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Mitigating landfill gas emissions: the effectiveness of HDPE covers in reducing atmospheric concentrations of H_2S, NH_3, and PM_{10}

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We investigated the effectiveness of high-density polyethylene (HDPE) covers in reducing landfill emissions of hydrogen sulphide (H_2S), ammonia (NH_3), and inhalable particulate matter smaller than 10 μm in diameter (PM_{10}) at the Waste Management Centre Marišćina (Croatia) by comparing air quality data from 2018, prior to the installation of the HDPE cover, with data from 2021, post-installation. The results demonstrate a significant reduction in H_2S and PM_{10} concentrations (36.76 % and 24.18 %, respectively). However, NH_3 levels unexpectedly increased by 20.48 %, suggesting the presence of additional sources of ammonia in the vicinity of the centre or changes in landfill microenvironment. Our findings highlight the effectiveness of HDPE covers in controlling specific landfill emissions and the need for a comprehensive environmental management strategy to address all pollutants. Future research should also investigate the long-term effects of HDPE cover on landfill emissions and how they could contribute to broader environmental goals, such as reducing greenhouse gas emissions and improving air quality.

KEY WORDS: ammonia; air quality; bioreactor landfills; hydrogen sulphide; particulate matter; pollution mitigation; waste management

Air pollution from landfill sites is a complex environmental issue that poses significant risks to public health and local ecosystems and contributes to global climate change (1–3). Among the various pollutants emitted from landfills, malodorous compounds such as ammonia (NH_3) and hydrogen sulphide (H_2S) are particularly problematic (4, 5). These compounds, which are formed from the decomposition of organic waste, not only create unpleasant odours but have the potential to adversely affect the health of nearby residents and workers. Ammonia can irritate the respiratory tract and exacerbate conditions like asthma (4), while hydrogen sulphide, known for its characteristic rotten egg smell, is toxic even at low concentrations and can be deadly at higher concentrations (5). Inhalable particulate matter (PM_{10}), on the other hand, affects both the respiratory and cardiovascular systems. Exposure to PM_{10} has been linked to increased mortality and morbidity from diseases such as asthma, chronic obstructive pulmonary disease (COPD), heart attack, and stroke. The particles can penetrate deep into the lungs and even enter the bloodstream, causing systemic inflammation and oxidative stress, which can exacerbate existing health conditions and contribute to new ones, such as diabetes and hypertension. Vulnerable populations, including children, the elderly, and individuals with pre-existing health conditions, are particularly at risk (6–8).

Traditional landfill management practices, which often involve minimal measures to contain and treat gases and particulate matter, allow these pollutants to escape into the atmosphere (3). This lack of containment not only affects air quality but also leads to broader social and economic repercussions, including reduced property values and increased community opposition to landfill operations (9–11) as well as legal actions against waste management facilities (12) and escalation of management costs (13).

In response to these challenges, this study investigates an approach to controlling landfill emissions through the deployment of an intermediate high-density polyethylene (HDPE) cover equipped with a gas collection system. This technology has been implemented at a bioreactor landfill of the Waste Management Centre (WMC) Marišćina near Rijeka, Croatia since 2021, which had previously operated without such cover (year 2018). We, therefore, had a unique opportunity to measure the impact of this intervention on air pollution levels in the vicinity of the bioreactor landfill. By focusing on the quantitative analysis of key pollutants, namely hydrogen sulphide (H_2S), ammonia (NH_3), and particulate matter (PM_{10}), this study aimed to assess the effectiveness of intermediate HDPE covers in mitigating the release of these hazardous and malodorous compounds into the environment and their impact on air quality.

Mechanical-biological treatment of residual waste at WMC Marišćina

The WMC Marišćina is located near the town of Marčelji, north of Rijeka. It consists of a mechanical-biological treatment (MBT)

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plant, a wastewater treatment plant, and a bioreactor landfill and receives residual municipal solid waste to produce refuse-derived fuel (RDF).

Upon arrival, the waste is stored in a reception bunker and pre-shredded to a size of 20 cm. This pre-shredded material, consisting mainly of mixed municipal waste, is then loaded into bioreactors (Rottebox®, Herhof, Solms, Germany), where it is subjected to forced aeration to dry the waste. This bio-drying process prepares the waste for subsequent mechanical treatment and refining.

The mechanical treatment begins with passing the waste through a 20 mm vibrating sieve to separate the fines, which are primarily composed of organic material. The fines are then transported to a bioreactor landfill, where they serve as a substrate for landfill gas production, currently flared but planned to be used for energy recovery. The remaining material is then passed through a magnetic separator to extract ferrous metals, followed by an eddy current separator to remove non-ferrous metals.

After metal separation, the material is transported to an air classifier, which removes the heavy fraction, and then to a near-infrared (near-IR) optical separator. The optical separator is used to eliminate polyvinyl chloride (PVC) from the waste stream to reduce chlorine content in RDF. The residues from the mechanical processing are landfilled, while the recovered metals and RDF are sent to other facilities for material and energy recovery. The flow of residual waste through the various processing stages at WMC Marišćina is illustrated in Figure 1.

