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SEASONAL CORRELATION BETWEEN ATMOSPHERIC POLLUTION AND COVID-19 INCIDENCE DERIVED FROM SATELLITE AND GROUND-BASED OBSERVATIONS: A CASE STUDY OF SOFIA AND BURGAS

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Abstract
The epidemiological footprint and clinical severity of COVID-19 are significantly modulated by atmospheric contaminants, notably nitrogen dioxide (NO_2) and fine particulates. This research focuses on the seasonal dynamics of air quality in relation to COVID-19 within Bulgaria. By leveraging satellite-based tropospheric Absorbing Aerosol Indices (AAI) from the GOME-2 instruments, we mapped aerosol loading from mid-2020 through July 2024. Case studies for the municipalities of Sofia and Burgas integrated these satellite retrievals with localised ground-based measurements. Our observations revealed distinct, synchronised seasonal patterns: pollution and case numbers both peak during late winter, decline significantly in summer, and re-emerge as autumn progresses. A central outcome of this work is a robust GIS database that serves as an adaptable spatial platform for investigating various respiratory conditions and environmental health indicators.

1. Introduction

The baseline environmental condition in Bulgaria is characterised by significant exposure to particulate matter and gaseous pollutants, largely driven by domestic heating with solid fuels, an ageing vehicle fleet, and heavy industrial activities concentrated in specific regions such as Stara Zagora [1–3]. Studies have demonstrated that long-term exposure to these pollutants not only increases the prevalence of pre-existing cardiovascular diseases (CVD) but also heightens the susceptibility of the population to respiratory infections [4, 5]. In major urban centres such as Sofia, Plovdiv, and Varna, the convergence of high population density and localised pollution hotspots creates an environment where respiratory pathogens can propagate more effectively [4].

Bulgaria faces a unique set of challenges regarding extreme weather events and persistent air pollution from fossil fuel burning and traffic congestion [4]. This is of growing concern, as air pollution was the second-leading risk factor for approximately 8.1 million cases of premature mortality globally in 2021. In the EU-27, a total of 327,000 deaths were attributable to exposure to PM2.5, NO_2, and O_3 and concentrations above the 2021 WHO guideline levels [1]. Bulgaria, specifically, suffers from the highest CVD mortality rate in the EU, often exacerbated by the release of proinflammatory mediators in the lungs in response to inhaled pollutants. These mediators trigger oxidative stress and systemic inflammation, leading to endothelial dysfunction and atherosclerotic plaque formation [4].

Comparative Air Quality Standards and Bulgaria's Compliance

The regulatory landscape in Bulgaria is shaped by both European Union (EU) directives and World Health Organisation (WHO) guidelines. However, a stark disparity remains between these two frameworks, particularly following the 2021 update to WHO guidelines [1, 6]. While EU standards provide a legal threshold, the WHO guidelines reflect a stricter health-based ideal that highlights the ongoing risks even at concentrations currently deemed legal under regional law [1].

Table 1. Comparison of WHO 2021 annual air quality guidelines and EU limit values with observed typical ranges for major atmospheric pollutants in Bulgarian urban areas (2020–2022)

Pollutant	2021 WHO Annual Guideline (µg/m^3)	EU Annual Limit Value (µg/m^3)	Typical Bulgarian Urban Range (2020–2022)
$PM_{2.5}$	5	20	15.0 – 25.2 [7, 8]
PM_{10}	15	40	25.0 – 45.0 [10, 11]
NO_2	10	40	18.0 – 35.0 [9]
SO_2	40 (24-hour)	125 (24-hour)	5.0 – 15.0 [3, 7]

The systematic failure to meet the lower WHO thresholds in Bulgarian cities has profound implications for the pandemic's impact. For instance, in Sofia, approximately one-fifth (20%) of all ischemic heart disease (IHD) hospitalisations are attributable to exposure [4, 9]. All Sofia residents live in neighbourhoods where levels exceed WHO guidelines, illustrating a significant baseline vulnerability of the respiratory and cardiovascular systems before any viral infection occurs [9].

Urban Microclimates and Topographical Influences

The topographical features of Bulgaria, especially the valley settings of Sofia and Plovdiv, exacerbate the accumulation of pollutants. In Sofia, the surrounding Balkan Mountains and Vitosha Massif contribute to frequent temperature inversions during the winter months [4, 10]. Under these conditions, the atmospheric boundary layer (ABL) remains stable, trapping emissions from traffic and domestic heating near the surface. This "bowl effect" increases pollution in central urban areas through flow convergence at night, when atmospheric conditions lack vertical mixing, leading to the accumulation of emitted pollutants near the surface [4, 10].

