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Article

Air quality in Bulgaria—Monitoring data, perspectives, scientific research

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Abstract: This paper addresses air quality in Bulgaria, a pressing environmental issue with monitoring data indicating persistent challenges in urban areas due to pollutants like PM10 and NO_2. Bulgaria's government operates a comprehensive air quality monitoring network, offering real-time data to track pollutants across multiple regions. Scientific research in this area focuses on identifying pollution sources, assessing public health impacts, and developing models for pollution control. Efforts to improve air quality include implementing stricter regulations, investing in green technologies, and conducting public awareness campaigns. Future research emphasizes sustainable urban planning, the adoption of renewable energy, and advanced monitoring technologies to strengthen air quality management in Bulgaria.

Keywords: air quality in Bulgaria; monitoring data; concentration levels of air pollutants; statistical analysis; pollution prevention; scientific research

1. Introduction

This article reviews the main aspects of air quality and pollution prevention in Bulgaria. It presents the following information: impact on health and the environment; geographic breakdown; norms and characteristics of air pollution in Bulgaria; monitoring systems, data, and reports on air quality in Bulgaria; national and international regulations; and recommendations for future research and policy. The most important question for our overview article on air quality in Bulgaria is: "What are the main sources of air pollution in Bulgaria, how can we predict their current concentrations and how do they affect public health and the environment?". This question brings together the key elements of the topic: identifying the sources of pollution, measuring, modeling and predicting their effects, and evaluating existing research to deal with the problem. Examining it allows not only the assessment of the current situation, but also recommendations to improve air quality and reduce health and environmental risks.

This overview article is a continuation of our previous studies, which are listed in references. Our results highlight the importance of air pollution control and the need for sustainable policies to improve health and the environment.

2. Air quality and human health

Air quality directly impacts health and life. Air pollution is a major environmental cause of various diseases in Europe and Bulgaria. While air quality has improved over the past two decades, significant harmful effects persist [1].

Air pollution arises from both anthropogenic and natural sources. Man-made sources encompass emissions from transportation, industrial activities, household heating, and coal-fired power plants. Vehicles emit pollutants like carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM). Industrial processes release sulfur dioxide (SO_2), volatile organic compounds (VOCs), and heavy metals. Natural sources include volcanic eruptions, forest fires, and dust storms, which contribute pollutants such as ash, dust, and gases [1].

Common air pollutants include particulate matter (PM10 and PM2.5), which can penetrate deep into the lungs and bloodstream, causing health issues; carbon dioxide (CO_2), a greenhouse gas; carbon monoxide (CO), a toxic, colorless, and odorless gas from incomplete combustion; sulfur dioxide (SO_2) from burning fossil fuels and volcanic activity, causing respiratory problems and acid rain; nitrogen oxides (NO_x) from vehicle engines and industrial processes, contributing to respiratory issues, ground-level ozone, and smog; volatile organic compounds (VOCs) causing respiratory problems and contributing to ozone formation; ozone (O_3) formed from NO_x and VOCs in sunlight, causing respiratory issues; and heavy metals like lead, cadmium, and mercury, which are toxic [1].

Air pollution significantly affects human health, causing chronic respiratory and cardiovascular diseases, lung cancer, and issues in the nervous and reproductive systems. Respiratory problems include asthma, bronchitis, and chronic obstructive pulmonary disease, with fine particulate matter (PM2.5) being particularly harmful. Pollutants like PM2.5 and NO_2 are linked to cardiovascular diseases, such as heart attacks and strokes. Carcinogenic pollutants increase the risk of lung and other cancers. Emerging evidence suggests air pollution impacts the central nervous system, potentially leading to cognitive decline and neurological disorders. Additionally, air pollution is associated with adverse reproductive outcomes, including reduced fertility, preterm birth, and low birth weight [1].

3. Bulgaria—Location and geographic characteristics

Bulgaria is a European country located in the southeastern part of the continent, occupying the eastern part of the Balkan Peninsula. It is bordered by Romania to the north, Serbia, and North Macedonia to the west, Greece and Turkey to the south, and the Black Sea to the east. The land area of Bulgaria is 111,002 square kilometers.

The total length of Bulgaria's borders is 2245 km, of which 1181 km is land and 1064 km are water. Of the water borders, 686 km are rivers and 378 km are along the Black Sea. The Danube River, from the mouth of the Timok River to the city named Silistra, serves as the natural border between Bulgaria and Romania (see **Figures 1–3**) [2–4].

Figure1. Map of Europe, Bulgaria in red [1].

Figure 2. Map of Bulgaria with main towns [2].

Figure 3. Map of Bulgaria with districts [3].

The topography of Bulgaria varies greatly with significant vertical dissection [5]. The country is divided into five altitude zones with 70% of the land situated below 600 m. Lowlands, plains, and hilly areas dominated the landscape. The average altitude of Bulgaria is 470 m, decreasing from south to north and west to east.

Bulgaria's territory is divided into five physio geographic zones: the Danube Plain, which covers a large part of northern Bulgaria south of the Danube River. The terrain transitions from the lowlands in the west to a hilly plateau in the east, with an average altitude of 178 m. The climate is temperate continental, with hot summers and cold winters, and annual precipitation ranging from 500 to 600 mm. Stara Planina

Region: Stara Planina, or the Balkan Mountains, separate northern and southern Bulgaria. This region includes several areas: Pre-Balkan, Stara Planina, Trans-Balkan Fields, and Middle Highlands (Srednogorie). The mountain range is approximately 550 km long, with Botev Peak being the highest at 2376 m. The climate varies from moderately continental in the north to moderately transitional continental in the south. Kraishte-Tundzhan Zone: This western region features a series of low mountains and valleys. The climate here is temperate transitional continental, with a mountainous influence in the west and weak Mediterranean influence in the plains. The Struma River passes through this area, and the plains are drained by the Maritsa and Tundzha Rivers. Osogovo-Rhodope Zone: This area is characterized by high mountains, including the Rhodopes, Rila, and Pirin ranges. It is home to Musala, the highest peak in Bulgaria and the Balkan Peninsula, at 2925 meters. The climate is moderately transitional continental with strong mountain influences, and the valleys of the Struma and Mesta Rivers experience Mediterranean influences. Black Sea Zone: This zone includes the lowlands along the Black Sea coast, which are wider near Varna and Burgas and narrower in the southern and central parts. The climate is influenced by proximity to the sea. The rivers in this zone are relatively short, and the largest natural lakes in the country are found here, including Burgas, Varna, and Beloslav [5].

