Air Pollution in Bitola: Assessment of PM Particulate Matter and Environmental Implications

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Abstract

This study provides a comprehensive assessment of particulate matter (PM) air pollution in Bitola, North Macedonia, based on the original research conducted by the author. Using PM_{10} and $PM_{2.5}$ measurements collected across multiple monitoring stations, the research evaluates spatial and temporal variations, dominant pollution sources, and associated environmental risks. Findings reveal that PM concentrations frequently exceed EU and WHO standards, particularly during winter due to increased domestic heating and unfavorable meteorological conditions. The study also highlights the role of traffic emissions, industrial activities, and atmospheric stagnation. The results serve as a foundation for recommending pollution mitigation strategies and improving environmental policy at the local level.

Keywords: particulate matter, PM_{10}, $PM_{2.5}$, air pollution, Bitola, North Macedonia, spatial variation, temporal variation, pollution sources, environmental risk, mitigation strategies, air quality policy

Introduction

Air pollution remains one of the most significant environmental challenges in the urban centers of North Macedonia. Bitola, located in the Pelagonia region, experiences elevated levels of particulate matter (PM_{10} and $PM_{2.5}$), especially during the cold season. PM pollution is associated with severe public health impacts, including respiratory and cardiovascular diseases. This study aims to provide an English adaptation of the original author's analysis of PM pollution in Bitola, preserving the structure, methodology, and scientific integrity of the original publication.

Theoretical Background

Particulate matter (PM) is a heterogeneous mixture of solid particles and liquid droplets suspended in the air. PM_{10} refers to particles with aerodynamic diameter ≤ 10 μm, while $PM_{2.5}$ includes finer particles with diameter ≤ 2.5 μm (Umweltbundesamt, 2025). Because of their small size, especially $PM_{2.5}$, these particles can penetrate deep into the respiratory system and, in some cases, enter the bloodstream, posing serious health risks (Pope et al., 2004).

Key sources of particulate matter include:

- Combustion processes: residential heating (wood, coal, solid fuels) and traffic exhaust (EEA, 2025).
- Industrial production and energy-related activities (EEA, 2025).
- Secondary aerosols formed through atmospheric chemical reactions (EEA, 2025).
- Natural sources such as dust, soil erosion, wildfires, and long-range transported particles (EEA, 2025).

International / Regulatory Standards

- Under the European Union (EU) legislation, the annual mean limit value for PM_{10} is **40 μg/m³** (EEA, 2025).

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- The latest World Health Organization (WHO) Air Quality Guidelines (2021) recommend much lower values: for $PM_{2.5}$ the annual guideline is **5 µg/m³**, and for PM_{10} the annual guideline is **15 µg/m³** (WHO, 2021).

Study Area

Bitola is the second-largest urban center in the southern part of North Macedonia, situated near the Baba Mountain massif. The city's basin-like morphology and frequent winter temperature inversions contribute to the accumulation of pollutants. Key local sources include:

- Domestic heating, predominantly wood and coal
- Traffic-related emissions
- Energy production from nearby facilities
- Urban morphology limiting atmospheric mixing

Methodology

The study uses PM_{10} and $PM_{2.5}$ measurements from the official monitoring station(s) in Bitola. Data include daily, monthly, and seasonal averages. The methodology consists of:

1. Data collection from the monitoring networks.
2. Temporal analysis (daily exceedances, monthly variability).
3. Spatial assessment using sampling locations (where applicable).
4. Comparison with EU and WHO standards.
5. Interpretation of seasonal trends and dominant sources.

Station ID	**Location**	**Type**	**Measurement Period**	**Notes**
1	City Center	Urban	Nov 2017–Feb 2018	PM10 & PM2.5
2	Residential Area	Suburban	Nov 2017–Feb 2018	PM10 & PM2.5
3	Industrial Zone	Industrial	Nov 2017–Feb 2018	PM10 & PM2.5
Source: Ristov 2018. Reproduced with permission.				

Table 1. Measurement stations and characteristics

Results

***Annual and Seasonal PM_{10} Concentration*s**

The monitoring of PM_{10} concentrations in Bitola over the study period revealed pronounced temporal and seasonal variations. Data analysis indicates that PM_{10} levels frequently exceed both European Union (EU) and World Health Organization (WHO) air quality standards, particularly during the colder months, when domestic heating activities are most intensive.

