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ASSESSMENT OF POLLUTANT LOAD AND POTENTIAL IMPACT OF THE SNOWPACK IN BRĂILA MUNICIPALITY

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ABSTRACT

Urban snowpack represents a highly effective matrix for monitoring atmospheric deposition, as it has the capacity to accumulate pollutants originating from anthropogenic activities during the cold season. The present study aims to assess the contamination levels of snow collected from different functional areas of the Brăila municipality, as well as to estimate the potential impact of pollutants on soil and surface waters during the melting period. Snow samples were collected from areas characterized by intense road traffic, residential zones, industrial sectors, and green spaces, in order to highlight the spatial variability of contaminants. Laboratory analyses included the determination of physicochemical parameters (pH, total dissolved solids, and electrical conductivity), major ionic species (Cl^-, SO_4^{2-}, NO_3^-, NH_4^+, Ca^{2+}, Mg^{2+}), and selected heavy metals (Pb, Cd, Fe), which are relevant indicators for identifying sources of urban pollution. The assessment of pollution levels was carried out using specific indices, such as the contamination factor and the pollution load index. The obtained results highlight the influence of anthropogenic activities on the chemical composition of urban snow and emphasize its role as a vector for pollutant transfer to soils and drainage systems during snowmelt. Ultimately, this study contributes to a better understanding of seasonal urban pollution processes and provides a scientific basis for the development of sustainable environmental management measures.

KEYWORDS: urban snow, atmospheric deposition, anthropogenic pollutants

1. Introduction

Urban environments are subject to increasing anthropogenic pressure generated by road traffic, residential heating, industrial activities, and processes associated with urban infrastructure. During the cold season, the snowpack represents an efficient natural matrix for capturing atmospheric pollutants, accumulating suspended particles, soluble ions, and heavy metals deposited through both wet and dry deposition processes [1]. Due to its high specific surface area and relatively long exposure period, snow acts as a short-term integrator of anthropogenic emissions, reflecting the level of atmospheric contamination in urban ecosystems.

Seasonal snow accumulation plays a dual role from an environmental perspective. On the one hand, it temporarily immobilizes atmospheric pollutants, reducing their concentrations in the air; on the other hand, during the melting period, it can generate a concentrated input of contaminants into the soil, surface waters, and urban drainage systems [2]. Numerous studies have reported elevated concentrations of chlorides, sodium, nitrates, sulphates, and heavy metals in urban snow, particularly in areas characterized by intense traffic and industrial activities [3].

The use of salt-based de-icing materials, vehicle component wear (brake pads, tires), fossil fuel combustion, and corrosion processes represent major anthropogenic sources influencing the chemical composition of the snowpack [4]. Consequently, chemical analysis of snow has become a relevant tool for identifying pollution sources, assessing the spatial distribution of contaminants, and estimating the risks associated with their transfer to environmental compartments during snowmelt. Parameters such as pH, electrical conductivity, concentrations of major ions, and heavy metal content are frequently used as indicators of urban anthropogenic pressure [5].

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The Brăila municipality, located in southeastern Romania, represents a relevant case study due to its mixed urban–industrial profile, increasing road traffic intensity, residential heating practices, and proximity to the Danube River. Specific climatic conditions in the region favour seasonal snow accumulation, providing an opportunity for the integrated assessment of atmospheric deposition. However, data regarding the chemical composition of urban snow in medium-sized Romanian cities remain limited, highlighting the need for systematic investigations.

The present study aims to characterize the physicochemical composition of urban snow collected from various functional areas of Brăila municipality, analyse the spatial variability of major ions and heavy metals, identify potential anthropogenic sources of contamination, and evaluate the implications for soil and surface waters in the context of snowmelt. The findings contribute to understanding the seasonal dynamics of contaminants in urban ecosystems and support the development of sustainable environmental management strategies.

2. Materials and methods

2.1. Study area and sampling selection

The study was conducted in the municipality of Brăila, located in southeastern Romania, which is characterized by a temperate continental climate with cold winters favourable to snow accumulation [6]. To highlight the spatial variability of urban pollutants, four types of functional areas were selected:

- High-traffic areas: The Dorobanților Blvd.–Calea Călărași intersection; the Buzăului Road–Vizirului Road intersection; the Calea Călărași–Independenței Blvd. intersection; the Historic Centre; and a shopping centre parking area (Vărsătura);
- Residential areas: The Radu Negru neighborhood – one sample collected from a yard and one from the street;
- Industrial areas: The Chiscani chemical platform and the Brăila Shipyard;
- Green spaces: Monument Park – one sample collected from the interior and one from the park entrance (Buzăului Road).