Implementation of improved gas management strategies (2019–2021)

In response to the operational inefficiencies and environmental concerns (foul odours) noted in 2018, the landfill management team implemented several modifications to the bioreactor operational procedures. The first step involves covering the fine fraction with a low-density polyethylene (LDPE) cover on top of a 10 cm layer of soil at the end of each working day. The second step involves covering most of the landfill area with HDPE membranes welded together to prevent landfill gas escape. To further reduce landfill gas emissions, the landfill working area has been reduced to a maximum of 3,000 m². This allows for a better control of landfill gas emissions and provides more efficient gas collection and extraction. For this purpose, a gas collector has been deployed, connecting all individual vents. A central blower is then used to create negative pressure within the gas collection system and the landfill body and minimise the venting of the landfill gas into the atmosphere. The excess gas is currently being burnt in a process known as flaring, which involves controlled combustion of gas that cannot be captured or utilised. This method, while effective in reducing immediate safety and environmental risks posed by venting raw gas, results in the release of carbon dioxide and other emissions. Having recognised the potential for more sustainable energy use, the WMC plans to replace flaring with an electric energy generator that will convert landfill gas into electricity. A schematic of the current venting system is given in Figure 2.

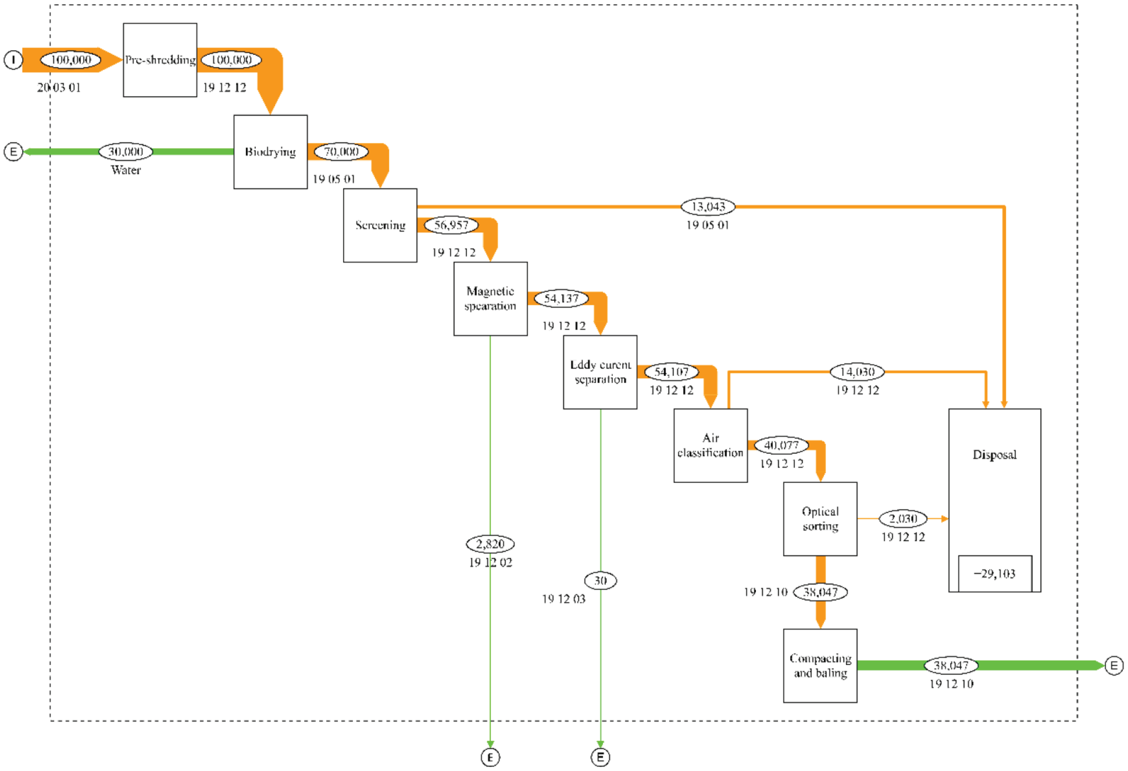

Figure 1 Material flow of residual waste in the mechanical-biological treatment plant at the WMC Marišćina, Croatia; I – import flow; E – export flow