Analysis of the urban heat island (UHI) effect in Sofia reveals an average summer increase of 2.5˚C, which further complicates the dispersion of secondary pollutants [10]. The modification of urban landscapes has led to the formation of human-induced heat islands, affecting both air quality and disease burden. In Sofia, the risk of IHD increased primarily at cold temperatures, whereas in Plovdiv and Varna, both high and low temperatures were associated with IHD hospitalisations [4].

Mechanistic Linkages Between Air Pollutants and SARS-CoV-2

The biological and physical pathways through which atmospheric pollutants influence COVID-19 incidence are multifaceted, involving both the modulation of the host's immune response and the potential role of particles as viral carriers [5, 12].

Particulate Matter as Viral Vectors

Fine particulate matter, specifically, has been hypothesised to act as a "carrier" for the SARS-CoV-2 virus. These particles, characterised by a large surface area and high porosity, can adsorb viral droplets [5, 12]. The inhalation of these coronavirus-laden particles allows for deeper penetration into the respiratory system, potentially reaching the distal alveoli and subsequently entering the bloodstream [7, 12]. Studies utilising Aerosol Optical Depth (AOD) and the Absorption Aerosol Index (AAI) from satellite sensors have shown that regions with higher aerosol concentrations often correlate with increased clusters of respiratory distress cases [5]. Furthermore, the presence of can reduce the diffusion coefficient of viruses, effectively keeping them suspended in the breathing zone for longer periods [12].

Impairment of Immune Defence Mechanisms

Beyond acting as carriers, pollutants like and are known to induce systemic inflammation and oxidative stress within the lungs [4, 12]. Prolonged exposure impairs the function of alveolar macrophages and bronchial epithelial cells, which are the first line of defence against inhaled pathogens [4]. This inflammatory priming renders individuals more susceptible to severe manifestations of COVID-19, including pneumonia and prolonged recovery periods [5]. In Bulgaria, the spatial distribution of NO_2, mapped via the TROPOMI sensor, reveals that urban residents face a chronically elevated risk profile that likely contributed to the high COVID-19 case fatality rate [5, 13], NO_2-induced inflammation exacerbates immune responses, impairing the body's ability to combat infections effectively [5].

Remote Sensing and Ground-Based Data Integration

The assessment of seasonal correlations in Bulgaria relies on a hybrid monitoring approach, reconciling the high temporal frequency of ground stations with the comprehensive spatial coverage provided by satellite instruments [2, 14, 15]. The specific objectives of this study are:

1. To analyse the seasonal behaviour of Covid-19 and key pollutants (PM and NO_2) in two contrasting municipalities, Sofia and Burgas.
2. To develop a GIS database that integrates all relevant datasets and supports future applications to other respiratory diseases.

2. Materials and Methods

2.1. Study Area

Our research focuses on the territory of Bulgaria in Southeastern Europe, a region characterised by a complex administrative and demographic landscape. A critical factor in our modelling is the heterogeneous distribution of the population, which exhibits high-density clustering in major metropolitan hubs such as Sofia and Burgas, while remaining significantly sparse in rural and mountainous zones.

Furthermore, the operational structure of the Bulgarian healthcare system directly influences the granularity of our available data. Because comprehensive medical facilities and hospitals are primarily centralised in regional urban centres, patients from smaller, underserved settlements are forced to seek care in these hubs. Consequently, public health metrics and COVID-19 statistics are systematically aggregated and reported at the municipal level rather than at finer, more localised levels. This centralised reporting mechanism imposes an inherent limitation on the spatial resolution of our epidemiological analysis, precluding a more granular investigation into neighbourhood-level transmission dynamics.

2.2. Satellite Aerosol Products

GOME-2 Absorbing Aerosol Index

The Absorbing Aerosol Index (AAI) indicates the presence of elevated absorbing aerosols such as desert dust, biomass burning smoke and volcanic ash in the troposphere. AAI separates the spectral contrast at two UV wavelengths caused by absorbing aerosols from that due to Rayleigh scattering, surface reflection, gaseous absorption and scattering by non-absorbing particles. AAI is a unitless quantity; positive values are indicative of absorbing aerosols in the atmosphere, whereas near-zero or negative values generally correspond to weak or non-absorbing aerosol conditions [16].

In this study, we use monthly Level-3 AAI data derived from GOME-2 observations and distributed through the Tropospheric Emission Monitoring Internet Service (TEMIS) [17, 18]. The Level-3 product provides AAI values on a regular latitude-longitude grid with a spatial resolution of 1°. For the period

June 2020 – July 2024, we use data from the MetOp-B platform, which offers stable coverage over the study period. With 1° grid spacing, 17 grid cells fully cover the Bulgarian territory (Fig. 1).

