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Impacts of exposure to air pollution, radon and climate drivers on the COVID-19 pandemic in Bucharest, Romania: A time series study

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ABSTRACT

During the ongoing global COVID-19 pandemic disease, like several countries, Romania experienced a multi-waves pattern over more than two years. The spreading pattern of SARS-CoV-2 pathogens in the Bucharest, capital of Romania is a multi-factorial process involving among other factors outdoor environmental variables and viral inactivation. Through descriptive statistics and cross-correlation analysis applied to daily time series of observational and geospatial data, this study aims to evaluate the synergy of COVID-19 incidence and lethality with air pollution and radon under different climate conditions, which may exacerbate the coronavirus' effect on human health. During the entire analyzed period 1 January 2020–21 December 2021, for each of the four COVID-19 waves were recorded different anomalous anticyclonic synoptic meteorological patterns in the mid-troposphere, and favorable stability conditions during fall-early winter seasons for COVID-19 disease fast-spreading, mostly during the second, and the fourth waves. As the temporal pattern of airborne SARS-CoV-2 and its mutagen variants is affected by seasonal variability of the main air pollutants and climate parameters, this paper found: 1) the daily outdoor exposures to air pollutants (particulate matter PM2.5 and PM10, nitrogen dioxide-NO_2, sulfur dioxide-SO_2, carbon monoxide-CO) and radon - ^{222}Rn, are directly correlated with the daily COVID-19 incidence and mortality, and may contribute to the spread and the severity of the pandemic; 2) the daily ground ozone-O_3 levels, air temperature, Planetary Boundary Layer height, and surface solar irradiance are anticorrelated with the daily new COVID-19 incidence and deaths, averageingful for spring-summer periods. Outdoor exposure to ambient air pollution associated with radon is a non-negligible driver of COVID-19 transmission in large metropolitan areas, and climate variables are risk factors in spreading the viral infection. The findings of this study provide useful information for public health authorities and decision-makers to develop future pandemic diseases strategies in high polluted metropolitan environments.

1. Introduction

The COVID-19 ongoing pandemic disease produced by Severe Outdoor Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) has hit globally 224 countries with more than 511 milion cases and more than 6 milion fatalities (Johns Hopkins Coronavirus Resource Center, 2022; Worldometer Info, 2022). During more than two years pandemic period the SARS-CoV-2 genome has suffered rapid mutations (Alpha: B.1.1.7, B.1.1.7 + E484K; Beta: B.1.351; Gamma: P.1; Delta: B.1.617.2; and Omicron: B.1.1.529), associated with different degrees of transmissibility and severity globally and COVID-19 disease presented multiwaves patterns (Poudel et al., 2022; Petersen et al., 2021; Otto et al., 2021; Yuki et al., 2020; Byun et al., 2021; Baay et al., 2020), and health emergency worldwide (Berber et al., 2021; Yu and Li, 2021; Azuma et al., 2020).

As future viral waves are likely to occur, with unpredictable height and breadth of the waves is an imperious need to understand the evolution of COVID-19 pandemic risk in relation with environmental factors

Abbreviations: SARS-CoV-2, Severe Outdoor Respiratory Syndrome Coronavirus 2; COVID-19, Coronavirus Disease 2019; SARS-CoV, Severe Outdoor Respiratory Syndrome Coronavirus; MERS-CoV, Middle East respiratory syndrome coronavirus; DNC-Daily, New COVID-19 positive cases; DND, Daily New COVID-19 Deaths; PM, Particulate Matter; PM1(1 μm), PM2.5 (2.5 μm) and PM10(10.0 μm) diameter; O3, Ozone; NO2, Nitrogen dioxide; SO2, Sulfur dioxide; CO, Carbon monoxide; 222Rn, Radon; PBL, Planetary Boundary Layer height; T, Air temperature; RH, Air relative humidity; w, Wind speed intensity; SI, Surface solar global irradiance; NOAA, National Oceanic and Atmospheric Administration U.S.A.

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(Rayan, 2021; Bakhshandeh et al., 2021; He et al., 2021; Bontempi et al., 2020; Baay et al., 2020; Wong et al., 2020; Luo et al., 2020; Mu et al., 2020; Chen et al., 2021a). In spite of considering current vaccines to be safe, anyway concerns arise about the effective duration of vaccines with the emergence of new variants.

During February 26, 2020 with the first confirmed case, and the last decade of December 2021, Romania experienced four successive waves of COVID-19 viral infections with more than 1.85 milion confirmed new cases, of which 16.97% in Bucharest and more than 59 thousand deaths, of which 8.83% in Bucharest metropolitan city (MAI, 2022). Multi- and inter-disciplinary international scientific efforts are needed in order to understand and minimize diffusion patterns of SARS-CoV-2 in urban environmental conditions (that is, whether it is a seasonal virus) (Anand et al., 2021; Soriano et al., 2021).

Among COVID-19 pandemic multi-risk factors, outdoor and indoor environmental exposures are interlinked with social, demographic, and evolutionary (Destoumieux-Garzon et al., 2022). Clinical and host-specific genetic factors may be related to environmental seasonality risk factors for SARS-CoV-2 infection and outcomes (D'Amico et al., 2022; Casado-Aranda et al., 2021; Iqbal et al., 2021; Nishiura et al., 2020; Luo et al., 2020; Walls et al., 2020; Cao et al., 2020). Outdoor environmental factors (climate and air quality) are mainly responsible for the dispersal, diffusion, and infectivity rate of the SARS-CoV-2 pathogens and their new variants virions (Yuan et al., 2021; Hassanzadeh et al., 2020; Islam et al., 2021; Huang et al., 2020; Amin et al., 2020).

Particulate matter -PM in different size fractions (PM1 μm, PM2.5 μm, and PM10 μm) and gaseous air pollutants (ozone-O_3, nitrogen dioxide-NO_2, sulfur dioxide-SO_2, carbon monoxide-CO) may have an important impact on COVID-19 disease transmission (Marquès and Domingo, 2021, 2022; Marquès et al., 2022; Zoran et al., 2021, 2022; Domingo et al., 2020; López-Feldman et al., 2021). Due to their increased oxidative toxicity, epidemiologic studies have shown a connection between outdoor (Shao et al., 2022; Xu et al., 2022; Ho et al., 2021; Bakadia et al., 2021; Cao et al., 2021; Copat et al., 2020; Mu et al., 2021; Rahimi et al., 2021) acute and chronic exposure (Wang et al., 2022) to high levels of air pollutants in large urban areas, that are responsible for respiratory and cardiovascular morbidity and higher mortality rates (Hvidtfeldt et al., 2021; Domingo and Rovira, 2020; Leirião et al., 2022; Prinz and Richter, 2022; Khan et al., 2019; Travaglio et al., 2021). Was demonstrated that long-term exposure to particulate matter PM10 concentrations above WHO guidelines implemented by the Directive 2008/50/EU and the US-EPA, exacerbate COVID-19 health outcomes. Hence, should be updated accordingly to protect human health (Marquès et al., 2022).

Another important characteristic of air pollutants particulate matter is its associated natural radioactivity, which refers to the presence of α- and β-emitting radioisotopes attached to particulate matter, which is mostly attributed to radon - ^{222}Rn progeny that is present in the atmosphere due to anthropogenic, terrestrial or cosmogenic sources (Crova et al., 2021; Zoran et al., 2012; Blomberg et al., 2020; Hosoda et al., 2021; Penache and Zoran, 2019a). Radon (^{222} Rn) is a noble gas emitted from the Earth's crust (soil, water, vegetation) that could decay into short-lived (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214} Po) and long-lived radionuclides (^{210}Pb, ^{210}Po). Most of its long-lived progeny attach to aerosol particles in the accumulation mode (0.1–1 μm) with a average aerodynamic diameter of 555 nm (Grundel and Porstendörfer, 2004; Zoran et al., 2015), and after inhalation and deposition, radon progeny can continue to decay and produce high α-radiation exposure to the lung. Several scientific papers pointed out that short-term or long-term inhaled particulate matter containing radon progeny in both outdoor and indoor spaces may be associated with lung inflammation or neuroinflammation (Asadi et al., 2020; Seposo et al., 2020; Blomberg et al., 2019; Keith et al., 2012; Seltenrich, 2019; Hosoda et al., 2021; Loffredo et al., 2021; Sugiyama et al., 2020), which in addition to SARS-COV-2 pathogens attached to aerosols, can lead to severe medical consequences, and contribute to increased COVID-19 mortality (Macias-Verde et al., 2021; Maya et al., 2020). Changes in the air pollution and climate variables due to urbanization affect urban environmental health, and frequently increase the risk/hazard of viral infections probability (Shahbaz et al., 2021; Domingo et al., 2020; Rebuli et al., 2021; Chong et al., 2022).

Urban climate and air quality drivers are linked of heavy air pollution episodes for several days (Pandolfi et al., 2014) that can be associated with events like haze, lower atmospheric inversions (Yuan et al., 2021; Zoran et al., 2008; Baldasano, 2020) and transborder air pollution (Saharan dust intrusions, or other industrial pollutants) (Salvador et al., 2021). Is well known that during stagnant anticyclonic air conditions, that favour accumulation at the ground level of air pollutants, outdoor exposure to high levels of air pollutants can increase the susceptibility to morbidity and mortality from respiratory infections (Mu et al., 2021; Zhou et al., 2021; Romano et al., 2020; Cohen and Kupferschmidt, 2020; Perrone et al., 2012; Perrone et al., 2014; Wang et al., 2022; Wang et al., 2021; Coccia, 2020; Manoj et al., 2020).

The lower atmospheric system can be a significant transport vector for airborne microbiome (bacterial, fungal, viral) communities and their seasonal shift in both the concentration and biodiversity under influence of local and regional meteorological parameters (air temperature, relative humidity, pressure, wind speed intensity, and direction, Planetary Boundary Layer heights -PBL, surface solar irradiance) variability especially in urban areas (Xia et al., 2022; Tignat-Perrier et al., 2020; Zoran et al., 2020b).