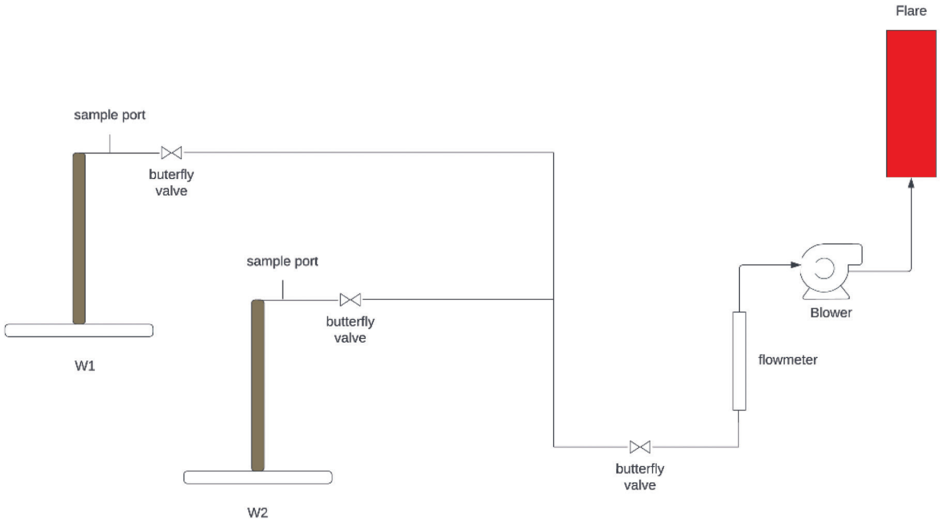

Figure 2 Active venting system schematic at the HDPE cover WMC Marišćina landfill. W1 – gas well 1; W2 – gas well 2

MATERIALS AND METHODS

Study area and pollutant monitoring

The monitoring station (Figure 3) was placed approximately 1 km downwind from the WMC to effectively capture and measure emissions that may be transported by prevailing winds to residential areas. This placement is critical for assessing the potential dispersion of pollutants, including harmful gases and particulate matter, that could pose significant health risks to local residents. By continuously tracking emission levels in this key location, the station provides real-time data essential for evaluating the environmental impact of waste management activities.

Residential settlements in the area surrounding the monitoring station have no significant industrial activities, except for the asphalt mixing plant (asphalt plant) located to the north of the WMC (Figure 3). Vehicular traffic in the area is relatively low.

Air quality data were collected continuously for 365 days over the year 2018, that is, before the placing of the HDPE cover, and for 365 days in 2021, after the cover had been set in place. H_2S, NH_3, and PM_{10} concentrations were measured using a fixed-site air quality monitoring station equipped with automatic sensors calibrated for their detection. Readings were taken every two seconds and averaged over 24 hours to provide a comprehensive dataset of daily pollutant levels throughout both years and to enable assessing temporal and seasonal variations in pollutant emissions.

The monitoring station was fully renovated at the end of 2018 and is now equipped with the following analysers for monitoring real-time concentrations of pollutants in ambient air: Horiba APSA-370-CU1 (Horiba Ltd., Kyoto, Japan) for H_2S, Horiba APNA-370-CU2 (Horiba) for NH_3, and Horiba APDA-372 (Horiba) for PM_{10}, $PM_{2.5}$, and PM_1 fractions of suspended particulate matter.

Data pre-processing and seasonal distribution

Raw data were pre-processed to ensure accuracy and consistency. First, the dataset was inspected for missing values, which were interpolated where feasible. Before the analysis, the data were carefully reviewed and validated to determine whether they should be included in the analysis or not. Peak air quality values were identified using the interquartile range (IQR) method, which can statistically detect outliers in a dataset by analysing the spread of values. This involves calculating the range between the first quartile (25th percentile) and the third quartile (75th percentile), which represents the middle 50 % of the data. Values that fall outside this range (third quartile minus 1.5 times the IQR and first quartile plus 1.5 times the IQR) are considered potential outliers, which is how we identified peak air quality measurements that deviated significantly from the typical range. This method provides a robust way to analyse and interpret variations in air quality data.

To analyse the seasonal variations in pollutant levels, we distributed the data into four seasons: winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November). This distribution allowed us to see how seasonal factors might influence pollutant emissions.

Statistical analysis

Means, medians, and ranges of H_2S, NH_3, and PM_{10} levels for both 2018 and 2021 were computed by season. To determine whether there were statistically significant differences in H_2S, NH_3, and PM_{10} between 2018 and 2021, we used the Mann-Whitney *U* test, as it does not require normal distribution of data.

To quantify the relationship between pollutant concentrations, we used the Spearman's rank correlation coefficient (Spearman's r). This method is particularly useful when the data are ordinal, not

