Cumulative effects of air pollution and climate drivers on COVID-19 multiwaves in Bucharest, Romania

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ABSTRACT

Over more than two years of global health crisis due to ongoing COVID-19 pandemic, Romania experienced a five-wave pattern. This study aims to assess the potential impact of environmental drivers on COVID-19 transmission in Bucharest, capital of Romania during the analyzed epidemic period. Through descriptive statistics and cross-correlation tests applied to time series of daily observational and geospatial data of major outdoor inhalable particulate matter with aerodynamic diameter ≤ 2.5 μm (PM2.5) or ≤ 10 μm (PM10), nitrogen dioxide (NO$_2$), ozone (O$_3$), sulfur dioxide (SO$_2$), carbon monoxide (CO), Aerosol Optical Depth at 550 nm (AOD) and radon (^{222}Rn), we investigated the COVID-19 waves patterns under different meteorological conditions. This study examined the contribution of individual climate variables on the ground level air pollutants concentrations and COVID-19 disease severity. As compared to the long-term average AOD over Bucharest from 2015 to 2019, for the same year periods, this study revealed major AOD level reduction by ~28 % during the spring lockdown of the first COVID-19 wave (15 March 2020–15 May 2020), and ~16 % during the third COVID-19 wave (1 February 2021–1 June 2021). This study found positive correlations between exposure to air pollutants PM2.5, PM10, NO$_2$, SO$_2$, CO and ^{222}Rn, and significant negative correlations, especially for spring-summer periods between ground O$_3$ levels, air temperature, Planetary Boundary Layer height, and surface solar irradiance with COVID-19 incidence and deaths. For the analyzed time period 1 January 2020–1 April 2022, before and during each COVID-19 wave were recorded stagnant synoptic anticyclonic conditions favorable for SARS-CoV-2 virus spreading, with positive Omega surface charts composite average (Pa/s) at 850 mb during fall-winter seasons, clearly evidenced for the second, the fourth and the fifth waves. These findings are relevant for viral infections controls and health safety strategies design in highly polluted urban environments.

1. Introduction

The ongoing global COVID-19 pandemic - which nowadays (on 12 August 2022) has exceeded 593,567 million cases and about 6.449 million fatalities in 230 countries (Anon, 2022f, 2022l; Johns Hopkins Coronavirus, 2022) - is a strong reminder that urbanization has impacted the communities and infectious diseases transmission, that it's an urgent need to enforce the local capacities resilience to prevent the spread of viral infections. Till 12 August 2022, Romania experienced six

COVID-19 waves, with more than 3150,037 infections and over 66,311 deaths. Currently, besides Delta variant of concern (B.1.617.2), the SARS-CoV-2 (B.1.1.529) Omicron identified in late November 2021, due to its high pathogenicity (Poudel et al., 2022; Petersen et al., 2021; Otto et al., 2021; Dawood, 2022) is the predominant variant in Romania. The burden of more than 37 major out of 67 mutations in Omicron spike suggests an increased transmissibility but a reduced virulence, which was observed during the last COVID-19 waves worldwide. Improved stability of Omicron enhances attachment, which in the case of indoor

and outdoor particulate matter is very relevant (Cui et al., 2022; Khandia et al., 2022).

Assessment of the environmental drivers related to the epidemiological behavior of this outbreak has a vital role in preventing its spreading. The rapid spread of the COVID-19 viral infections in large urban areas, characterized by high urbanization and dynamic landchange systems, people's mobility and economic development considers air pollution and climate variability among the determinants of SARS-CoV-2 pathogens transmission at the local and regional level and associated risk factors (Rayasam et al., 2022).

As unpredictable future viral multiwave patterns are likely to occur, is an essential need to understand the pattern of COVID-19 pandemic risk and its association with environmental, socioeconomic, demographic, host-specific genetic, clinical, therapeutic, and evolutionary risks (D'Amico et al., 2022; Casado-Aranda et al., 2021; Mu et al., 2020; Bakhshandeh et al., 2021; He et. al., 2021; Bontempi, 2021; Bontempi et al., 2020; Baay et al., 2020; Luo et al., 2020; Chen et al., 2021b; Rayan, 2021; Cevik et al., 2021; Marquès et al., 2022; Cao et al., 2020). Among multi risk exposure factors in the susceptibility of COVID-19 in large urban areas, outdoor short-term and long-term exposure to air pollutants and radon under specific meteorological conditions may play a significant role in spatiotemporal spreading of SARS-CoV-2 pathogens and COVID-19 disease severity (Bontempi et al., 2020; Iqbal et al., 2021; Soriano et al., 2021; Destoumieux-Garzon at al., 2022; Shi, Qi, 2022).

Bucharest metropolitan city in Romania is considered one of the world's and European's most polluted hotspots cities (Anon, 2019, 2022h). During the last years, in spite of decreased levels of air pollution below the EU and WHO air quality guidelines targeting the exposure of the population to outdoor air pollutants, sometimes in Romania are reported higher concentrations above the established daily or annual limits for inhalable particulate matter (PM2.5 or PM10), and gaseous pollutants (O_3, NO_2, SO_2, and CO), potential associated with health risks. According to European Environment Agency air quality standards, Bucharest, with a 16.4 $\mu g/m^3$ concentration of fine particulate matter PM2.5 is classified to have poor air quality for levels from 15 to below 25 $\mu g/m^3$ (Anon, 2022a; EEA 2021; WMO 2020; WMO 2006). Coronavirus-laden PM2.5 and PM10 particulate matter, so named "pathogenic " may have induced intra-host mutagenesis in the SARS-CoV-2 genome, diminishing cardio respiratory system immunity (Yates et al., 2022; Manisalidis et al., 2020). With the daily PM2.5 and PM10 peaks, airborne pollutants may act as active viral vectors of COVID-19 disease (Yuan et al., 2021; Baron, 2021, 2022; Shao et al., 2022; Hvidtfeldt et al., 2021; Travaglio et al., 2021).

Like previous epidemiologic studies, this paper considers the contribution of short-term and long-term outdoor pollution exposure on viral COVID-19 pandemic disease transmission (Marquès et al., 2022; Domingo et al., 2020; Marquès and Domingo, 2022; Jiang et al ., 2021; Rawat et al., 2021; Xia et al., 2022; López-Feldman et al., 2021; Zoran et al., 2021; Zoran et al., 2022; Prinz and Richter, 2022; Bakadia et al., 2021; Lavigne et al., 2022).

Total Aerosol Optical Depth at 550 nm (AOD), a marker of air pollution was introduced in conjunction with air pollutants variables. As a measure of the aerosol column concentration over a large urban area, AOD represents the attenuation of sunlight by aerosols being a fundamental variable used to study aerosol loading in the atmosphere (Chabane, Arif, 2021; Ranjan et al., 2020; Filonchyk et al., 2021). Is an important scientific challenge to understand the influence of the aerosol concentrations on the rates of viral disease contamination in urban agglomerated areas. Of particular interest is the investigation of the temporal pattern of AOD on SARS-CoV-2 virulence and propagation (Kumar, 2020; Dumka et al., 2021; Shao et al., 2022; Setti et al., 2020a, 2020b; Contini, Costabile, 2020; Pozzer et al., 2020). Due to their increased oxidative toxicity, acute and chronic exposure to high ground levels of air pollutants in large urban regions is associated with higher cardiorespiratory comorbidity and mortality rates (Wang et al., 2022; Xu et al., 2022; Ho et al., 2021; Bakadia et al., 2021; Cao et al., 2021,

2020; Copat et al., 2020; Mu et al., 2021; Rahimi et al., 2021; Domingo and Rovira, 2020).

As a novelty, this study considers also contribution of natural radioactive gas radon- ^{222}Rn and its progeny, α- and β-emitting radioisotopes short-lived (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) and long-lived radionuclides (^{210}Pb, ^{210}Po) in the lower atmosphere (Hosoda et al., 2021; Penache, Zoran, 2019a; Crova et al., 2021; Blomberg et al., 2020; Zoran et al., 2012). Is well known that most of its long-lived progeny attach to aerosol particles (0.1–2.5 μm) (Grundel and Porstendörfer, 2004; Zoran et al., 2015), which can be inhaled and deposited on lung, continuing to decay and produce high α-radiation exposure to the respiratory system, being associated with lung inflammation or neuroinflammation (Sugiyama et al., 2020; Loffredo et al., 2021; Asadi et al., 2020; Seposo et al., 2020; Blomberg et al., 2019; Seltenrich, 2019). In synergy with SARS-COV-2 pathogens attached to aerosols, particulate matter may contribute to increased COVID-19 severity and lethality (Macias-Verde et al., 2021; Maya et al., 2020).

Cumulative effects of climate drivers and associated climate risks induced by climate change (Manzanedo and Manning, 2020) and their seasonal variability with short-term and long-term exposure to outdoor air pollutants in large metropolitan areas have adverse health effects at city and regional levels and frequently increase the risk/hazard of viral infections probability (Yuan et al., 2021; Baldasano, 2020; Pfahl et al., 2015; Zoran et al., 2008; Zhou et al., 2018; Air Pollutants, Air, CDC, 2021; Molepo et al., 2019). Also, heavy urban air pollution episodes for several days (Pandolfi et al., 2014) can be associated with local specific meteorological conditions, like haze, lower atmospheric inversions, and with trans-border air pollution events (Saharan dust intrusions, or other transports of industrial pollutants (Salvador et al., 2021). Is recognized also, the significant role of synoptic stagnant anticyclonic air conditions in the accumulation at the ground level of high air pollutants concentrations, as a transport vector for airborne viral infections, which can contribute to increased morbidity and mortality from COVID-19 disease (Manoj et al., 2020; Mu et al., 2021; Zhou et al., 2021; Romano et al., 2020; Cohen and Kupferschmidt, 2020; Wang et al., 2022; Coccia, 2021).