Monument Park

Călărași – Independenței intersection

Radu Negru neighbourhood

Chiscani chemical platform

Fig. 1. *Fresh snow sampling areas (Brăila, February 2026)*

For each type of area, three fresh snow samples were collected, as illustrated in Figure 1. The sampling locations are presented on the map of Brăila municipality in Figure 2.

2.2. Sampling and preservation

Snow samples were collected from the upper layer (0-5 cm) to avoid contamination from the soil or previously accumulated dust. Each sample (~0.5 kg) was placed in a sealed polyethylene bag and labelled with the sample code, date, and location. The snow was allowed to melt at room temperature under sealed conditions to obtain an aqueous extract. The resulting volume was measured and homogenized. In the laboratory, samples were stored at a constant temperature of 4 °C prior to analysis.

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2.3. Analytical Methods

The collected snow samples were analysed for physicochemical parameters, selected ions, and heavy metals, as follows:

- pH: potentiometric method;
- Total dissolved solids (TDS) and electrical conductivity (EC): conductometric method;
- Cl^-: volumetric method with potassium chromate;
- SO_4^{2-}, NO_3^-, NH_4^+: spectrophotometric methods;
- Ca^{2+}, Mg^{2+}: volumetric method with murexide and Eriochrome Black T indicators, respectively;
- Pb, Cd, Fe: spectrophotometric methods.

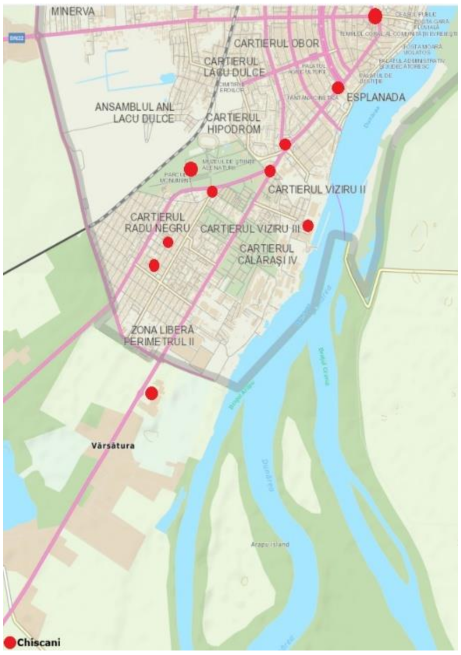

Fig. 2. *Snow sampling locations mapped in Brăila* [7]

3. Results and Discussion

3.1. Physicochemical parameters

The analysis of snow samples collected from the Brăila municipality reveals significant variations in physicochemical parameters, pH, total dissolved solids (TDS), and electrical conductivity (EC), depending on land use type and potential pollution sources, as shown in Table 1. The pH values ranged between 5.37 and 6.42, indicating a generally mild acidity. This acidity is typical of urban precipitation and can be associated with atmospheric pollutants such as nitrogen oxides (NOx) and sulphur dioxide (SO_2), originating primarily from road traffic and industrial activities [8]. The lowest pH values were recorded in high-traffic areas and near the former Chiscani chemical platform, suggesting a strong anthropogenic influence. In contrast, values closer to neutrality in the residential area (Radu Negru – street) and inside Monument Park may be explained by the presence of alkaline mineral particles in the atmosphere from soil resuspension, road dust, and construction materials.

Table 1. *Physicochemical parameters of snow samples*

Analyzed area	pH	TDS (mg/L)	EC (µS/cm)
Dorobanților – Călărașilor Road	5.37	10.5	6.72
Buzăului Road – Vizirului Road	5.62	13.0	8.32
Călărașilor Road – Independenței	5.86	20.1	12.86
Historic Center	5.97	3.7	2.37
Shopping center parking	5.41	63.9	40.90
Radu Negru – yard	5.91	7.9	5.06
Radu Negru – street	6.42	3.4	2.18
Chiscani chemical platform	5.39	42.2	27.01
Brăila Shipyard	5.75	9.5	6.08
Monument Park – interior	6.10	10.5	6.72
Monument Park – entrance	5.96	23.6	15.10

These particles, rich in carbonates (especially $CaCO_3$), can neutralize acidic compounds, leading to increased pH values [9]. Regarding total dissolved solids (TDS), values ranged widely from 3.4 mg/L to 63.9 mg/L, reflecting variability in the dissolved pollutant load. The highest values were recorded in the shopping centre parking area (63.9 mg/L), followed by the Chiscani chemical platform (42.2 mg/L), indicating significant pollutant accumulation. These levels can be attributed to intense anthropogenic activities, including traffic emissions, particulate deposition, and potential industrial discharges.

