

Influence of Atmospheric Stability on Air Quality in the Vicinity of Prudinec/Jakuševac Landfill

I. Bešlić,^a S. Sopčić,^{a*} D. Mihajlović,^b and V. Vadić^c

^a Institute for Medical Research and Occupational Health, Ksaverska c. 2, 10 000 Zagreb, Croatia

^b Croatian Meteorological and Hydrological Service, Ravnice 48, 10 000 Zagreb, Croatia

^c EKONERG–Energy and Environmental Protection Institute, Koranska 5, 10 000 Zagreb, Croatia

This work is licensed under a
Creative Commons Attribution 4.0
International License



Abstract

To evaluate the impact of meteorological conditions on air quality in the vicinity of the Prudinec/Jakuševac landfill in Zagreb, daily concentrations of particulate matter (PM₁₀), hydrogen sulphide (H₂S), and ammonia (NH₃), monitored over a five-year period (2020–2024), were analysed. Under meteorological conditions in which the mixing layer height (MLH) falls below 1,000 m, an inversion layer forms above the city, suppressing vertical air mixing and leading to atmospheric stability and pollutant accumulation. The results showed that nearly 80 % of stable conditions occurred during the cold season (autumn and winter) of the study period. During these stable episodes, 88 % of all daily PM₁₀ limit exceedances and 70 % of H₂S exceedances were recorded. Comparable PM₁₀ concentrations were measured at several monitoring stations across Zagreb, suggesting that the landfill is not a dominant source of PM₁₀ pollution. The seasonal pattern of H₂S concentrations at the landfill showed higher levels during winter, opposite to the pattern observed at the nearby Central Wastewater Treatment Plant of the City of Zagreb (CUPOVZ).

This behaviour indicates the landfill is most likely a specific local source of H₂S. NH₃ concentrations were higher during the warm season both near the landfill and at CUPOVZ, suggesting different dominant emission sources. The differing seasonal patterns of PM₁₀, H₂S, and NH₃ indicate that these pollutants originate from distinct dominant emission sources. In the south-eastern part of Zagreb, agriculture and livestock farming are likely among the main contributors to NH₃ emissions.

Keywords

Air quality, mixing layer height, PM₁₀, hydrogen sulphide, ammonia

1 Introduction

Higher living standards, expanding urban areas, and increased consumption associated with modern lifestyles have generated large volumes of waste. The composition of landfill waste is highly variable and largely unknown. As a result, numerous chemical and microbiological processes occur within the waste body, producing substantial quantities of landfill gas during decomposition. Air quality monitoring near landfills is therefore particularly important, as pollutants released during waste decomposition may pose risks to human health, affect quality of life, and impact surrounding ecosystems.^{1,2} Biodegradation of waste proceeds through four distinct phases, primarily influenced by water and oxygen content, ambient temperature, humidity, and precipitation.³ As described by Vujević *et al.*⁴, the first phase begins with aerobic degradation driven by available oxygen. Within 2–3 weeks, oxygen concentrations decrease from 20 % to 0 %, accompanied by a decline in nitrogen concentrations. The second phase is dominated by anaerobic microorganisms that become active once oxygen is depleted. During this phase, methane (CH₄) production remains low, while carbon dioxide (CO₂) levels can reach up to 80 % of the total landfill gas. The third phase marks the onset of intense CH₄ production, with methanogenic microbes increasing its concentration up to 70 % of the gas mixture. In the fourth phase, anaerobic microbial activity

declines, reducing overall biogas production. Combined, CO₂ and CH₄ account for more than 90 % of landfill gas. In modern waste management systems, this gas is captured and directed to specialised treatment facilities. In addition to CH₄ and CO₂, ammonia (NH₃) and hydrogen sulphide (H₂S) are emitted, especially during the anaerobic phases;⁵ however, they may also originate from other sources. For example, H₂S is known to be produced during oil refining, paper manufacturing, and wastewater treatment processes, while NH₃, in addition to these sources, primarily originates from agriculture and livestock farming.⁶ These compounds are characterised by unpleasant, irritating odours and potential health risks,^{7,8} which is why they are regularly monitored near primary emission sources such as landfills.

The Prudinec/Jakuševac landfill is the primary disposal site for municipal and non-hazardous industrial waste for the City of Zagreb and surrounding areas. Its history dates back to the 1960s, when uncontrolled waste disposal began, soon becoming a serious environmental concern for the city.⁹ Remediation began in 1995 and included the installation of an impermeable base, leachate water treatment systems, and landfill gas management systems. According to official technical documentation, the total capacity of the Prudinec/Jakuševac landfill is approximately 15.12 million m³ of waste, distributed across six disposal areas of various sizes.¹⁰ By 2012, approximately 11 million m³ of waste had been deposited. Recent estimates indicate that Prudinec/Jakuševac currently contains approximately 15 million tons of waste, suggesting that it is approaching full

* Corresponding author: Suzana Sopčić, PhD
Email: ssopcic@imi.hr

capacity and remains a continuing challenge for Zagreb's waste management system. In the near future, the existing landfill is expected to be replaced with a modern waste management centre designed to minimise environmental impact and improve the quality of life of local residents.¹¹ Due to the continuous delivery of waste and ongoing landfill remediation activities at the Prudinec/Jakuševac landfill, as well as its proximity to a residential area, concentrations of particulate matter with an aerodynamic diameter smaller than 10 μm (PM_{10}) are also regularly monitored, as exposure poses risks to both respiratory and cardiovascular systems.¹² Limit values for air pollutant concentrations are defined by European Union directives and national regulations.^{13,14} However, EU legislation provides limit values (LVs) only for PM with regard to the protection of human health, while odour nuisance is regulated differently across EU Member States, and no harmonised binding framework exists. In the Republic of Croatia, limit values related to quality of life (odour nuisance) are prescribed for H_2S , NH_3 , mercaptans, and formaldehyde.¹⁵ Table 1 presents the statistical parameters used in the evaluation on air quality, living conditions, and potential odour nuisance.¹³ In addition to the annual mean limit for PM_{10} , legislation prescribes a maximum number of daily exceedances to account for short-term pollution peaks that could otherwise be obscured by annual averaging.