Among the climate variables with a potential effect on SARS-CoV-2 virus persistence outdoors, surface solar irradiance (SI) is one of the most important climate parameters involved in the reduction of SARS-CoV-2 and its new variants pathogens (Schuit et al., 2020). If solar UV C irradiation is highly effective in inactivating SARS CoV 2 replication on contaminated surfaces (Biasin et al., 2021), UVB and UVA in sunlight are the primary virucidal agents in the environment (Herman et al., 2020; Heβling et al., 2020; Sagripanti and Lytle, 2020; Coohill and Sagripanti, 2009). The role of climate variables seasonality at local and regional scales has long been recognized in modulating regional air quality and mutual interaction with viral infections like COVID-19 disease (Liu et al., 2021; Rayan, 2021; Du et al., 2018; Zoran et al., 2021, 2022; Uetake et al., 2019; Yuan et al., 2021).

In this study, we focus on the analysis of the SARS-CoV-2 viral infection fast diffusion and lethality in relation to environmental variables, that could affect bioaerosols/droplets transmission and viral survival under different synoptic-scale weather patterns, and tend to induce changes in multi-scale circulation and the subsequent evolution of Planetary Boundary Layer heights during the four COVID-19 waves in Bucharest metropolitan city in Romania.

In order to control and minimize the effects of future waves of viral infections on the economies and public health of metropolitan cities, the environmental factors that threaten the spread of COVID-19 should be determined, and decision-makers should take necessary prevention measures.

The main aim of this paper is to explore the synergy between the changes in the exposure to air pollution and climate-related factors, which may exacerbate the SARS-CoV-2 viral' effect on human health and the COVID-19 incidence and lethality in Bucharest, capital of Romania. Based on applied statistical analyses of daily in-situ and geospatial time series data recorded during several seasons and over a long time period (1 January 2020–21 December 2021), this study aims:

1) To analyze the influence of some air quality variables (PM2.5, PM10, O_3, NO_2, SO_2, CO, including ^{222}Rn) and weather parameters (air temperature, relative humidity, wind intensity, pressure, Planetary Boundary Layer height, surface solar irradiance, synoptic meteorological patterns) on COVID-19 disease incidence and mortality, and.
2) To incorporate the most influential environmental factors, which can trigger the spread of SARS-CoV-2 viral infection in a „per waves

comparative analysis" of COVID-19 disease during the first, pre-second, second, third, and fourth pandemic waves.

In spite of existing several global studies, that analyzed the role of air pollutants and climate variables on the incidence and severity of COVID-19, currently, there are no studies that consider the cumulative impacts of radon (^{222}Rn) effects, as a source of exposure to ionizing radiation both outdoor as well indoor, that can contribute to additional adverse effects to the human respiratory system and COVID-19 pattern temporal evolution. Accurate estimation of the local and regional mutual seasonality of the environmental and epidemiologic conditions can provide timely information on the characteristics of the effects of the COVID-19 disease evolution on the future pandemic waves in large urban areas.

2. Methodology

2.1. Study area description

Bucharest city, the 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 along the Dâmbovița River in a flat region, with a total surface of 625 km^2, being the tenth-largest city in Europe and the largest in the South-Eastern part of the continent. Also, due to high urbanization, Bucharest metropolitan city is the largest urban carbon emitter among all Romanian cities The test area, presented in Fig. 1 includes the city of Bucharest and the surrounding peri-urban areas, having a complex environment that includes buildings, roads, green and blue structures. The metropolitan region of Bucharest, which covers 5080 km^2 is made up of 7 counties is a predominant agricultural rural space under intense urbanization and suburbanization processes. The climate in Bucharest is temperate humid continental, influenced mainly by the alternate or simultaneous influences Tropical of the Western Climate circulation, the East-European Anticyclone, the Mediterranean Cyclones, and the advection, with hot, humid summers and cold, snowy winters (Zoran et al., 2008, 2013). Bucharest's traffic follows an increasing trend, mainly due to extended car use, ~1.5 million vehicles per day present for 1.794 million residents (Worldpopulation, 2021), compared to the EU average of 505,000 passenger cars per 1 million inhabitants (EEA, 2020). Thirdly, another source of air pollution within the city is heating based on fossil fuels such as coal and natural gas. Traffic-related pollution to extensive use of old cars is responsible for recorded high concentration levels of air pollutants like NO_2, O_3, CO, SO_2, and particulate matter PM2.5 and PM10, which sometimes exceed critically standard limits for Romania and the European Union (Zoran et al., 2019a).

2.2. Data collection

The time series analysis of climate and air pollution seasonality relationship with COVID-19 incidence and mortality seasonality in Bucharest is based on a large global dataset built by collecting information from various freely available sources from January 1, 2020 up to December 21, 2021.

- COVID-19 data

Coronavirus COVID-19 incidence data (Total cumulative, Daily New cases, Daily New Deaths and Total Deaths) cases recorded in Romania and Bucharest have been provided by the following websites: https://www.worldometers.info, https://www.statista.com/, (Johns Hopkins Coronavirus Resource Center, 2022). Accumulated COVID-19 and Daily New confirmed positive data for 26 February 2020–21 December 2021 period for Bucharest city region were provided by https://www.mai.gov.ro/.

- Air quality and climate data

Time series data of daily average values of air pollutants concentrations PM2.5, PM10, O_3, NO_2, SO_2, and CO for Bucharest selected stations have been collected from https://www.copernicus.eu/en/c

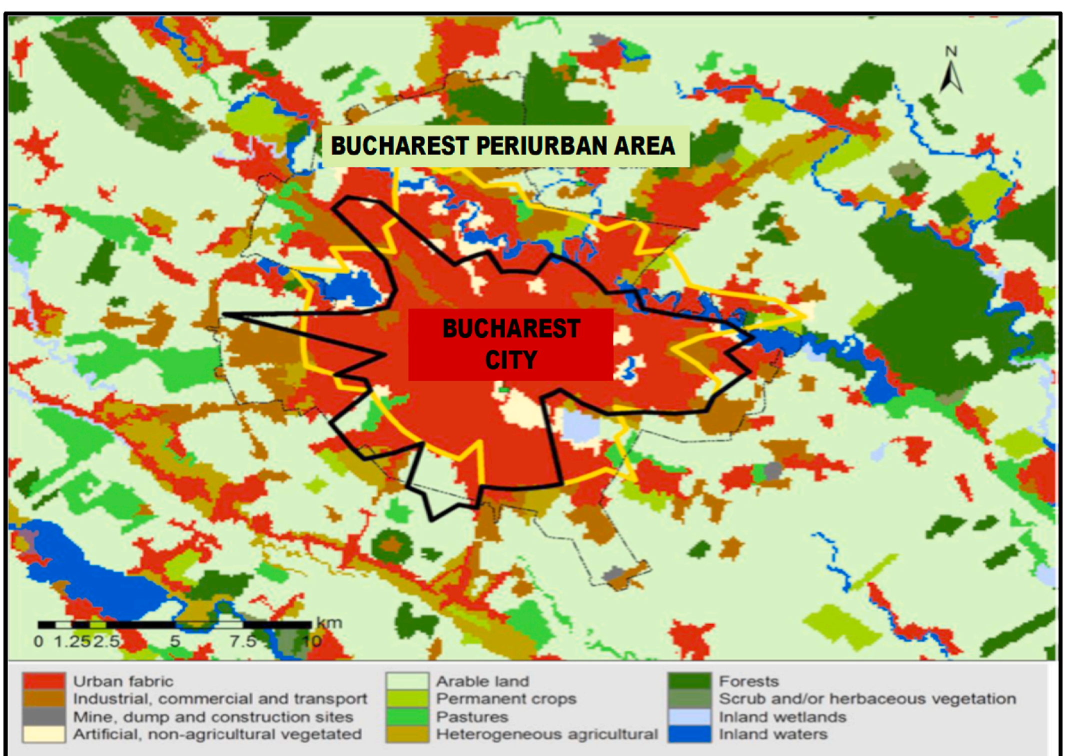

Fig. 1. Study test site Bucharest capital of Romania.

opernicus-services/atmosphere, https://aqicn.org/city/romania/municipiul-bucuresti/and from <u>https://www.eea.europa.eu/air quality</u>.

Daily atmospheric radon (^{222}Rn) concentration was monitored in the periurban area Magurele at 10.67 km of Bucharest city center, and 1.75 m height level using an "AlphaGUARD" (PQ2000 PRO, Genitron Instruments GmbH, Germany), placed in a Stevenson's Screen (well-ventilated, weatherproof enclosure), which also recorded main meteorologic parameters (atmospheric pressure, temperature and relative humidity). Radon monitor contains a pulse-counting ionization chamber (using alpha spectroscopy), which is suitable for continuous monitoring of radon concentration in the range (2 Bq/m^3 - 2 M Bq/m^3), with a sensitivity of 4.5 cpm at 100 Bq/m^3 and a stable long-term calibration factor. Time series of daily average ^{222}Rn concentrations for the time period January 1, 2020–21 December 2021 were used for the analysis.