In contrast, the lowest TDS values were observed in residential areas and in the Historic Centre, suggesting reduced contamination or more efficient dispersion. Electrical conductivity (EC) shows a similar trend, confirming the direct relationship between these parameters. EC values ranged from 2.18 µS/cm to 40.90 µS/cm, with the highest values corresponding to areas previously identified with elevated TDS. Thus, the shopping centre parking area and the industrial platform represent critical points in terms of ionic load, while green and residential areas exhibit lower values, closer to the natural background levels.

Comparative analysis by land-use type shows that high-traffic and industrial areas exhibit higher TDS and EC values, confirming the impact of anthropogenic activities on precipitation quality [8]. In contrast, green spaces, particularly inside Monument Park, show lower values, making them suitable as reference areas for natural background conditions. The differences observed between the park entrance and its interior suggest the influence of traffic from adjacent areas on snow quality. The results highlight a clear correlation between land use and snow pollution levels, demonstrating that snow can serve as a reliable indicator of air quality and atmospheric deposition in urban environments [9].

The pH values (5.37–6.42) indicate a slightly acidic character of the snow, which, upon melting, may contribute to local soil acidification and to the mobilization of certain metals, particularly in areas with intense traffic and industrial activity. The concentrations of dissolved salts and the corresponding electrical conductivity values, which are higher in anthropogenically influenced areas (e.g., parking lots, industrial platforms), suggest an increased input of salts and dissolved compounds that may infiltrate into the soil and subsequently reach surface waters through runoff. Although no specific regulatory limits exist for snow, these results can be tentatively correlated with water quality requirements [10, 11], which impose the maintenance of an appropriate physico-chemical balance in water bodies. Thus, the analysed snow represents a diffuse source of pollution, with a potentially moderate, yet relevant impact in an urban context.

3.2. Major ion concentrations

The analysis of major ions in snow samples collected from Brăila highlights the variable influence of anthropogenic activities on precipitation chemistry.

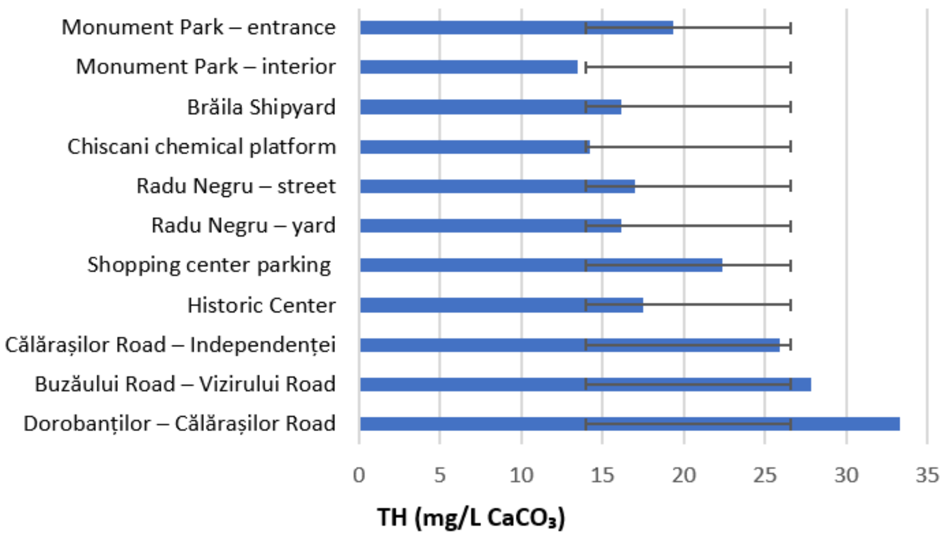

Fig. 3. *Total hardness (TH) in the studied snow samples*

In high-traffic areas, such as Dorobanților Blvd.–Calea Călărași and the Vărsătura parking area, chloride (Cl^-, 35–57 mg/L) and sulphate (SO_4^{2-}, 22–26 mg/L) concentrations are significantly higher compared to those in green areas, reflecting contributions from road traffic and industrial aerosols.