It is very important to consider the differences in micro and macroclimate conditions, in large urban areas, which can significantly influence the SARS-CoV-2 virus circulation. Seasonal variability of meteorological parameters like as air temperature, relative humidity, pressure, wind speed intensity and direction, PlanetaFry Boundary Layer heights (PBL), surface solar irradiance variability and synoptic meteorological patterns may have a great impact on air quality and viral infections course (Tignat-Perrier et al., 2020; Zoran et al., 2020b; Mhuireach et al., 2019). Spatiotemporal distribution of air pollutants concentrations emitted by multi sources at the ground level are mostly modulated by the evolution of the atmospheric mixing layer PBL height (Xia X.et al., 2022). PBL height is one of the major urban climate parameters influencing surface air quality, being responsible for the vertical transport of mass, momentum and moisture between the ground surface and the free atmosphere. Also, surface solar radiation is involved in the reduction of SARS-CoV-2 and its new variants pathogens (Schuit et al., 2020) through inactivating SARS CoV 2 replication on contaminated surfaces by UVC radiation (Biasin et al., 2021), and virucidal action of UVB and UVA components (Herman et al., 2020; Heßling et al., 2020; Sagripanti, Lytle, 2020; Coohill, Sagripanti, 2009). Local and regional climate variability can contribute to the transmission of airborne SARS-CoV-2 pathogens over large distances via bioaerosols (Liu et al., 2021; Rayan, 2021; Zoran et al., 2021, 2022; Yuan et al., 2021). The cumulated effect of climate variables and air pollution can be detrimental for human health, especially during pandemic viral diseases waves, as they can act synergistically on the same immunity and cardiorespiratory systems, raising the risk to develop and exacerbate adverse conditions for premature mortality especially in vulnerable people and the elderly (Lelieveld et al., 2015; WMO, 2021; Weilnhammer et al., 2021).

The current paper presents a comprehensive and long- term analysis

of COVID-19 multiwave viral infection, and short- and long-term exposure related to outdoor air pollutants and climate seasonality in Bucharest metropolitan city in Romania. Such factors may affect bio-aerosols/droplets spreading and virions survival under different synoptic-scale meteorological patterns. In order to analyze the relative contributions of meteorological factors to spatiotemporal changes of urban air quality in relation with COVID-19 incidence and mortality, this study implements descriptive statistics, cross-correlation for time series analysis of daily observational and geospatial data of major outdoor air pollutants (PM2.5, PM10, NO₂, O₃, SO₂, CO).

As a plus, this study considers cumulative impacts of ^{222}Rn effects, as a source of exposure to ionizing radiation, which may contribute to additional adverse effects to the human respiratory system.

Besides, this study examines the effect of total or partial lockdowns and some other restrictions on reducing the severity of air pollution during pandemic period. Therefore, the temporal pattern of AOD was analyzed during the COVID-19 pandemic period in Bucharest, including total lockdown in the spring 2020 period, which coincided with the most pronounced quarantining efforts to combat COVID-19.

Differences in seasonal variation of COVID-19 viral infection incidence and mortality have been correlated with seasonal variations of associated meteorological variables (air temperature, relative humidity, wind intensity, air pressure, Planetary Boundary Layer height, surface solar irradiance, synoptic atmospheric circulation patterns), which can trigger the spread of SARS-CoV-2 viral infection in a per waves comparative analysis" during the first, pre-second, second, third, fourth and fifth pandemic waves. Also, this research may assist a comprehensive understanding of seasonal environmental impacts on COVID-19 pandemic seasonality spreading in urban agglomerations and help policymakers to implement appropriate control and mitigation measures during the future pandemic waves.

2. Methodology

2.1. Study test area

This study was carried out in Bucharest city, the tenth-largest city in Europe and the largest in the South-Eastern part of the continent. Bucharest, Romania'capital centered at (44.43°N, 26.10 °E) area, is located in the South-Eastern part of Europe and South-Eastern part of Romania in a plain landscape along the Dâmbovița River in a flat region,

with a total surface of 625 km². The study test area (Fig. 1) includes the city of Bucharest and the surrounding peri-urban areas with complex environments (built, green and blue structures), under intense urbanization process. Its climate is temperate continental, under influences of the Western European Climate circulation, the Mediterranean Cyclones, and the East-European Anticyclone, with hot, humid summers and cold, sometimes snowy, or haze and smog formation during winters and extreme climate events (Zoran et al., 2008, 2013). The Bucharest metropolitan region, with about 1.794 million residents (Anon, 2021a), is one of the main leading economic zones of Romania. In recent decades, rapid industrial development has caused serious environmental problems in this region, Bucharest being considered one of the largest urban carbon emitters among all Romanian cities, and one of the most air polluted cities in Europe. Air pollution in this region is also attributed to use for heating of fossil fuels such as coal and natural gas, traffic-related use of old cars characterized by high PM2.5, PM10, NO₂, O₃, CO, SO₂ concentrations, which sometimes exceed standard limits for Romania and the European Union (Anon, 2020a; Zoran et al., 2019a; Grigorescu et al., 2021; Iorga et al., 2015).

2.2. Data collection

In this section, we summarize different data used throughout our study. The daily time series analysis of climate and air pollutants including radon seasonality relation with COVID-19 incidence and mortality in Bucharest metropolitan city used a large global dataset built by collecting information from various freely available sources from January 2020 up to April 2022.

2.2.1. COVID-19 data

This study uses the COVID-19 infection data cases recorded in Romania and Bucharest (Total cumulative, Daily New Cases-DNC, Daily New Deaths-DND and Total Deaths) were provided by COVID-19 information websites (Worldometer, 2022; Johns Hopkins Coronavirus, 2022; Anon, 2022h). Also, accumulated COVID-19 and DNC data for 26 February 2020–1 April 2022 period for Bucharest metropolitan city were provided by the Romanian websites (Anon, 2022; MS, 2022). Two COVID-19 (DNC and DND) variables were used in this study.

2.2.2. Air pollution and radon data

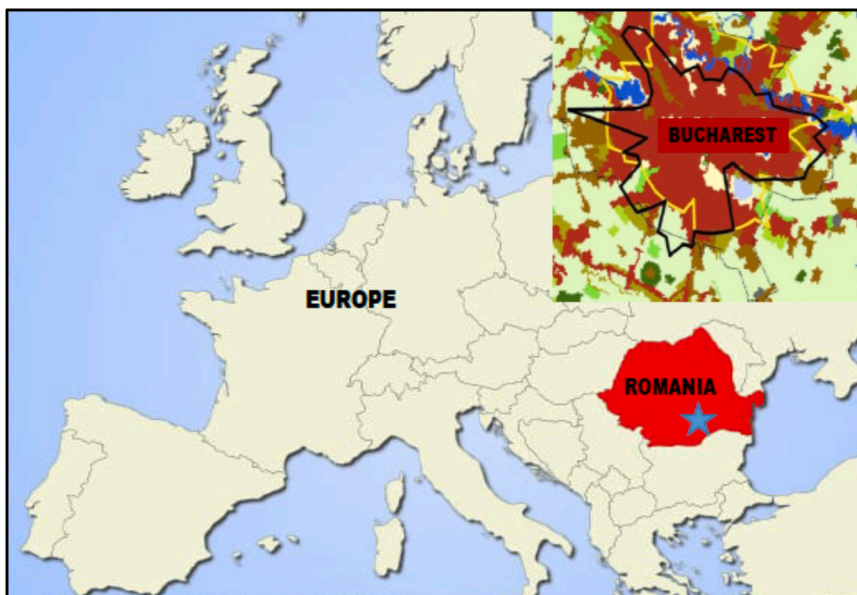Daily average time series data of air pollutants concentrations

Fig. 1. Bucharest metropolitan city, capital of Romania on Europe map.

PM2.5, PM10, O₃, NO₂, SO₂, and CO for Bucharest selected stations have been collected from Copernicus data base (Anon, 2022i), AQICN (Anon, 2022c) and from European Environmenal Agency (Anon, 2022a).

This paper used the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) derived AOD at 550 nm product provided by NASA and Copernicus Atmosphere Monitoring Service (CAMS) (Anon, 2022k).

Daily atmospheric radon (^{222}Rn) concentration was continuously measured in Bucharest at 1.75 m height level using an "AlphaGUARD" –PQ2000 PRO, Genitron Instruments monitor, placed in a Stevenson's Screen (well-ventilated, weatherproof enclosure), which also recorded main meteorologic parameters (air pressure, temperature and relative humidity). Time series of daily average ^{222}Rn concentrations for the time period 1 January 2020 − 1 April 2022 were used for this analysis.

2.2.3. Climate and meteorologic synoptic variables data

Daily time series of meteorological data, including average temperature (T), relative humidity (RH), air pressure (p), average wind speed intensity (w), as well as maximum (Tmax) and minimum air temperatures (Tmin) for Bucharest metropolitan region were collected from the Modern-Era retrospective analysis for Research and Applications, Version 2 (MERRA-2) (Anon, 2022k), Weather Wunderground (Anon, 2022g), Copernicus Climate Change Service (C3S) datasets (Anon, 2022i) and weather stations operated by the Romanian National Meteorological Administration (Anon, 2022j).