Time series of meteorological data, including daily average temperature (T), daily average relative humidity (RH), and daily average wind speed for Bucharest metropolitan region were collected from Weather Wunderground (https://www.wunderground.com/), and Copernicus Climate Change Service (C3S) datasets (https://climate.copernicus.eu) and weather stations operated by the Romanian National Meteorological Administration (www.anm.ro). Daily average surface solar global irradiance time series data have been provided by Copernicus Atmosphere Monitoring Service (CAMS) McClear Clear-Sky Irradiation service at http://www.soda-pro.com/web-services/radiation/cams-mcclear. Daily Planetary Boundary Layer PBL height time-series data were collected from NOAA's Air Resources Laboratory (https://ready.arl.noaa.gov). In order to describe urban air quality of Bucharest metropolitan area, in Romania this paper considered daily average Global Air Quality Index (AQI) according to classification of air quality (http://www.eurad.uni-koeln.de) and EU regulations, which is defined by formula:

$$AQI = Max\left(\frac{O_3(24h)}{100}, \frac{NO_2(24h)}{90}, \frac{PM10(24h)}{50}, \frac{SO_2(24h)}{125}, \frac{CO(24h)}{10000}\right)x50 \quad (1)$$

where O_3(24 h), NO_2(24 h), PM10(24 h), SO_2(24 h), CO(24 h) represent daily average values of respectively ozone, nitrogen dioxide, particulate matter in diameter size 10 μm, sulfur dioxide and carbon monoxide present in the urban air. Based on the global criteria for main air pollutants, air quality index is classified in six classes from very good to very poor (respectively**:** < 10-very good; 10–20- good; 20–30- satisfactory; 30–50 – sufficiently; 50–80- poor; > 80- very poor).

In order to analyze lower atmospheric circulation conditions associated with people's exposure to air pollutants and COVID-19 disease fast diffusion in Bucharest city during 1 January 2020–December 21, 2021, we extracted geopotential heights at 500 mb anomalies surface charts provided by NASA, Reanalysis Data Project NCEP/NCAR PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). Base on meteorological information of daily geopotential height 500 hPa anomalies (at about 5.5 km height above the ground), positive anomalies are associated with the anticyclones stability, blocking systems, and negative anomalies with cyclones conditions.

2.3. Descriptive statistical analysis

The multiwaves pattern of COVID-19 in the Bucharest area makes possible the further analysis of climate variables drivers, with descriptive statistical analysis for transient correlations that identify similar variation in the daily time series meteorological and air quality including radon (considered independent variables) data together daily COVID-19 incidence and mortality data (considered dependent variables) over selected localized windows of time, corresponding to the pre-COVID-19, the first, pre-second, second, third and fourth COVID-19 waves in Bucharest metropolitan area.

First, a descriptive analysis was performed to provide an overview of COVID-19 viral infection temporal evolution and air quality during the entire study period. Next, for daily time series of data have been used a multivariate linear regression model to fit the dependent variables (COVID-19 incidence and mortality) for each independent variable: daily average ambient air pollutants at ground level (particulate matter PM2.5, PM10, O_3, NO_2, SO_2, CO, and ^{222}Rn) and daily average meteorological parameters (air temperature- T, air relative humidity- RH, wind speed intensity –w, air pressure, surface solar irradiation-SI) and daily average Planetary Boundary Layer - PBL.

The dependence between pairs of daily time series air pollutants and meteorological variables, as well as COVID-19 incidence and mortality data, were quantified in this study by standard tools of statistical analysis, Pearson, Spearman, and Kendall rank correlation, and rank-correlation non-parametric test coefficients. 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 non-normal distribution, Spearman rank correlation was employed to identify the linear correlation between the following variables: (1) air pollutants PM2.5, PM10, NO_2, SO_2, CO, and O_3 concentrations together ^{222}Rn, meteorological parameters and (2) COVID-19 incidence and mortality ratesAll statistical analyses were achieved using ORIGIN 10.0 software, version 2021 for Microsoft windows.

3. Results and discussion

3.1. Temporal evolution of COVID-19 viral infection in Bucharest

While the COVID-19 pandemic disease is still in progress, like other European countries, between its start in early spring 2020 till early winter 2021, Romania experienced a four-wave pattern of COVID-19 pandemic, with enhanced severity in large metropolitan city Bucharest (Fig. 2). The epidemiological trend of the COVID-19 disease transmission in Bucharest city in relation with air pollution and climate variables in this study was investigated during four waves and five different time-windows periods: a first COVID-19 wave (26 February 2020–15 June 2020) including total lockdown during 15 March 2020–15 May 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–January 31, 2021); the third COVID-19 wave (1 February 2021–1 June 2021); the fourth COVID-19 wave (1 September 2021–21 December 2021).

During the second, the third, and the fourth COVID-19 waves, to curb the spread of SARS-CoV-2 pathogens, a variety of semi-lockdown measures were implemented in Bucharest. Severe hospitalized cases and death rates were higher than in the first and the pre-second COVID-19 waves, possibly attributed to synoptic meteorological conditions, air quality changes, much more infectivity rates driven by new predominant variants, summer relaxation periods, and not fully vaccinated people. Anyway, the non-vaccinated population demonstrated much higher infectivity and mortality rates, the complete vaccination schedule against COVID-19 decreases the risk of death by 14 times and the risk of infection by 10 times (DSPB, 2022; Vaccination-COVID-19, 2021), conclusions which have been clearly demonstrated by studies in other countries (Saban et al., 2022; Rawat et al., 2021). Timely and proper intervention policies, such as intensive contact tracing followed by quarantine and isolation, and intense vaccination procedure can effectively reduce the spreading risk of the new more contagious SARS-CoV-2 variants (Cevik et al., 2021; Diao et al., 2021).

3.2. Association between air pollutants, radon and COVID-19 multiwaves dynamics

3.2.1. Impact of air pollutants on COVID-19 waves

Due to increased urbanization with associated land cover changes and high road traffic and old cars emissions, Bucharest metropolitan city

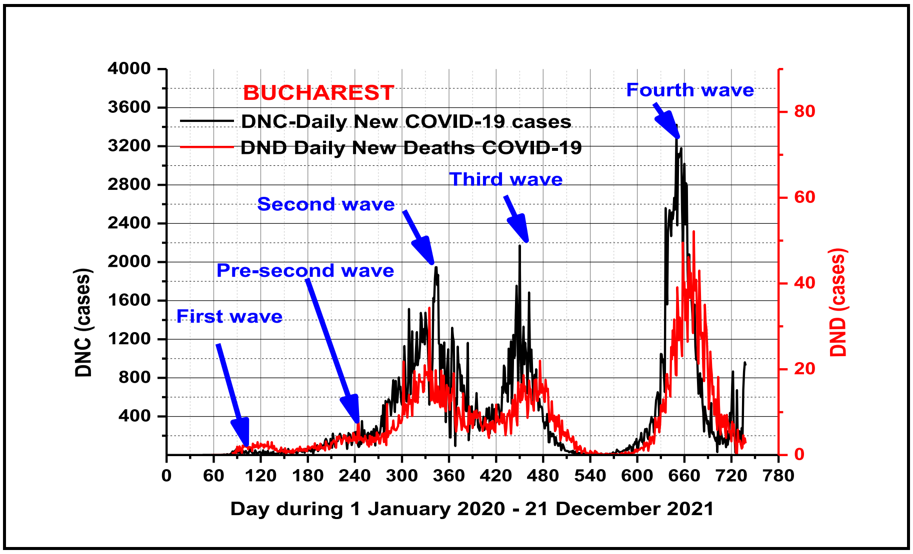

Fig. 2. COVID-19 epidemiologic four-waves pattern in Bucharest, capital of Romania during January 1, 2020–December 21, 2021.

experiences outdoor daily high air pollution levels of PM2.5, PM10, O_3, NO_2, SO_2, CO. Observational analysis was focused on changes in the air quality of Bucharest for the following air pollutants particulate matter PM2.5 and PM10, nitrogen dioxide- NO_2, sulfur dioxide-SO_2, and carbon monoxide- CO, during the pre-lockdown, the first, the pre-second, the second, the third and the fourth COVID-19 waves with one total or other

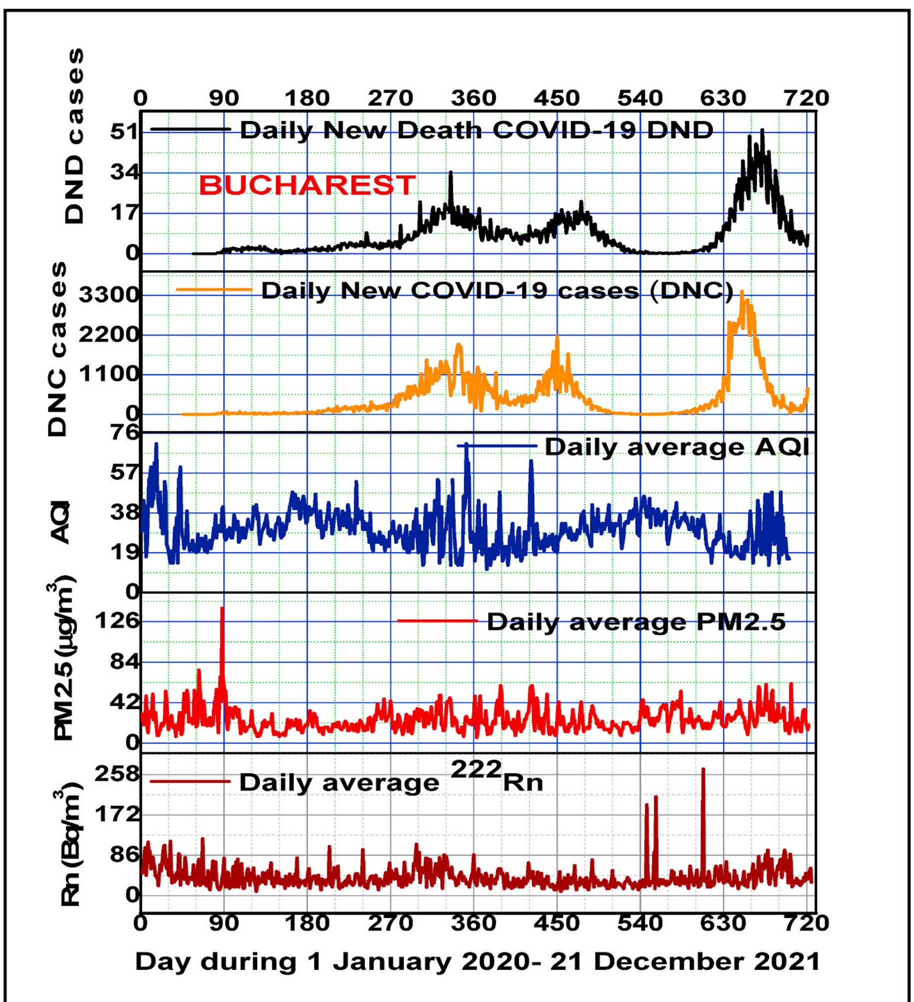

Fig. 3. Temporal patterns of daily average ground levels of PM2.5, ^{222}Rn concentrations and Air Quality Index (AQI) in relation with daily new confirmed COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) cases during the entire analyzed COVID-19 pandemic period in Bucharest metropolitan city.

partial lockdowns and two relaxation periods spanning from January 1, 2020 to December 21, 2021.