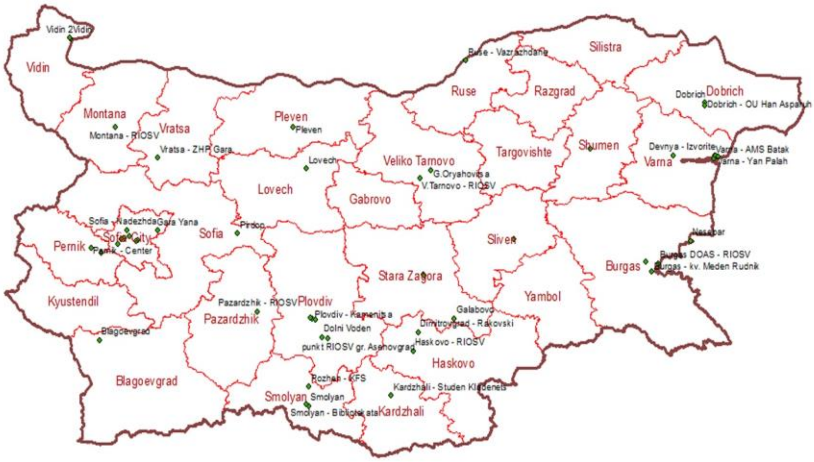

Fig. 1. Administrative division of Bulgaria into 28 municipalities and locations of official ground-based monitoring stations (GMSs)

2.3. Seasonal Analysis for Sofia and Burgas

To investigate seasonal relationships between COVID-19 and air pollution, we focus on two municipalities: Sofia (the capital and largest city, with relatively uniform distribution of population, health services and monitoring stations within a single municipality) and Burgas (a large coastal municipality with distinct geographic characteristics and the largest municipal area among the 28).

For both Sofia and Burgas, we compute monthly mean concentrations of PM1, PM2.5 and PM10 from IQAir sensors and, where available, from official GMSs. For Sofia, the Hipodruma station provides simultaneous measurements of PM2.5, PM19 and NO_2, which we use to construct seasonal cycles for these pollutants. The monthly mean AAI from satellite data is also averaged over the entire country and separately over Sofia and Burgas.

The seasonal cycle of COVID-19 is represented by the monthly mean number of active cases in each municipality. To highlight recurrent patterns, we compute the multi-year mean seasonal cycle of active cases and of each pollutant by averaging the same month over the years 2020–2024.

2.4. Statistical Analysis

The statistical analysis was designed to (i) characterise the spatial variability of air pollution and Covid-19 across the 28 Bulgarian municipalities, and (ii) examine the temporal (seasonal) co-variability between pollution indicators and COVID-19 in Sofia and Burgas.

2.4.1. Seasonal cycles and temporal co-variability

For Sofia and Burgas, we constructed monthly mean time series of:

- active Covid-19 cases,
- ground-based PM1, PM2.5, PM10 and NO_2 concentrations,
- satellite AAI (aggregated over the relevant municipality or over the national territory, as specified).

Given the limited length of the time series and the strong annual cycle of both pollution and Covid-19, we focused on the mean seasonal cycle. For each variable X and for each calendar month m (January–December), we averaged all available values for that month over the years 2020–2024:

(1) $$\overline{X}(m)=\frac{1}{N_m}\sum_{k=1}^{N_m} X_k(m)$$

where Nm is the number of years with data for month m, and $X_k(m)$ is the monthly mean in year k. This averaging reduces the influence of inter-annual variability and highlights recurrent seasonal patterns.

To facilitate comparison of the shapes of the seasonal cycles across variables with different units and magnitudes, we also considered normalised seasonal cycles, obtained by dividing $\overline{X}(m)$ by the annual mean of X or by expressing monthly deviations from the annual mean as anomalies:

(2) $$X'(m)=\overline{X}(m)-\frac{1}{12}\sum_{m'=1}^{12} \overline{X}(m').$$

The similarity between the seasonal cycles of Covid-19 and those of the pollutants was quantified using Pearson correlation coefficients computed across the 12 monthly mean values (or anomalies) for each pair of variables. These correlations were interpreted with caution, recognising that the 12 points are not independent over time and that both series are strongly influenced by common meteorological and behavioural drivers.

To explore potential time lags between pollution and Covid-19, we additionally examined lagged correlations between monthly pollution and Covid-19 series at lags of 0–2 months (pollution leading Covid-19). Given the short time series and the coarse monthly resolution, these lag analyses are purely exploratory.

Software and significance considerations

All statistical analyses and graphical representations were performed using standard scientific computing software and GIS tools for spatial aggregation and mapping. Throughout the paper, we report correlation coefficients and non-parametric test results primarily as descriptive measures of association. Given the observational nature of the data, the relatively small number of spatial units (28 municipalities) and the potential presence of unmeasured confounders, we do not attempt formal causal inference. Instead, statistical results are interpreted in conjunction with physical reasoning and with consistency across multiple independent data sources (satellite, ground-based and low-cost sensors).