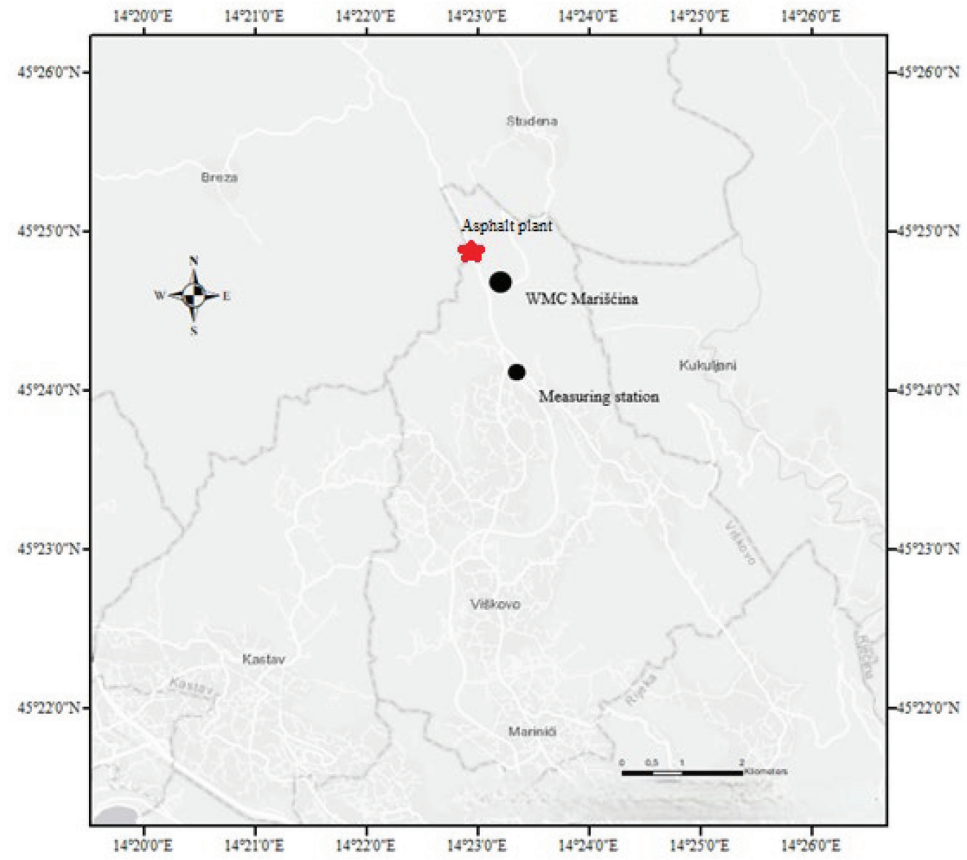

Figure 3 Locations of the WMC Marišćina, monitoring station, and the local asphalt plant (red star)

distributed normally, or when the relationship between variables is not necessarily linear.

All data pre-processing and statistical analyses were run on Python's Pandas data analysis library (Wes McKinney, version 2.0.3, New York City, NY, USA). Matplotlib and Seaborn libraries were used for data visualisation.

RESULTS

Table 1 shows seasonal mean and median levels of H_2S, NH_3, and PM_{10} measured near the WMC landfill in 2018 (baseline) and 2021 (after the HDPE cover was set in place). The decrease in H_2S and PM_{10} levels between the two monitoring years suggests that the HDPE cover effectively reduced their emissions throughout the year.

In contrast, NH_3 medians soared in the spring of 2021 and continued to be higher than respective seasonal medians in 2018. This increase in NH_3 levels and variability in 2021 may point to other emission sources in the area and calls for further investigation.

Changes in pollutant levels near the WMC between 2018 and 2021 are even clearer with time series analysis presented in Figure 4. The 2018 H_2S levels exhibited greater variability than those measured in 2021, whereas variability in NH_3 and PM_{10} was less pronounced over the studied years.

Our trend analysis (Figure 5) shows a general upward trend for H_2S in 2018, which became stable following the installation of the HDPE cover. NH_3 had a rising trend in 2018 but a distinct decline in 2021. The PM_{10} trends, in contrast, remained relatively stable across both years.

Figure 6 histograms and kernel density estimates (KDE) highlight further the differences in atmospheric concentrations of H_2S, NH_3, and PM_{10} between 2018 and 2021. In 2018, the distributions of all three pollutants were more spread out with heavier tails, indicating higher variability and a higher prevalence of peak atmospheric concentrations of pollutants. This variability is particularly pronounced with PM_{10}, suggesting multiple contributing sources or varying emission intensities throughout the year. One such source could be the asphalt plant mentioned earlier. In contrast, the 2021 data exhibit more peaked distributions with narrower spreads, indicating more consistent pollutant levels and fewer extreme events.

Table 1 Hydrogen sulphide (H_2S), ammonia (NH_3), and particulate matter (PM_{10}) concentrations near the Marišćina Waste Management Centre in 2018 and 2021 by season