Table 1 – Limit values for the protection of human health (PM_{10}) and quality of life – odour nuisance (H_2S , NH_3)¹³

Tablica 1 – Granične vrijednosti za zaštitu zdravlja ljudi (PM_{10}) i kvalitetu življenja – dodijavanje mirisom (H_2S , NH_3)¹³

Pollutant	Averaging period	Limit values / $\mu\text{g m}^{-3}$	Permitted exceedances per year
PM_{10}	24-h	50	not more than 35 times
	annual	40	–
H_2S	1-h	7	not more than 24 times
	24-h	5	not more than 7 times
NH_3	24-h	100	not more than 7 times

It is well established that air pollution accumulates under stable meteorological conditions, typically characterised by vertical temperature profiles.¹⁶ Under normal atmospheric conditions, the troposphere exhibits a negative environmental lapse rate, meaning that air temperature decreases with altitude. This vertical temperature gradient promotes buoyant motion and vertical mixing, facilitating pollutant dispersion. During a temperature inversion, however, a layer of warmer air overlies cooler air near the surface, suppressing vertical air movement and limiting atmospheric mixing. As a result, pollutants emitted at ground level remain confined within the lower atmosphere, often leading to elevated pollution concentrations and deteriorated air quality.^{17,18} This phenomenon is particularly pronounced in urban environments, where temperature inversions trap vehicular exhaust, smoke, dust, etc., thereby contributing to poor air quality and smog formation.¹⁹ Temperature in-

versions most frequently develop at night or in the early morning, when rapid ground cooling causes the air near the surface to become colder than the air above. The temperature profile during an inversion event is illustrated in Fig. 1.

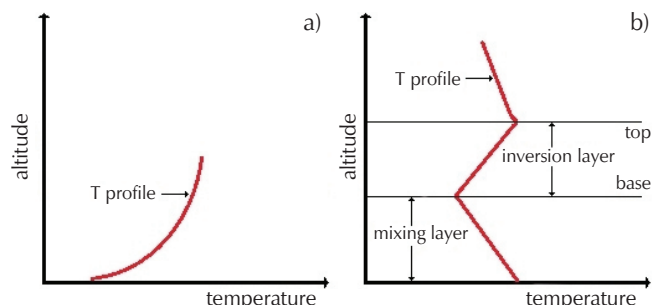


Fig. 1 – Temperature inversion profile

Slika 1 – Temperaturni profil tijekom inverzije

From the ground upward, air temperature typically decreases with height, allowing pollutants to disperse vertically. The lowest atmospheric layer responsible for this dispersion is known as the mixing layer. Above it lies an elevated inversion layer, where temperature increases again and vertical motion is suppressed. When the mixing layer is shallow, pollutants remain confined near the ground. The height of the mixing layer evolves from stable conditions (at night) to neutral or unstable conditions (during the day), reaching a maximum in the early afternoon. Consequently, the mixing layer height measured by radiosondes at 12:00 UTC serves as a reliable indicator of long-term atmospheric stability. Elevated inversions typically result from anticyclonic subsidence or warm-air advection aloft.²⁰ The City of Zagreb, situated at approximately 150 m above sea level, is bordered by Mount Medvednica to the north and the Žumberak Mountains (Žumberačko gorje) to the south-west, both exceeding 1,000 m in height. When the mixing layer height falls below 1,000 m, an inversion forms over the city, trapping pollutants within a confined atmospheric volume. Given these geographical factors, the aim of this study was to analyse daily PM_{10} , H_2S , and NH_3 concentrations collected over a five-year period at the special purpose air quality monitoring station Jakuševac, located near the landfill. This study represents the first investigation in Croatia to examine pollutant concentrations in relation to mixing layer height as an indicator of atmospheric stability. To the best of our knowledge, it also represents the first assessment of air quality in the vicinity of a landfill site that explicitly incorporates mixing layer height as a measure of atmospheric stability.

2 Experimental

2.1 Measuring location

The Prudinec/Jakuševac landfill is located in the south-eastern part of Zagreb, on the right bank of the Sava River, approximately 400 m from the residential area of Jakuševac

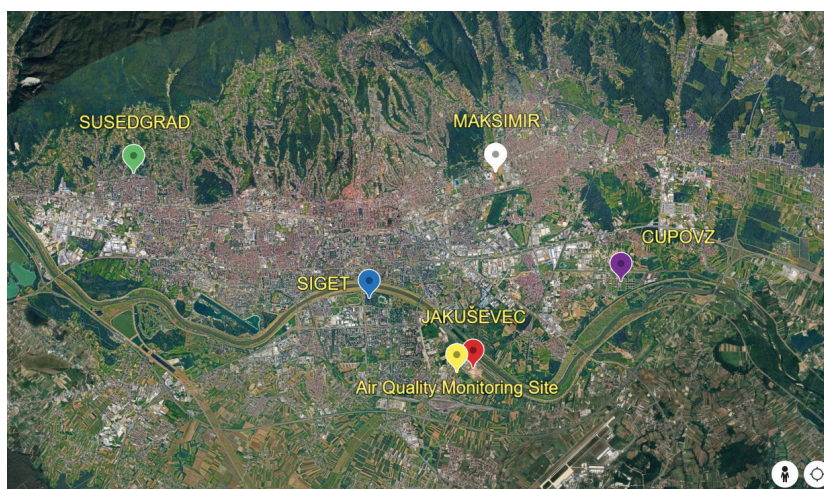


Fig. 2 – Geographical location of the Prudinec/Jakuševac landfill (red marker), the Central Wastewater Treatment Plant of the City of Zagreb (CUPOVZ) (purple marker), local air quality monitoring sites: Jakuševac (yellow), Siget (blue), Susedgrad (green), and meteorological station Maksimir (white). (Source: Google Earth)

Slika 2 – Geografski položaj odlagališta Prudinec/Jakuševac (crveno), Centralnog uređaja za pročišćavanje otpadnih voda (CUPOVZ) (ljubičasto), lokalnih postaja za praćenje kvalitete zraka: Jakuševac (žuto), Siget (plavo) i Susedgrad (zeleno) i meteorološke postaje Maksimir (bijelo). (Izvor: Google Earth)

(Fig. 2, red marker). The air quality monitoring station is situated approximately 300 m west of the landfill, within the residential area (Fig. 2, yellow marker). The Prudinec/Jakuševac landfill is operated by Čistoća, a subsidiary of Zagreb Holding, while air quality monitoring is conducted by authorised laboratories in accordance with national regulations. Air quality monitoring near the Jakuševac landfill has been carried out as part of the City of Zagreb's air quality monitoring network since 2014.

Earlier targeted air quality measurements within the landfill's zone of influence began in the mid-1990s during remediation activities. Fig. 2 also shows the locations of additional air quality monitoring stations used for comparison of daily PM_{10} concentrations: the traffic station in Siget (southern Zagreb, blue marker), the industrial station in Susedgrad (north-western Zagreb, green marker), the Central Wastewater Treatment Plant of the City of Zagreb (CUPOVZ), located approximately 10 km east-north-east of the landfill (purple marker), and the meteorological station in Maksimir.