3. Results and Discussions

We investigated the seasonal relationship between atmospheric pollution and COVID-19 incidence across 28 Bulgarian administrative regions over four years (June 2020 – July 2024), employing an innovative multi-source data integration approach combining GOME-2 satellite observations with ground-based measurements from both official monitoring stations and low-cost sensor networks [5, 19]. The central finding demonstrates that neither the Absorbing Aerosol Index (AAI) nor nitrogen dioxide (NO_2) alone adequately reproduce the spatial pattern of COVID-19 cumulative incidence. In contrast, their combination in a defined Pollution Index exhibits substantially improved spatial correspondence with the distribution of COVID-19 cases across Bulgarian municipalities [5]. This multi-pollutant approach represents a significant methodological advancement over single-pollutant analyses [20, 21] and aligns with emerging evidence that COVID-19 outcomes are modulated by complex interactions among multiple environmental stressors rather than by isolated pollutants [20, 21].

The observed seasonal cycles characterised by winter maxima, summer minima, and renewed autumn increases were consistent across geographically distinct regions (Sofia and Burgas), reinforcing the hypothesis that COVID-19 transmission in temperate continental climates exhibits pronounced seasonality driven by synergistic interactions between meteorological conditions and pollution levels [20]. The parallel seasonal evolution of pollution and COVID-19 incidence provides indirect support for mechanistic pathways through which chronic and acute air pollution exposure may enhance viral susceptibility and disease severity [21].

3.1. Seasonal Behaviour of Covid-19 and PM in Sofia and Burgas

Fig. 2 and Fig. 3 show the seasonal distribution of COVID-19 active cases in Sofia and Burgas, together with the seasonal cycles of PM1, PM2.5, and PM10 derived from IQAir sensors in both cities. The seasonal cycle of COVID-19 exhibits pronounced peaks during the first two to three months of the year, a clear minimum in summer and a renewed increase in the last two months of the year. The two municipalities display very similar seasonal patterns of Covid-19, despite their different geographical and climatic conditions.

The seasonal cycles of PM1, PM2.5, and PM10 also show the highest concentrations during winter and early spring, consistent with increased emissions from domestic heating and reduced dispersion efficiency. Concentrations decrease in summer, when atmospheric mixing is stronger and heating-related emissions are reduced, and then increase again in late autumn. The overall seasonal patterns of PM are comparable in Sofia and Burgas, although absolute levels and the relative amplitudes of the peaks may differ.

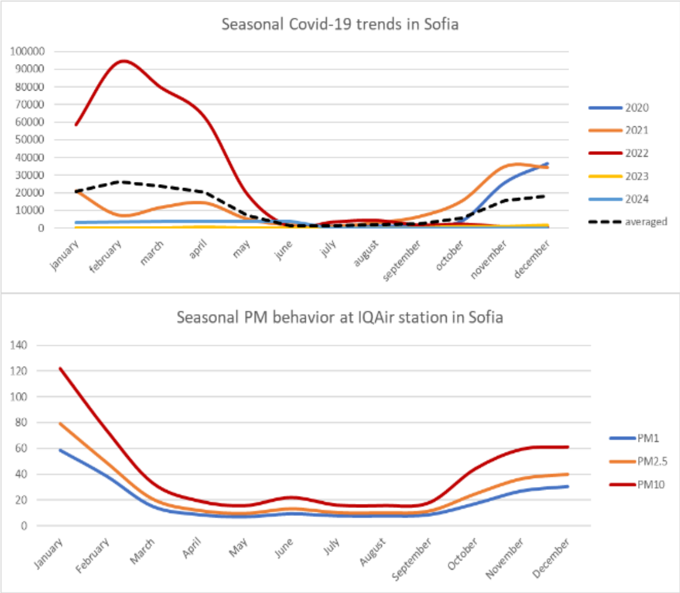

Fig. 2. Seasonal cycles of active COVID-19 cases and PM1, PM2.5 and PM10 concentrations in Sofia derived from IQAir sensors