A comparative per-waves analysis of the main air pollutants concentrations between the same pre-pandemic time windows of (2015–2019) and COVID-19 periods show changes of air pollution levels (PM2.5 and PM10) exposure across the Bucharest city as a result of the lockdown or semi-lockdowns interventions. Air pollutants concentrations were mean-centered and scaled to a one standard deviation change so that estimated effects were for a one standard deviation change in long-term pollution exposure applied per each period of COVID-19 multiwaves. For the first COVID-19 wave with total lockdown, PM2.5 and PM10 concentrations recorded reductions of 12%, and respectively of 27% (Table 1S). Small reductions have been recorded for PM2.5 and PM10 ground level concentrations during the pre-second, the second, the third COVID-19 waves, and small increases of 4% and respectively 3% for PM2.5 and PM10 during the fourth COVID-19 wave. Our findings show similar results like other studies found, that the emissions of primary air pollutants from anthropogenic sources were significantly reduced during COVID-19 pandemic event, especially during lockdown periods (Adams, 2020; Ahmadi et al., 2020; Guevara et al., 2021; Biswal et al., 2021; Collivignarelli et al., 2020; Tobias and Querol, 2020; Coccia, 2021).

Besides seasonal variability, our results show associated increased values of the daily average particulate matter PM2.5, PM10, air quality index AQI and radon during the second and the fourth COVID-19 waves in Bucharest, with the high numbers of total daily new of COVID-19 cases (DNC) and deaths (DND) (Fig. 3). Being positive correlated with viral disease transmission, outdoor exposure to PM2.5 and PM10 had a tendency to increase COVID-19 incidence and mortality. These findings are supported by previous scientific studies (Tung et al., 2021; Wang et al., 2022; Setti et al., 2020a; Setti et al., 2020b; Chakrabarty et al., 2021; Wang et al., 2021; Zhu et al., 2020; Belosi et al., 2021), where they found a significant correlation between the daily PM10 exceedances and COVID-19 spreading.

According to other studies (Wen et al., 2022; Baron, 2021, 2022; Baron, and Camilleri, 2021; Linillos-Pradillo et al., 2021; Sagawa et al., 2021; Facciola et al., 2021; Bourdrel et al., 2021; Iqbal et al., 2021), this paper may support the hypothesis that particulate matter, especially PM2.5 in cities can be considered as an environmental mutagen, involved in short to medium term mechanisms of induced intra-host mutagenesis in the SARS-CoV-2 genome, through diminishing pulmonary function. According to scientific studies, aerosolized respiratory viruses have a great potential for diffusion the viral infections, that ambient air pollutants could be a possible virus carrier (Xu et al., 2022; Bu et al., 2021; Amin et al., 2020; Carraturo et al., 2020; Cevik et al., 2021; Borisova and Komisarenko, 2020).

The results presented in Table 1 emphasize 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 the entire investigated pandemic period 26 February 2020–December 21, 2021.

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 city during the entire analyzed pandemic period 26 February 2020–December 21, 2021.

Bucharest	Daily average of ground air pollutant concentration						
COVID-19 incidence	PM2.5 (μg/m^3)	PM10 (μg/m^3)	O_3 (μg/m^3)	NO_2 (μg/m^3)	SO_2 (μg/m^3)	CO (μg/m^3)	^{222}Rn (Bq/m^3)
Daily New confirmed cases (DNC)	0.31*	0.32*	−0.46*	0.25*	0.38*	0.47*	0.16*
Daily New Deaths (DND)	0.33*	0.38*	−0.49*	0.26*	0.38*	0.47*	0.14*

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 $p < 0.01$.

In good accordance with existing literature (Shao et al., 2022; Xu et al., 2022; Lipsitt et al., 2021; Frontera et al., 2020; Zoran et al., 2020a, 2020b; Islam et al., 2021; Amin et al., 2020; Hassanzadeh et al., 2020; Li et al., 2020; Páez-Osuna et al., 2022), this study demonstrates a positive moderate correlation between outdoor exposure to daily average air pollutants PM2.5, PM10, NO_2, SO_2, CO concentrations, and increased daily new COVID-19 confirmed (DNC) cases and deaths (DND). A possible explanation may also indicates that air pollutants exposure may enhance virus-induced lung damage and inflammation, suggesting contribution to COVI-19 pathogenesis (Domingo et al., 2020; Marquès et al., 2021; Huang et al., 2020; Zhu et al., 2020; Feng et al., 2022; Leirião et al., 2022).

An opposite anticorrelation was observed for daily average ground ozone level concentration, that during summer periods contributes at the decrease of the daily new COVID-19 confirmed (DNC) cases and deaths (DND). While some studies found positive correlations between new confirmed cases with ground levels O_3 concentrations (Stufano et al., 2021; Xie and Zhu, 2020; Azuma et al., 2020), other, like our study found a negative correlation with ozone, especially during summer seasons (Blanco et al., 2021; Zoran et al., 2021; Fuller et al., 2020).

The daily average of ground level average ozone concentrations follow also a seasonal pattern variation, but the concentrations during the four COVID-19 waves were increased in comparison with the pre-lockdown the same time windows periods.

In comparison with the same period of time (2015–2019), during the total lockdown of the first wave in Bucharest (15 March 2020–May 15, 2020), O_3 at ground level concentrations recorded an increase of 1.49 factor (explained by traffic –and industrial related sources reduction and partially by spring seasonality), and daily average NO_2 at ground level concentrations recorded a decrease of 51%. Similar results have been confirmed also by several studies worldwide (Guevara et al., 2021; Biswal et al., 2021; Bontempi, 2021), that explain COVID-19 severity associated with lungs inflammatory reactions.

Comparative analysis with five years pre-pandemic period (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 and industrial sources reduction). In case of the fourth COVID-19 wave associated with the highest rates of COVID-19 transmission in Bucharest, SO_2 recorded an increase of 12%, and CO an increase of 6%. As can be seen in Table 1, this study found moderate 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 can impact the transmission and severity of SARS-CoV-2 pathogens during analyzed pandemic fall-winter periods in Bucharest.

However, stagnant atmospheric conditions recorded in Bucharest during the second, the third, and the fourth COVID-19 waves (Table 1S) favour the accumulation of the main gaseous air pollutants NO_2, SO_2, and CO (among other pollutants), associated with high viral infectivity rates and deaths. Is well known that exposure to nitrogen dioxide, sulfur dioxide and carbon monoxide causes respiratory symptoms and changes in airway physiology, being important contributors for associated COVID-19 comorbidities. These findings are supported by other scientific studies (Tung et al., 2021; Wang et al., 2022; Setti et al., 2020a; Penache and Zoran, 2019b), where they found a significant correlation between the daily average gaseous pollutants concentrations exceedances and COVID-19 spreading.

Temporal seasonality patterns of daily average ground levels of O_3, NO_2, SO_2, CO concentrations in relation with daily new confirmed COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) cases during the entire COVID-19 pandemic period in Bucharest metropolitan city are presented in Fig. 4.

Our results show that environmental pollution in Bucharest metropolitan city and the COVID-19 pandemic are significantly connected: higher levels of local and regional air pollutants increase the number of deaths of COVID-19, leading to a more severe course of the pandemic during the second and the third COVID-19 waves. It seems that plausible mechanisms linking urban air pollution to the spread and course of COVID-19 viral infection are: long-term exposure to urban air pollution linked to medical pre-conditions such as illnesses of the respiratory and immune systems that can exacerbate the course of the COVID-19 (Setti et al., 2020b; Chakrabarty et al., 2021; Wang et al., 2021); short-term exposure to air pollution that leads to inflammatory reactions and lower immune responses to new viral infections (Setti et al., 2020a, 2020b; Carugno et al., 2018); higher levels of air pollution increase the ability of viruses for airborne infection by prolonging the time the virus remains in open atmosphere (Gkatzelis et al., 2021).

3.2.2. Impact of radon on COVID-19 waves

If fine particulate matter PM2.5 is considered the fourth leading risk factor for death and disability in the world (GBD, 2020; WHO, 2016; Xu et al., 2020), radon- ^{222}Rn is the second cause of lung cancer, behind smoking (Hosoda et al., 2021). Joint short-term and long-term exposure to particulate matter and radon substantially increases the risk of human respiratory system damage. In order to assess the impact of the particulate matter and attached radon and its progeny on COVID-19 incidence and mortality during the recorded multiwaves with one total and other partial lockdowns and relaxation periods between 1 January 2020–December 21, 2021, daily time series patterns of the main air pollutants including radon have been analyzed.

Like particulate matter (PM2.5, PM10) and other gaseous pollutants O_3, NO_2, SO_2, CO, atmospheric radon presents typical diurnal, seasonal and inter-annual temporal variability patterns (Fig. 3).