Bulgaria's climate is temperate transitional continental, with mountainous influences in the west and Mediterranean influences in the plains, especially in the southeastern region [6]. The average annual temperature ranges from 10 ℃ to 12.2 ℃. Winters are harsh, particularly in the plains, while the Black Sea coast experiences milder winters owing to maritime influences. The summer temperatures in the western plains peaked in July, reaching 23–24 ℃. The lowest average monthly winter temperature was observed in January. In Bulgaria, January temperatures are negative (around −3 ℃), even at low altitudes of 100–200 m. In the eastern part of the country, the Black Sea's climatic influence and less pronounced temperature inversions result in milder winters. In the western part of the Danube plain, the highest annual temperature amplitude is 25 ℃.

4. Air pollution—Norms and characteristics for Bulgaria

Air pollution, the presence of biological and chemical substances in air that deviate from their natural composition or are present in excessively high amounts, can harm plants, animals, and humans. It is a concern at local, pan-European, and global levels. Anthropogenic and natural phenomena are the main sources of air contamination. Common air pollutants include particulate matter (PM2.5, PM10), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide (NO), aldehydes, radioactive substances, hydrocarbons, sulfur dioxide (SO_2), and ozone (O_3).

European and Bulgarian legislation, such as Ordinance No. 14 [7], and Ordinance No. 7 [8]. set standards for maximum permissible concentrations of pollutants in ambient air.

The Clean Air Act defines standards and indicators for ambient air quality, emission control, and relevant bodies' rights and obligations for air quality management. It regulates harmful emission limitations from various sources, stipulating that the construction, design, and operation of emission source sites must comply with its requirements [9]. The Environmental Protection Act serves as a framework for other environmental laws, regulating the main frameworks for protecting environment components and outlining procedures for Environmental Assessment (EA), Environmental Impact Assessment (EIA), permit management, regimes, and financing [10]. In 2010, the Bulgarian Minister of Environment and Water and the Minister of Health issued Ordinance No. 12 on standards for various air pollutants [11].

Table 1 presents the official norms of permissible concentrations of air pollutants in Bulgaria.

Table 1. Norms of permissible concentrations of air pollutants in Bulgaria [7–12].

Norm	Averaging period	Value
1	2	3
Sulphur dioxide SO_2		
Hourly average rate for the protection of human health	1 h	350 µg/m^3 (not to be exceeded more than 24 times in a calendar year)
Average 24/7 norm for the protection of human health	24 h	125 µg/m^3 (not to be exceeded more than 3 times in a calendar year)
Norm for the protection of natural ecosystems (not applied in the immediate vicinity of sources)	One calendar year and winter (1 October to 31 March)	20 µg/m^3
Nitrogen dioxide (NO_2) and oxides of nitrogen NO_x		
Hourly average rate for the protection of human health	1 h	200 µg/m^3 (not to be exceeded more than 18 times in a calendar year)
Annual average rate for the protection of human health	One calendar year	40 µg/m^3
Norm for the protection of vegetation (not applied in the immediate vicinity of the sources)	One calendar year	30 µg/m^3 ($NO + NO_2$)
Fine particulate matter (PM10)		
Average 24/7 norm for the protection of human health	24 h	50 µg/m^3 (not to be exceeded more than 35 times in a calendar year)
Annual average rate for the protection of human health	One calendar year	40 µg/m^3
Fine particulate matter (PM2.5)		
Stage 1		
Annual average rate for the protection of human health	One calendar year	25 µg/m^3
Stage 2		
Annual average rate for the protection of human health	One calendar year	20 µg/m^3
Carbon monoxide CO		
Conservation norm of human health	maximum eight-hour average over the day	10 g/m^3

5. Ecological monitoring in Bulgaria

Ecological monitoring involves systematic, repeated measurements of environmental conditions using consistent methods in the same locations over time, enabling long-term comparisons essential for understanding ecosystem health changes due to factors like climate change, contamination, invasive species, urbanization, and extreme natural events. Long-term data help elucidate species-environment interactions.

The European Environment Agency (EEA) [12] acts as the Union's Air Pollution Data Center, aiding in the enforcement of EU air emissions and quality legislation, evaluating EU air pollution policies, and developing strategies to enhance air quality in Europe. The EEA's work includes:

First, publicly sharing a range of air pollution data.

Second, documenting and assessing air pollution trends, policies, and measures in Europe.

Third, investigating trade-offs and synergies between air pollution and policies in areas like climate change, energy, transport, and industry.

These efforts aim to improve air quality and environmental health across Europe, ensuring policies are informed by accurate, up-to-date data and comprehensive analysis. Each EU country develops its own monitoring systems for ambient air quality measurements [13–16].

Bulgaria is divided into six regions for atmospheric air quality (AQ) assessment and management, as approved by Order No. 257/25.03.2022 of the Minister of Environment and Waters, in accordance with European and national legislation. The Bulgarian National Environmental Monitoring System [15] assesses AQ across these regions: the agglomerations of Sofia, Plovdiv, and Varna, and the North Danube, South-West, and South-East regions. AQ data analysis is conducted by region, considering the specific characteristics of each monitored populated area.

The National Air Quality Monitoring System (NAQMS) of the Ministry of Environment and Water (MoEW) comprises 48 stationary points, including 9 points with manual sampling followed by laboratory analysis, 30 Automatic Measuring Stations (AMS), 5 automatic measuring systems using differential optics atomic absorption spectrophotometry, and 4 AMS for monitoring AQ in forest ecosystems at "Rozhen," "Yundola," "Vitinya," and "Staro Oryahovo". The NAQMS activity is regulated by the Order of the Minister of Environment and Water No. RD-489/26.06.2019, specifying the number and type of points, controlled atmospheric pollutants, and measurement methods and means [15].

Manual air monitoring stations operate only during daylight hours (four samples per day, five days a week). The recorded average hourly concentrations from these stations inform AQ assessments, but daily norm comparisons are impractical due to the limited sampling period, rendering the data mostly indicative, except for PM10, lead, cadmium, and surface-active substances, which are sampled over 24 h [15]. The air quality system also includes six mobile automatic stations (MAS) in regional laboratories in Sofia, Plovdiv, Pleven, Stara Zagora, Varna, and Ruse. These stations, distributed across the country, provide additional measurements in areas lacking stationary points or during emergencies. MAS activities follow schedules approved by the Minister of Environment and Water.