2.2 Measurement Data

Daily PM_{10} samples were collected using a Sven Leckel SEQ 47/50 sampler operating at an air flow rate of $55 \text{ m}^3 \text{ day}^{-1}$. Sampling was conducted on Whatman QM-A quartz fibre filters (47 mm diameter). Mass concentrations of PM_{10} were determined by the Institute for Medical Research and Occupational Health (IMROH) using the reference gravimetric method (EN 12341).²¹

Before and after sampling, filters were conditioned under controlled laboratory conditions ($20 \pm 1 \text{ }^\circ\text{C}$; $47.5 \pm 2.5 \text{ \% RH}$) and weighed.

Mass concentrations of hydrogen sulphide (H_2S) and ammonia (NH_3) were determined using Horiba APSA 370/CU-1 and Horiba APNA 370/CU-2 analysers, respectively. All measurements were conducted and provided by EKON-ERG. Quality assurance procedures followed EN 14212 for H_2S (measured by ultraviolet fluorescence with an oxidation catalyst),²² and EN 14211 for NH_3 (measured by chemiluminescence with an oxidation catalyst).²³ Hourly H_2S and NH_3 concentrations were averaged to obtain daily mean values. Meteorological data, including daily average air temperature and mixing layer height (MLH) at 12:00 UTC, were obtained from the Croatian Meteorological and Hydrological Service (DHMZ). MLH was determined from radiosonde measurements using the Richardson number method.²⁴ These measurements are continuously conducted at the Maksimir meteorological station. For the purposes of this study, a five-year dataset (2020–2024) was analysed. Statistical analysis of the data was carried out using the *TIBCO Statistica* software package (Version 14.0.0.5).

3 Results and discussion

3.1 Analysis of PM_{10} concentrations

Fig. 3 presents the time series of PM_{10} concentrations at the Jakuševac site over a five-year period. Higher PM_{10} concentrations were observed during the cold seasons compared with the warmer seasons. Similar seasonal behaviour

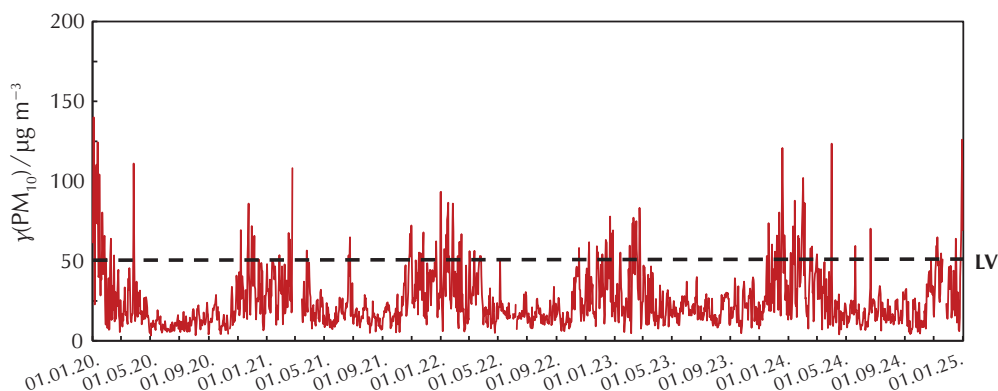


Fig. 3 – Daily mass concentrations of PM₁₀ at the Jakuševac monitoring site in the period from 2020 to 2024

Slika 3 – Dnevne masene koncentracije PM₁₀ lebdećih čestica na mjernejoj postaji Jakuševac u periodu od 2020. do 2024. godine

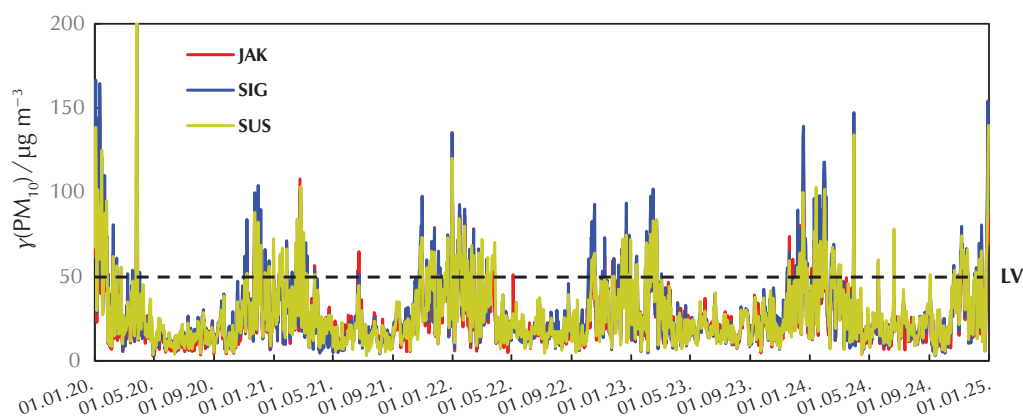


Fig. 4 – Comparison of daily PM₁₀ mass concentrations at monitoring sites Jakuševac (JAK), Siget (SIG), and Susedgrad (SUS), in the period from 2020 to 2024

Slika 4 – Usporedba dnevnihi vrijednosti masenih koncentracija PM₁₀ na mjernim postajama Jakuševac (JAK), Siget (SIG) i Susedgrad (SUS), u razdoblju od 2020. do 2024. godine

of PM₁₀ mass concentrations were registered at the Ksaverska cesta and Zagreb-3 monitoring sites.²⁵

To assess whether the Prudinec/Jakuševac landfill is a dominant local source of PM₁₀, concentrations measured at the Jakuševac monitoring site were compared with those recorded at two other Zagreb air quality monitoring stations, Siget and Susedgrad (Fig. 4). The Siget station is categorised as a traffic site, whereas Susedgrad represents an industrial location within the monitoring network. A comparison of daily PM₁₀ concentrations across all three stations reveals highly similar behaviour, making it difficult to distinguish location-specific contributions.

Fig. 5 displays the average annual PM₁₀ mass concentrations at each monitoring site. The lowest values were recorded at the Jakuševac station, indicating that the landfill is unlikely to be a dominant source of PM₁₀ pollution in its vicinity. Moreover, average annual concentrations remained below the annual limit value of 40 μg m⁻³ (Table 1) at all three locations. Although exceedances of the daily limit value (50 μg m⁻³) were observed, particularly during the winter months, the number of these exceedances was

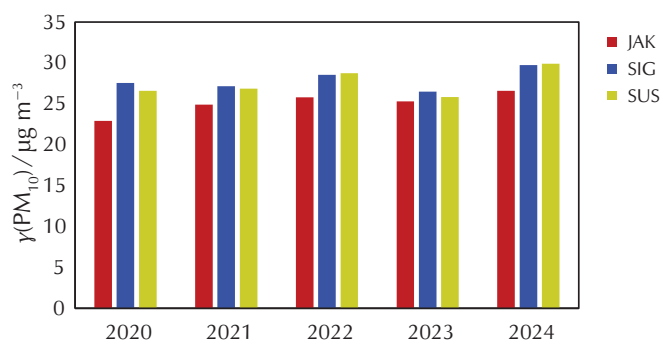


Fig. 5 – Annual average mass concentrations of PM₁₀ at monitoring sites Jakuševac (JAK), Siget (SIG), and Susedgrad (SUS)

Slika 5 – Prosječna godišnja masena koncentracija PM₁₀ na mjernim postajama Jakuševac (JAK), Siget (SIG) i Susedgrad (SUS)

lowest at the Jakuševac monitoring site (Table 2). This further supports the conclusion that the landfill is not the primary contributor to PM_{10} levels in the area.