Also, ^{222}Rn provides accurate information about urban pollution levels near the ground as well as of atmospheric dynamics conditions, 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 periods with elevated values under persistent synoptic inversion events, when outdoor radon concentrations may be higher for several days (Zoran et al., 2015).

For the entire COVID-19 pandemic period, daily outdoor radon exposure in Bucharest metropolitan city had a weak positive correlation with daily new COVID-19 confirmed (DNC) cases and deaths (DND) (rDNC = 0.16, $p < 0.01$), and DND (daily new deaths) (rDND = 0.14, $p < 0.01$) (Table 1), but cumulative association with particulate matter in both size fractions PM2.5 and PM10 may have a higher negative impact on respiratory system.

Also, during the entire COVID-19 investigated period in this study was recorded a daily average of outdoor ^{222}Rn of (38.33 ± 21.56) Bq/m^3 in the range of (8.7–270) Bq/m^3, values that are comparable with the daily annual outdoor ^{222}Rn concentration measured during pre-pandemic COVID-19 period (2015–2019) years, of an average value of

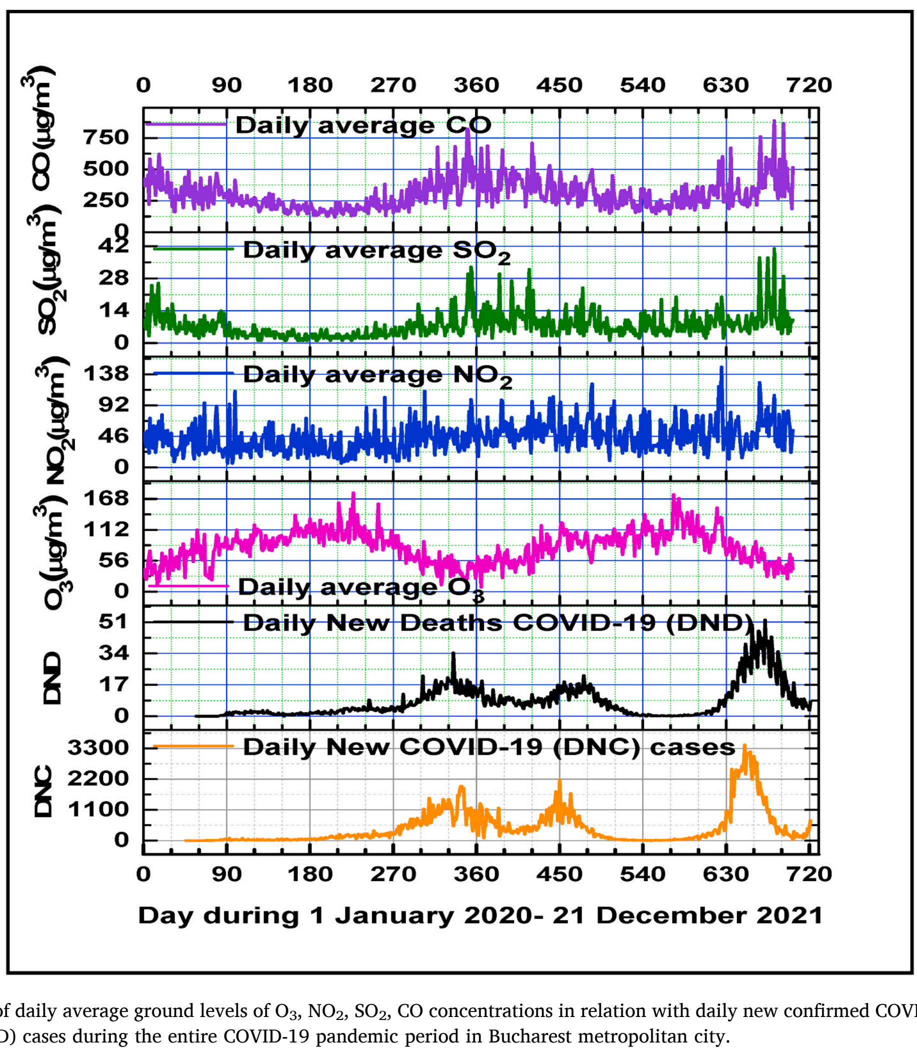

Fig. 4. Temporal patterns of daily average ground levels of O_3, NO_2, SO_2, CO concentrations in relation with daily new confirmed COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) cases during the entire COVID-19 pandemic period in Bucharest metropolitan city.

35.7 Bq/m^3, in the range of (11.0–115.0) Bq/m^3 (Zoran et al., 2019b). The measured indoor radon concentrations in different buildings in Bucharest city were placed in the range of (42.0–154.0) Bq/m^3 with an average value of 109.4 Bq/m^3 (Calin et al., 2019), values that do not exceed the threshold limits established by European legislation, but may have a high potential risk of indoor exposure, under low ventilation dwellings.

This article focused on outdoor radon- ^{222}Rn due to the availability of time series monitoring data, being known that it is the dominant source to internal exposure, and long-term outdoor and indoor radon exposure induced damages to bronchial epithelial cells and the human lung through increasing oxidative stress (La Verde et al., 2022; Suarez-Lopez et al., 2021). Was recognized 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 can become comparable (Borro et al., 2021). In some geologic areas with high natural background radiation, outdoor radon concentrations could be high and comparable to those indoors, the enhanced outdoor radon concentrations might be as a result of atmospheric conditions (Hosoda 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.Radon is recognized as a public health issue and joint exposure to radon, air pollutants and SARS-CoV-2 pathogens substantially increases the risk of developing severe COVID-19 viral infections. However, in the circulated air in 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 both the distribution and colony of indoor microbial populations, and ^{222}Rn in air concentrations.

Was demonstrated that the inhaled doses of indoor radon on humans during COVID-19 lockdown and the associated cancer risk may increase from 0.76% to 17.55% (Maya et al., 2020). While in the open spaces airborne transmission of SARS-CoV-2 pathogens (Kayalar et al., 2021) by droplets and aerosols largely depends on particulate matter concentrations and distribution, meteorological and stability conditions, in indoor environments, airborne transmission depends mainly on the pathogens concentrations and ventilation conditions.

In light of the increasing evidence of the airborne transmission risks of the SARS-CoV-2 coronavirus and its new variants, this study considers an imperious need to ensure the adequate indoor air quality in residential buildings has arisen. It is essential to understand the linkage between exposure to radon and its progeny both outdoor and indoor in relation with COVID-19 incidence and other viral infections to come. The reduction of indoor radon levels is an important task from the viewpoint of radiological protection and COVID-19 spreading.

3.3. *Association between climate parameters variability, air pollution and COVID-19 waves patterns*

3.3.1. *Impacts of climate parameters on COVID-19 transmission*

In order to describe the meteorological conditions over Bucharest metropolitan region, which can be involved in the transmission and severity of COVID-19 disease during different seasons over the entire investigated time period (January 1, 2020–21 December 2021), this study analyzed the temporal patterns of daily average climate parameters (air temperature-T at 2 m height, air temperature amplitude Tmax-Tmin, relative air humidity-RH, atmospheric pressure-p, wind speed intensity-w, Planetary Boundary Layer height-PBL, surface solar irradiation-SI). For per-waves analysis climate variables used in this study were mean-centered and scaled to a one standard deviation change so that estimated effects were for a one standard deviation change in long-term exposure applied per each period of COVID-19 multiwaves (Table 2S).

During the entire pandemic studied period, based on Spearman rank correlation analysis, Table 2 clearly shows that daily new COVID-19 incidence and mortality cases were inversely correlated with daily average air temperature (rDNC = −0.48, $p < 0.01$; rDND = −0.58, $p < 0.01$). According to the results of this study, cold weather is much more susceptible for the daily new COVID viral infection transmission in Bucharest than in case of warm weather conditions as can be seen in Fig. 5. Our results suggest that increase in the temperature decreases the viability, stability, survival of SARS-CoV-2 pathogens and transmission of COVID-19. 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). Although most studies indicated an inverse association of viral community spread with temperature, some findings reported a positive relationship between temperature and the number of COVID19 cases (Menebo, 2020; Li et al., 2020; Xie and Zhu, 2020; Bashir et al., 2020; Xie and Zhu, 2020; Pani et al., 2020; Islam et al., 2021) and few studied found no correlation (Briz-Redón and Serrano-Aroca, 2020).

This effect may explain also the lower incidence and lethality of COVID-19 during summer hot periods in a temperate city like Bucharest in Romania. Our results are in good agreement with other studies, which demonstrated that air temperature and relative humidity parameters are involved in the transmission of the SARS-CoV-2 viral infection, playing an important role in the COVID-19 mortality rate (Byun et al., 2021; Chen et al., 2021a, b; Ma et al., 2020; Shi et al., 2020; Adams, 2020; Ahmadi et al., 2020; Poole, 2020).

The findings of this study highlight a moderate positive correlation between daily air relative humidity and new COVID-19 cases (DNC) and deaths (DND) as can be seen in Fig. 5 and Table 2, Spearman rank correlation coefficients being respectively $r = 0.37$, $p < 0.01$, and $r = 0.40$, $p < 0.01$, for the entire analyzed pandemic period in Bucharest. Contrary to expectations, the current study found that air high moisture content accelerated the increase in the daily new confirmed cases and deaths. Similar results were found by other studies (Haque and Rahman, 2020; Sarkodie and Owusu, 2020).

Moreover, statistically, the weaker positive correlations were also recorded in Bucharest city between daily average atmospheric pressure and COVID-19 incidence and deaths throughout the entire study period with respect to both correlation coefficient results (rDNC = 0.23, $p < 0.01$; rDND = 0.29, $p < 0.01$).