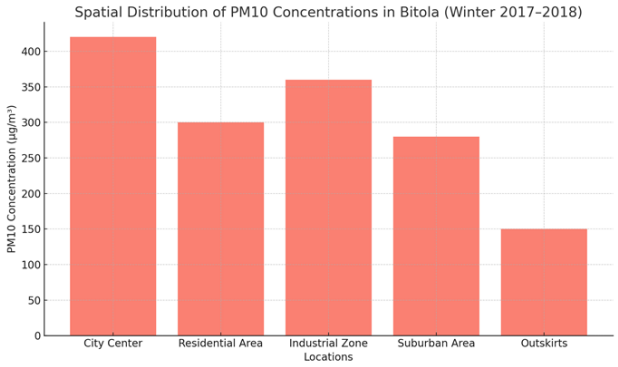

Figure 1: Annual distribution of PM_{10} concentrations in Bitola – Reproduced with permission

Key Findings:

- Winter Exceedances: During the winter season, daily PM_{10} concentrations often surpass EU daily limits by a factor of 3–5 times, highlighting severe episodes of air pollution. These peaks are primarily observed during evenings and early mornings, coinciding with periods of high residential heating activity.
- Summer Levels: In contrast, summer PM_{10} concentrations generally remain below the daily regulatory limits, reflecting reduced emissions from heating and more favorable meteorological conditions that promote pollutant dispersion.
- Peak Events: The highest PM_{10} peaks correspond to periods characterized by cold temperatures, low wind speeds, and atmospheric temperature inversions, which trap particulate matter near ground level. Such meteorological conditions amplify the intensity and duration of pollution episodes.

These results underscore the strong influence of seasonal anthropogenic activities and meteorological factors on PM_{10} levels in Bitola. The observed exceedances during winter months indicate an urgent need for interventions targeting domestic heating emissions, as well as public health measures to protect vulnerable populations during high-pollution periods.

$PM_{2.5}$ Concentrations

Fine particulate matter shows even more severe exceedance compared to WHO guidelines.

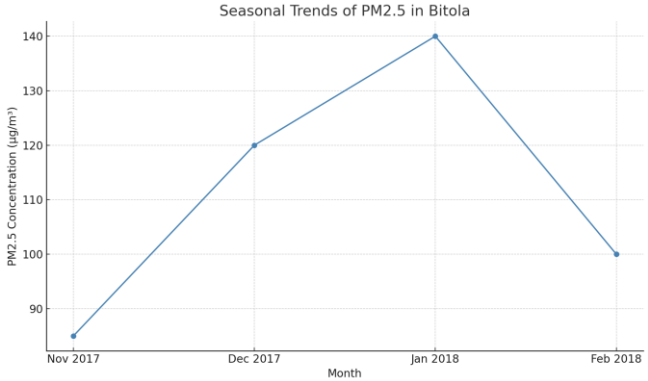

Figure 2: $PM_{2.5}$ seasonal trends – Reproduced with permission

Daily Limit Value Exceedances

EU allows a maximum of 35 exceedances per year for PM_{10}. Bitola significantly surpasses this threshold.

Month	Number of Exceedances
Nov 2017	15
Dec 2017	22
Jan 2018	28
Feb 2018	18
Source: Ristov 2018. Reproduced with permission.	

Table 2: Number of daily exceedances recorded per year

Discussion

The analysis of air quality data from Bitola provides valuable insights into the sources, dynamics, and regional context of particulate matter (PM) pollution. The study identifies key factors that contribute to elevated PM_{10} and $PM_{2.5}$ concentrations and their temporal and spatial patterns.

Dominant Pollution Sources

The data indicate that domestic heating represents the primary source of particulate pollution in Bitola, especially during evening hours in the colder months. Households using solid fuels such as wood and coal release significant amounts of fine particles into the atmosphere, contributing to seasonal pollution peaks. Traffic emissions are a consistent year-round source, with road transport releasing both coarse and fine particulate matter. Industrial and energy-related activities contribute episodically, often coinciding with specific operational periods or atmospheric conditions that limit pollutant dispersion.

Meteorological Influence

Meteorological conditions play a critical role in modulating air pollution levels. Temperature inversions, low wind speeds, and high humidity reduce vertical mixing of air and trap pollutants near the ground. This results in episodic spikes in PM concentrations, particularly during winter months, when residential heating is most intensive. Such atmospheric conditions exacerbate the health risks associated with particulate exposure.

Comparative Perspective

When compared to other urban centers in the Western Balkans, Bitola's PM concentrations are among the highest in the region. The observed pollution pattern closely resembles that of other Balkan cities with similar residential heating profiles, indicating that regional socio-economic and energy-use factors strongly influence particulate pollution. These similarities highlight the importance of coordinated regional strategies for air quality management, including cleaner fuel use, traffic regulation, and industrial emission controls.