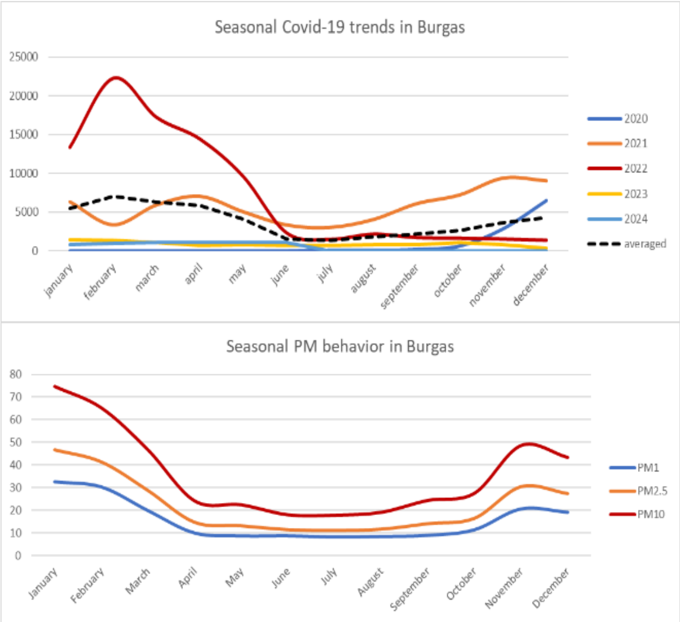

Fig. 3. Seasonal cycles of active COVID-19 cases and PM1, PM2.5 and PM10 concentrations in Burgas derived from IQAir sensors

The similarity between the seasonal cycles of COVID-19 in Sofia and Burgas is further illustrated in Fig. 4, which shows almost identical multi-year mean monthly profiles of active cases in the two municipalities.

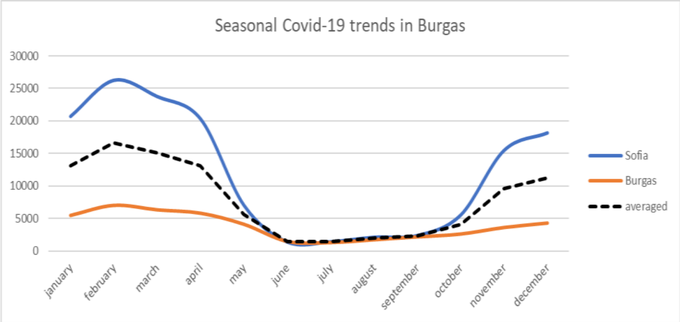

Fig. 4. Multi-year mean seasonal cycle of active COVID-19 cases in Sofia and Burgas

3.2. Seasonal Behaviour of AAI and Ground-Based Pollutants

Fig. 5 presents the seasonal behaviour of AAI over the entire Bulgarian territory, derived from GOME-2 MetOp-A and MetOp-B data, as well as the average from both satellites. The seasonal AAI curves exhibit a characteristic pattern, with enhanced absorbing aerosol loading during periods when Saharan dust intrusions and other aerosol episodes are more frequent, and lower AAI values during cleaner periods. The multi-year average provides a stable climatology of absorbing aerosols over Bulgaria.

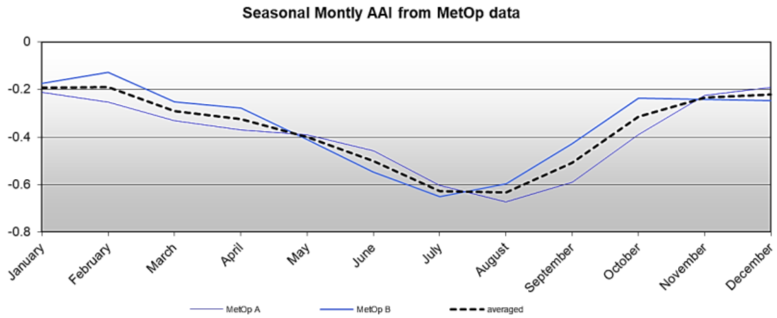

Fig. 5. Seasonal evolution of AAI from MetOp GOME-2 data averaged over the Bulgarian territory

Fig. 6 presents the seasonal trends of PM2.5, PM10 and NO_2 in Sofia, obtained from the Hipodruma GMS station. The seasonal cycles of ground-based PM and NO_2 closely resemble the patterns observed in the satellite-derived AAI climatology and in the low-cost sensor data. In particular, both satellite and ground measurements indicate higher aerosol and NO_2 pollution in winter, lower levels in summer and transitional behaviour in spring and autumn.