Table 2 – Annual number of days exceeding the daily PM_{10} limit value at three monitoring sites

Tablica 2 – Godišnji broj dana s prekoračenjem dnevne granične vrijednosti za PM_{10} na tri mjerne postaje

	2020	2021	2022	2023	2024
Jakuševac	33	24	33	29	36
Siget	44	41	50	32	51
Susedgrad	41	38	56	30	52

3.2 Analysis of H_2S mass concentrations

Fig. 6 shows the daily mass concentrations of H_2S measured at the Jakuševac monitoring site. A similar pattern to that of PM_{10} is evident, with the highest values recorded

during the cold seasons. Daily concentrations of H_2S only occasionally exceeded the limit value of $7 \mu g m^{-3}$, however, in recent years, there were no exceedances above this legally prescribed threshold. Since there are no continuous H_2S measurements available at other locations in Zagreb, it is difficult to directly confirm whether the landfill is the dominant source of H_2S . However, approximately 10 km east of the landfill is the Central Wastewater Treatment Plant of the City of Zagreb (CUPOVZ), where H_2S and NH_3 concentrations are measured seasonally, one month in summer and one in winter.^{26–31} At CUPOVZ, measurements are conducted at five different locations within the facility. To enable a meaningful comparison with the Jakuševac monitoring site, measurements from all five CUPOVZ locations were averaged to obtain a single daily concentration value representing the CUPOVZ site. Additionally, the measurement periods at the Jakuševac site were adjusted to match the timeframes of the CUPOVZ sampling campaigns. Comparison of H_2S levels measured in the winter and summer at both the Jakuševac and the CUPOVZ site is shown in Fig. 7.

Opposite seasonal behaviour in H_2S mass concentrations was observed at two monitoring sites. At the Jakuševac site,

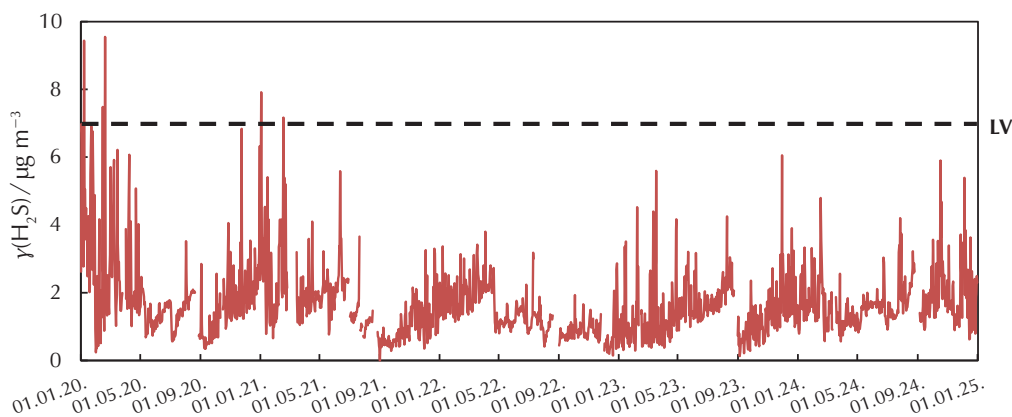


Fig. 6 – Daily mass concentrations of H_2S measured at the Jakuševac monitoring site
Slika 6 – Dnevna masena koncentracija H_2S izmjerena na mjernoj postaji Jakuševac

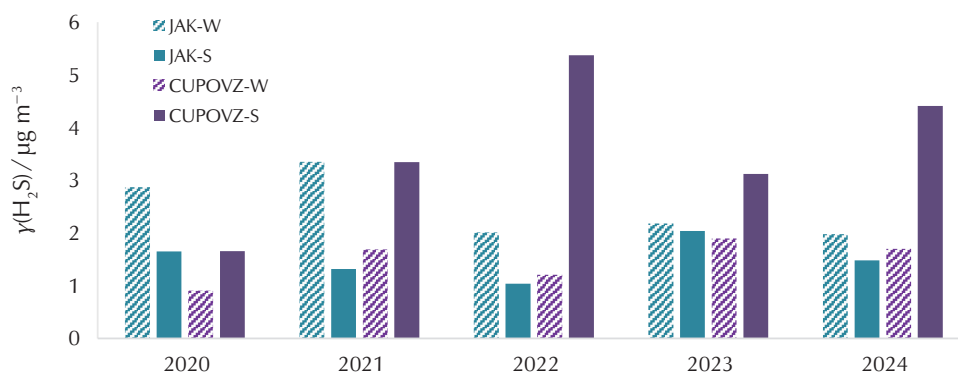


Fig. 7 – Average H_2S mass concentrations measured during winter (W) and summer (S) at Jakuševac (JAK) monitoring site and CUPOVZ

Slika 7 – Prosječne sezonske masene koncentracije za H_2S mjerene tijekom zime (W) i ljeta (S) na mjernoj postaji Jakuševac (JAK) i CUPOVZ

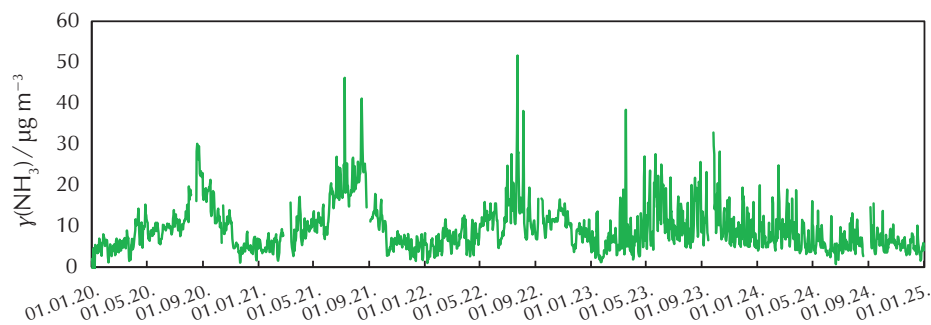


Fig. 8 – Daily mass concentrations of NH_3 measured at the Jakuševac monitoring site
Slika 8 – Dnevne masene koncentracije NH_3 izmjerene na mjernoj postaji Jakuševac

