between particulate matter and the COVID-19 related infection and mortality around the world. Results from China, Italy and the USA are similar and point to a positive association between air pollution and risk of COVID-19 but only in short-time observation [58–60]. As our study considered an entire year and not one or two months, connections between COVID-19 infection rates and mortality were observed only for certain periods of time, highlighting the impact of other cofactors such as population density and the number of tests performed. Our nationwide analysis provided evidence on positive associations between exposure to air pollutants and monthly new COVID-19 confirmed cases mainly in periods of lower PM2.5 level. We can conclude that the direct relationship between PM and the incidence and mortality of COVID-19 in a long-term follow-up has not been proven. However, the importance of monitoring air pollution levels, particularly PM2.5 and PM10, cannot be ignored, especially in Poland, where the highest concentrations of PM are recorded among the countries of the European Union [4]. It seems that other factors related to the spread of the virus have a much greater impact than the air pollution measured by PM2.5 and PM10 indicators. Such factors may turn out to be clinically important data such as age, sex or comorbidities not included in this analysis. Therefore, it is advisable to conduct further studies in this field that could address gaps in our knowledge and allow us to better understand the links between environmental exposure, lifestyle, socioeconomic status and COVID-19 cases and deaths.

Limitations

The study is subject to some limitations. First, monthly and annual average levels of PM2.5 and PM10 were calculated for entire provinces, limiting the distinction between cities and rural areas. People living outside urbanized areas might have been exposed to different air pollution levels. Second, our data might potentially suffer from under-reporting of COVID-19 related infections and deaths. In our opinion, under-reporting might have occurred as diagnostic references for COVID-19 infections changed throughout the study period and various guidelines were used to assess patients showing COVID-19 symptoms. Hence, whereas the first and second wave of pandemic can be observed in presented data, it may not be entirely accurate. Third, we did not stratify the analysis by age group and sex, which can be important factors in COVID-19 infections. As previously stated, data limitations made it impossible to take age and gender into consideration. Thus, our results cannot be generalized to the entire population, and the calculated relative risks should be interpreted with caution.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

The data used in the study are available on the following websites:

- https://basiw.mz.gov.pl/index.html#/visualization?id=3651 [18].
- https://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/rocznik-demograficzny-2019,3,13.html [19].
- http://powietrze.gios.gov.pl/pjp/archives?lang=en [20].

Conflicts of interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bj.2021.11.006.

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