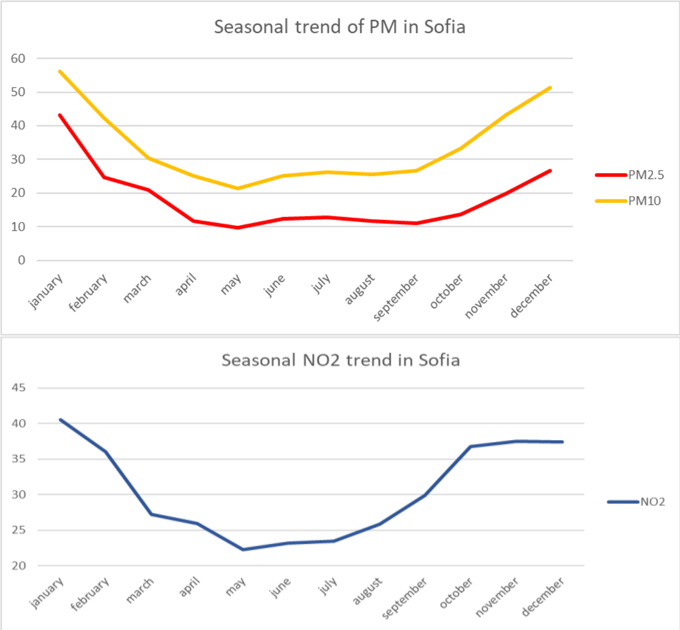

Fig. 6. Seasonal trends of PM2.5, PM10 and NO_2 concentrations in Sofia based on measurements from the Hipodruma GMS station

Overall, the seasonal trends in pollution derived from satellite and ground-based data are consistent with one another and with the seasonal pattern of Covid-19, particularly the winter maxima and summer minima. The main difference is that the spring increase of COVID-19 cases tends to persist somewhat longer than the corresponding increase in PM and NO_2 concentrations.

3.3. Comparison with National Studies in Bulgaria

Our study advances these local findings in several critical dimensions:

Temporal Extent: The current four-year observation period (June 2020 – July 2024) substantially exceeds shorter timeframes of prior studies, capturing additional COVID-19 waves and enabling more robust assessment of long-term pollution exposure effects on cumulative disease burden rather than short-term daily case fluctuations [5, 19].

Pollutant Characterisation: Whereas previous work examined PM10, NO_2, and CO individually, the present study introduces AAI as a satellite-derived proxy for absorbing aerosol loading [22] and develops a novel combined Pollution Index that integrates AAI and NO_2 [5]. This composite metric explicitly recognises that respiratory health impacts arise from multi-pollutant exposures and that satellite-based AAI provides complementary information to trace gas retrievals, particularly for characterising elevated aerosol layers from dust transport and biomass burning that may not be captured by surface PM measurements [5, 22].

Data Integration: The current study integrates observations from three independent platforms: GOME-2 [23] and ground-based networks, including both official stations and low-cost sensors, providing cross-validation and enhanced spatiotemporal coverage [24]. The integration of satellite remote sensing with ground-based measurements has proven effective for overcoming spatial discontinuities in monitoring networks [24].

GIS Framework: A dedicated GIS database developed for this study provides a structured, scalable framework for spatial analyses of respiratory disease-environment relationships that can be extended to other health outcomes and pollutants [5, 19].

3.4. Comparison with Studies in Similar Climatic Zones (Temperate Continental Climate)

European Temperate Regions

The seasonal COVID-19 patterns observed in Bulgaria with pronounced winter peaks, summer minima, and autumn resurgence closely parallel findings from comprehensive multi-country European analyses [15]. Research has documented strong negative correlations between monthly average temperature and daily COVID-19 mortality across multiple temperate European countries, suggesting that colder temperatures may be associated with increased COVID-19 deaths [20].

Quantitative estimates of seasonal forcing magnitude indicate a 42.1% (95% CI: 24.7%–53.4%) reduction in the time-varying reproduction number (Rt) from peak winter to peak summer across 143 European temperate regions. This quantitative estimate of seasonal forcing magnitude aligns with the qualitative seasonal cycles observed in both Sofia and Burgas, reinforcing the interpretation that seasonality represents one of the dominant modulating factors of COVID-19 transmission in temperate climates, operating in concert with air pollution exposure [20].

Central and Eastern European Regional Studies

Research analysing air quality monitoring data and COVID-19 spread across Central and Eastern European and Balkan countries during the 2020–2021 winter period, with a particular focus on regions where residential heating from fossil fuel combustion drives elevated winter PM2.5 concentrations, revealed strong correlations between PM2.5 and COVID-19 outcomes [20]. These correlation coefficients indicate significant relationships, particularly in contexts with high winter pollution from domestic heating.

Our findings corroborate and extend this regional evidence in several ways:

First, Bulgaria's heating infrastructure and energy mix resemble those of neighbouring Central and Eastern European countries, with widespread use of solid-fuel heating (wood, coal) in both urban and rural areas, contributing to elevated winter PM levels and combustion-related pollutants. The seasonal pollution maxima observed in Sofia and Burgas during late winter align temporally with peak heating demand and are consistent with the emission profile documented in regional analyses [20].