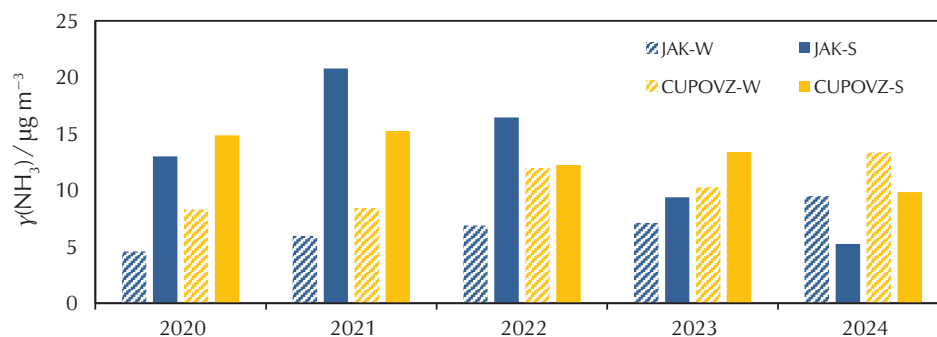


Fig. 9 – Average NH_3 mass concentrations measured during winter (W) and summer (S) at Jakuševac (JAK) and CUPOVZ measuring site

Slika 9 – Prosječne sezonske masene koncentracije za NH_3 mjerene tijekom zime (W) i ljeta (S) na mjernoj postaji Jakuševac (JAK) i CUPOVZ

the highest concentrations occurred during winter, while at the CUPOVZ site, higher concentrations were recorded during summer. This contrasting seasonal pattern at two relatively close sites suggests that the observed concentrations reflect the dynamics of local emission sources. It is therefore likely that both the Prudinec/Jakuševac landfill and the CUPOVZ facility act as the dominant H_2S source within their respective immediate surroundings, rather than representing a shared dominant source across a broader area. Moreover, the distinct operational and emission dynamics of these facilities likely result in differing temporal trends in the observed H_2S concentrations.

3.3 Analysis of NH_3 mass concentrations

Fig. 8 presents the daily mass concentrations of NH_3 at the Jakuševac monitoring site near the landfill. The observed pattern differs from those of PM_{10} and H_2S , as higher NH_3 concentrations were recorded during the warmer months, while lower concentrations prevailed during the colder months. This seasonal pattern was consistent throughout the study period, except in 2024, when the behaviour deviated. During the period of five years, there were no exceedances of the limit values ($100 \mu\text{g m}^{-3}$).

When comparing daily patterns in H_2S and NH_3 mass concentrations at the Jakuševac site (Figs. 6 and 8), distinct seasonal patterns are observed, suggesting different dominant emission sources. While the landfill likely contributes to local NH_3 levels, it does not appear to be the primary source. To further investigate potential NH_3 sources, seasonal concentration data from the CUPOVZ site were also analysed. As in the case of H_2S , NH_3 concentrations from the five CUPOVZ locations were averaged to obtain daily values for comparison with those at the Jakuševac site. The measurement periods at Jakuševac were also aligned with the CUPOVZ sampling campaigns. The seasonal behaviour of NH_3 at both sites shows a very similar pattern, with higher concentrations during the winter and lower during the summer (Fig. 9). An exception occurred in 2024, when the opposite pattern was observed, with peak concentrations during winter. These findings indicate the presence of mixed NH_3 emission sources rather than a single dominant seasonal contributor. Given that agriculture and livestock farming are well-established sources of NH_3 , these activities are also the most probable contributors to the elevated concentrations.³² The lower summer NH_3 concentrations observed in 2024 could potentially be associated with a reported reduction in livestock numbers; however, no official data confirming this reduction is currently available. Therefore, this observation remains preliminary and warrants further investigation in future studies, including continued monitoring in 2025.

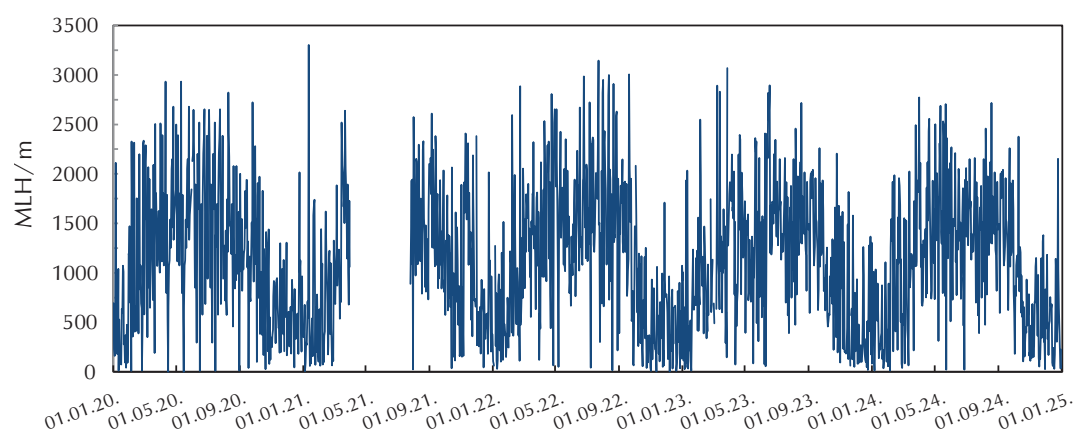


Fig. 10 – Mixing layer height (MLH) in the period from 2020 to 2024

Slika 10 – Visina sloja miješanja (MLH) u razdoblju od 2020. do 2024. godine

3.4 Distribution of mixing layer height at 12:00 UTC

The MLH was determined from radiosonde observations using the Richardson number method, with measurements conducted at 12:00 UTC since the mixing layer typically reaches its maximum height around early afternoon. Fig. 10 presents the MLH values over a five-year period. A data gap between April 1 and July 25, 2021, occurred due to instrument maintenance. In total, MLH data were available for 1,692 days. The results indicate that MLH was lowest during the cold part of the year.

Over the five-year period in the City of Zagreb, mixing layer heights (MLH) below 1,000 m were recorded on 739 days, representing 43.7 % of the total measurement days. Of these occurrences, 47.2 % were observed in winter and 31.0 % in autumn, indicating that nearly 80 % of low MLH events (below 1,000 m) occurred during the cold seasons. Table 3 summarises the distribution of days with MLH < 1,000 m, which corresponds to stable atmospheric conditions. A similar seasonal distribution and pattern were reported for Zagreb in the period from 1977 to 1982 by Lončar et al.³³ confirming the previously identified relationship between PM₁₀ and low mixing layer height.