6. Air quality data for Bulgaria

In this section, some official air quality data for Bulgaria are briefly presented [15–18]. (see **Table 2**)

Table 2. Emissions of harmful substances in ambient air for 2020 by groups [16].

Emission source groups	SO_x* (× 1000 t/y)	NO_x** (× 1000 t/y)	NMVOC (× 1000 t/y)	NH3 (× 1000 t/y)	CO (× 1000 t/y)	Hg t/y	Cd t/y	Pb t/y	RAN t/y	DIOX g/y	PM10 (×1000 t/y)	PM2.5 (× 1000 t/y)
No1 Thermal power plants	26.93	13.45	0.71	0.02	4.47	0.448	0.317	2.35	0.064	2.39	0.22	0.18
No2 Domestic combustion	5.10	2.93	20.82	2.32	151.35	0.047	0.460	1.59	14.68	28.99	25.88	25.18
No3 Combustion processes in industry (Including. energy production)	1.57	2.63	0.28	0.16	2.18	0.027	0.07	0.24	0.000	0.49	0.43	0.37
No4 Non-combustion production processes	30.83	4.92	6.69	1.16	19.20	0.057	0.495	4.26	0.00	9.54	6.70	1.81
No5 Extraction and processing of fossil fuels	3.39	1.43	7.27	0.01	0.496	0.025	0.025	0.025	0.000	0.028	0.91	0.15
No6 Solvent use	0.0028	0.01	13.94	0.02	0.2455	0.0001	0.06	0.73	0.0017	0.0004	0.86	0.61
No7 Road transport	0.04	35.91	6.85	0.70	44.83	0.016	0.006	1.158	0.2245	1.445	2.76	2.17
No8 Other transport	1.74	12.36	1.19	0.001	26.88	0.002	0.0026	0.1386	0.0125	0.017	0.50	0.49
No9 Waste treatment and disposal	0.003	0.018	1.33	1.18	0.10	0.058	0.005	0.033	0.0001	6.098	0.35	0.35
No10 Agriculture	0.0002	17.93	13.91	37.15	0.03	0.00006	0.0004	0.00005	0.0009	0	6.14	0.41
Total***	69.60	91.60	73.00	42.70	249.78	0.68	1.43	10.52	14.99	49.20	44.75	31.72

*—Calculated as sulfur dioxide.
**—Calculated as nitrogen dioxide.
***—emissions from the nature sector are not included, due to lack of up-to-date data.

On the next **Table 2** one could see emissions of harmful substances in ambient air for Bulgaria for 2020 by groups (in tons per year).

Figures 4–6 illustrate PM10 concentration levels in three Bulgarian towns along the Danube River: Ruse, Vidin, and Svishtov. **Figure 7** presents the PM10 levels in Pleven, located in northern Bulgaria. The graphs reveal numerous days when PM10 concentrations surpassed the daily limit of 50 $\mu g/m^3$. PM10 pollution remains a significant issue for air quality in Bulgaria. In 2020, the Danube plain recorded the highest average daily norm exceedances at the Automated Measuring Station (AIS) "Vidin 2" with 77 exceedances, followed by the "Nikopol" AIS with 68 exceedances.

Emissions of harmful substances into the atmospheric air from road and other transport in 2020 are shown in **Table 3** in tons per year.

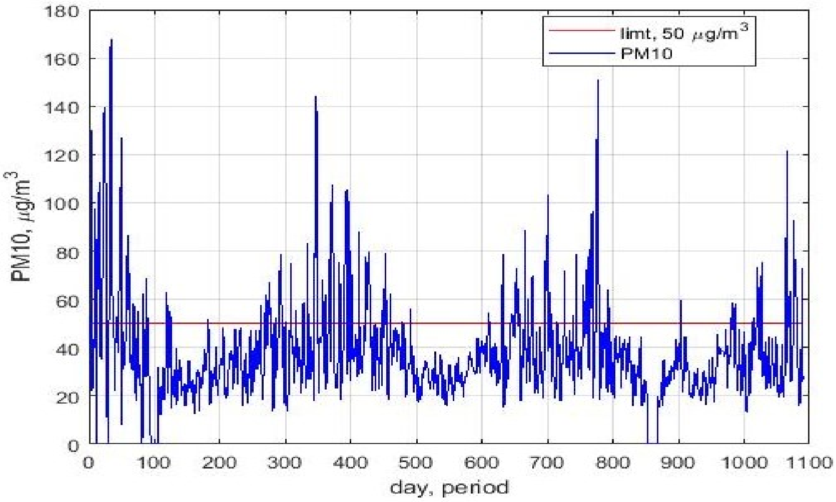

Figure 4. PM10 measured values for period 1 January 2017–31 December 2019 for the city of Ruse, Bulgaria (blue line) and permissible daily limit 50 μg/m^3 (red line).

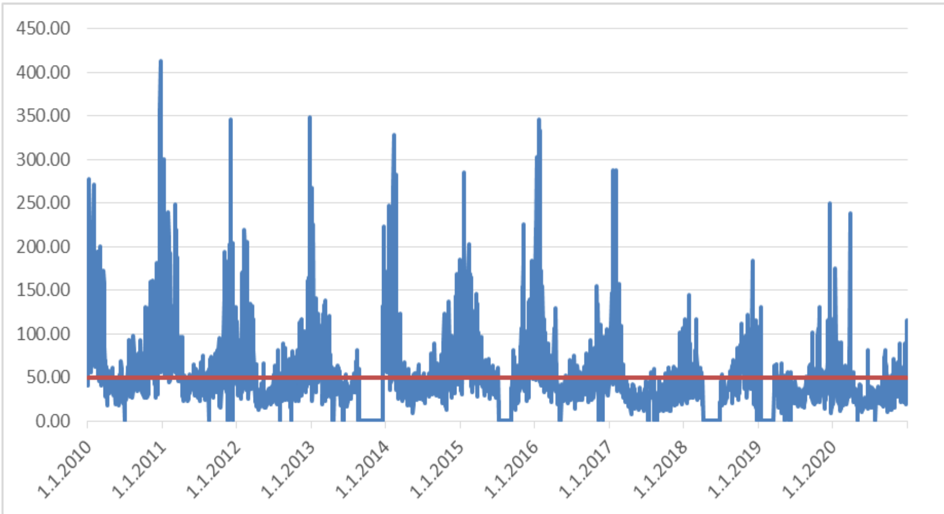

Figure 5. Average daily values of PM10 levels in the town of Vidin, Bulgaria for the period 2010–2020 (blue line) and permissible daily limit 50 μg/m^3 (red line).