Second, the multi-pollutant approach employed, integrating satellite AAI (sensitive to absorbing aerosols, including black carbon from biomass/coal combustion) with NO_2 (a marker of combustion processes), provides a more mechanistically interpretable representation of the complex winter pollution mixture in Central and Eastern Europe [5, 22]. Absorbing aerosols have distinct toxicological properties and optical signatures, and their explicit characterisation via satellite AAI offers complementary insights to ground-based PM measurements [5, 22].

Third, the four-year study period extends beyond initial pandemic phases, enabling assessment of whether pollution-COVID-19 relationships persist across multiple viral variants and evolving population immunity landscapes [19]. The continued correspondence observed between pollution levels and COVID-19 incidence through July 2024 suggests that environmental modulation of respiratory disease transmission may be robust across different epidemiological contexts [5].

3.5. Satellite Remote Sensing: Advantages and Limitations

The dual-satellite approach leverages the complementary strengths of the GOME-2 instruments. GOME-2 on MetOp platforms provides a long-term data record (MetOp-A since 2006) with consistent AAI retrievals, enabling multi-year trend analysis [23, 25]. Recent algorithmic improvements for GOME-2 NO_2 retrievals, including extended spectral fitting windows, refined air mass factor calculations with explicit aerosol corrections, and improved treatment of instrumental degradation, have enhanced accuracy and consistency across the MetOp series [23, 25].

3.6. Seasonal Cycles and Meteorological Drivers

The parallel seasonal evolution of pollution and COVID-19 observed in Sofia and Burgas winter maxima, summer minima, and autumn resurgence reflects the complex interplay of meteorological, emission, and behavioural factors characteristic of temperate continental climates [19, 20, 26]. Research has demonstrated that COVID-19 transmission rates in temperate climates respond dynamically to daily average temperature, with colder temperatures correlating with higher infection rates. This aligns with the timing of COVID-19 peaks in Bulgaria (late winter), when average daily temperatures are consistently low [20]. Low temperatures enhance viral stability in respiratory droplets, increase indoor occupancy and crowding, and reduce ventilation rates, all favouring respiratory virus transmission [20, 26]. Winter pollution maxima in Bulgaria result from increased residential heating emissions (from wood and coal combustion, producing PM, black carbon, and gaseous pollutants), reduced atmospheric mixing heights that trap pollutants near the surface, and stagnant anticyclonic conditions common in southeastern Europe during winter [21]. These pollution peaks coincide temporally with COVID-19 incidence peaks, creating synergistic exposure conditions where respiratory systems compromised by air pollution encounter peak viral circulation [21]. The renewed increase in both pollution and COVID-19 during late autumn likely reflects the onset of the heating season, transition to cooler temperatures and reduced absolute humidity, and increased indoor activities [20, 26]. This pattern is consistent with influenza seasonality in temperate regions and supports the hypothesis that COVID-19 exhibits endemic seasonal behaviour comparable to that of other respiratory viruses [20, 26].

3.7. Low-Cost Sensor Networks: Emerging Data Source

The integration of low-cost sensor (LCS) network data alongside official monitoring stations represents a significant methodological advancement [19, 24]. Recent guidance emphasises the strategic value of LCS networks when combined with satellite observations and air quality models for enhanced environmental monitoring [19, 24]. Key advantages include spatial density for capturing neighbourhood-scale pollution gradients, real-time data streams, and community engagement fostering public awareness [19, 24]. Individual LCS devices have inherent limitations in measurement accuracy compared to reference-grade monitors [24]. However, aggregation strategies can mitigate these limitations and yield data suitable for epidemiological exposure assessment [24].

3.8. GIS Database Framework: Scalability and Future Applications

The dedicated GIS database integrates satellite-derived pollution metrics (AAI, NO_2) aggregated to municipal boundaries, ground-based air quality measurements, COVID-19 epidemiological data by municipality, and administrative /sociodemographic variables [8]. This framework is scalable to other geographic regions, temporal periods, and health outcomes [19]. Beyond COVID-19, the GIS database can support spatial epidemiological analyses of seasonal influenza, respiratory syncytial virus (RSV), pneumonia, and chronic respiratory disease [5, 19].

4. Conclusions

This study demonstrates a clear and consistent seasonal relationship between COVID-19 incidence and atmospheric pollution across Bulgaria from June 2020 to July 2024. Both epidemiological and environmental indicators exhibit synchronised temporal dynamics, with pronounced peaks during late winter, declines in summer, and renewed increases in autumn. This alignment is particularly evident in major urban centres such as Sofia and Burgas, suggesting that common controlling factors, most notably meteorological conditions and human behavioural patterns, simultaneously influence pollutant accumulation and viral transmission. Wintertime conditions, characterised by increased residential heating emissions, temperature inversions, and prolonged indoor exposure, appear to create an environment conducive to both elevated air pollution and intensified spread of respiratory infections.