Table 3 – Seasonal distribution of days with mixing layer height (MLH) below 1,000 m

Tablica 3 – Sezonska raspodjela dana s visinom sloja miješanja (MLH) manjom od 1,000 m

Season	Number of days	% of all measured days	% of MLH < 1,000 m days
Winter	349	20.6	47.2
Spring	90	5.3	12.2
Summer	71	4.2	9.6
Autumn	229	13.5	31.0
Total/%	739	43.7	100

3.5 Correlation of concentration levels with meteorological parameters

A correlation analysis was conducted to explore the relationship between PM₁₀, H₂S, and NH₃ concentrations and meteorological parameters, specifically MLH and average daily temperature. As shown in Table 4, the correlation coefficients are not high, but all are statistically significant ($p < 0.05$).

Table 4 – Correlation matrix between PM₁₀, H₂S, and NH₃, and meteorological parameters, mixing layer height (MLH), and average daily temperature ($t/^\circ\text{C}$).

Tablica 4 – Korelacijska matrica između PM₁₀, H₂S, NH₃ i meteoroloških parametara, visina graničnog sloja (MLH) i prosječne dnevne temperature ($t/^\circ\text{C}$).

	MLH	$t/^\circ\text{C}$	PM ₁₀	H ₂ S	NH ₃
MLH	1.000	0.484	-0.381	-0.165	0.148
$t/^\circ\text{C}$		1.000	-0.518	-0.274	0.498
PM ₁₀			1.000	0.343	-0.160
H ₂ S				1.000	-0.079
NH ₃					1.000

The positive correlation between MLH and temperature indicates that lower MLH values are more frequent during colder periods, which is consistent with the highest number of low-MLH days occurring in winter (Table 3). Negative correlations between PM₁₀ concentrations and both MLH and temperature, indicating that elevated PM₁₀ levels tend to occur under stable atmospheric conditions characterised by low mixing layer heights and lower ambient temperatures. However, during winter, pollutant emissions across the entire city increase, further contributing

to elevated PM₁₀ concentrations as a result of intensified residential heating and increased vehicular traffic.^{25,34} A similar pattern was observed for H₂S concentrations, indicating that levels tend to increase under stable atmospheric conditions during the cold season. This effect is particularly pronounced in winter, when persistent temperature inversions trap pollutants near the surface, a phenomenon clearly evident at the Prudinec/Jakuševac landfill (Fig. 7). However, H₂S emissions from the CUPOVZ wastewater treatment plant appear to be less influenced by atmospheric stability, likely due to its open terrain and location farther from surrounding mountains like Medvednica and Žumberačko gorje, which enhance inversion formation over Zagreb. In contrast, NH₃ concentrations displayed positive correlations with both MLH and temperature, indicating that NH₃ levels tend to rise during warmer periods and under conditions of increased atmospheric mixing. This behaviour supports the assumption that NH₃ originates from sources influenced more by temperature than by atmospheric stability, such as agricultural and livestock activities, as well as more intense organic decomposition.

4 Conclusion

The five-year dataset (2020–2024) of daily concentrations of PM₁₀, H₂S, and NH₃ revealed strong seasonal variations. Elevated levels of PM₁₀ and H₂S were consistently recorded during the cold seasons, particularly under stable atmospheric conditions characterised by a low MLH. Correlation analysis confirmed negative relationships between pollutant concentrations and both MLH and average daily temperature, indicating that reduced atmospheric mixing and lower temperatures favour surface accumulation of pollutants. Importantly, the winter increase in pollutant concentrations cannot be attributed solely to meteorological conditions. During the cold season, intensified residential heating and increased vehicular traffic contribute to higher primary emissions of particulate matter and gaseous pollutants across the city. Therefore, the elevated winter concentrations likely result from the combined effect of enhanced emissions and unfavourable dispersion conditions. Similar PM₁₀ patterns were observed at multiple monitoring sites across Zagreb, where annual average concentrations were even higher than at Jakuševac, indicating that the landfill is not a dominant source of PM₁₀. In contrast, elevated H₂S levels in winter appear to result from a combination of local landfill emissions and stable meteorological conditions. The opposite seasonal behaviour observed at the CUPOVZ wastewater treatment facility further supports the conclusion that H₂S concentrations reflect local emission dynamics, with the Prudinec/Jakuševac landfill being a more plausible dominant source in its vicinity. NH₃ concentrations followed a different seasonal pattern, with higher levels during summer (except in 2024), and showed positive correlations with MLH and temperature, pointing to a separate emission source. The reversed seasonal pattern of NH₃ observed in 2024 represents a notable deviation from previous years and warrants further investigation to determine whether it reflects a temporary anomaly or a shift in emission dynamics. The similarity of NH₃ patterns at both Jakuševac and CUPOVZ indicates a broader re-

gional influence rather than a site-specific source. These findings indicate that neither the landfill nor the CUPOVZ is likely the dominant source of NH₃; instead, emissions are more plausibly associated with surrounding agricultural and livestock activities. Future research should therefore incorporate data on agricultural practices, livestock numbers, and fertiliser application periods to better constrain the origin of NH₃ emissions. Altogether, the results imply that NH₃ and H₂S are most likely originating from different dominant emission sources, while their observed concentrations are strongly modulated by seasonal meteorological conditions.

ACKNOWLEDGEMENTS

Measurements of PM₁₀, H₂S, and NH₃ at the air quality monitoring station Jakuševac were funded by “Zagrebački holding”, subsidiary Čistoća, and are available at the webpage <https://iszz.azo.hr/iskzl/> of the Ministry of Environmental Protection and Green Transition of Croatia. This study was performed using the facilities and equipment funded by the European Regional Development Fund, Project KK.01.1.1.02.0007 “Research and Education Centre of Environmental Health and Radiation Protection – Reconstruction and Expansion of the Institute for Medical Research and Occupational Health” and supported by the European Union – Next Generation EU (Program Contract of 8 December 2023, Class: 643-02/23-01/00016, Reg. no. 533-03-23-0006) – EnvironPollutHealth. We also thank the Croatian Meteorological and Hydrological Service (DHMZ, Croatia) for providing meteorological data.