Table 3. Emissions of harmful substances in the atmospheric air from road and other transport in 2020, t/y [16].

Groups of transport emission sources	SO_x * (×1000 t/y)	NO_x** (× 1000 t/y)	NMVOC (× 1000 t/y)	CO (× 1000 t/y)	Pb, t/y	PM_{10} (× 1000 t/y)	PM2.5 (× 1000 t/y)
Road transport	0.04	35.91	6.85	44.83	1.16	2.76	2.17
Other transport	1.74	12.36	1.19	26.88	0.139	0.50	0.49
Total transport	1.77	48.28	8.04	71.71	1.30	3.26	2.65
Share of transport in national emissions (%)	2.55	52.70	11.02	28.71	12.33	7.29	8.36

*—calculated as sulfur dioxide
**—calculated as nitrogen dioxide.

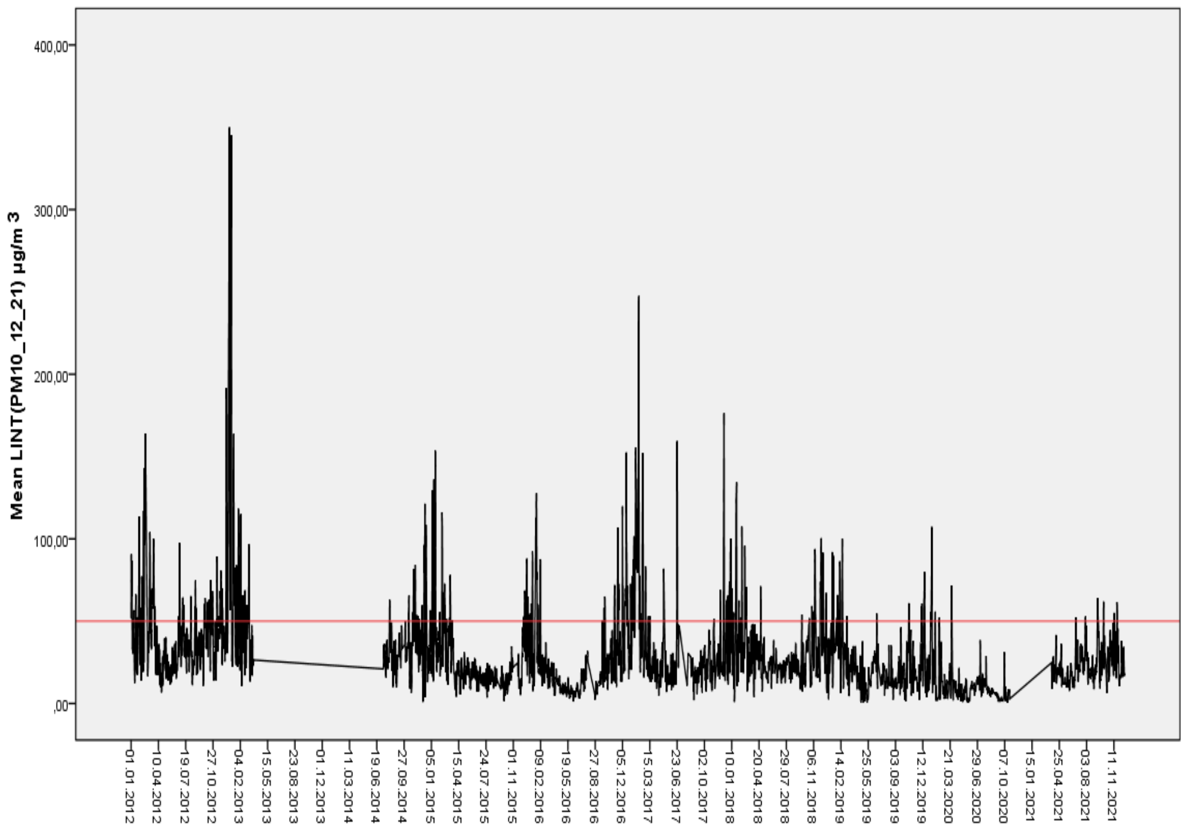

Figure 6. PM10 concentration levels for the period 1 January 2012–20 December 2021 for the city of Svishtov, Bulgaria (black line) and permissible daily limit 50 µg/m^3 (red line).

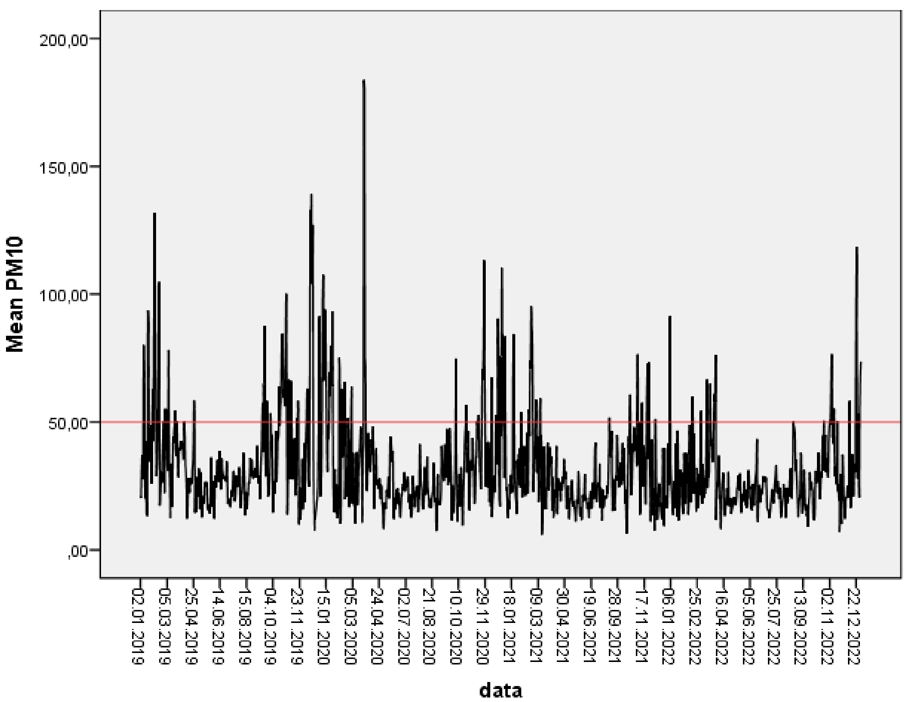

Figure 7. PM10 concentration levels for the period 2 January 2019–30 December 2022 for the city of Pleven, Bulgaria (black line) and permissible daily limit 50 µg/m^3 (red line).