Time series data of daily average surface solar global irradiance (SI) for Bucharest city have been delivered by Copernicus Atmosphere Monitoring Service (CAMS) McClear Clear-Sky Irradiation service (Anon, 2022e).

Daily Planetary Boundary Layer PBL height (PBL) time-series data were provided by NOAA's Air Resources Laboratory (Anon, 2022d).

For lower atmospheric circulation analysis associated with people's exposure to air pollutants and COVID-19 disease fast transmission in Bucharest urban region during 1 January 2020–1 April 2022, we used Omega surface charts at 850 mb provided by NASA, Reanalysis Data Project NCEP/NCAR PSD, Boulder, Colorado, USA (Anon, 2022b). This paper used atmospheric pressure levels of 850 mb (corresponding to elevation levels of ~1458 m), defined as mesoscale (mid-altitude) as heights above 100 m and below 1500 m (Sommerfeld et al., 2019). Based on synoptic meteorological circulation in Omega at 850 mb surface charts, downwards airflows are associated with high stability conditions given by positive values of omega in Pa/s, while upwards airflow are associated with instability conditions, given by negative values of omega surface charts.

2.3. Statistical analysis used

This study investigated the environmental variables (air quality and climate) drivers impact on the incidence and severity of the COVID-19 pandemic in Bucharest region during COVID-19 multiwaves pandemic evolution. The time scale resolution for all variables was on a daily basis. The comparative analysis of the daily average concentrations of the main air pollutants during COVID-19 multiwaves was compared to available average concentrations recorded during the same time windows of years 2015–2019. For transient correlations was used descriptive statistical analysis, that identify similar variation in the daily average time series meteorological parameters and exposure to air pollutants including radon (considered independent variables) data, together daily COVID-19 incidence and mortality data (considered dependent variables) over the five COVID-19 waves.Cross-correlation analysis was used to evaluate the similarity between two-time series data, and to explore the relationship between combined daily air pollutants concentrations (PM2.5, PM10, O₃, NO₂, SO₂, CO, including ^{222}Rn), AOD and climate parameters with the daily of COVID-19 new infections and deaths. In its application, one of the main limitations is the different distribution characteristics of data sets correlated. Also, the

normality of data was evaluated through Kolmogorov-Smirnov Tests of Normality for daily time-series data sets. As the data on daily new COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) showed a non-normal distribution, Spearman rank correlation was adopted to identify the existing correlations with selected independent variables (air pollutants including ^{222}Rn -radon, and climate). The strength and sign orientation of the interactions between pairs of variables, is measured by *r*, that for Spearman correlation is expressed by the following equation:

$$r = 1 - \frac{6 \times \sum d_i^2}{n(n^2 - 1)} \tag{1}$$

where d_i is the difference between the two parameter ranks, n represents the number of alternatives, and the values r = +1 and –1 show perfect positive and negative correlations, respectively, while 0 shows no correlation. The corresponding parameter „p-value," indicates if the result of an experiment is statistically significant. P values of < 0.01 and < 0.05 were considered statistically significant. Though correlation and p-value provide us with the existing relationship between the two variables, care should be taken to interpret them correctly. Our analysis demonstrates that non-parametric statistical tests are more suitable compared with parametric statistical tests for non-normally distributed data, which are present in our time series air pollutants and climate variables data. All data statistical analyses were processed using ORIGIN 10.0 software, version 2021 for Microsoft windows.

3. Results and discussion

3.1. Spread of COVID-19 pandemic in Bucharest

The epidemiological trend of the COVID-19 disease transmission in Bucharest city was investigated during five waves and seven different time-windows periods: Pre-pandemic period (1 January 2020–25 February 2020); A first COVID-19 wave (26 February 2020–15 June 2020); Pre-second COVID-19 wave which started with increasing social activities and tourism (15 July 2020–30 September 2020); The second COVID-19 wave (1 October 2020– 31 January 2021); The third COVID-19 wave (1 February 2021–1 June 2021); The fourth COVID-19 wave (1 September 2021–21 December 2021) and The fifth COVID-19 wave (22 December 2021–1 April 2022).

During the pandemic period Alpha, Beta, Gamma, Delta, and the final Omicron variants of SARS-CoV-2 have emerged as a result of several mutations in the virions structure. During the first COVID-19 wave of low intensity in Bucharest, the Romanian government imposed an emergency state and a full lockdown between 15 March 2020 and 15 May 2020 (Fig. 2). The pre-second COVID-19 wave during summer 2020, associated with some relaxation measures and increasing economic and tourism activities, has a moderate intensity. The second COVID-19 wave with a peak on 30 November 2020, had a higher
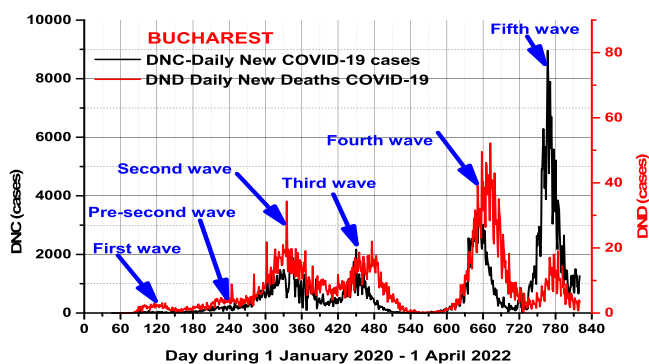

Fig. 2. Temporal evolution of COVID-19 multiwaves in Bucharest, capital of Romania for study period (1 January 2020 –1 April 2022).

intensity than previous waves (101,018 new confirmed COVID-19 and 1421 deaths in Bucharest), being associated with some lifted restrictions and winter holidays.

The third COVID-19 wave peaked on 20 April 2021 was characterized by delayed social distancing reinforcement, the national vaccination campaign, longer duration but lower viral infections and fatalities rates than the second COVID-19 wave. The fourth COVID-19 wave with a peak on 17 October 2021 hits seriously Bucharest with almost 120,986 recorded deaths, the vast majority of severe cases and deaths occurring in unvaccinated or not fully vaccinated individuals. At the end of December 2021, started the fifth COVID-19 wave till 1 April 2022. For the entire analyzed pandemic period, Bucharest metropolitan city registered more than 5750 deaths of the total confirmed positive COVID-19 cases of more than 540,000 cases (representing 1.09 %).

3.2. Temporal patterns of air pollutants and radon during COVID-19 multiwaves

3.2.1. Effects of air pollutants on the COVID-19 pandemic viral disease

To evaluate the impact of air pollutants and attached radon and its progeny on COVID-19 incidence and mortality during the recorded five-waves with one total and other partial lockdowns and relaxation periods between 1 January 2020–1 April 2022, daily time series patterns of the main air pollutants including radon have been analyzed.

The results in Table 1 present Spearman rank correlation coefficients and p values between COVID-19-incidence cases (daily new confirmed cases-DNC and deaths-DND), and daily average of the main air pollutants concentrations for investigated metropolitan Bucharest city during entire analyzed pandemic period 26 February 2020–1 April 2022.

In good accordance with existing literature, this study found a positive correlation between outdoor exposure to daily average air pollutants $PM2.5$, $PM10$, NO_2, SO_2, CO concentrations, and daily new COVID-19 confirmed (DNC) and deaths (DND) cases (Shao et al., 2022; Li et al., 2020; Domingo et al., 2020; Marquès et al., 2021; Frontera et al., 2020; Zoran et al., 2020a, 2020b; Islam et al., 2021; Huang et al., 2020a, 2020b; Amin et al., 2020; Hassanzadeh et al., 2020; Zhu et al., 2020).

The results in Table 2. present **c**umulative statistics of the total daily new COVID-19 incidence and deaths cases per waves periods and the daily average of main air pollutants concentrations including radon recorded during 26 February 2020 –1 April 2022 in Bucharest metropolitan city.

As can be seen in Table 1, Spearman rank correlation analysis over the entire analyzed pandemic period in Bucharest shows that daily new COVID-19 incidence and mortality cases were weekly positive correlated with daily average ground levels of fine particulate matter $PM2.5$ concentrations (rDNC= 0.35, p < 0.01; rDND= 0.37, p < 0.01), and

Table 1

Spearman rank correlation coefficients and p values between COVID-19-incidence cases, and daily average of the main air pollutants concentrations for investigated metropolitan Bucharest region during the entire analyzed pandemic period, 26 February 2020–1 April 2022.

Bucharest	Daily average of ground air pollutant concentration						
COVID-19 incidence	PM2.5 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)	O_3 ($\mu g/m^3$)	NO_2 ($\mu g/m^3$)	SO_2 ($\mu g/m^3$)	CO ($\mu g/m^3$)	^{222}Rn (Bq/m^3)
Daily New confirmed cases (DNC)	0.35*	0.34*	-0.47*	0.27*	0.39*	0.48*	0.18*
Daily New Deaths (DND)	0.37*	0.39*	-0.51*	0.29*	0.41*	0.49*	0.17*

Note: PM2.5 (Particulate Matter of 2.5 μm size), PM10 (Particulate Matter of 10 μm size), O_3 (ozone), NO_2 (nitrogen dioxide), SO_2 (sulfur dioxide), CO (carbon monoxide), ^{222}Rn (radon activity), * indicate p < 0.01

respectively with coarse particulate matter $PM10$ concentrations (rDNC= 0.34, p < 0.01; rDND= 0.39, p < 0.01).