List of abbreviations and symbols Popis kratica i simbola

γ	– mass concentrations, $\mu\text{g m}^{-3}$
t	– temperature, °C
PM ₁₀	– particulate matter with aerodynamic diameter smaller than 10 μm
H ₂ S	– hydrogen sulphide
NH ₃	– ammonia
MLH	– mixing layer height
JAK	– Jakuševac
SIG	– Siget
SUS	– Susedgrad
CUPOVZ	– Centralni uređaj za pročišćavanje otpadnih voda
DHMZ	– Državni hidrometeorološki zavod

References Literatura

1. O. O. Sonibare, J. A. Adeniran, I. S. Bello, Landfill air and odour emissions from an integrated waste management facility, *J. Environ. Heal. Sci. Eng.* **17** (1) (2019) 13–28, doi: <https://doi.org/10.1007/s40201-018-00322-1>.
2. Q. Yuan, A. Zougrana, Systematic review of environmental and human health risk assessments in municipal solid waste

- management, *Discov. Sustain.* **6** (1) (2025) 931–952, doi: <https://doi.org/10.1007/s43621-025-01544-8>.
3. K. Brown, W. L. Hall, M. Snook, K. Garvin (Eds.), *Sustainable Land Development and Restoration*, Butterworth-Heinemann, Amsterdam, 2010, pp. 1–528, url: <https://linkinghub.elsevier.com/retrieve/pii/C2009020239X>.
 4. D. Vujević, M. Čalopek, M. Novosel and A. Anić Vučinić, *Sastav Odlagališnog Plina Na Odlagalištu Otpada Prudinec/Jakuševac*, *Environ Eng – Inženjerstvo okoliša* **1** (1) (2014) 33–41, url: <https://hrcak.srce.hr/129444>.
 5. J. James, I. B. Otugbuali, *Ammonia Emission Levels at Dumpsites and its Fluctuation with Some Atmospheric Properties*, *Res. J. Pure Sci. Technol.* **7** (6) (2024) 107–19, doi: <https://doi.org/10.56201/rjpt.v7.n06.2024.pg107.119>.
 6. S. N. Behera, M. Sharma, V. P. Aneja, R. Balasubramanian, *Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies*, *Environ. Sci. Pollut. Res.* **20** (11) (2013) 8092–8131, doi: <https://doi.org/10.1007/s11356-013-2051-9>.
 7. F. Hidayatullah, S. A. Mulasari, L. Handayani, *Health Risk Analysis of Hydrogen Sulfide (H₂S) and Ammonia (NH₃) Exposure at Piyungan Landfill*, *Environ. Earth. Sci. Res. J.* **8** (1) (2021) 48–52, doi: <https://doi.org/10.18280/eesrj.080105>.
 8. D. Resiere, J. Florentin, R. Névrière, *Evaluating the ten-year health impact of hydrogen sulfide (H₂S) and ammonia (NH₃) exposure from sargassum seaweed invasions in the Caribbean: Public health implications*, *Harmful Algae* **152** (2026) 103027, doi: <https://doi.org/10.1016/j.hal.2025.103027>.
 9. URL: [https://net.hr/danas/vijesti/pocelo-je-nicati-jos-1960-ih-strucnjaci-procjenjuju-da-ima-mjesta-za-jos-3-godine-odlaganja-sto-onda-s-jakusevcem-f6a8a35e-9803-11ee-ad9f-0ee8f36581c7? \(15. 1. 2026.\)](https://net.hr/danas/vijesti/pocelo-je-nicati-jos-1960-ih-strucnjaci-procjenjuju-da-ima-mjesta-za-jos-3-godine-odlaganja-sto-onda-s-jakusevcem-f6a8a35e-9803-11ee-ad9f-0ee8f36581c7? (15. 1. 2026.))
 10. ECOINA za zaštitu okoliša. Tehničko – tehnološko rješenje postojećeg postrojenja odlagališta otpada Prudinec/Jakuševac, 2014., url: https://mzost.gov.hr/UserDocImages/Okolišna_dozvola/OUZO-postojeće/Tehnisko-tehnolosko_rjesenje_%28Jakuševac%29.pdf.
 11. URL: [https://www.tehnoeko.com.hr/otpad/tomasevic-jakuševac-konacno-odlazi-u-povijest/a/10605 \(15. 1. 2026.\)](https://www.tehnoeko.com.hr/otpad/tomasevic-jakuševac-konacno-odlazi-u-povijest/a/10605 (15. 1. 2026.))
 12. C. A. Pope, D. W. Dockery, *Health Effects of Fine Particulate Air Pollution: Lines that Connect*, *J. Air Waste Manage. Assoc.* **56** (6) (2006) 709–742, doi: <https://doi.org/10.1080/10473289.2006.10464485>.
 13. Vlada Republike Hrvatske, *Uredba o razinama onečišćujućih tvari u zraku*, NN 77/2020, 2020, pp. 1–5.
 14. European Commission. *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe*, *Official Journal of the European Communities* (2008) 1–43.
 15. European Commission, *Directive 2024/2881/EC of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe*, *Official Journal of the European Union* **2881** (2024) 1–70.
 16. Y. Langeron, C. Staquet, *Persistent inversion dynamics and wintertime PM₁₀ air pollution in Alpine valleys*, *Atmos. Environ.* **135** (2016) 92–108, doi: <https://doi.org/10.1016/j.atmosenv.2016.03.045>.
 17. V. Yavuz, *An analysis of atmospheric stability indices and parameters under air pollution conditions*, *Environ. Monit. Assess.* **195** (8) (2023) 934–964, doi: <https://doi.org/10.1007/s10661-023-11556-4>.
 18. A. R. Toro, M. Kvakić, Z. B. Klaić, D. Koračin, S. R. G. E. Morales, G. M. A. Leiva, *Exploring atmospheric stagnation during a severe particulate matter air pollution episode over complex terrain in Santiago, Chile*, *Environ. Pollut.* **244** (2019) 705–714, doi: <https://doi.org/10.1016/j.atmosenv.2016.03.045>.
 19. M. T. Nejad, K. J. Ghalehtemouri, H. Talkhabi, Z. Dolatshahi, *The relationship between atmospheric temperature inversion and urban air pollution characteristics: a case study of Tehran, Iran*, *Discov. Environ.* **1** (17) (2023) 1–15, doi: <https://doi.org/10.1007/s44274-023-00018-w>.
 20. S. Shahi, J. Abermann, G. Heinrich, R. Prinz, W. Schöner, *Regional Variability and Trends of Temperature Inversions in Greenland*, *J. Clim.* **33** (21) (2020) 9391–9407, doi: <https://doi.org/10.1175/JCLI-D-19-0962.1>.
 21. European committee for standardization. *Ambient air – Standard gravimetric measurement method for the determination of the PM₁₀ or PM_{2.5} mass concentration*, 2023, pp. 1–64.
 22. European committee for standardization. *Ambient air – Standard method for the measurement of the concentration of sulphur dioxide by ultraviolet fluorescence (EN 14212:2012)*, 2012, pp. 1–100.
 23. European committee for standardization. *Ambient air – Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence (EN 14211:2012)*, 2012, pp. 1–100.
 24. D. Vickers, L. Mahrt, *Evaluating Formulations of Stable Boundary Layer Height*, *J. Appl. Meteorol.* **43** (11) (2004) 1736–1749, doi: <https://doi.org/10.1175/JAM2160.1>.
 25. S. Sopčić, G. Pehnc, I. Bešlić, *Specific biomass burning tracers in air pollution in Zagreb, Croatia*, *Atmos. Pollut. Res.* **15** (8) (2024) 1–15, doi: <https://doi.org/10.1016/j.apr.2024.102176>.
 26. V. Gluščić, M. Šilović Hujic, I. Bešlić, S. Davila, G. Pehnc, *Razine sumporovodika, amonijaka i merkaptana u zraku na području Centralnog uređaja za pročišćavanje otpadnih voda grada Zagreba*, *Kem. Ind.* **69** (13) (2020) 65–74, doi: <https://doi.org/10.15255/KUI.2020.026>.
 27. Institut za medicinska istraživanja i medicinu rada, *Izvjestaj o praćenju kvalitete zraka u zoni utjecaja CUPOVZ-a u Zagrebu u 2022. godini*, 2022, url: https://eko.zagreb.hr/UserDocImages/arhiva/dokumenti/okoli%C5%A1/zrak/2022/Izvjestaj%20CUPOVZ_2022_print.pdf.
 28. Institut za medicinska istraživanja i medicinu rada, *Izvjestaj o praćenju kvalitete zraka u zoni utjecaja CUPOVZ-a u Zagrebu u 2021. godini*, 2021, url: <https://eko.zagreb.hr/2021/5637>.
 29. Institut za medicinska istraživanja i medicinu rada, *Izvjestaj o praćenju kvalitete zraka u zoni utjecaja CUPOVZ-a u Zagrebu u 2023. godini*, 2023, url: https://eko.zagreb.hr/UserDocImages/zrak%20izvje%C5%A1%C4%87a%202023/Izvjestaj%20CUPOVZ_2023.pdf.
 30. Institut za medicinska istraživanja i medicinu rada, *Izvjestaj o praćenju kvalitete zraka u zoni utjecaja CUPOVZ-a u Zagrebu u 2024. godini*, 2024, pp. 1–77, url: https://eko.zagreb.hr/UserDocImages/zrak_izvješća_2024/Izvjestaj_CUPOVZ_2024_HRV_print.pdf.
 31. Institut za medicinska istraživanja i medicinu rada, *Izvjestaj o praćenju kvalitete zraka u zoni utjecaja CUPOVZ-a u Zagrebu u 2020. godini*, 2020, pp. 1–74., url: https://eko.zagreb.hr/UserDocImages/zrakizvješća2021/Zagreb_zrak_2020_revizija_srpanj2021.pdf.
 32. EKONERG d.o.o., *Nacrt prijedloga akcijskog plana za poboljšanje kvalitete zraka na području Grada Zagreba za razdoblje od 2023. do 2028. godine*, 2023, url: https://eko.zagreb.hr/UserDocImages/arhiva/dokumenti/okoli%C5%A1/zrak/2023/AkcijskiPlan_JavniUvid_20012023_komplet.pdf.