Figures 8 and **9** illustrate the number of exceedances of the daily average norm and the average annual concentration of PM10 from 2016 to 2020 at the "Ruse-

Vazrazhdane" monitoring point [15]. A trend of decreasing average annual PM10 concentrations and fewer exceedances of daily norms is evident (see **Figures 8** and **9**). However, in 2020, there was an increase in the average day and night PM10 concentrations compared to 2019 at "Ruse-Vazrazhdane" [16].

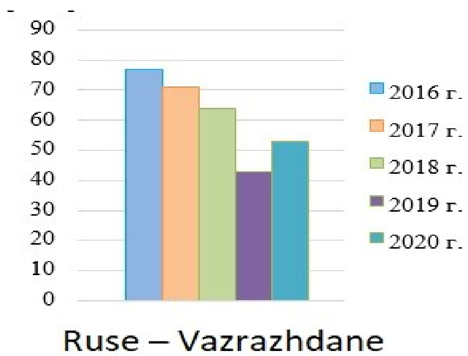

Figure 8. Exceedances of the daily average PM10 limit for the period 2016–2020, measured in the city of Ruse, Bulgaria [16].

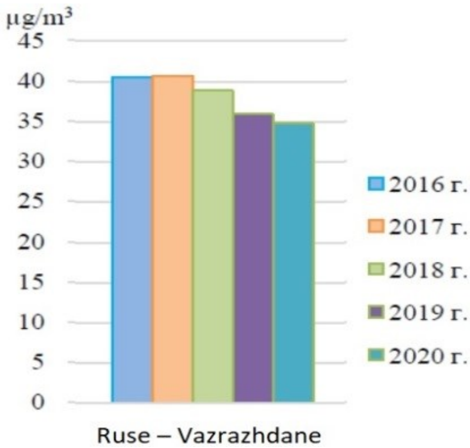

Figure 9. PM10 average annual concentration levels for the period 2016–2020, measured in the city of Ruse, Bulgaria, µg/m^3 [16].

PM10 air contamination shows distinct seasonal patterns, with exceedances primarily occurring in winter due to the use of solid fuels for domestic heating. Adverse weather conditions, such as low wind speed, fog, and temperature inversions, also contribute to higher PM10 levels. Additionally, materials used for winter road maintenance can elevate daily PM10 concentrations during this period. Domestic heating is the major source of fine particulate matter, responsible for 58% of PM10 and 79% of PM2.5 emissions. For PM2.5, road transport is another significant source, accounting for 7% of emissions. Thus, the primary causes of excessive particulate matter pollution are solid fuel heating in winter and emissions from vehicles and public transport [16,19].

Air pollution from fine dust particles remains a significant issue for Bulgaria. Despite a reduction in recorded PM10 concentrations in recent years, air quality is still unsatisfactory. In Bulgaria, the percentage of the population exposed to excessive PM10 levels is substantially higher than the European average (10%–19% for 2015–

2019), reaching 60.2%. This figure means that 3.3 million people in monitored areas are exposed to this air contamination.

These calculations were conducted using the European Environmental Agency's methodology, which assumes that in each settlement where PM10 levels exceed the norm, the entire population is affected by the negative effects of dust particles. In 2020, the percentage of the population in Bulgaria affected by excessive PM10 levels remained almost unchanged from 2019, when it was 60.8%.

From 2000–2019, nearly 42% of the EU member states' population was exposed to excessive PM10 pollution in 2003 [16–18]. In 2021, the highest number of daily norm exceedances (ADN) were recorded at the "Plovdi—Complex Thrace" Automated Measuring Station (AIS) with 85 exceedances, followed by "Silistra AIS S1" with 60 exceedances, and "Dolni Voden" with 57 exceedances [17].

According to the Report [16], emissions of S, NO_x, NMVOC, and PM2.5 in the Bulgarian North Danube Region decreased from 2005 to 2019. However, PM2.5 emissions increased by 4% from 2019 to 2020, mainly due to household sector emissions, with domestic heating being the primary source in 2020. Ammonia emissions increased by 1.46% from 2019 to 2020, with agriculture as the main source. Thermal power plants account for 39% of SO_2 emissions in Bulgaria [15–18], with a decrease of 7 kt from 2019 to 2020. Major sources of NO_x include road transport (39%), thermal power plants (15%), other transport (13%), and agriculture (20%). Agriculture emits 87% of ammonia, while non-fuel production processes contribute 10%, domestic combustion (29%), solvent use (19%), and agriculture (19%).

Figures 10–14 depict graphs of various gaseous air pollutants in Ruse, Bulgaria, from 1 January 2015 to 20 December 2021. **Figure 10** shows O_3 (mean 44.8965 µg/m^3, maximum 103.99 µg/m^3, Std. Deviation 19.23307), **Figure 11** presents SO_2 (mean 10.2703 µg/m^3, maximum 211.85 µg/m^3, Std. Deviation 16.20928), **Figure 12** illustrates NO (mean 21.3058 µg/m^3, maximum 77.82 µg/m^3, Std. Deviation 10.27385), **Figure 13** depicts CO (mean 9.6385 µg/m^3, maximum 65.57 µg/m^3, Std. Deviation 3.68259), and **Figure 14** shows NO_2 (mean 0.4296 µg/m^3, maximum 3.54 µg/m^3, Std. Deviation 0.29168). According to EU law, the concentration limits for gaseous pollutants are as follows: SO_2 (1-hour mean—350 µg/m^3, 24-hour mean—125 µg/m^3), NO_2 (1-hour mean—200 µg/m^3, annual mean—40 µg/m^3), CO (maximum daily 8-hour mean—10 µg/m3), and O_3 (maximum daily 8-hour mean—120 µg/m^3) (see **Table 1**).