Also this study found significant anticorrelations between daily average Planetary Boundary Layer heights over Bucharest city and daily new COVID-19 confirmed cases and mortality as follows: rDNC = −0.53, $p < 0.01$ and respectively rDND = −0.57, $p < 0.01$. High levels of daily PBL of (1607.19 ± 526.06) m registered during the first COVID-19 wave in Romania may explain the low severity of the first COVID-19 wave in Bucharest city in comparison with the rest of some European

Table 2
Spearman rank correlation coefficients and p values between COVID-19-incidence cases, and daily average of climate variables for investigated metropolitan Bucharest city during entire analyzed pandemic period 26 February 2020–December 21, 2021.

Bucharest	Daily average climate parameter					
COVID-19 incidence	PBL (m)	T (°C)	RH (%)	w (km/h)	SI (W/m^2)	p (hPa)
Daily New confirmed cases (DNC)	−0.53*	−0.48*	0.37*	−0.12*	−0.64*	0.23*
Daily New Deaths (DND)	−0.57*	−0.58*	0.40*	−0.11*	−0.62*	0.29*

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 $p < 0.01$.

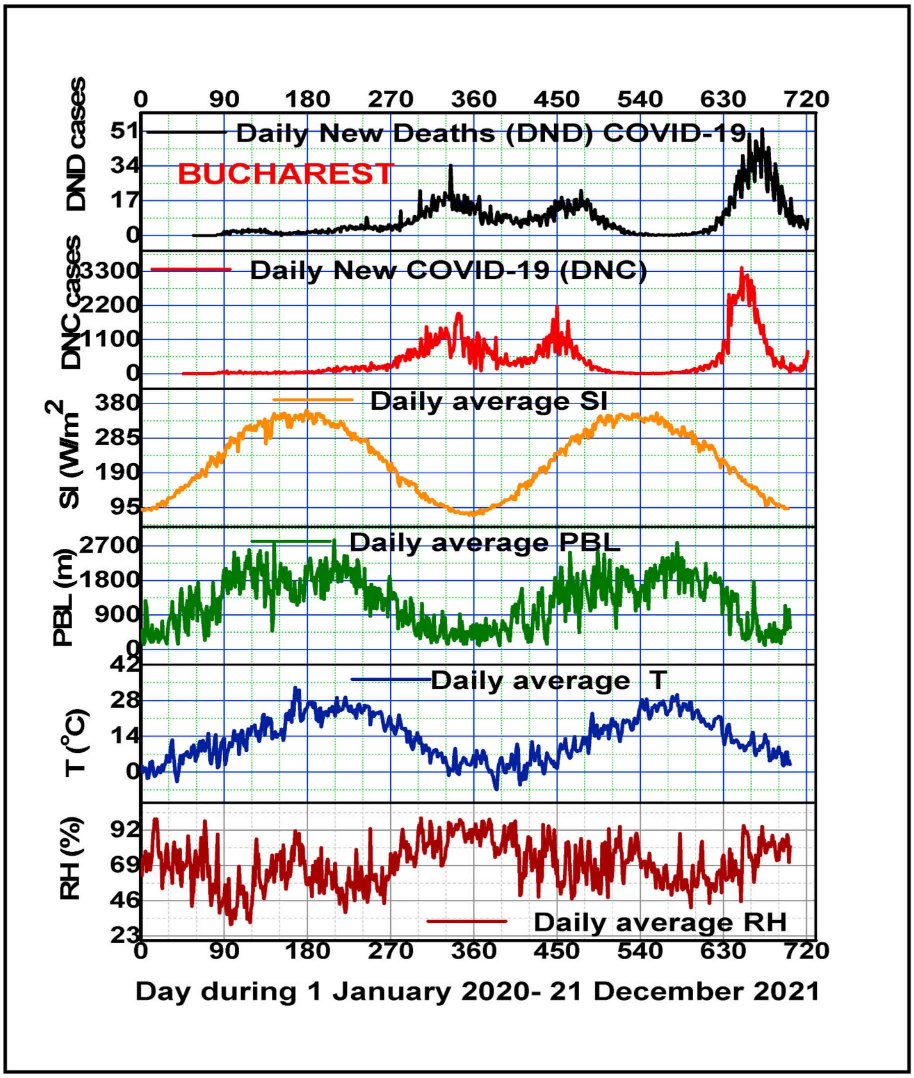

Fig. 5. Temporal patterns of daily average air temperature and relative humidity, Planetary Boundary Layer height and surface solar irradiance in relation with daily new COVID-19 positive cases (DNC) and daily new COVID-19 deaths (DND) during the four COVID-19 pandemic waves in Bucharest region.

metropolitan cities (D'Amico et al., 2022; Zoran et al., 2020a; Zoran et al., 2020b; Zoran et al., 2021). An opposite situation was recorded during the second, and the fourth COVID-19 waves when the daily average PBL heights recorded abnormally low values per each wave and season, being respectively of (538.74 ± 293.26) m, and (920.23 ± 603.25) m, that can explain high rates of infectivity and deaths in Bucharest city. Being related to the vertical mixing dynamics and dilution or accumulation of pollutants and bioaerosols (bacteria, fungi, and viruses) near the ground level (Tang et al., 2016), Planetary Boundary Layer height (PBL) is involved directly in COVID-19 spreading, especially in urban areas. If lower levels of PBL heights may be associated with increased viral pathogens concentrations at the near surface, and higher transmission rates, higher levels of PBL heights usually found in the summer periods are responsible of pathogens dilution and lower rates of viral diseases spreading.

The most statistically significant negative correlations were observed for surface solar irradiance and daily new COVID-19 confirmed cases and mortality as follows: ($rDNC = -0.64$, $p < 0.01$; $rDND = -0.62$, $p < 0.01$). The results of the current study were consistent with the outcomes of other studies, emphasizing that the increase in temperature and solar radiation caused a decreasing trend in the COVID-19 incidence cases and deaths (Srivastava, 2021; Rahimi et al., 2021; Rosario et al., 2020).

Based on cross-sectional variation, this paper demonstrates the important role of climate variables at urban and regional scales in the COVID-19 pandemic disease spreading (Chen et al., 2021b). As temporal variability of COVID-19 disease is a function of independent air pollution and meteorological seasonal variables, it is also seasonal sensitive. Like other viral infections (human influenza virus, coronaviruses, etc.) SARS-CoV-2 and its new variants of concern and interests could exhibit seasonal patterns (Byun et al., 2021; Zoran et al., 2021), and multi-wave patterns.

Besides socio-demographic factors, the fast diffusion of the SARS-CoV-2 pathogens and high rates of COVID-19 incidence and lethality can be attributed to high levels of air pollution and natural radioactivity, and local and regional meteorology like as low PBL height levels, low solar irradiance and air temperature, low wind speed, which means atmospheric stability, preventing the dispersion of air pollutants containing viruses and bacteria (Liu et al., 2021; Barouki et al., 2021; Araújo and Naimi, 2020).

3.3.2. Linkage between climate variability and air pollution

To integrate controls on particulate matter PM2.5, PM10 in forms of aerosols and bioaerosols (fungi, bacteria, and viruses), and gaseous pollutants O_3, NO_2, SO_2, CO including ^{222}Rn on pandemic viral infections transmission it is necessary to understand the impacts of climate and synoptic meteorology on these variables. Thereby, the complex linkages between synoptic forcing, regional transport, and air pollution in Bucharest during several seasons of pandemic COVID-19 waves were investigated using long-term daily time series observational, geospatial, and reanalysis data.

For the entire COVID-19 analyzed period in Bucharest, this study found positive significant correlations (Table 3) between daily average radon concentrations in Bucharest and: daily average concentrations of PM2.5 ($r = 0.44$, $p < 0.01$), PM10 ($r = 0.35$, $p < 0.01$), NO_2 ($r = 0.38$, $p < 0.01$), SO_2 ($r = 0.21$, $p < 0.01$), and CO ($r = 0.28$, $p < 0.01$). Also, the daily average ground level O_3 concentration has an opposite seasonal pattern with PM2.5, PM10, NO_2, SO_2, CO, and radon ($r = -0.21$, $p < 0.01$).

Also, the results in Table 3 show positive and high correlations between the daily average ground levels ozone concentration and air temperature ($r = 0.75$, $p < 0.01$), Planetary Boundary Layer heights ($r = 0.73$, $p < 0.01$), and surface solar irradiance ($r = 0.76$, $p < 0.01$), and inversely correlations with air relative humidity ($r = -0.64$, $p < 0.01$), and air pressure ($r = -0.29$, $p < 0.01$). The daily average of ground nitrogen dioxide concentration levels show an inverse correlation with climate parameters than ozone. The daily average of particulate materials (PM2.5 and PM10), nitrogen dioxide, sulfur dioxide, carbon monoxide, and radon present inverse correlations with PBL heights, air temperature, wind speed intensity, and surface solar irradiance, while low and positive correlations with air relative humidity. The findings are well correlated with the existing literature (Adams, 2020; Ahmadi et al., 2020; Poole, 2020; Ma et al., 2020; Miao and Liu, 2019; Xie and Zhu, 2020), having a high impact on COVID-19 spread.

Seasonal variation of both air pollutants and viral bioaerosols (Guzman, 2021; Gong et al., 2020; Du et al., 2018; Gao et al., 2015) in the lower atmosphere, associated with climate seasonal variability can explain also the increased COVID-19 DNC and DND cases during the winter season (Duval et al., 2021). Like for other temperate countries, in Romania and its capital Bucharest, there is a linkage between climate variables seasonality and direct impacts on COVID-19 viral infection seasonality. This result was demonstrated also by other studies (D'Amico et al., 2022; Zoran et al., 2022).

In good accordance with existing literature, this study found also that air pollution and climate variability may promote the transmission of SARS CoV-2 pathogens and increase the incidence and mortality of COVID-19 cases in Bucharest, capital of Romania. Environmental factors are mainly responsible for the dispersal, transmission, and infectivity rate of the SARS-CoV-2 pathogens and their new variants virions (Islam et al., 2021; Huang et al., 2020; Amin et al., 2020; Hassanzadeh et al., 2020).