For the entire analyzed pandemic period in Bucharest our analysis found a decreased value of the daily average $PM2.5$ concentration of (24.63 ± 12.05) μg/m^3 in comparison with the daily average $PM2.5$ concentration recorded for pre-pandemic period 2015–2019 of (32.61 ± 13.21) μg/m^3. A similar result was found for $PM10$ concentrations for the same reported periods, namely (61.92 ± 24.50) μg/m^3 during the entire pandemic period and (76.32 ± 26.18) μg/m^3 for pre-pandemic period 2015–2019. These registered reduced values of $PM2.5$ and $PM10$ concentrations may be attributed to total or partial lockdown restrictions adopted to limit the SARS-CoV-2 spreading in Bucharest metropolitan city. Futher, improvement of urban air quality may have a high impact on human health and environment, results confirmed by several other studies (Xu et al., 2022; He et al., 2021; Morales-Solís et al., 2021; Lipsitt et al., 2021; Chakrabarty et al., 2021).

Also, considering contribution of seasonal variability of ground levels of air pollutants concentrations, this analysis underlines the critical role of increased concentrations of daily average particulate matter $PM2.5$ and $PM10$ during the second, the fourth and the fifth COVID-19 waves in Bucharest and recorded high numbers of total daily new of COVID-19 new cases (Table 2). The is a mutual seasonal variability of outdoor particulate matter and COVID-19 incidence and deaths (Fig. 3). The seasonal variations in $PM2.5$ and $PM10$ were driven mainly by changes in meteorological conditions (e.g., wintertime thermal inversions) and increase in local or regional heating emissions during the transitions from winter to summer and conversely.

Due to complex interaction between environmental factors and humans, this finding is consistent with the results of previous studies, and support the hypothesis that particulate matter, especially $PM2.5$ in cities can be considered as an anthropogenic environmental mutagen of SARS-CoV-2 genome with diminishing pulmonary function, and emergence of new variants (Baron, 2022, 2021; Baron, and Camilleri, 2021; Sagawa et al., 2021; Facciola et al., 2021; Habibi et al., 2020).

Opposite to $PM2.5$ and $PM10$, during the entire analized period, ground levels of O_3 concentrations presented an inverse seasonal variation, with lower values during fall-winter seasons and higher values during spring -summer periods (Fig. 4). Traffic and industrial related sources reduction during lockdown periods under the influence of different meteorological factors amplified its concentrations in comparison with the same five years pre-pandemic period recorded during 2015–2019 (for the first COVID-19 wave by 1.49 during the lockdown). Significant anti-correlations of the daily average of ground level ozone with DNC cases (rDNC= −0.47, p < 0.01) and DND (daily new deaths) (rDND= −0.51, p < 0.01) can explain the attenuation of COVID-19 intensity during summer seasons. Increases of ground ozone concentrations during total lockdowns were also detected in other big cities (Grange et al., 2021; Mendez-Espinosa et al., 2021; Ordoñez et al., 2020).

Dramatic improvement to air quality, especially NO_2, was observed in Bucharest city under COVID-19 lockdown restrictions. Over the whole pandemic period, besides seasonal inversely variation pattern of NO_2 with O_3, its ground level concentrations recorded the decreased values as compared with the pre-pandemic five years period, attributed to lower traffic rates, mostly during lockdowns (for the first wave COVID-19 lockdown of 51 %, during pre-second wave period with 28 %, during the third COVID-19 wave with 18 %). NO_2 decreased concentrations were recorded in full lockdowns for other cities in the world (Collivignarelli et al., 2021; Guevara et al., 2021; Bauwens et al., 2020; Biswal et al., 2021).

Comparison with five years pre-pandemic period during 2015–2019 shows seasonal patterns variations of the daily average SO_2 and CO concentrations, and significant decreased values of 49 % and respectively, 27 % during the total lockdown of the first COVID-19 wave (explained by traffic reduction). During the fourth COVID-19 wave SO_2 recorded an increase of 12 %, and CO of 6 %, which can be correlated

Table 2

Cumulative statistics of the total daily new COVID-19 incidence and deaths cases per waves periods and the daily average of main air pollutants concentrations, recorded during 26 February 2020 –1 April 2022 in Bucharest metropolitan city.

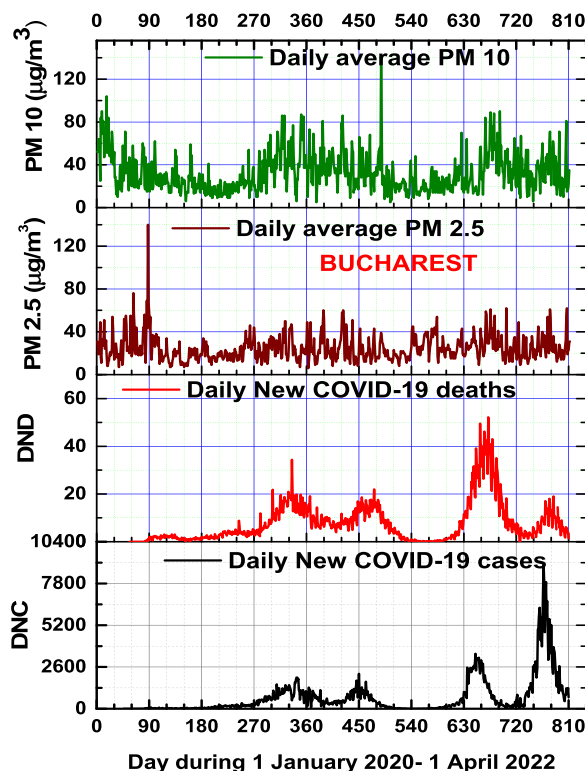| Time period	Daily New COVID cases (DNC)	Daily New COVID Deaths (DND)	Daily average ±SD PM2.5 (µg/m³)	Daily average ±SD PM10 (µg/m³)	Daily average ± SD O_3 (µg/m³)	Daily average ± SD NO_2 (µg/m³)	Daily average ± SD SO_2 (µg/m³)	Daily average ± SD CO (µg/m³)	Daily average ± SD ^{222}Rn (Bq/m³)
First COVID wave and lockdown 26.02.2020–15.06.2020	2399	126	23.86 ± 18.09	65.03 ± 13.26	28.1 ± 7.02	7.61 ± 4.01	4.9 ± 2.79	254.8 ± 68.3	36.13 ± 16.66
Pre-second COVID wave 15.07.2020–30.09.2020	13,649	266	20.77 ± 7.80	60.09 ± 12.78	37.21 ± 9.61	10.85 ± 4.29	3.33 ± 1.63	193.8 ± 49.1	34.28 ± 15.79
Second COVID wave 01.10.2020–31.01.2021	101,018	1421	24.77 ± 11.15	72.58 ± 27.40	14.87 ± 5.63	14.91 ± 5.61	9.07 ± 5.83	377.4 ± 132.1	43.22 ± 18.79
Third COVID wave 01.02.2021–01.06.2021	64,848	1166	22.00 ± 10.79	61.05 ± 26.27	28.37 ± 7.94	12.34 ± 5.39	9.11 ± 5.31	334.8 ± 99.3	28.36 ± 12.13
Fourth COVID wave 01.09.2021–21.12.2021	120,986	2098	28.21 ± 10.53	60.59 ± 24.16	22.63 ± 10.58	14.89 ± 6.80	11.03 ± 7.04	373.3 ± 146.9	43.99 ± 20.61
Fifth COVID-19 wave 22.12.2021–01.04.2022	235,185	584	25.13 ± 11.65	67.72 ± 22.82	18.48 ± 5.31	10.01 ± 4.38	8.37 ± 4.19	336.29 ± 130.18	37.48 ± 16.32

Fig. 3. Temporal distributions of daily average ground levels of PM2.5, PM10 concentrations and daily new COVID-19 cases (DNC) and deaths (DND) during the entire COVID-19 pandemic period in Bucharest city.

Fig. 4. The temporal patterns of daily average ^{222}Rn, O_3, NO_2, SO_2, CO and Daily New COVID-19 cases in Bucharest metropolitan city during pandemic period.

with the high rates of COVID-19 transmission and mortality in Bucharest. As can be seen in Table 1, this study found positive correlations of daily average of gaseous air pollutants NO_2, SO_2, and CO concentrations with DNC (daily new confirmed) cases and DND (daily new deaths), which could contribute to the cummulative impacts of lower atmospheric pollution on transmission and severity of SARS-CoV-2 pathogens during analyzed pandemic fall-winter periods in Bucharest.