The presence of chlorides (Cl^-) identified in snow samples collected from high-traffic areas, such as major intersections and large parking lots, can be largely attributed to the use of de-icing agents based on salts such as NaCl, $CaCl_2$, and $MgCl_2$, applied to prevent ice formation and ensure traffic safety. These salts readily dissolve during snowmelt, leading to increased Cl^- concentrations in the resulting meltwater and, consequently, in soils and surface waters. This phenomenon may result in increased soil salinity, alterations in the ionic balance of aquatic ecosystems, and adverse effects on chloride-sensitive organisms [12]. Nitrates (NO_3^-, 0.5–1.4 mg/L) and ammonium (NH_4^+, 0.85–1.05 mg/L) indicate a moderate influence of nitrogen oxides originating from traffic, as well as, to some extent, from agricultural and industrial sources, while also contributing to the partial neutralization of acidity. In residential areas, ion concentrations are lower (Cl^- 30–32 mg/L; SO_4^{2-} 15–16 mg/L), suggesting a reduced anthropogenic impact. In contrast, the Chiscani chemical platform and the shipyard exhibit elevated SO_4^{2-} and NH_4^+ levels, highlighting direct industrial inputs. Green areas, particularly the interior of Monument Park, record the lowest values for all measured ions, indicating conditions close to the natural background and a greater capacity for pollutant filtration.

Alkaline ions, Ca^{2+} and Mg^{2+}, present especially in urban and industrial areas, originate from mineral dust, resuspended soil, and construction materials, and play an essential role in the neutralization of precipitation acidity, which correlates with pH values closer to neutrality in residential areas and parks [8, 9]. This neutralization reduces the immediate impact of acidity on soils and surface waters; however, elevated Cl^- and SO_4^{2-} levels in traffic-affected and industrial areas may contribute to increased soil salinity and surface water conductivity, promoting metal mobilization and alterations in the ecological balance [8].

During snowmelt, within impervious areas, dissolved ions are transported to adjacent soils and urban drainage networks, which may affect both soil structure and water quality. Although the determined values do not exceed the permissible limits regulated for precipitation, it is necessary to maintain an appropriate physico-chemical balance of surface waters and to protect aquatic ecosystems through recurrent monitoring. All total hardness (TH) values are below 40 mg/L $CaCO_3$, indicating low hardness levels that fall within the maximum permissible concentrations. High-traffic areas and parking lots (e.g., Dorobanților Boulevard, Vărsătura) exhibit higher hardness values (22–33 mg/L $CaCO_3$), as well as higher concentrations of Ca^{2+} and Mg^{2+} ions, likely due to urban dust and the resuspension of construction materials. Industrial areas and green spaces (Chiscani, park interior) show lower TH values (13–16 mg/L $CaCO_3$), closer to natural background conditions. Low-hardness precipitation contributes less to the formation of calcareous deposits in soils or drainage systems.

3.3. Heavy metals

Figure 4 presents the analysis of heavy metals Pb, Cd, and Fe in snow samples from the city of Brăila. The results highlight a distribution of the analysed metals correlated with the degree of anthropogenic influence and the type of area. High-traffic and industrial zones exhibit higher concentrations of lead and cadmium, suggesting a continuous input of atmospheric pollutants from road traffic and industrial sources, including fossil fuel emissions, tire wear, construction materials, and industrial processes [13, 14].

Iron (Fe) concentrations are higher in the Chiscani chemical platform and the shipyard (180–200 µg/L), indicating deposition associated with industrial activities and the presence of iron in urban aerosols and dust. In contrast, residential areas and green spaces, such as Radu Negru District and Monument Park, exhibit much lower concentrations (Pb 7–10 µg/L; Cd 2.5–3 µg/L; Fe 50–65 µg/L), approaching natural background levels for precipitation and reflecting a moderate anthropogenic impact. Heavy metals in snow represent a potential risk to soils and surface waters. During snowmelt, Pb, Cd, and Fe can be transported into soils and drainage systems, where they may alter soil chemical properties, influence nutrient availability, and affect aquatic ecosystems through bioaccumulation or direct toxicity [15]. High-traffic and industrial areas pose a greater risk, whereas green and residential zones act as buffer areas, reducing pollutant input to the urban and aquatic environment.

The determined concentrations of heavy metals in the collected snow samples do not exceed the permissible limits established by water quality and soil protection legislation [11, 16].