Year	Season	Count	Mean	SD	Min	Q1	Median	Q3	Max
					H_2S (mg/m^3)				
2018	Autumn	91	1.33	1.36	0.20	0.55	0.90	1.50	9.70
	Spring	92	0.83	0.28	0.40	0.60	0.80	1.00	1.70
	Summer	92	0.67	0.28	0.30	0.48	0.60	0.80	1.50
	Winter	90	1.32	1.27	0.20	0.70	0.90	1.18	7.10
2021	Autumn	91	0.58	0.19	0.30	0.50	0.50	0.70	1.40
	Spring	92	0.64	0.19	0.20	0.50	0.60	0.80	1.10
	Summer	92	0.70	0.19	0.30	0.60	0.70	0.80	1.10
	Winter	90	0.70	0.43	0.20	0.40	0.60	0.80	2.50
					NH_3 (mg/m^3)				
2018	Autumn	91	1.77	0.83	0.30	1.15	1.60	2.25	4.10
	Spring	92	1.46	0.69	0.30	1.00	1.30	1.80	3.60
	Summer	92	1.55	0.91	0.10	0.90	1.45	2.10	4.30
	Winter	90	1.65	0.95	0.30	0.90	1.50	2.20	4.40
2021	Autumn	91	1.71	0.59	0.70	1.30	1.50	1.90	4.30
	Spring	92	2.31	0.92	0.90	1.70	2.07	2.70	5.40
	Summer	92	1.88	0.73	0.40	1.30	1.80	2.40	3.60
	Winter	90	1.85	0.74	0.70	1.40	1.70	2.18	4.30
					PM_{10} (mg/m^3)				
2018	Autumn	91	20.15	7.08	8.00	14.57	19.16	24.51	40.30
	Spring	92	22.06	12.17	7.10	15.55	19.60	25.90	108.60
	Summer	92	18.40	6.13	8.16	14.01	17.64	21.68	35.80
	Winter	90	20.43	8.60	5.70	14.11	18.23	26.48	48.40
2021	Autumn	91	16.09	8.69	3.50	9.60	15.00	21.40	54.20
	Spring	92	12.05	7.60	2.50	7.05	9.95	13.85	39.20
	Summer	92	15.73	10.85	2.40	9.88	13.45	17.80	79.80
	Winter	90	17.62	14.06	3.30	8.53	14.05	22.03	83.80

Q1 – 1st quartile; Q3 – 3rd quartile; SD – standard deviation

Comparison of atmospheric pollutant levels between 2018 and 2021 and their correlations

The Mann-Whitney *U* test reveals statistically significant differences ($p<0.05$) in the levels of all three pollutants between 2018 and 2021 (Figure 7). Figure 8 shows even more clearly that H_2S and PM_{10} levels dropped, whereas NH_3 levels increased after the HDPE cover was set up, suggesting possible other sources of ammonia emissions in the vicinity of the bioreactor landfill, shifts in waste composition, operational changes, or potential accumulation of ammonia beneath the HDPE cover. Figure 9 shows the relationship between NH_3, H_2S, and PM_{10} levels obtained with the Spearman's rank correlation analysis for 2018 and 2021. In 2018, before the landfill was covered with an HDPE membrane, H_2S, NH_3, and PM_{10} had a moderate positive correlation, which suggests that emissions of these pollutants were likely influenced by a shared underlying process, such as waste decomposition and the lack of containment, leading to the concurrent release of gases and particulates into the air. In 2021, after the landfill was covered with an HDPE membrane, H_2S showed a weaker correlation with both NH_3 and PM_{10} compared to 2018. This change may indicate that the HDPE membrane disrupted the simultaneous release of these pollutants by containing H_2S more effectively than PM_{10} or NH_3 and could reflect independent emission mechanisms. Overall, the reduced correlations in 2021 suggest that HDPE was effective in modifying the interaction between emission processes, leading to a more controlled and segmented release of pollutants.

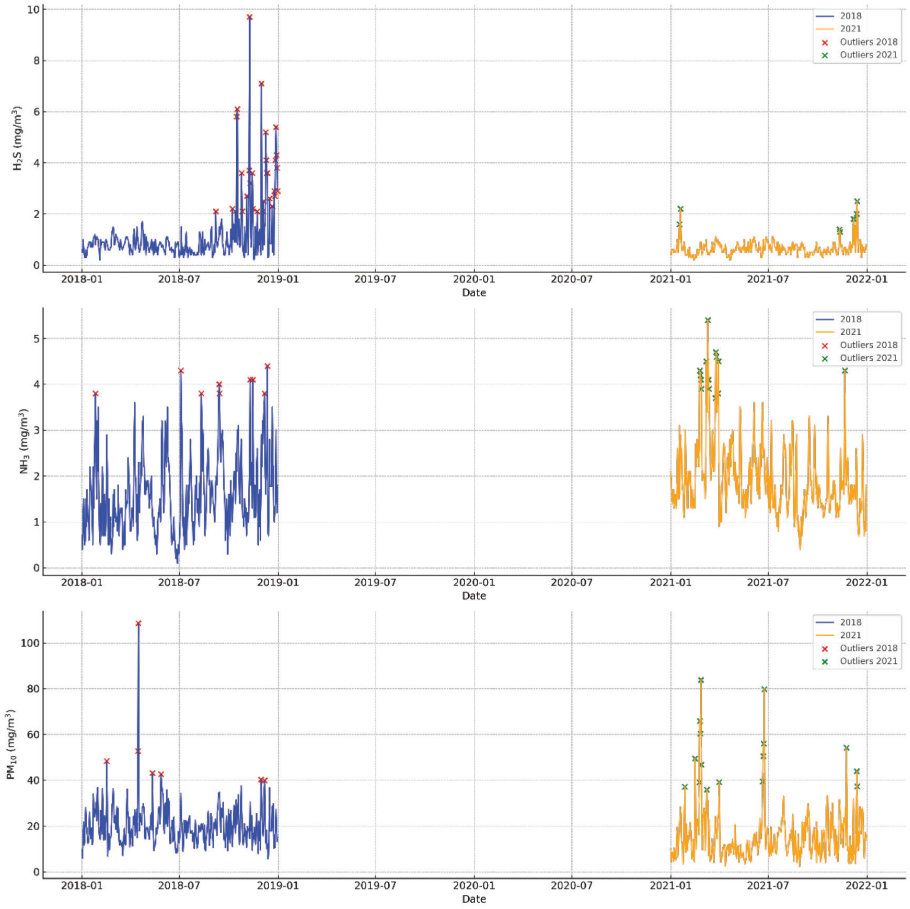

Figure 4 Time-trends of 24-hour averaged concentrations of H_2S, NH_3, and PM_{10} in 2018 (blue) and 2021 (orange). Peak air quality values are indicated by red (2018) and green (2021) crosses