Also, stagnant atmospheric conditions in Bucharest during the second, the third, the fourth and the fifth COVID-19 waves inhibited dispersion of the main gaseous air pollutants NO_2, SO_2, and CO (among other pollutants), associated with high viral infectivity rates and deaths. Is known that exposure to both SO_2 and CO causes respiratory symptoms and changes in airway physiology, being important contributors for
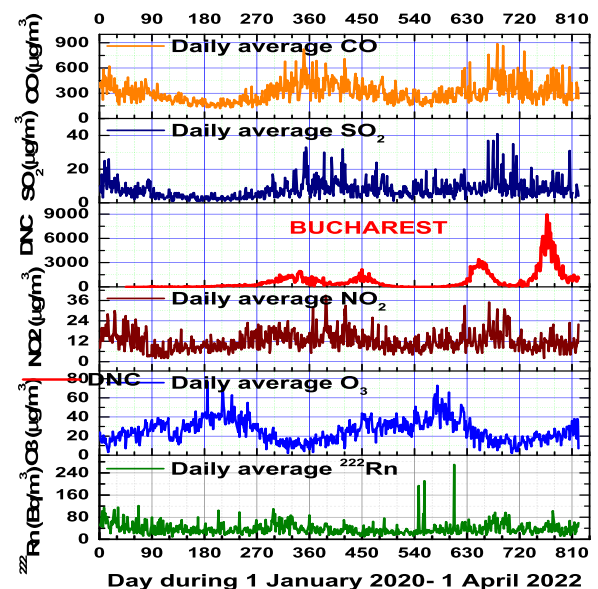
associated comorbidity. These findings are supported by other scientific studies (Tung et al., 2021; Wang et al., 2022; Setti et al., 2020a, 2020b; Chakrabarty et al., 2021; Wang et al., 2021; Gkatzelis et al., 2021; Penache, Zoran, 2019a, 2019b), where they found a significant correlation between the daily average gaseous pollutants concentrations exceedances and COVID-19 spreading.

3.2.2. Effects of radon- ^{222}Rn on the COVID-19 pandemic viral disease

For the entire analyzed COVID-19 pandemic period, daily outdoor radon exposure in Bucharest metropolitan city shows low positive correlations with DNC (daily new confirmed) cases (rDNC=0.18, p < 0.01), and DND (daily new deaths) (rDND=0.17, p < 0.01) (Table 1). Like particulate matter (PM2.5, PM10) and other gaseous pollutants O3, NO2, SO2, CO, atmospheric radon concentrations exhibit typic diurnal, seasonal and inter-annual temporal variability patterns (Fig. 4). ^{222}Rn provides information about the current state of urban pollution levels near the ground as well as of atmospheric condition changes, being used as a tracer of the lower tropospheric vertical mixing effects better than commonly used meteorology-based stability patterns. On a diurnal

scale, the peak of outdoor radon concentration is recorded in the early morning hours (Mullerova et al., 2018) and on seasonal, in winter with elevated values under persistent synoptic inversion events, when outdoor radon concentrations may be higher for several days (Zoran et al., 2015).

If fine particulate matter PM2.5, one of the main contributor to air pollution is considered the fourth leading risk factor for death and disability in the world (GBD C, 2020; Anon, 2016; Xu et al., 2020), ^{222}Rn is the second cause of lung cancer, behind smoking (Hosoda et al., 2021). Joint short-term and chronic exposure to particulate matter and alpha ionizing radiation of ^{222}Rn substantially increases the risk of respiratory tract illnesses damage (Z. Huang et al., 2020; S. Huang et al., 2020; Shahbazi-Gahrouei et al., 2013; Vieira et al., 2019; Marsh and Bailey, 2013). Environmental radioactive nuclei from background radon sources (natural terrestrial and extra-terrestrial) can attach to respirable PM, which once inhaled are deposited on the respiratory tract and can translocate into systemic circulation, and contribute to the development of both pulmonary and systemic endothelial dysfunction in human lungs (Chauhan et al., 2012; Mohamed et al., 2014).

During the entire COVID-19 pandemic period in this study, the daily mean value of outdoor ^{222}Rn concetration was of (38.67 ± 22.64) Bq/m^3, value that is comparable with the daily mean of outdoor ^{222}Rn concentration measured during the pre-pandemic COVID-19 period (2015–2019) (Zoran et al., 2019b). If will be considered the cumulative interaction with the daily measured indoor radon concentrations contribution with an average value of 109.4 Bq/m^3 in different buildings in Bucharest city (Calin et al., 2019), the daily impact of inhaled radon on human health will be consistent. However, in the case of Bucharest city this exposure to ionizing radiation is not exceeding the threshold limits established by European legislation. Both the recorded outdoor and indoor radon time series show consistent daily variations with elevated concentrations in the morning and lower concentrations in the afternoon, the diurnal concentration patterns being influenced by meteorological parameters, the drivers of varying indoor radon concentrations being strongly interconnected (Schubert et al., 2018).

It was established that for most cases, the outdoor radon risk was orders of magnitude less than the indoor risk, but under extremely specific meteorological and topographical conditions it could become comparable (Borro et al., 2021). Due to its negative impact on respiratory system, this study considers both outdoor ^{222}Rn, as well as indoor radon in insufficient ventilated buildings as a potential additive factor for COVID-19 incidence and lethality in Bucharest city. Indoor ventilation technologies for both ^{222}Rn and SARS-CoV-2 pathogens transmission must be very well selected (Elsaid et al., 2021). Scientific studies demonstrate that in the circulated air in the indoor environment is generated a marked space diffusion of infectious diseases including novel pathogenic SARS-CoV-2 virus droplets and aerosols (Correia et al., 2020; Chirico et al., 2020; Sodiq et al., 2021). The source and circulation pathways of building ventilation systems affect the distribution and colony of indoor microbial populations and ^{222}Rn in air concentrations. Under normal conditions, people are spending on average 90 % of their time indoors, of which 60–70 % inside houses, and given that about 70 % of a person's yearly exposure to ionizing radiation comes from inhalation (Anon, 2006; Kang et al., 2020). There it is essential to understand the linkage between exposure to particulate matter and attached radon's progeny both outdoor and indoor in relation to COVID-19 incidence and other viral infections to come.

3.2.3. Aerosol optical depth analysis during COVID-19 pandemic multiwaves

One of the key results of this research underlines a significant reduction of the AOD levels over Bucharest metropolitan city (~28 %) during the spring total lockdown period (15 March-15 May 2020) associated with the first COVID-19 wave, and (~16 %) during the third COVID-19 wave with few some restrictions, as compared to the long-term average AOD level (2015–2019) for the same periods of the year
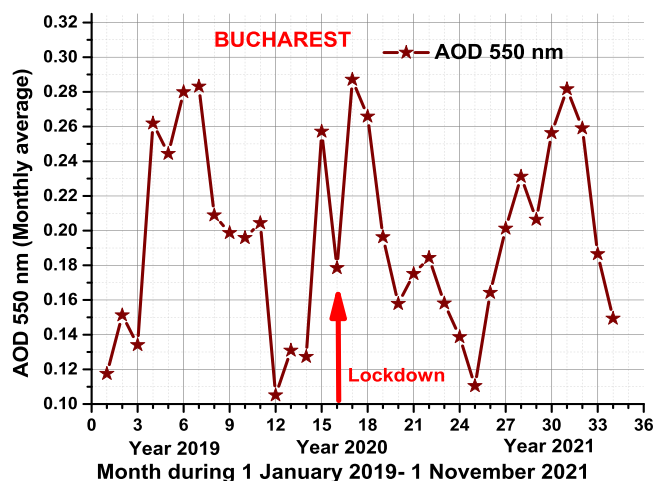

Fig. 5. The monthly variation of the total Aerosol Optical Depth at 550 nm over Bucharest city during pre-pandemic and pandemic period from available MERRA-2 products.

(Fig. 5). Several studies analyzed and reported the reduction in surface level of particulate matter and increase/decrease in trace gases ozone/nitrogen dioxide during the lockdown periods, however, only a few studies investigated the changes aerosol optical depth (AOD) using data from satellite and/or model simulations (Chabane, Arif, 2021; Le, et al., 2020; Filonchyk et al., 2021; Ming et al., 2021; Forster et al., 2020).

Seasonal variation of AOD over the metropolitan area of Bucharest during analyzed COVID-19 pre- and pandemic period demonstrated clear annual course with maxima in spring and summer and minimum in autumn and winter. High AOD values can be attributed to hygroscopic growth of aerosols, formation of secondary aerosols and pollutants as a result of agricultural biomass combustion after crop harvesting in the periurban areas, which entails pollutants accumulation in this region. In spring the whole area of the metropolitan region is exposed to increased dust concentrations, which comes from the transboundary sources like Saharan intrusions leading to increase of AOD (Marmureanu et al., 2019).

Over the entire analyzed pandemic period in Bucharest the daily new COVID-19 new cases and deaths were positively correlated with daily PM2.5/AOD and PM10/AOD ratios (rDNC= 0.25, p < 0.01; and rDNC= 0.45, p < 0.01), and respectively DND cases with daily PM2.5/AOD and PM10/AOD ratios (rDND= 0.17, p < 0.01; rDND= 0.27, p < 0.01).

To assess the significance of the MERRA-2 derived AOD in relation with PBL heights and transmission of COVID-19 viral disease in Bucharest city, this paper adopted linear regression between AOD and PBL heights ($R^2 = -0.875$), that make clear the related influences of PBL heights during several seasons and important regional and transported pollution levels. These results are in a total consensus with previous scientific studies in the field (Acharya et al., 2021; Chabane and Arif, 2021).

Like other studies (Ho et al., 2021; Bu et al., 2021; Fang et al., 2021), this research demonstrates the high negative impact of outdoor exposure to high ground levels of air pollutants recorded in Bucharest metropolitan city on COVID-19 pandemic incidence and deaths and suggests the urgent need for reduction of air pollutants sources. Lockdown implementation actions are welcome during strong pandemic waves causing air quality improvement (Rahman et al., 2021; Han et al., 2023; Orak, Ozdemir, 2021; Jin et al., 2021).