Table 2. *Major ion concentrations (mg/L)*

Area	Cl^-	SO_4^{2-}	NO_3^-	NH_4^+	Ca^{2+}	Mg^{2+}
Dorobanților – Călărași Road	35.45	26	0.9	0.85	10.2	1.89
Buzăului Road – Vizirului Road	49.63	24	1.1	0.95	8.5	1.6
Călărași Road – Independenței	49.63	23	1.2	1.00	7.9	1.5
Historic Center	33.46	18	0.7	0.60	5.2	1.1
Shopping center parking	56.72	22	1.4	1.05	6.01	1.78
Radu Negru – yard	30.4	15	0.6	0.50	4.8	1.0
Radu Negru – street	31.54	16	0.7	0.55	5.0	1.1
Chiscani chemical platform	42.54	24	0.9	1.56	3.61	1.26
Brăila Shipyard	28.36	30	1.0	0.80	4.5	1.2
Monument Park – interior	21.27	12	0.5	0.40	3.9	0.9
Monument Park – entrance	34.24	20	0.8	0.70	5.6	1.3

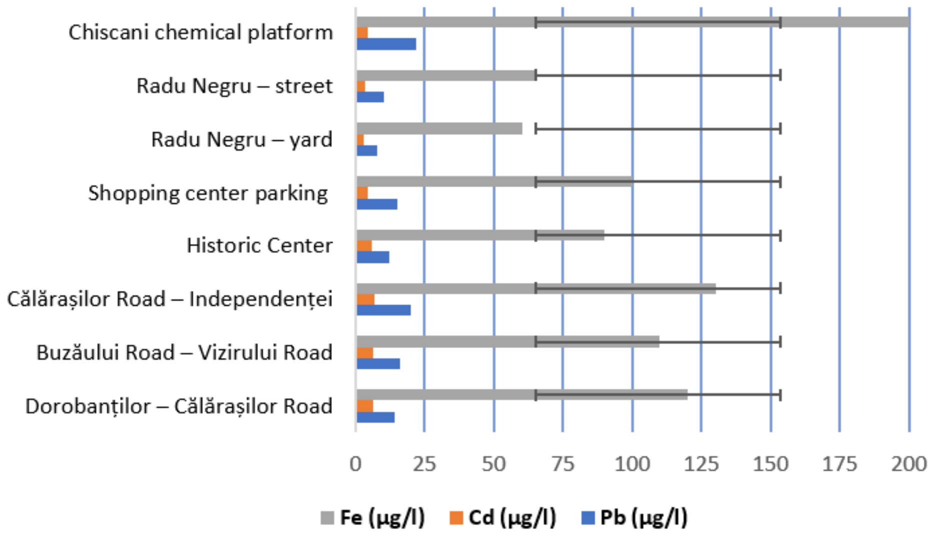

Fig. 4. *Concentrations of Pb, Cd, and Fe in the studied snow samples*

4. Conclusions

According to the chemical analysis of snow collected in the city of Brăila, the following observations were made:

- Slightly acidic pH values (5.37–6.42) reflect the input of atmospheric pollutants from traffic and industrial areas, while residential areas and green spaces show values closer to neutrality due to the presence of alkaline mineral particles that contribute to neutralization.
- Higher total dissolved salts and electrical conductivity in parking lots and industrial platforms indicate an increased input of dissolved salts and urban-industrial pollutants. Green and residential areas show lower values, reflecting a reduced anthropogenic impact and a natural filtration capacity.
- The presence of Cl^-, SO_4^{2-}, and NO_3^- ions highlight the influence of traffic and industrial activities, while NH_4^+ partially contributes to acidity neutralization.
- The analysed metals (Pb, Cd, Fe) exhibit the highest concentrations in high-traffic and industrial areas, likely due to vehicle wear or corrosion processes; however, in the analysed samples, the presence of these metals indicates moderate anthropogenic deposition. In residential areas and green spaces, values are close to natural background levels, suggesting a low impact.

Snow acts as a vector of diffuse pollution, transporting ions and heavy metals to soils and surface waters. In urban and industrial areas, this phenomenon can lead to partial acidification, increased soil salinity, and metal mobilization, affecting aquatic ecosystems and soil structure. Therefore, continuous monitoring of snow and precipitation is recommended to identify trends in urban and industrial pollution, alongside the promotion and maintenance of green spaces, which serve as buffer zones and natural filters for pollutants.

A comparative analysis of the physico-chemical parameters and the concentrations of major ions and heavy metals in snow samples collected in the city of Brăila indicates that all determined values fall within the limits established by current legislation regarding the discharge of wastewater into sewer networks and natural receptors [17-19]. Furthermore, a comparison with surface water quality standards shows that the levels of the analysed heavy metals (Pb, Cd, Fe) do not exceed indicative ecological risk thresholds. Nevertheless, they may contribute in the long term to alterations in soil properties and to an increased pollutant load in surface waters, particularly under conditions of repeated snow deposition and melt events.

Therefore, it can be concluded that, although spatial variations are determined by anthropogenic influences (traffic, industrial activities, and the use of de-icing materials), the analysed snow does not exhibit contamination levels exceeding the maximum permissible concentrations, and the potential impact on soils and surface waters remains generally low to moderate, which is characteristic of an urban environment.

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