Air pollution, climate and other environmental factors like wastewaters, etc., can favour the growth, multiplication and spread of SARS-CoV-2 pathogens mostly for people with low immunity systems (Lavine et al., 2021). Additional considered risk factors for the fast-spreading of COVID-19 disease among the vulnerable populations during the outbreak can be rapid urbanization, industrialization, globalization and migration of people (Candido et al., 2020; Coccia, 2021). In a conclusion, seasonal variability of climate parameters and outdoor exposure to near the ground air pollutants concentrations may have a significant impact on the severity of COVID-19 disease transmission and its seasonality.

3.4. Synoptic atmospheric circulation patterns related to COVID-19 waves evolution

Is considered that under some local and regional climate conditions, the probability of outdoor airborne transmission depends on virus-laden aerosol concentrations, its viability and lifetime, and the minimum dose necessary to transmit the disease. During stagnant air and atmospheric inversions over several days are recorded high levels of air pollutants in large European cities (Garrido-Perez et al., 2018).

For the entire analyzed period (1 January 2020–21 December 2021), during each of the COVID-19 multiwaves in Bucharest were recorded anomalous anticyclonic synoptic meteorological patterns in the mid-troposphere, with stability conditions favorable for COVID-19 disease fast spreading. The epidemiologic trend of the COVID-19 pandemic disease transmission in Bucharest during the entire investigated period can be uniquely categorized according to the five different periods and four waves and associated public health measures implemented in the metropolitan region and Romania:

1) A first COVID-19 wave (26 February 2020–15 June 2020)
2) Pre-second COVID-19 wave which started with increasing social activities and tourism (15 July 2020–30 September 2020)
3) The second COVID-19 wave (1 October 2020–January 31, 2021)
4) The third COVID-19 wave (1 February 2021–1 June 2021)
5) The fourth COVID-19 wave (1 September 2021–21 December 2021)

The above-mentioned COVID-19 multiwaves were captured through the epidemiologic surveillance system of severe symptomatic confirmed COVID-19 cases and might hide additional peculiar features of the pandemic in Bucharest. Synoptic meteorological conditions over the Bucharest area during the five analyzed COVID-19 periods were provided by NCEP/NCAR Reanalysis Intercomparison Tool/NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado, by composite anomaly maps of 500 hPa geopotential heights.

For the first COVID-19 wave, based on NCEP/NCAR Reanalysis Intercomparison Tool provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado, Fig. 6a presents satellite positive composite anomaly pattern in the upper troposphere of 500 mb geopotential

Table 3
Spearman rank correlation coefficients and p values between daily mean of the main air pollutants and climate variables in Bucharest metropolitan city during the entire analyzed period (1 January 2020–December 21, 2021).

Factors	PM2.5	PM10	O_3	NO_2	SO_2	CO	Rn	T	RH	SI	w	p
PM10	0.51*											
O_3	−0.39*	−0.29*										
NO_2	0.40*	0.54*	−0.31*									
SO_2	0.27*	0.64*	−0.33*	0.52*								
CO	0.27*	0.81*	−0.47*	0.52*	0.70*							
Rn	0.44*	0.35*	−0.21*	0.38*	0.21*	0.28*						
T	−0.33*	−0.47*	0.75*	−0.29*	−0.42*	−0.60*	−0.11*					
RH	0.16**	0.23*	−0.64*	0.23*	0.21*	0.32*	0.09***	−0.47*				
SI	−0.49*	−0.52*	0.76*	−0.48*	−0.46*	−0.59*	−0.32*	0.77*	−0.51*			
w	−0.07***	−0.34*	−0.08**	−0.39*	−0.27*	−0.29*	−0.23*	−0.11**	−0.11**	−0.05***		
p	0.22*	0.32*	−0.29*	0.22*	0.27*	0.33*	0.08***	−0.42*	−0.03***	−0.34*	−0.17**	
PBL	−0.40*	−0.48*	0.73*	−0.44*	−0.41*	−0.51*	−0.23*	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), O_3 (ozone), NO_2 (nitrogen dioxide), SO_2 (sulfur dioxide), CO (carbon monoxide), ^{222}Rn (radon activity), 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; * and ** indicate $p < 0.05$ and $p < 0.01$ respectively and *** indicates $p > 0.05$.

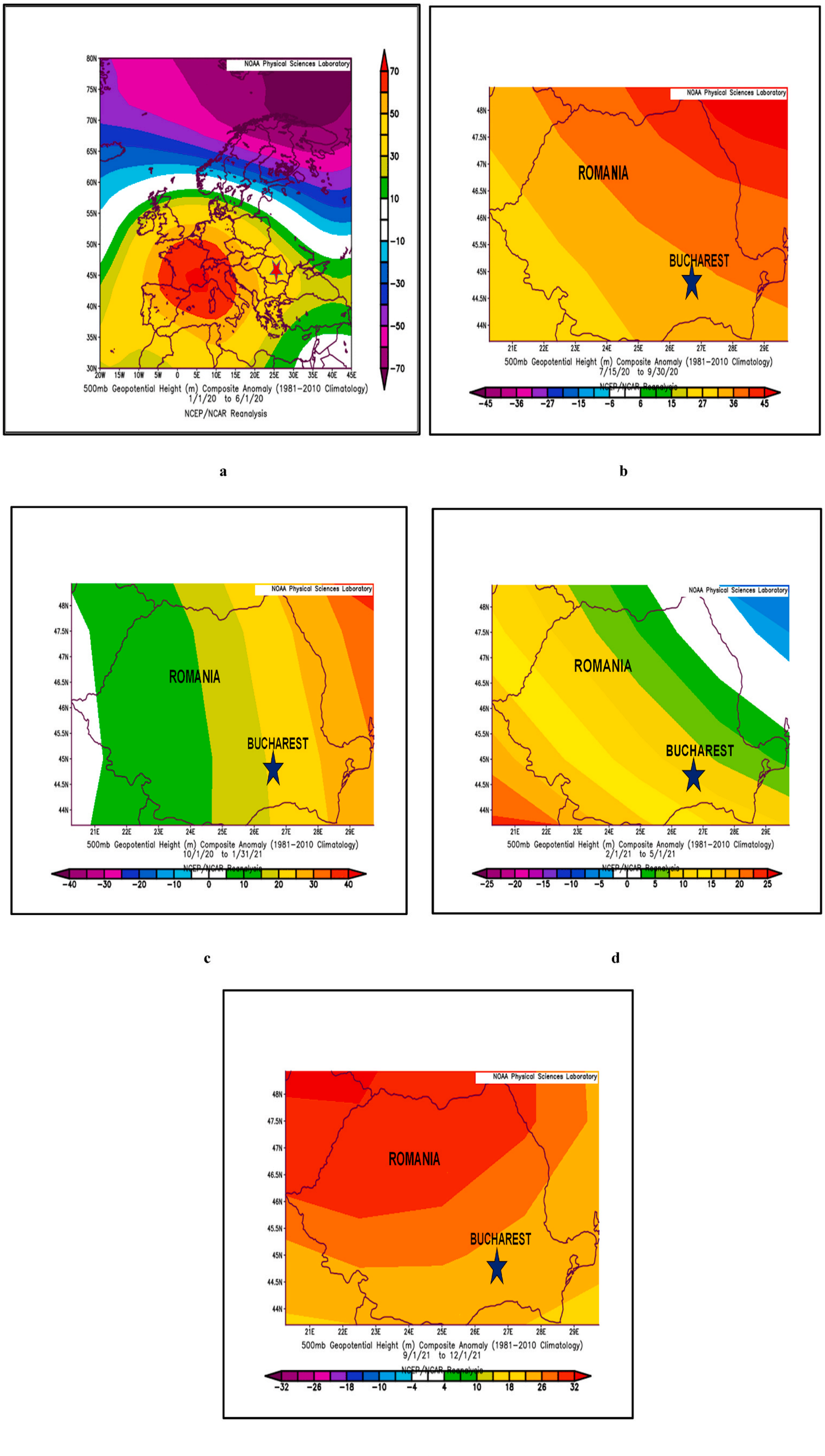

Fig. 6. a. Composite anomaly map of 500 mb geopotential (**b**). Composite anomaly map of 500 mb geopotential height over Europe during the first COVID-19 wave Romania during the pre-second COVID-19 wave in Bucharest.(**c**). Composite anomaly map of 500 mb geopotential (**d**). Composite anomaly map of 500 mb geopotential height height over Romania during the second over Romania during the third COVID-19 wave in Bucharest.(**e**). Composite anomaly map of 500 mb geopotential height.

height (m) map at 5.5 km height, as compared to the climatology average (1981–2010) period over Europe, where can be seen that during before and the first COVID-19 wave, over Romania and Bucharest have recorded low positive anomalies (light yellow colors) associated with the lower stability conditions in comparison with Italy, France, and Spain, where have been recorded strong anticyclonic conditions (atmospheric inversion) and higher geopotential anomalies (red color), that favour accumulation of air pollutants near the ground, associated with higher COVID-19 incidence and mortalities rates. Also, in Bucharest during the first COVID-19 wave have been registered high levels of PBL heights (Table 2S), that favored the dilution of pollutants including radon at the ground level and limited SARS-CoV-2 viral infection transmission, being recorded (2399 DNC cases, and 126 DND cases per wave).

In case of the pre-second COVID-19 wave, higher levels of PBL heights associated with the presence of anomalous synoptic anticyclonic circulations, and positive anomalies of isobaric surface heights of geopotential at 500 mb recorded (Fig. 6b)over Bucharest limited the air pollutants accumulation near the ground with a direct impact on COVID-19 spreading (13,649 DNC cases, and 266 DND cases per wave).