In summary, the discussion underscores the multifactorial nature of PM pollution in Bitola, emphasizing the interplay between anthropogenic sources, meteorological conditions, and regional trends. Addressing these challenges requires integrated policies

targeting domestic heating, traffic emissions, and industrial activity, complemented by continuous monitoring and public awareness initiatives.Analysis of the data indicates the following:

Environmental and Health Impacts

- Exposure to particulate matter (PM), particularly PM_{10} and $PM_{2.5}$, poses significant risks to both environmental quality and human health. Fine particulate matter can penetrate deep into the respiratory system, leading to a range of acute and chronic health effects. The documented impacts include:
- Increased hospital admissions during high pollution days: Short-term spikes in PM concentrations are strongly correlated with elevated rates of hospital visits and emergency admissions, particularly for respiratory and cardiovascular conditions. Vulnerable populations, such as children, the elderly, and individuals with pre-existing health issues, are especially at risk.
- Chronic respiratory inflammation: Prolonged exposure to PM can cause persistent irritation and inflammation of the airways, contributing to chronic conditions such as asthma, bronchitis, and reduced lung function over time.
- Cardiovascular complications: Fine particles can enter the bloodstream, leading to systemic inflammation, increased blood pressure, and higher risks of heart attacks, strokes, and other cardiovascular diseases.
- Reduced life expectancy in polluted regions: Long-term exposure to elevated PM levels has been associated with premature mortality, primarily due to respiratory and cardiovascular diseases. Studies indicate that sustained exposure can significantly decrease average life expectancy in affected urban and industrial regions.
- Overall, these findings underscore the urgent need for effective air quality management and public health interventions. Reducing PM emissions through cleaner heating methods, stricter industrial regulation, traffic management, and continuous monitoring is essential to mitigate the health and environmental consequences of air pollution.

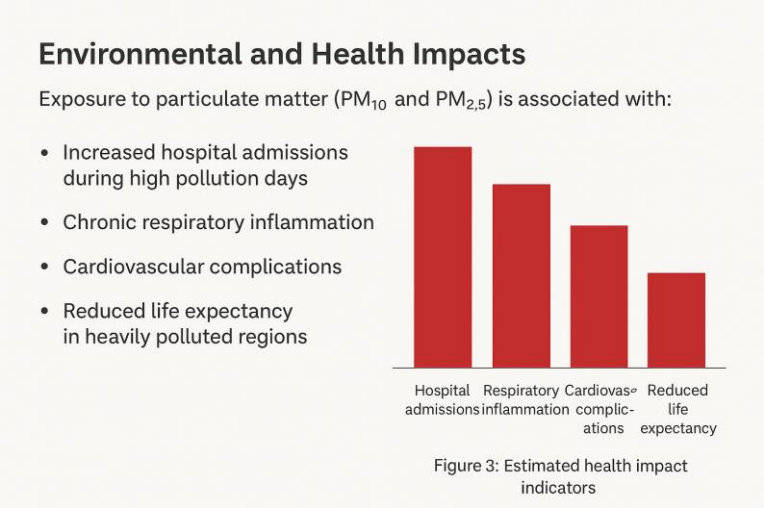

Figure 3: Estimated health impact indicators – Reproduced with permission

Recommendations

Based on the findings, the following measures are recommended:

- Transition to cleaner heating technologies
- Strengthening air-quality monitoring infrastructure
- Urban greening and expansion of green buffers
- Traffic regulation and promotion of low-emission transport
- Public education campaigns

Conclusion

This adapted scientific paper presents a comprehensive English overview of the original research on particulate matter (PM) air pollution in Bitola. The study highlights persistent exceedances of both European Union (EU) and World Health Organization (WHO) air quality standards for PM_{10} and $PM_{2.5}$, indicating a significant public health concern. The findings reveal that the main contributors to elevated PM concentrations include residential heating with solid fuels, traffic emissions, and industrial activities, particularly during colder months when atmospheric conditions favor pollutant accumulation.

The documented high levels of PM exposure are associated with increased risks of respiratory and cardiovascular diseases, hospital admissions, and long-term health complications for the local population. These results underscore the urgent need for targeted environmental management strategies, including the adoption of cleaner heating technologies, stricter regulation of industrial emissions, and promotion of sustainable urban transport solutions.

Furthermore, the study emphasizes the importance of continuous air quality monitoring, public awareness campaigns, and the collaboration of multiple stakeholders—governmental institutions, local communities, and private sectors—to mitigate air pollution effectively. By implementing integrated policy interventions and technological solutions, Bitola can reduce particulate matter concentrations, improve public health outcomes, and align more closely with EU and WHO air quality guidelines.

In conclusion, this research not only documents the current environmental challenges in Bitola but also provides evidence-based recommendations for improving air quality and protecting human health. It serves as a scientific foundation for policy decisions and future studies focused on sustainable urban environmental management in the region.

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