This study analyzed the five most important air pollutants identified by the Environmental Protection Agency among which CO, particulate matter in two size fractions PM2.5 and PM10, O3, NO2, and SO2. Also, this paper considered not only the effects of each air pollutant on human health, but the cumulative effects of pollutants including radon, because in reality, communities and individuals are exposed to mix sources of air

pollution (urban traffic, heavy industry, etc.), that emit a mixture of all these pollutants (Air Pollutants | Air | CDC. Published 2021).

3.3. Effects of climate variables on COVID-19 multiwaves patterns

3.3.1. Climate parameters variability and COVID-19 waves

Significant negative correlations between COVID-19 incidence (daily new cases and deaths) were found with PBL heights over Bucharest metropolitan area during the entire pandemic period (26 February 2020 and 1 April 2022) as follows: (rDNC= −0.69; p < 0.01) and respectively (rDND= −0.71; p < 0.01). Recorded high levels of daily PBL heights of (1607.19 ± 526.06) m during the first COVID-19 wave in Romania may explain the low intensity of the first COVID-19 wave in Bucharest city in comparison with the rest of some European metropolitan cities (D'Amico et al., 2022; Zoran et al., 2020a, 2020b, 2021).

An opposite situation was recorded during the second, the fourth and the fifth waves when the daily average PBL heights recorded abnormally low values per each wave, being respectively of (538.74 ± 293.26) m, (920.23 ± 603.25) m, and (846.74 ± 463.01) m, values which can explain high rates of infectivity in Bucharest.

Being considered as one of the most important climate variable, PBL height related to the vertical mixing dynamics and dilution or accumulation of pollutants and bioaerosols (bacteria, fungi, and viruses) near the ground level, it is involved in COVID-19 spreading, especially in urban areas (Tang et al., 2016). Lower levels of PBL heights may be associated with increased viral pathogens concentrations at the near surface, and higher transmission rates. The effect of daily average meteorological variables on COVID-19 incidence cases DNC and DND was examined using Spearman correlation tests (Table 3).

Similarly, air low temperatures and surface solar irradiance were correlated with a higher COVID-19 daily new cases and deaths (r = −0.49, p < 0.01; and r = −0.59; p < 0.01), and respectively (r = −0.65, p < 0.01; r = −0.63, p < 0.01). Such inverse associations of COVID-19 viral infections with air temperature have been reported also by (Tian et al., 2021; Srivastava, 2021; Jiang et al., 2021; Li et al., 2020; Benedetti et al., 2020; Bolaño-Ortiz et al., 2020; Sanchez-Lorenzo et al., 2021; Luo et al., 2020; Orak, 2022). Also, the seasonal pattern of daily average surface solar irradiance is closely related to lower daily incidence and mortality of COVID-19 cases recorded during late spring, summer, and early autumn periods with higher sunshine levels.

In a good accordance with scientific literature in the field, this paper considers that surface solar UV (UVA and UVB) irradiance may reduce the virions transmission, through virus inactivation during specific time periods of exposure (Sagripanti, Lytle, 2020; Santos et al., 2013). Also, solar radiation contributes to vitamin D synthesis in the body, that plays an essential role in the immunity system improvement (Luo et al., 2021; Jayawardena et al., 2021; Ilie et al., 2020; Padhi et al., 2020).

Also, this study reveals positive linear correlations between daily average air relative humidity and air pressure with COVID-19 daily new

cases and deaths (r = 0.38, p < 0.01; and r = −0.41; p < 0.01) and respectively (r = 0.24, p < 0.01; and r = −0.30; p < 0.01).

Our findings are consistent with other studies, which demonstrated that relative humidity has a great influence in the propagation of the SARS-CoV-2 viral infection, and COVID-19 mortality rate (Byun et al., 2021; Chen et al., 2021a, 2021b; Ma et al., 2020; Shi et al., 2020; Adams, 2020; Ahmadi et al., 2020; Poole, 2020). As a key meteorological variable, air relative humidity is related to the nucleation and size of aerosol droplets, as a medium to infect new hosts (Arias, De Las Heras, 2021; Yang and Marr, 2012; Yang et al., 2012, 2020; Ismail et al., 2022).

In addition, wind rose diagram (Fig. 6) indicates that during the entire pandemic period the highest COVID-19 cases fits in with wind direction blows, the dominant wind direction in Bucharest blows to the South-SouthWest and South parts of the analyzed area with wind speed analyzed in the range from 2.41 to 24.14 km/h, with a daily average value of 8.99 km/h.

Results of this study reveal that a low wind speed is a high contributor to increase COVID-19 daily new cases and daily deaths cases in agglomerated urban area of Bucharest, with Spearman correlation coefficients respectively (r = −0.32; p < 0.01), and (r = −0.31; p < 0.01). Seasonal variability of meteorological parameters in a temperate climate of Bucharest is well linked of COVID-19 disease seasonality, cold fall-winter seasons are associated with higher viral infections transmission, as can be seen in Fig. 7.

The complex interactions and their mutual feedback effects between air pollutants including radon, and climate variables under seasonal, local and regional spatiotemporal variations may have a significant role on viral infections transmission and severity.

The results in Table 4 presents Spearman correlation coefficients and p values between climate variables and daily average ground levels of air pollutants PM2.5, PM10, O₃, NO₂, SO₂, CO, ^{222}Rn concentrations and AOD during the entire COVID-19 analyzed period in Bucharest.

As an essential climate variable responsible of COVID-19 spatio-temporal spreading, PBL height is anti-correlated with PM2.5 (r = −0.41), PM10 (r = −0.49), NO_2 (r = −0.44), SO_2 (r = −0.41), CO (r = −0.51), ^{222}Rn (r = −0.23), air relative humidity (r = −0.65) and air pressure (r = −0.30), and direct correlated with O_3 (r = 0.74), air temperature (r = 0.69), surface solar irradiance (r = 0.81) and wind speed intensity (r = 0.38).

Like as previous studies have shown, the current research considers that understanding of the PBL heights relevant role in viral infections spreading, and the vertical distribution of aerosols in large metropolitan area of Bucharest is crucial for explaining seasonal changes in surface aerosol concentrations, especially for the observation and study of air pollution transports between urban and periurban areas, as well as at regional scale (Wen et al., 2022; Kang et al., 2019; Caggiano et al., 2019;

Table 3

Spearman rank correlation coefficients and p values between COVID-19-incidence cases, and daily average of climate variables for investigated metropolitan Bucharest region during entire analyzed pandemic period 26 February 2020–1 April 2022.

Bucharest	Daily average climate parameter					
COVID-19 incidence	PBL (m)	T (ºC)	RH (%)	w (km/h)	SI (W/m²)	p (hPa)
Daily New confirmed cases (DNC)	-0.69*	-0.51*	0.39*	-0.15*	-0.72*	0.24*
Daily New Deaths (DND)	-0.71*	-0.61*	0.44*	-0.13*	-0.73*	0.30*

Note: PBL (Planetary Boundary Layer height), T (air temperature), RH (air relative humidity), SI (surface solar irradiance), w (wind speed intensity) and p (air pressure), at ground level; * indicate p < 0.01
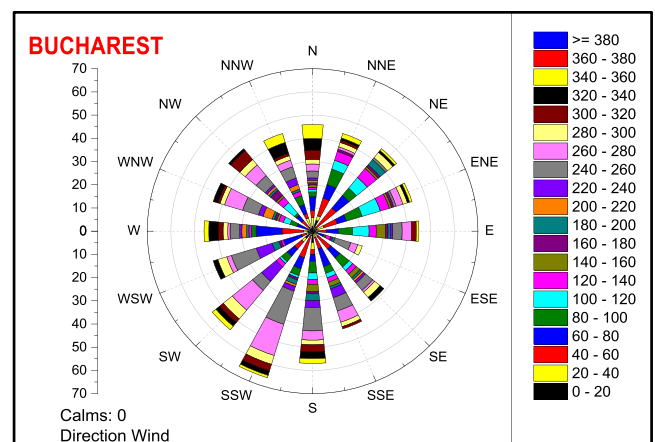

Fig. 6. Wind direction rose distribution over Bucharest metropolitan city during the entire pandemic period 26 February 2020–1 April 2022.
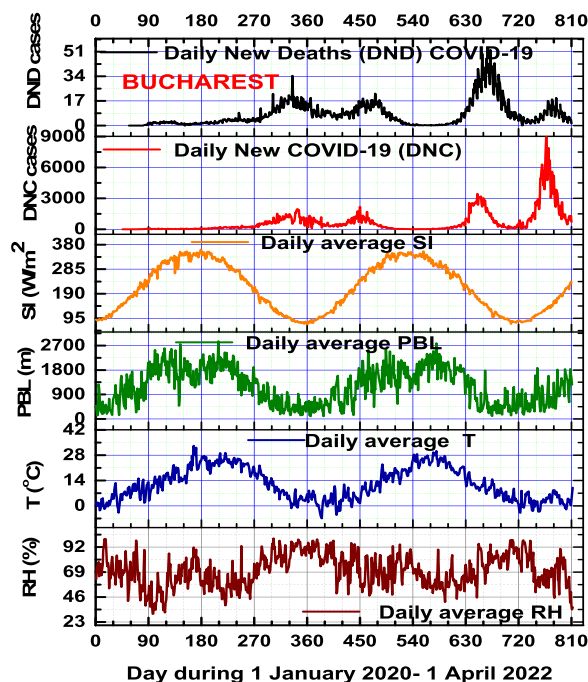
Fig. 7. The temporal patterns of daily average main climate parameters (air temperature, relative humidity, Planetary Boundary Layer height, Surface solar Irradiance, and Daily New COVID-19 Cases and Deaths in Bucharest metropolitan city during the five waves of COVID-19 pandemic period.