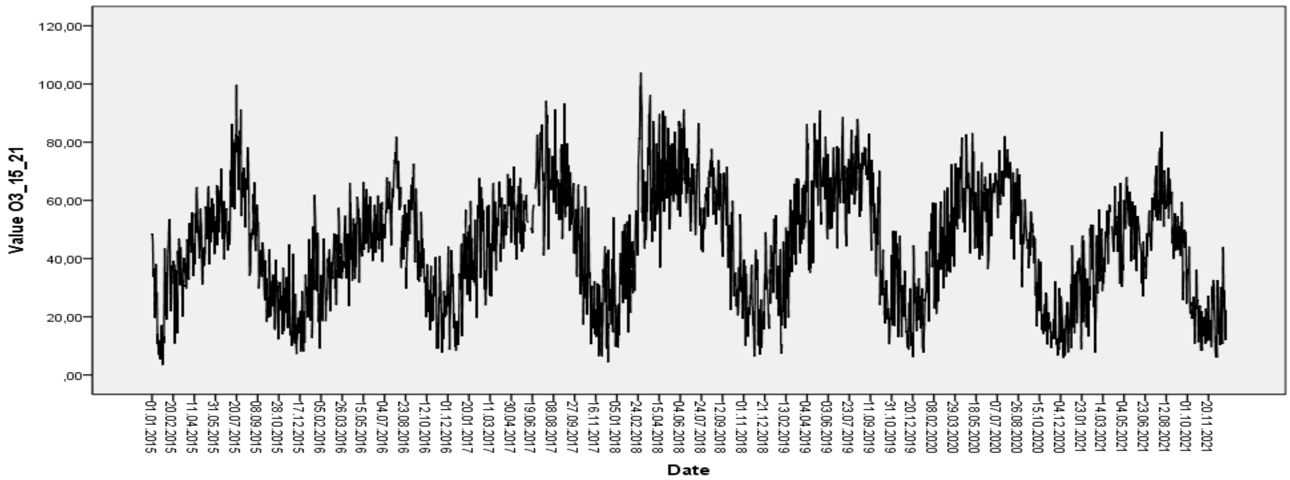

Figure 10. Graph for O_3 concentration levels for the period 1 January 2015–20 December 2021 for the city of Ruse, Bulgaria [17,19].

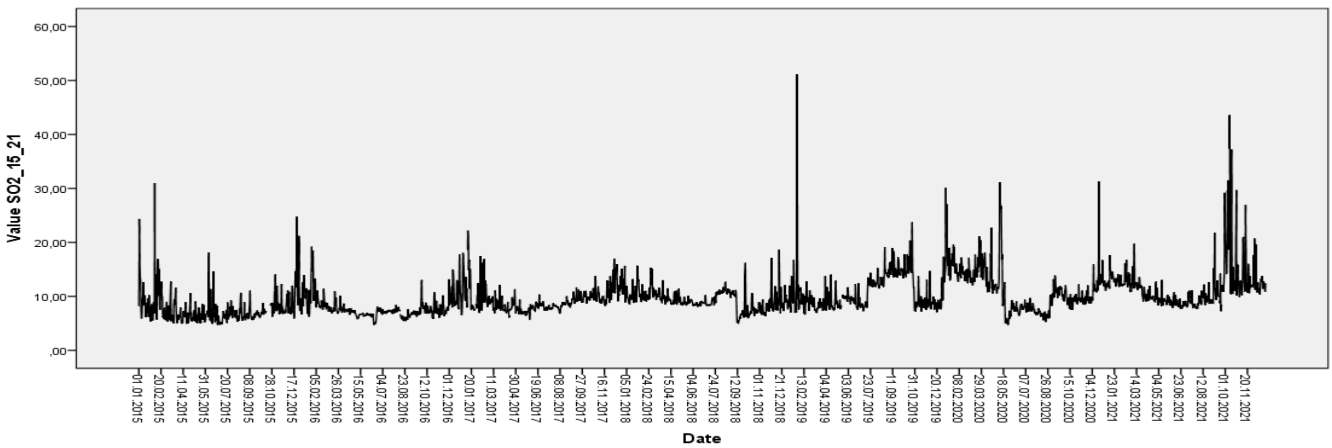

Figure 11. Graph for SO_2 concentration levels for the period 1 January 2015–20 December 2021 for the city of Ruse, Bulgaria [17,19].

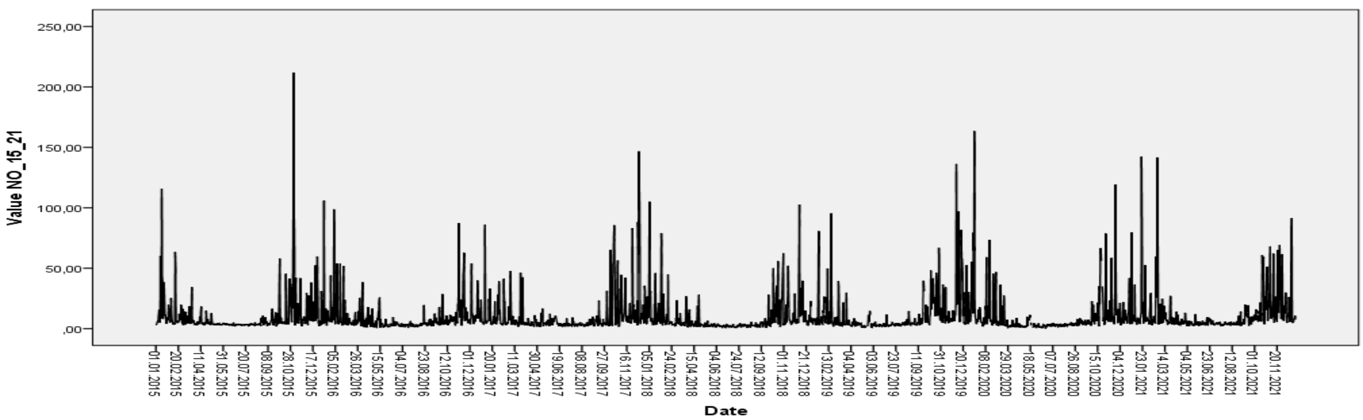

Figure 12. Graph for NO concentration levels for the period 1 January 2015–20 December 2021 for the city of Ruse, Bulgaria [17,19].

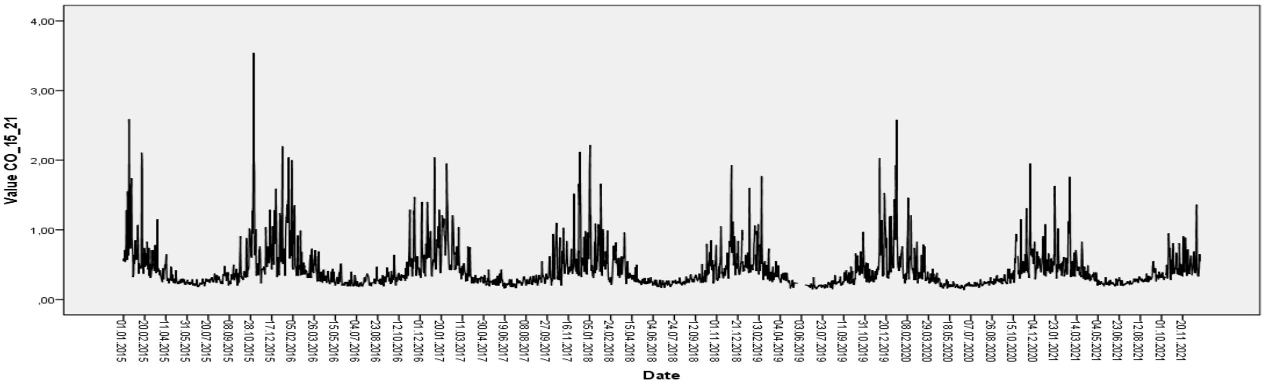

Figure 13. Graph for CO concentration levels for the period 1 January 2015–20 December 2021 for the city of Ruse, Bulgaria [17,19].