DISCUSSION

Our findings confirm the efficacy of HDPE covers in significantly reducing emissions of H_2S and PM_{10} from the WMC landfill. These results are consistent with previous research, which has demonstrated that HDPE covers can effectively contain and reduce emissions of landfill gases (14). The increase in NH_3 levels in ambient air following the installation of HDPE cover is somewhat unexpected, however, and suggests that while HDPE covers are effective for certain pollutants, they may alter the landfill's microenvironment and gas dynamics in such way that increases NH_3 emission. The reason for this is that NH_3 is typically a product organic waste decomposition under anaerobic conditions (15) and that the HDPE cover may have diminished or cut off oxygen supply and accelerated the anaerobic breakdown of nitrogenous materials into ammonia. Another reason could be that the type and composition of waste delivered to the landfill have changed between 2018 and 2021 in favour of nitrogen-rich waste materials, such as food waste.

Yet another reason for the observed increase in NH_3 may be other sources in the vicinity of the landfill, such as the asphalt plant north of the WMC. Although ammonia is not typically a by-product of standard asphalt production, emissions may arise from the use of nitrogen-containing chemical additives, such as those in warm mix asphalt technologies, or from incomplete combustion of fuels with nitrogen compounds in asphalt plants, or from the use of nitrogen-rich reclaimed or recycled materials, or from the use of ammonium-based dust suppressants.

Whatever the reason, our findings highlight the complexity of landfill gas management and the need for comprehensive monitoring systems that can detect and address unexpected shifts in emission profiles (16, 17).

Another important thing to consider when assessing air quality data is wind direction. Our analysis revealed that peak pollutant concentrations were observed when the wind was blowing from the northwest (NW), that is, directly from the WMC to the monitoring station. Peak concentrations of pollutant levels recorded during these episodes may reflect local atmospheric transport dynamics. Accounting for such directional influences is essential for accurately identifying the sources of ambient pollution and for developing targeted mitigation strategies.