Zhuet al., 2022).

This study found remarkable direct correlations between radon with PM2.5 (r = 0.44), and PM10 (r = 0.35). Because, particulate matter in both size fractions (PM2.5 and PM10) is considered to be implicated in the pathogenesis of COVID-19 and its variants (Bourdrel et al., 2021; Iqbal et al., 2021; Linillos-Pradillo et al., 2021), its positive significant correlation with ^{222}Rn can have a serious impact on the increased transmissibility and immune escape, being naturally selected to promulgate de pandemic. Also, the most important impact of an increase in PM2.5 and PM10 aerosol concentrations in Bucharest urban areas is reflected by local climate, through the significant reduction of surface solar irradiance.

However, there was a positive correlation between AOD and surface solar irradiance. These results could be used to assess the impacts of air

pollution on climate change at urban local and regional scales on human health.

The results in Table 4 show relevant positive correlations of daily average O_3 at ground level concentrations with air temperature (r = 0.75), PBL heights (r = 0.74), and surface solar irradiance (r = 0.77), and inversely correlations with NO_2 (r = −0.31), air relative humidity (r = −0.64), and air pressure (r = −0.29). The daily average of NO_2 at ground level concentrations shows anti-correlations with the main climate parameters: air temperature (r = −0.29), surface solar irradiance (r = −0.49), wind speed intensity (r = −0.39) and PBL heights (r = −0.44). The findings of this paper, sustained by other existing studies in the field (Adams, 2020; Ahmadi et al., 2020; Poole, 2020; Ma et al., 2020; Miao and Liu, 2019; Xie and Zhu, 2020), have a high impact on understanding of COVID-19 transmission in Bucharest metropolitan city.

Also, our results found relevant direct correlations between exposure to air pollutants (PM2.5, PM10, NO_2, SO_2, CO) including ^{222}Rn, and inversely correlation, especially for spring-summer periods between ground ozone- O_3 levels, air temperature, Planetary Boundary Layer height, and surface solar irradiance with COVID-19 new incidence cases and deaths, demonstrated per each COVID-19 wave and for the entire pandemic period. Therefore, seasons when the pandemic has been stronger are the cold late autumn/winter/early spring in the temperate continental climate of Bucharest metropolitan city.

In conclusion, the climate variables can have a great influence on SARS-CoV-2 pathogens transmission, and can be considered by health decision makers to define the urban areas with a higher potential risks of COVID-19 viral infection spreading.

3.3.2. Synoptic atmospheric circulation associated with COVID-19 five-waves

Based on time series daily data of the vertical wind velocity (omega (Pascal/s) at 850 hPa (~1.4 km above from mean sea level) from National Center for Atmospheric Research (NCAR)/NCEP that perform global data assimilation from observational and satellite data, this study provided a complex per-waves analysis of Omega composite average (Pa/s) at 850 mb surface charts over Bucharest metropolitan city as compared to the climatology average (1981–2010) period, during the entire analyzed pandemic period (1 January 2020–1 April 2022).

Before and during each of COVID-19 waves have been observed positive values of Omega composite average surface maps at 850 mb (~ 1458 m elevation level), associated with anomalous anticyclonic synoptic conditions in the mid-troposphere, and stationary conditions, that potentially affect the urban air quality and favor COVID-19 disease

Table 4

Spearman rank correlation coefficients and p values between daily mean of the main air pollutants, AOD, AQI and climate variables in Bucharest during the entire analyzed pandemic period (26 February 2020–1 April 2022).

Factors	PM2.5	PM10	AOD	O_3	NO_2	SO_2	CO	Rn	AQI	T	RH	SI	w	P
PM10	0.51*													
AOD	0.17*	0.16*												
O_3	-0.39*	-0.29*	0.28											
NO_2	0.40*	0.54*	-0.18*	-0.31*										
SO_2	0.27*	0.64*	-0.11*	-0.33*	0.52*									
CO	0.27*	0.81*	-0.19*	-0.47*	0.52*	0.70*								
Rn	0.44*	0.35*	-0.11	-0.21*	0.38*	0.21*	0.28*							
AQI	0.12*	0.24*	0.28*	0.28*	0.08*	0.12*	0.15*							
T	-0.33*	-0.47*	0.37*	0.75*	-0.29*	-0.42*	-0.60*	-0.11*						
RH	0.16**	0.23*	0.03***	-0.64*	0.23*	0.21*	0.32*	0.09**	-0.10*	-0.47*				
SI	-0.52*	-0.55*	0.37*	0.77*	-0.49*	-0.47*	-0.60*	-0.34*	0.41	0.78*	-0.52*			
w	-0.08***	-0.35*	-0.03***	-0.08**	-0.39*	-0.27*	-0.29*	-0.23*	-0.03***	-0.11**	-0.11**	-0.05***		
p	0.22*	0.32*	-0.21*	-0.29*	0.22*	0.27*	0.33*	0.08**	-0.04***	-0.42*	-0.03***	-0.34*	-0.17**	
PBL	-0.41*	-0.49*	0.25*	0.74*	-0.44*	-0.41*	-0.51*	-0.23*	0.24*	0.69*	-0.65*	0.81*	0.03***	-0.30*

Note: PM2.5 (Particulate Matter of 2.5 μm size), PM10 (Particulate Matter of 10 μm size), AOD (Aerosol Optical Depth at 550 nm), O_3 (ozone), NO_2 (nitrogen dioxide), SO_2 (sulfur dioxide), CO (carbon monoxide), ^{222}Rn (radon activity), AQI (Air quality Index), PBL (Planetary Boundary Layer height), T (air temperature), RH (air relative humidity), SI (surface solar irradiance), w (wind speed intensity) and P (air pressure), at 2 m above the ground level; * and ** indicate p < 0.01 and p < 0.05 respectively and *** indicates p > 0.05

transmission, due to the downward airflows described by positive omega values in Bucharest metropolitan city (Fig. 8a–e).

In case of the first COVID-19 wave, Fig. 8a presents Omega surface chart at 850 mb over Romania, which shows upwards airflows described by negative omega values, that characterize non-stationary conditions, and that may explains few DNC (2399) and DND (126) cases recorded for Bucharest in comparison with other European metropolitan cities.

In case of the pre-second COVID-19 wave, Fig. 8b shows Omega surface chart at 850 mb over Romania, with associated downwards airflows described by positive omega values, that characterize stationary conditions, and explains an increased number of COVID-19 incidence and lethality. Like for the first COVID-19 wave when have been recorded elevated of daily average PBL heights levels (1607.19 ± 526.06) m, during pre-second COVID-19 wave higher levels of daily average PBL heights (1750.36 ± 425.52) m, characteristics for summer time period limited the air pollutants accumulation in Bucharest near the ground with a direct impact on COVID-19 spreading, been registered 13, 649 DNC cases and 266 DND cases.

During the second COVID-19 wave were recorded synoptic anticyclonic blocking atmospheric conditions, associated with positive downwards airflows (Fig. 8c) and lower levels of daily average PBL heights (538.74 ± 293.26) m, favorable for the main air pollutants accumulation near the ground, and explains an increased clinically severity and higher rates of new COVID-19 incidence and mortality in the Bucharest metropolitan region.

Fig. 8d shows Omega surface chart at 850 mb over Romania, with associated downwards airflows described by positive omega values, that also characterize stationary conditions registered during the spring-summer third COVID-19 wave of year 2021, and explains an increased number of COVID-19 incidence (64,848 DNC cases) and lethality (1166 DND cases). Associated higher values of daily average PBL heights of (1270.83 ± 567.58) m, may explain the lower COVID-19 severity than in the case of the second wave.

In case of the fourth COVID-19 wave, Fig. 8e provided by NCEP/NCAR Reanalysis Intercomparison Tool Omega chart presents anomalous synoptic anticyclonic conditions, with downwards airflows and positive values, that suggests proper conditions for air pollutants and SARS-CoV-2 viral pathogens accumulation near the ground, with associated severity of COVID-19 incidence and mortality (120,986 DNC cummulated cases and 2098 DND cummulated deaths per wave). Association with SARS-CoV-2 Delta more infectious variant and relative lower daily average PBL heights of (920.23 ± 603.25) m per wave contributed also at COVID-19 severity.

During the fifth COVID-19 wave Omega surface chart at 850 mb over Romania shows also synoptic anticyclonic blocking atmospheric conditions, and daily average PBL heights of (846.74 ± 463.01) m per wave, that favors air pollutants and viral pathogens accumulation near the ground. A higher number (235,185 DNC) of cumulated cases and a lower number (584 DND deaths) per wave have been recorded. The main interpretation associates the new SARS-CoV-2 Omicron more contagious variant (Poudel et al., 2022; Wouters et al., 2021), but less severe than Delta.

Due to its location in large depression-like structure, Romanian Plain surrounded by Carpathians Mountain barriers, especially during late fall and winter seasons, this study identified existence of strong tropospheric anticyclonic systems, that favor accumulation of virus-laden aerosol concentrations near the ground and COVID-19 disease transmission in Bucharest metropolitan city. However, both air pollution and COVID-19 exposure vary significantly by local topography and community. The chemodynamics of SARS-CoV-2 pathogens and particulate matter in different size fractions interactions may be responsible for the viral disease spreading during several seasons, and explains the existing correlations between urban air pollution episodes and five COVID-19 waves during the analyzed period in this study. The results are consistent with previous studies on the existing associated anticyclonic conditions with COVID-19 waves in some hotspot European countries

(Sanchez-Lorenzo, et al., 2021; Zoran et al., 2020a; Zoran et al., 2020b; Zoran et al., 2021). Recent decades have shown a clear increase in the frequency of blocking patterns over Europe and a simultaneous decrease in the number of low pressure systems Southwestern part. (Porebska and Zdunek, 2013; Tomczyk et al., 2019).