The observed co-occurrence of pollution peaks and COVID-19 surges points to potentially compounded public health risks. While causality cannot be inferred, the findings are consistent with established evidence that chronic exposure to pollutants such as PM2.5 and NO_2 may weaken respiratory defences and increase vulnerability to infection and adverse outcomes. In this sense, air pollution should be understood not only as an environmental issue but also as a contributing factor within broader respiratory disease dynamics, particularly under high-exposure winter conditions.

A key contribution of the study lies in its integrative methodological framework. By combining satellite-derived indicators (AAI, tropospheric NO_2), ground-based monitoring data, and measurements from low-cost sensor networks, the analysis achieves improved spatial and temporal representativeness compared to reliance on official monitoring systems alone. This is especially important in Bulgaria, where the limited number of stations measuring fine particulate matter constrains exposure assessment. The inclusion of citizen-science and commercial sensor data significantly enhances the ability to capture intra-urban variability, although these data sources require careful calibration and validation to ensure reliability.

The development of a unified GIS-based platform further strengthens the analytical approach by enabling the integration of heterogeneous datasets-environmental, epidemiological, and demographic- into a coherent spatial framework. This allows for more nuanced exploration of spatial patterns and supports scalable applications in environmental health monitoring and urban planning. The approach is transferable and can be adapted to other regions or extended to additional respiratory conditions.

Importantly, the study shows that composite indicators provide added analytical value. The combined Pollution Index, derived from AAI and NO_2, demonstrates a stronger spatial correspondence with COVID-19 distribution than individual pollutants considered in isolation. This supports the notion that population exposure to air pollution is inherently multi-dimensional, reflecting the interaction of different emission sources and atmospheric processes. By integrating both anthropogenic and natural aerosol components, the composite index offers a more comprehensive proxy for environmental health risk.

At the same time, several methodological limitations must be taken into account. Satellite-derived indicators such as AAI provide indirect information on aerosol presence and are influenced by factors such as vertical distribution and surface reflectance, limiting their ability to represent near-surface particulate concentrations accurately. The use of temporally aggregated data (monthly averages) obscures short-term variability that may be relevant for infection dynamics. In addition, COVID-19 case data are subject to uncertainties related to testing practices, reporting systems, and healthcare access, which may affect comparability over time and space.

Furthermore, the associations identified in this study are inherently correlational. Both air pollution levels and COVID-19 incidence are shaped by a complex set of confounding variables, including population density, socioeconomic conditions, mobility patterns, public health interventions, and weather variability. A more rigorous assessment of causal relationships would require advanced epidemiological modelling and higher-resolution datasets, which fall beyond the present scope.

Despite these limitations, the results provide robust evidence that integrating satellite observations, in situ measurements, and low-cost sensor data within a GIS framework offers valuable insight into the seasonal interplay between environmental quality and public health. The methodology is practical, scalable, and particularly relevant for regions with limited monitoring infrastructure. Future research should focus on refining the Pollution Index through the inclusion of additional pollutants (e.g., ozone), improving data harmonisation, and applying statistical models capable of disentangling causal pathways.

Overall, the study underscores the importance of coordinated environmental and public health strategies. Reducing air pollution, especially during winter, should be considered a key component of preparedness and prevention frameworks for respiratory diseases, including, but not limited to, COVID-19.

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Disclosure of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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СЕЗОННА КОРЕЛАЦИЯ МЕЖДУ АТМОСФЕРНО ЗАМЪРСЯВАНЕ И ЗАБОЛЕВАЕМОСТ ОТ COVID-19 ПО СПЪТНИКОВИ И НАЗЕМНИ НАБЛЮДЕНИЯ ЗА ТЕРИТОРИЯТА НА СОФИЯ И БУРГАС

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Резюме

Епидемиологичният отпечатък на COVID-19 се модерира значително от атмосферните замърсители, по-специално азотния диоксид (NO_2) и фините прахови частици. Настоящото изследване се фокусира върху сезонната динамика на качеството на въздуха във връзка с COVID-19 случаите в България. Чрез използване на спътникови данни за тропосферния индекс на поглъщащите аерозоли (AAI) от инструментите GOME-2, е картографирано аерозолното натоварване за периода от средата на 2020 г. до юли 2024 г. Изследваните общини София и Бургас са допълнени с данни от наземни измервания. Наблюденията разкриват отчетливи синхронизирани сезонни модели: както нивата на замърсяване, така и броят на случаите достигат пик в края на зимата, намаляват значително през лятото и отново нарастват с настъпването на есента. Основен резултат от това изследване е създаването на устойчива ГИС база данни, която служи като адаптивна пространствена платформа за изследване на различни респираторни заболявания и показатели за екологично здраве.