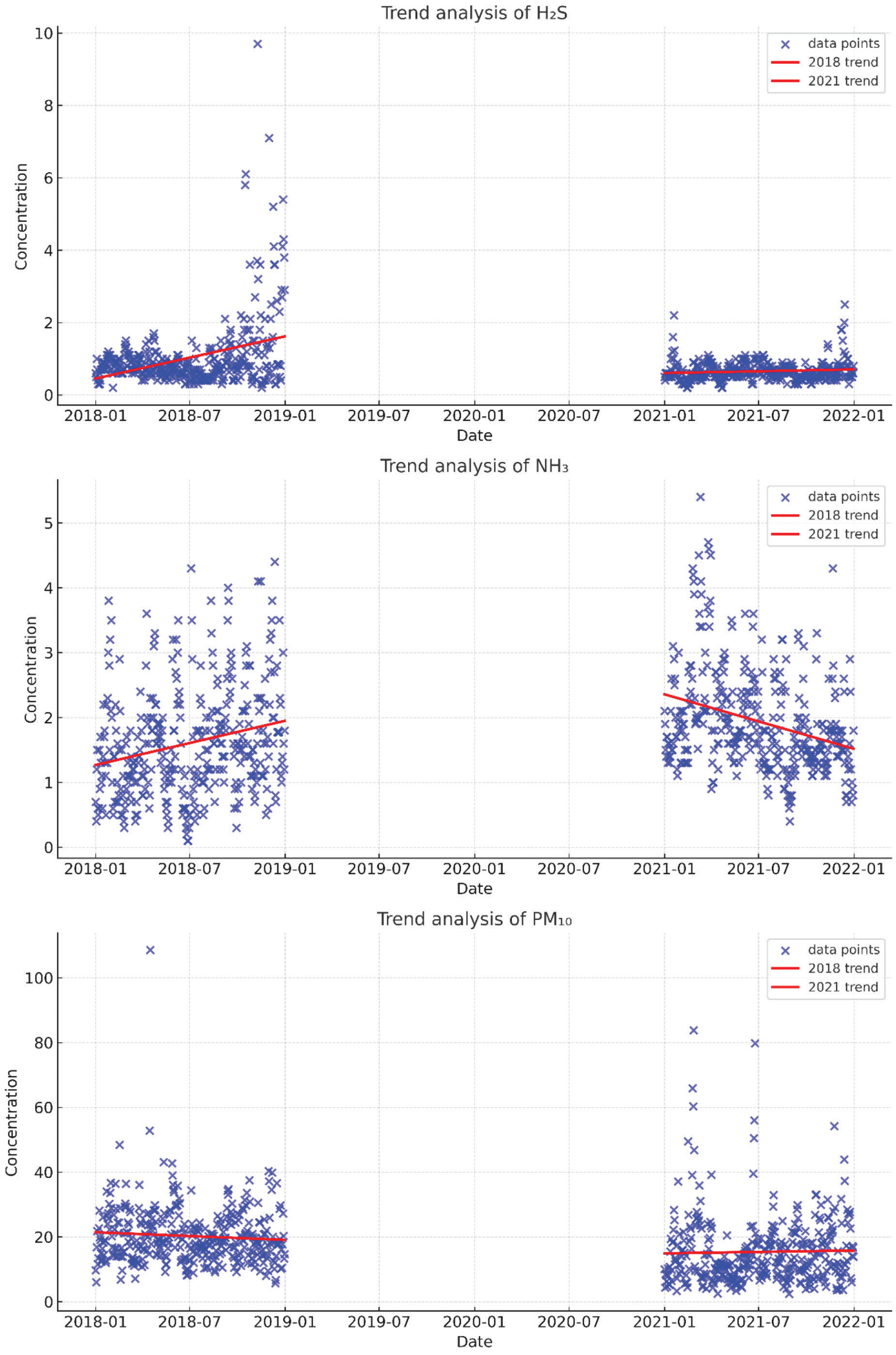

Figure 5 Linear trends in H_2S, NH_3, and PM_{10} concentrations (red line) measured near the WMC Marišćina with individual data points plotted separately for each year (blue crosses)

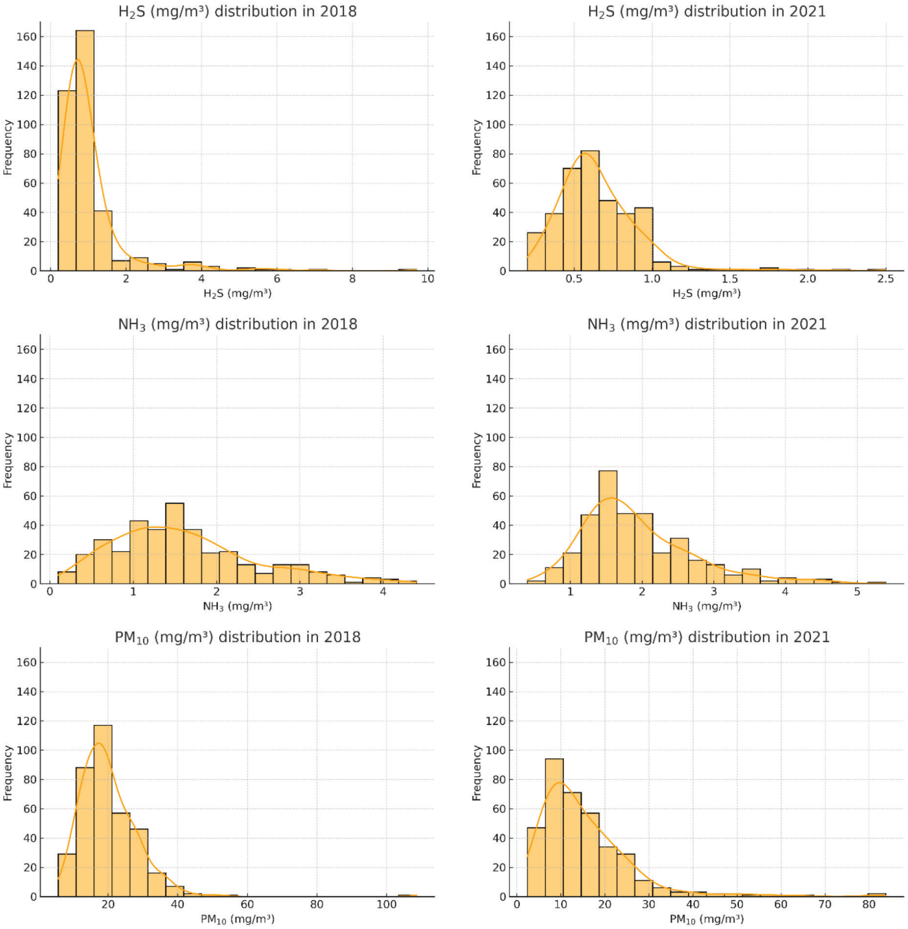

Figure 6 Distribution of H_2S, NH_3, and PM_{10} 24-hour averaged levels near the WMC Marišćina and their kernel density estimates