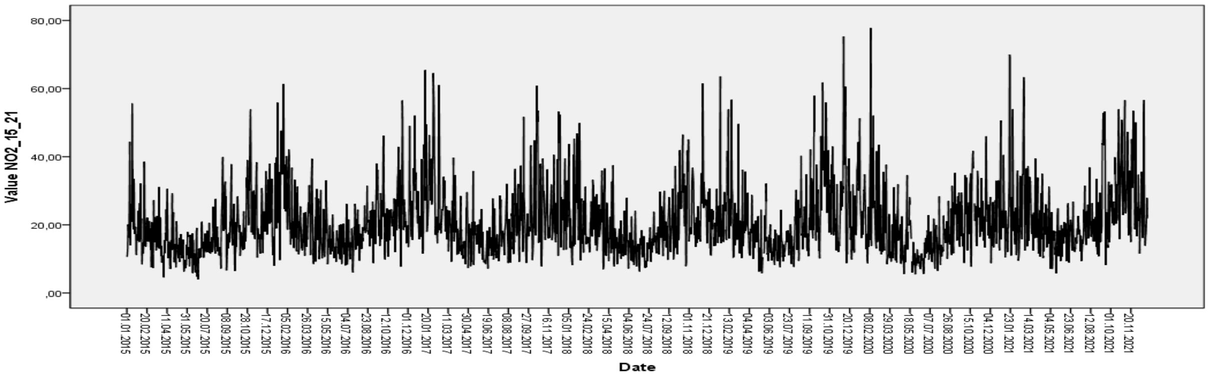

Figure 14. Graph for NO_2 concentration levels for the period 1 January 2015–20 December 2021 for the city of Ruse, Bulgaria [17,19].

Figure 15 shows the average annual concentration levels of PM2.5 recorded in 2020 in the city of Ruse, North Danube region [17, 19]. In 2020, Bulgaria's average annual PM2.5 exposure decreased from 20.74 µg/m^3 in 2019 to 18.84 µg/m^3 in 2020, with no exceedances recorded. In the city of Ruse, a North Danube region city, PM2.5 concentration levels are below the norm [16,19].

Bulgarians experienced no ozone levels surpassing the short-term target norm in 2020, while 12%–34% of the EU population faced elevated ozone from 2015–2019. Non-urban residents have higher ozone exposure due to urban ozone reduction by nitrogen oxide oxidation [17]. About 68% of Bulgarians lived in areas with benzo(a)pyrene pollution exceeding the target norm, significantly higher than the EU's 14%–17% average from 2017–2019.

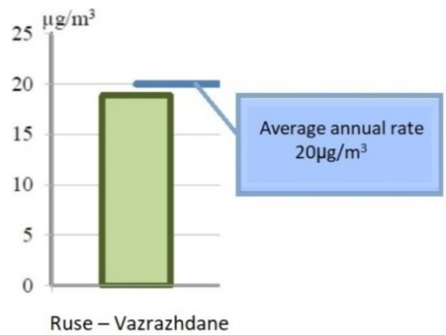

Figure 15. Average annual concentration levels of PM2.5 recorded in 2020 in the city of Ruse, North Danube region, µg/m^3 [17,19].

In 2020, Bulgaria's population did not face sulfur dioxide levels above the permissible daily average. In Europe, fewer than 0.1% of people encountered pollution levels over the norm. Monitoring stations for these calculations include urban and non-urban background sites, as well as transport-related locations, excluding industrial sites to ensure data represent residential areas. In 2021, in 25 populated locations, the average daily norm for PM10 was within the allowable excesses—up to 35 instances in one year.

In 2021, the Average Year Norm (AYN) for PM10 was met at all monitoring points, with sufficient data coverage (sufficient average circadian values were recorded to calculate the average annual concentration [17,19].

In Bulgaria, for 2020, 15 out of a total of 28 Bulgarian municipalities were included in the European Commission's procedure for non-compliance with the norms of the PM10 indicator. However, in 2021, compliance with these norms was achieved. These municipalities are Galabovo, Devnya, Blagoevgrad, Pirdop, Sliven, Stara Zagora, Lovech, Varna, Vratsa, Shumen, Dimitrovgrad, Pleven, Ruse, Veliko Tarnovo and Nessebar [16].

In 2022, a team of scientists from the National Institute for Meteorology and Hydrology created a methodology for determining the excess maximum allowable values of PM10, which are due to emissions from natural sources such as desert dust. Through this methodology, 2021 PM10 ADN excesses were determined due to the cross-border transmission of desert dust. The total number of reduced overruns due to the transfer of desert dust is 189 in 33 of the monitoring stations for which the methodology is applied [17–19].

7. Matematical modeling of air pollutant data for Bulgaria

Mathematical modeling of air pollutants involves the use of mathematical and statistical techniques to understand, predict, and control air pollution. These models can help in making informed decisions regarding air quality management and policy implementation.

Usually, data Sources for modelling are air quality monitoring stations, satellite observations, and meteorological data. Also often Preprocessing Steps are needed such as handling missing data, smoothing, and normalization to prepare the data for modeling. Model calibration and validation are important parts of the modeling process. Calibration—this is to adjust model parameters to fit the observed data. Validation: This method assesses model performance using independent datasets. Common metrics include Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and R-squared.

Recently in Bulgaria different mathematical models based on the air pollutant data are developed to forcast future contamination of the air [19–51]. These models take into account many parameters such as seasonality, atmospheric characteristics, interaction with other type of air pollutants and so on. All of them are good enough to predict correctly with very small errors future air contamination.

Mathematical methods and models which are used for air pollution studies for Bulgaria can be divided in several groups and they will be presented here very briefly.