Also, in the case of the second COVID-19 have been recorded anomalous synoptic anticyclonic blocking atmospheric circulations with positive anomalies of isobaric surface heights of geopotential at 500 mb, associated with favorable stability, stagnant conditions for the fast diffusion of the SARS-CoV-2 (Fig. 6c). Association with lower levels of daily average PBL heights (Table 2S) were favorable for the main air pollutants accumulation near the ground and COVID-19 spreading (Table 1S). However, clinically severe cases and lethality rates in Bucharest were higher than in the first COVID-19 wave.

In case of the third COVID-19 wave, during the spring-summer of 2021 year 2021, associated anomalous synoptic anticyclonic circulations, with downwards positive anomalies of isobaric surface heights of geopotential at 500 mb over Bucharest (Fig. 6d), explains an increased number of COVID-19 incidence (64,848 DNC cases) and mortality (1166 DND cases), while higher values of daily average PBL heights (Table 2S), may explain the lower COVID-19 severity than in case of the second wave (101,018 DNC cases, and 1421 DND cases per wave) associated with lower PBL heights.

During the fourth COVID-19 wave, Fig. 6e provided by NCEP/NCAR Reanalysis Intercomparison Tool presents satellite positive composite anomalous synoptic anticyclonic conditions, with downwards airflows in the upper troposphere of 500 mb geopotential height (m), 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 (Table 2S) per wave contributed also at COVID-19 severity. The comparative analysis of the second COVID-19 wave star-up in Bucharest with the fourth COVID-19 wave under similar anticyclone weather conditions, lower levels of daily average PBL height, may support the hypothesis that the strong atmospheric stability and associated climate factors seasonality are related with the fourth COVID-19 wave evolution.

Fig. 7 presents the Daily New COVID-19 Confirmed positive (DNC) cummulated cases and Daily COVID-19 deaths (DND) cummulated cases per waves in Bucharest metropolitan city during the recorded multi-waves (Tables 1S and 2S). The recorded differences in the response to the COVID-19 pandemic waves periods can be attributed to different infectivity rates of new variants of SARS-CoV-2 as well as to adopted prevention and interventions strategies both at the metropolitan and at the municipality level. Timely and proper intervention policies, such as intensive contact tracing followed by quarantine and isolation, and intense vaccination procedure can effectively reduce the spreading risk of the new more contagious SARS-CoV-2 variants (Cevik et al., 2021; Diao et al., 2021; Jin et al., 2021).

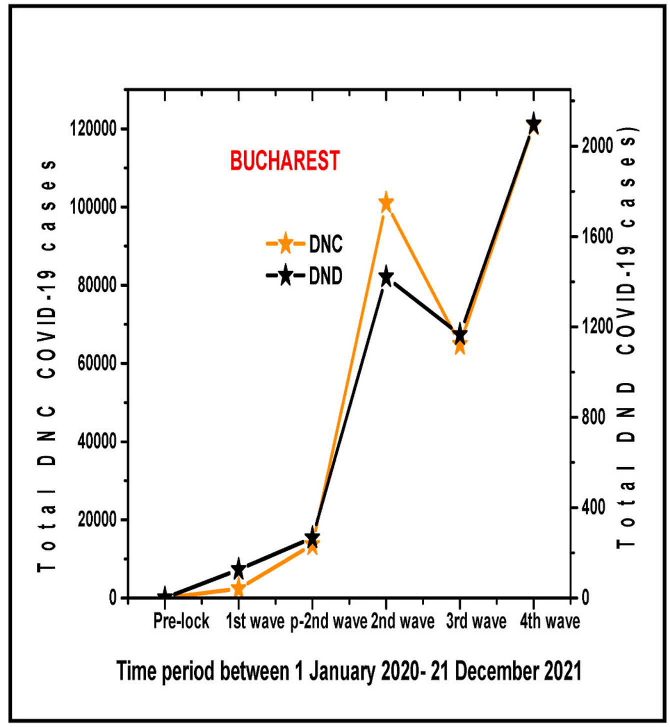

Fig. 7. Total Daily New COVID-19 Cases and Total Daily over Romania during the fourth COVID-19 wave in Bucharest. COVID-19 Deaths per study periods recorded in Bucharest city.

Bucharest's location in a large depression-like structure, Romanian Plain surrounded by Carpathians Mountain barriers is associated with strong tropospheric anticyclonic systems, that favour accumulation of virus-laden aerosol concentrations near the ground and COVID-19 disease transmission, especially during late fall and winter seasons, and explains the existing correlations between urban air pollution episodes and COVID-19 multiwaves. Like other studies on COVID-19 waves, their occurrence has been associated with strong anticyclonic systems blocking zonal circulation (Sanchez-Lorenzo et al., 2021; Zoran et al., 2021). During last decades was observed 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).

There is a broad scientific consensus in the field of environment-COVID-19 interaction (Domingo and Rovira, 2020; Sanchez-Lorenzo et al., 2021; Liu et al., 2021; Zoran et al., 2022; Rayan, 2021), and our analysis shows that seasonality of urban air pollution including radon, climate and synoptic atmospheric circulations patterns may play an important role in the airborne seasonality transmission of the COVID-19 disease. However, climate variables seasonality alone is not sufficient to stop the coronavirus transmission during the summer warm season. The results based on air pollution including radon and climatological characteristics of Bucharest metropolitan city in Romania displayed remarkable impacts on COVID-19 incidence and mortality.

4. Strengths and limitations

This paper includes the following strengths: 1) a longer observation time period over environmental factors related to COVID-19 epidemiology in the Bucharest metropolitan region, that spanned several seasons from January 1, 2020 till December 21, 2021, allowing us to examine a larger range of time series meteorological and air quality data, as opposed to data from just a season; 2) the influence of daily climatic parameters, and ground level air pollutants (PM2.5, PM10, O_3, NO_2, SO_2, CO, including ^{222}Rn) on the COVID-19 incidence (daily new confirmed and new deaths cases) were studied for the first time for Bucharest large city in Romania; 3) in spite of existing several studies that analyzed the role of outdoor air pollution and climate variables on the incidence and severity of COVID-19, currently there are no studies that consider environmental factors seasonal mutual relationship with ongoing COVID-19 pandemic event and the cumulative impacts of outdoor radon-^{222}Rn effects; 4) combined use of satellite and surface observations to study environmental factors-COVID-19 disease transmission; 5) lessons learnt from earlier publications on COVID-19 evolution were considered. Was also possible to make a comparison between the COVID-19 waves in Bucharest. Furthermore, in an observational time series analysis of COVID-19 epidemiologic data over a nearly two years period, we do not expect human individual risk factors to vary averageingfully over the study period.

The identified limitations of this study are: 1) despite the use of official COVID-19 incidence and mortality data reported in Romania, undertesting and underreporting throughout the course of the pandemic may produce uncertainties of COVID-19 cases, limiting this study's capability to capture all COVID-19 cases; 2) from an epidemiologic viewpoint: nevertheless, due to the unavailability of health variables related to comorbidities at the metropolitan level that are missing, although they are potentially contributing variables (Sarmadi et al., 2021); 3) a further limitation that restricts the explanatory power of this study concerning daily new COVID-19 incidence is the unknown number of asymptomatic cases, those who are asymptomatically infected are contagious (Kronbichler et al., 2020) and therefore, estimations of the relationship between air pollutants and COVID-19 may be biased by the unknown metropolitan distribution of asymptomatic cases; 4) also, from an epidemiologic viewpoint, nevertheless, due to the unavailability of health variables related to comorbidities at the metropolitan level that are missing, although they are potentially contributing variables (Sarmadi et al., 2021); 5) also, due to COVID-19-related economic and social policies and sanitary restrictions, like lockdowns and stay-at-home measures, it is possible to be unregistered air pollution at the ground levels, limiting correlation analysis results, for exposure of air pollutants to individuals with pre-existing comorbidities; 6) while the COVID-19 vaccine becomes widespread, virus transmission becomes more complex, at least in the case of the last more contagious variant of concern Omicron (Poudel et al., 2022; Wouters et al., 2021), that averages to consider also vaccination data, which may pose some restrictions to our analysis.

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

5. Conclusions and policy implications

We carried out a systematic analysis of the daily time-series data of the main air pollutants, meteorological and COVID-19 incidence and mortality, collected from Bucharest metropolitan city in Romania, to detect the existing 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 linkage between air pollutants exposure and pathogenesis of COVID-19 remain unknown, this research supports the hypothesis that exposure to outdoor high levels of air pollution increases the risk of COVID-19 incidence and mortality. Positive associations with COVID-19 rates were observed for PM2.5, PM10, NO_2, SO_2, CO and ^{222}Rn, and negative associations for O_3 ground levels during the entire pandemic period in Bucharest metropolitan city. Specifically, we noted clear inversely correlations 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. Recorded anomalous anticyclonic synoptic meteorological patterns in the mid-troposphere, associated with stability conditions during fall-winter periods favour COVID-19 disease fast-transmission, mostly during the second, and the fourth waves. Outdoor exposure to highly ambient air pollution associated with radon is a non-negligible driver of COVID-19 related incidence and deaths, and climate variables are risk factors in spreading of SARS-CoV-2 pathogens, which may suggest COVID-19 viral infection mutual seasonality. Climate conditions may play a significant role in reducing COVID-19 transmission especially in large urban areas as the pandemic continue, but continuous surveillance and adoption of prevention and control strategies under seasonal variability of environmental factors and the new SARS-CoV-2 variants of concerns will remain an important task for future viral infections.

As changing environmental risk factors, exposure to air pollution including radon, and climate variability are considered possible risk factors for increased COVID-19 disease severity and mortality during pandemic waves. Also, adopting air pollution regulations in metropolitan regions and decreased air pollution exposure may help the reduction in the burden of COVID-19, and possibly other viral respiratory diseases outcomes.

Credit author statement

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

Consent for publication

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

Consent to participate

Not applicable.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envres.2022.113437.

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