33. E. Lončar, Statistička analiza inverzija i visine sloja miješanja na području Zagreba, A Statistical Analysis of Inversions and Mixing Layer Heights, Hrvat. meteorol. čas. **26** (1991) 87–98, url: <https://hrcak.srce.hr/68454>.
34. M. G. G. Perrone, S. Vratolis, E. Georgieva, S. Török, K. Šega, B. Veleva, J. Osán, I. Bešlić, Z. Kertész, D. Pernigotti, K. Eleftheriadis, C. A. Belis, Sources and geographic origin of particulate matter in urban areas of the Danube macro-region: The cases of Zagreb (Croatia), Budapest (Hungary) and Sofia (Bulgaria), Sci. Total. Environ. **619-620** (2018) 1515–1529, doi: <https://doi.org/10.1016/j.scitotenv.2017.11.092>.

SAŽETAK

Utjecaj stabilnosti atmosfere na kvalitetu zraka u okolici odlagališta Prudinec/Jakuševac

Ivan Bešlić,^a Suzana Sopčić,^{a*} Domagoj Mihajlović^b i Vedran Vadić^c

U svrhu procjene utjecaja meteoroloških uvjeta na kvalitetu zraka u okolici odlagališta otpada Prudinec/Jakuševac u Zagrebu, analizirane su dnevne koncentracije lebdećih čestica (PM₁₀), sumporovodika (H₂S) i amonijaka (NH₃) praćene tijekom petogodišnjeg razdoblja (2020. – 2024.). U meteorološkim uvjetima kad visina sloja miješanja (MLH) padne ispod 1000 m, iznad grada se formira inverzijski sloj koji sprječava vertikalno miješanje zraka, što dovodi do stabilnih atmosferskih uvjeta i nakupljanja onečišćujućih tvari u zraku. Rezultati istraživanja pokazali su da se 80 % takvih stabilnih uvjeta javlja tijekom hladnog dijela godine. Za vrijeme takvih stabilnih atmosferskih uvjeta zabilježeno je 88 % svih prekoračenja dnevne granične vrijednosti za PM₁₀ te 70 % prekoračenja za H₂S. Usporedive razine PM₁₀ koncentracija izmjerene su na više mjernih postaja u Zagrebu, što upućuje na to da odlagalište Jakuševac nije dominantan izvor PM₁₀. Sezonski trend koncentracija H₂S na odlagalištu pokazao je više vrijednosti tijekom zime, što je suprotno od trenda zabilježenog na obližnjem Centralnom uređaju za pročišćavanje otpadnih voda grada Zagreba (CUPOVZ), gdje su najviše koncentracije izmjerene tijekom ljeta. Takvo ponašanje ukazuje na to da je odlagalište vrlo vjerojatno specifičan lokalni izvor sumporovodika. Koncentracije NH₃ bile su više tijekom toplog dijela godine, kako na Jakuševcu tako i na CUPOVZ-u, što upućuje na postojanje različitih dominantnih izvora emisija. Različiti sezonski trendovi koncentracija PM₁₀, H₂S i NH₃ ukazuju na njihovo porijeklo iz različitih izvora. U jugoistočnom dijelu Zagreba aktivnosti povezane s poljoprivredom i stočarstvom vjerojatno su među glavnim izvorima NH₃ emisije.

Ključne riječi

Kvaliteta zraka, visina sloja miješanja, PM₁₀, sumporovodik, amonijak

^a Institut za medicinska istraživanja i medicinu rada, Ksaverska c. 2, 10 000 Zagreb

^b Državni hidrometeorološki zavod, Ravnice 48, 10 000 Zagreb

^c EKONERC-Institut za energetiku i zaštitu okoliša, Koranska 5, 10 000 Zagreb

Izvorni znanstveni rad
Prispjelo 27. siječnja 2026.
Prihvaćeno 26. veljače 2026.