First, we will discuss statistical time series analysis, which is applied to analyze and forecast pollutant concentrations over time [21,41–43].

Regression analysis in statistical modeling is a set of statistical processes for estimating the relationships between a dependent variable (for example pollutant concentration) and one or more independent variables (for example some meteorological parameters as atmospheric temperature, pressure, humidity, wind characteristics and so on) [19,20,22,28,32,36–38].

Parametric stochastic—mainly with the methods: Autoregressive Integrated Moving Average (ARIMA), SARIMA, ARIMA with transfer functions—unidimensional and multidimensional; factor analysis with PCA, etc. [22,30,31,35,39, 40,42].

Machine learning methods are also used to study air quality—single models with Classification and Regression Trees (CART) and Multivariate Adaptive Regression Splines (MARS) models [44,46,47]; ensemble methods: Random Forest, Arcing (Arc-x4), CART Ensembles and Bagging, boosted gradient trees, PathSeeker (regularized regression) [22,45,47], and grouping (stacking) of the predictions of different models through a meta-model—we have with MARS, and with simple averaging [47].

In addition, discrete wavelet analysis for initial "denoising" of the data and extraction of trends and trend grouping with stacking are used to study air pollution data [48,49].

Markov chain [33] and decomposition techniques [34] are also used to model air pollution in two Bulgarian cities—Ruse and Silistra.

Gaussian Plume Models (a kind of deterministic model) is used to predict the dispersion of pollutants from a point source in the atmosphere in the city of Razgrad, Bulgaria [50].

Mathematical modeling of air pollutant data is a crucial tool for understanding and managing air quality in Bulgaria. By leveraging various models—deterministic, statistical, and hybrid approaches—we can accurately predict pollutant levels, assess the impact of different factors, and develop strategies to mitigate the adverse effects of air pollution on human health. It is also important to emphasize that Bulgaria possesses the scientific capacity to conduct this type of research effectively.

8. Air quality perspectives for Bulgaria

Europe has yet to achieve safe air quality levels, posing risks to both people and the environment. This deficiency significantly impacts Europe's natural systems, economy, labor productivity, and public health. Poor air quality is particularly detrimental in urban areas, causing severe health issues, and in ecosystems, where vegetation growth is hindered and biodiversity is lost due to eutrophication.

As an EU member, Bulgaria must adhere to all EU air quality regulations. Despite some improvements, Bulgaria remains one of Europe's most polluted countries, mainly due to emissions from coal-fired power plants, household heating, transportation, and industrial activities. Air pollution presents a substantial public health and environmental challenge.

Efforts to monitor, regulate, and reduce emissions are crucial for improving air quality and protecting human health. Ongoing action is necessary in Bulgaria and globally to address air pollution sources and mitigate their impacts. Future air quality improvements will require increased use of "green" and efficient technologies, such as better thermal insulation of buildings, alternative fuel sources in households and transport, and the best available technologies in industry.

Bulgaria has implemented various strategies combining regulatory measures, technological advancements, and community initiatives. Key methods include:

Regulatory measures involve enforcing air quality standards and environmental protection laws. The National Action Plan for Air Quality includes specific measures to reduce pollution across sectors. Municipal programs have developed action plans to reduce urban air pollution.

Technological measures include installing flue gas desulfurization (FGD) systems in coal-fired power plants to reduce sulfur dioxide emissions, using electrostatic precipitators (ESPs) and fabric filters in industrial plants to capture particulate matter, and employing selective catalytic reduction (SCR) technology to reduce nitrogen oxides (NO_x) emissions. Promoting renewable energy sources, modernizing power plants, expanding public transport networks, incentivizing electric and hybrid vehicle use, and implementing stricter vehicle emissions standards are essential steps.

Urban planning and infrastructure improvements, such as increasing green spaces, planting trees, implementing congestion charges, designating low-emission zones, optimizing traffic signals, and creating roundabouts, can help reduce air pollution. Green roofs, which reduce the need for air conditioning and heating, filter particles, and convert CO_2 into oxygen, have social, economic, and environmental benefits that positively impact climate change, flood prevention, biodiversity protection, and air purification (over 43% of total CO_2 emissions are released by buildings due to cooling, heating, etc.).

Public awareness campaigns, real-time air quality data provision, and encouraging the use of energy-efficient appliances and cleaner fuels are crucial community and behavioral initiatives.

Research and innovation, including continuous air quality monitoring, collaboration with international organizations, and working with research institutions, are essential for developing new technologies and strategies for air pollution control.

9. Conclusions

Bulgaria's state policy on protecting atmospheric air quality focuses on achieving and maintaining standards in line with legislative requirements. Since joining the EU, Bulgaria's responsibilities have expanded significantly, involving new commitments to implement various European directives and international agreements related to air quality protection.

The Ministry of Environment and Water, supported by the Directorate "Protection of Air Purity," oversees the comprehensive policy in this area. This includes developing regulatory documents, coordinating national programs, setting permissible emission standards for harmful substances from stationary sources, and fulfilling obligations under the Convention on Long-Range Transboundary Air Pollution [52]. The Ministry also implemented legislation to protect the ozone layer and limit the emissions of fluorine-containing greenhouse gases. Given that air quality is influenced by numerous factors that vary by locality, the Bulgarian municipalities play a crucial role in implementing protective measures. The Ministry supports local authorities in developing and executing municipal programs to reduce harmful emissions in areas where the air quality standards are exceeded.

The quality of atmospheric air in Bulgaria is monitored through a National Control System, which tracks the daily concentrations of key pollutants. While Bulgaria does not face chronic issues with most main pollutants, excessive levels of fine particles remain a challenge, primarily due to the use of local solid fuels for heating and an aging car fleet—a problem common in many EU member states. However, data from the national monitoring system indicated a recent decline in the number of exceedances of the average daily and annual concentrations of fine dust particles at nearly all monitoring points.

Positive trends in air quality are attributed to active policies and measures at all levels, including legislative harmonization with European standards, amendments to the Air Purity Act emphasizing municipal responsibility for air quality improvement, strengthened central government oversight, and the effective implementation of municipal programs. Additionally, integrating air purity protection into funding operational programs of relevant ministries has played a significant role.

Bulgaria's approach to reducing air pollution is multifaceted, encompassing regulatory measures, technological advancements, urban planning, community initiatives, and ongoing research. These comprehensive efforts are essential for overcoming significant air quality issues and improving the overall health and well-being of the population. Continued action and innovation are crucial for meeting air quality standards and safeguarding public health and the environment.

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