The response of viral infections to climate change and air pollution in large metropolitan areas requires strong international cooperation to achieve internationally-agreed reductions in greenhouse gas emissions (IPCC et al., 2021). Multi- and inter-disciplinary studies and models are needed to understand the significance of the environmental impacts on COVID-19 pandemic evolution, and associated potential risks to the environment due to adopted novel technologies and approaches for the mitigation of its effects (Fabiano et al., 2022; Li et al., 2022; Barouki et al., 2021). However adopting social restrictions during COVID-19 waves, and intense vaccination strategies in large urban areas may limit the severity of viral diseases like COVID-19 cases (Mallapaty, 2021; Awijen et al., 2022; Okuhara et al., 2022; Huang et al., 2022).

The findings of this paper cannot be interpreted as causal effects but may be considered as additional factors for COVID-19 pandemic viral infection transmission in large urban metropolitan areas. Also, this paper confirms that COVID-19 transmission surveillance under seasonal variability of environmental conditions, especially in large agglomerated urban areas, and the new variants of concerns such as Omicron and other descendants, will remain important as the pandemic continues. Further epidemiologic investigations are required to test the causality of air pollution and natural radioactivity, together climate variability for COVID-19 and other pandemic diseases incidence and severity.

4. Conclusions and policy implications

This study investigated the impact of environmental cumulative effects of anthropogenic air pollution and climate variability on COVID-19 multiwave severity in the metropolitan city of Bucharest, capital of Romania. Through of a systematic analysis of the daily time-series data of the main air pollutants including radon, Aerosol Optical Depth, meteorological and synoptic atmospheric conditions and COVID-19 incidence and mortality, this paper found the existing cross correlations between environmental variables and the transmission of SARS-CoV-2 pathogens during the entire pandemic period in such datasets. Although the molecular mechanisms involved in the interaction between air pollution exposure and pathogenesis of SARS-CoV-2 remain unknown, this research supports the hypothesis that exposure to cumulative high levels of air pollutants including radon increases the risk of COVID-19 incidence and mortality. During investigated pandemic period were recorded weekly positive associations with COVID-19 rates for PM2.5, PM10, NO_2, SO_2, CO and ^{222}Rn, and significant negative associations for ground levels of O_3 in Bucharest metropolitan city. Specifically, significant inversely correlations were found between meteorological variables air temperature, Planetary Boundary Layer height, and surface solar irradiance with daily new COVID-19 incidence and deaths, averageingful for spring-summer periods. At the mesoscale, registered anomalous anticyclonic synoptic meteorological patterns in the mid-troposphere, were associated with stability conditions during fall-winter periods, that favored COVID-19 viral disease fast-transmission, mostly during the second, and the fourth waves. Because, particulate matter in both size fractions (PM2.5 and PM10) is considered to be implicated in the pathogenesis of COVID-19 and its variants, its positive significant correlation with ^{222}Rn can have a serious impact on the increased transmissibility and immune escape, being naturally selected to promulgate de pandemic. Another finding of this study was the recorded reductions of AOD during the total lockdown period of the first and the third COVID-19 waves when anthropogenic emissions have been decreased substantially. The findings of the current study reveals that total or partial lockdowns restrictions implemented to minimize the spread of COVID-19 may contribute to air quality improvement and health safety strategies design, crucial for pre- and
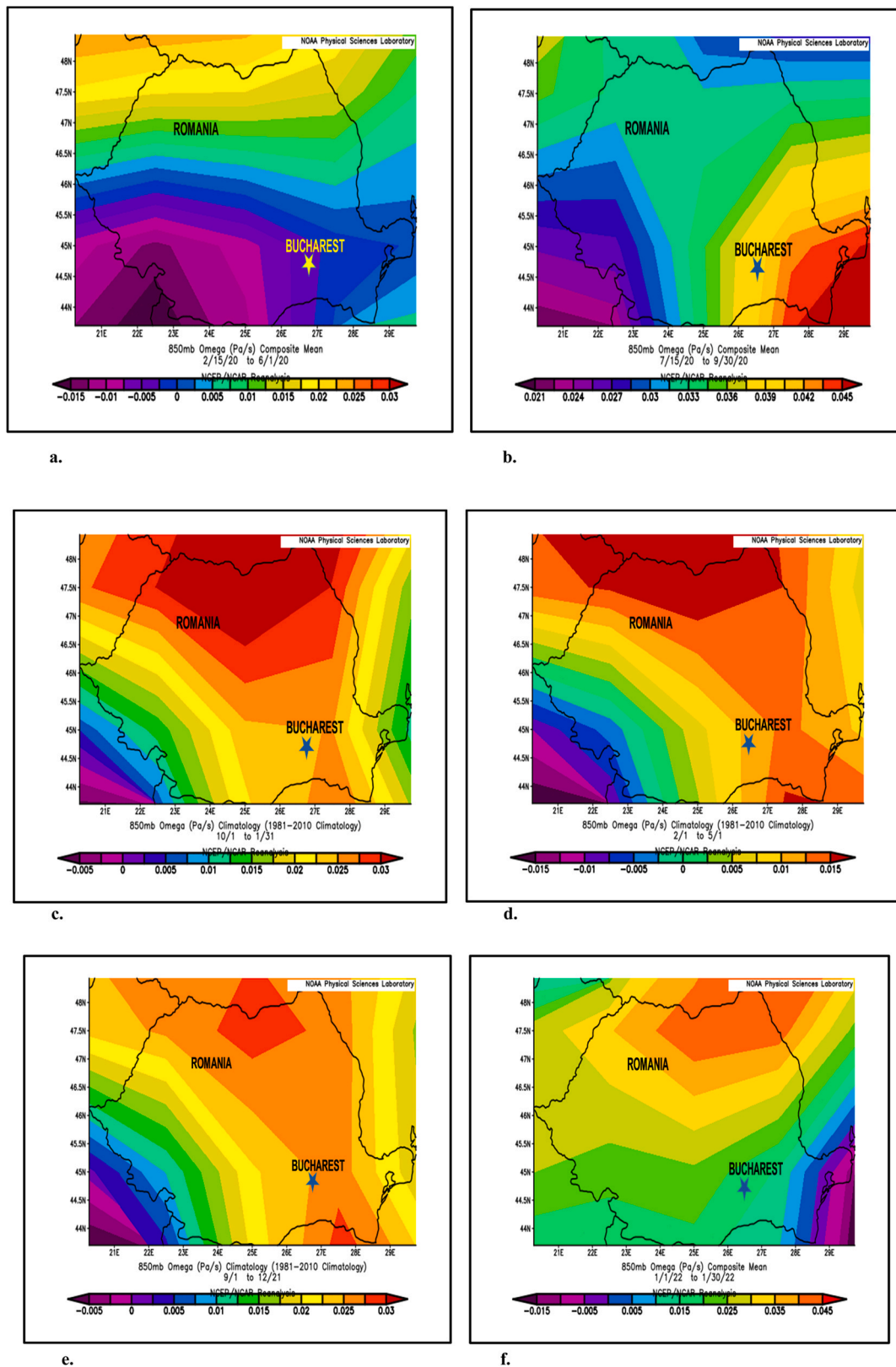
Fig. 8. a. Omega surface chart composite mean **b.** Omega surface chart composite mean (Pa/s). (Pa/s) at 850 mb over Romania during the at 850 mb over Romania during the pre-second COVID-19. first COVID-19 wave in Bucharest. wave in in Bucharest. c. Omega surface chart composite mean d. Omega surface chart composite mean (Pa/s) at (Pa/s) at 850 mb over Romania during the 850 mb over Romania during the third COVID-19 s COVID-19 wave in Bucharest. wave in Bucharest. 8e. Omega surface chart composite mean f. Omega surface chart composite mean (Pa/s). (Pa/s) at 850 mb over Romania during the at 850 mb over Romania during the fifth COVID-19 fourth COVID-19 wave in Bucharest. wave in Bucharest.

post-pandemic safety and health plans in large agglomerated metropolitan cities. This paper verified the capability of the main climate factors seasonality to support long-term seasonal variability of COVID-19 transmission and deaths along with sustainability of urban agglomerated areas. If COVID-19 and climate change are transboundary threats, that expand in space and time, air pollution is considered at urban local and regional scales, and sometimes at transboundary scales. The results of this paper demonstrates the imperious need of adopting novel clean technologies and safety actions for limiting urban population exposure at high levels of air pollutants under extreme climate events, especially during viral pandemic infections and minimizing impact on human health. However, this study aims to provide useful information on COVID-19 viral infection transmission related to seasonal variability of environmental drivers, which is essential for policymakers to formulate environmental health prevention and control strategies during pandemic events.

CRediT authorship contribution statement

Maria Zoran: Conceptualization, Methodology, Supervision, Writing – review & editing. **Roxana Savastru:** Methodology, Validation, Review. **Dan Savastru:** Methodology, Validation, Review. **Marina Tautan:** Methodology, Validation.

Declaration of competing interest

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

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Consent for publication

All the co-authors consent the publication of this work.

Consent to participate

Not applicable.

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