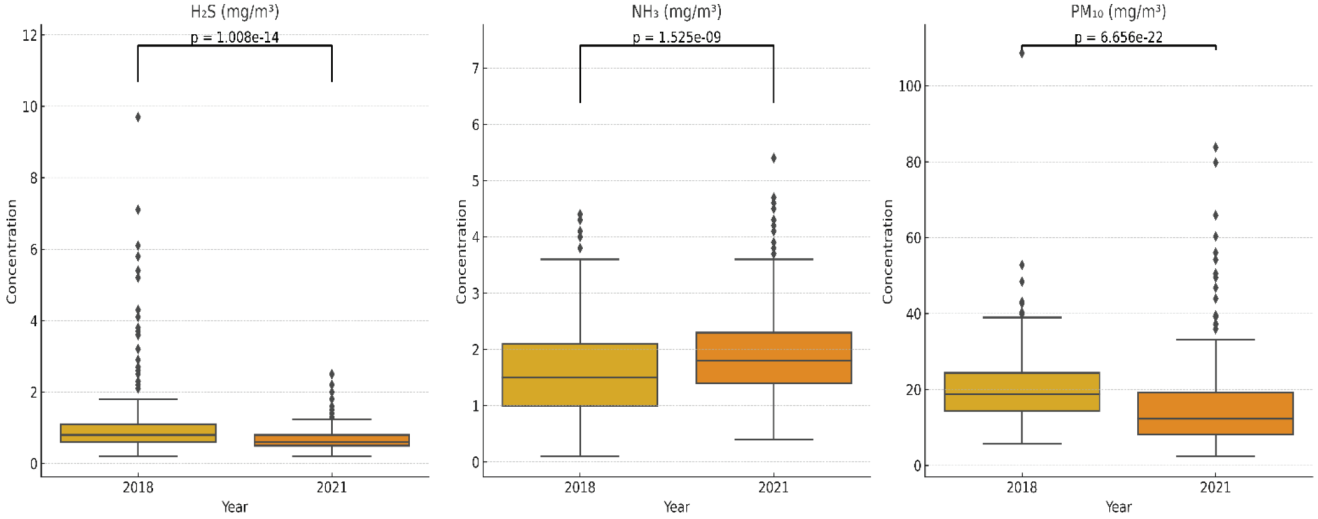

Figure 7 Comparison of 2018 and 2021 H_2S, NH_3, and PM_{10} levels measured near the WMC Marišćina. The central line within each box represents medians, while the edges of the box indicate the interquartile range (IQR). Whiskers extend to the minimum and maximum values within 1.5 times of the IQR, and any outliers are plotted as individual points

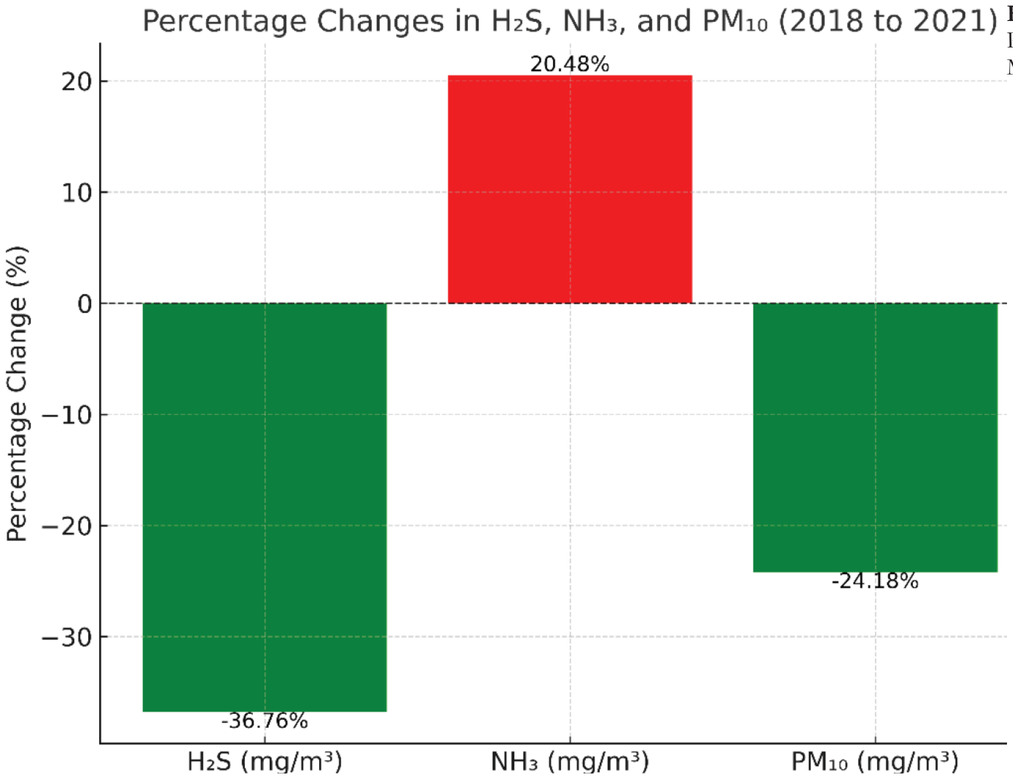

Figure 8 Changes in H_2S, NH_3, and PM_{10} measured near the WMC Marišćina from 2018 to 2021

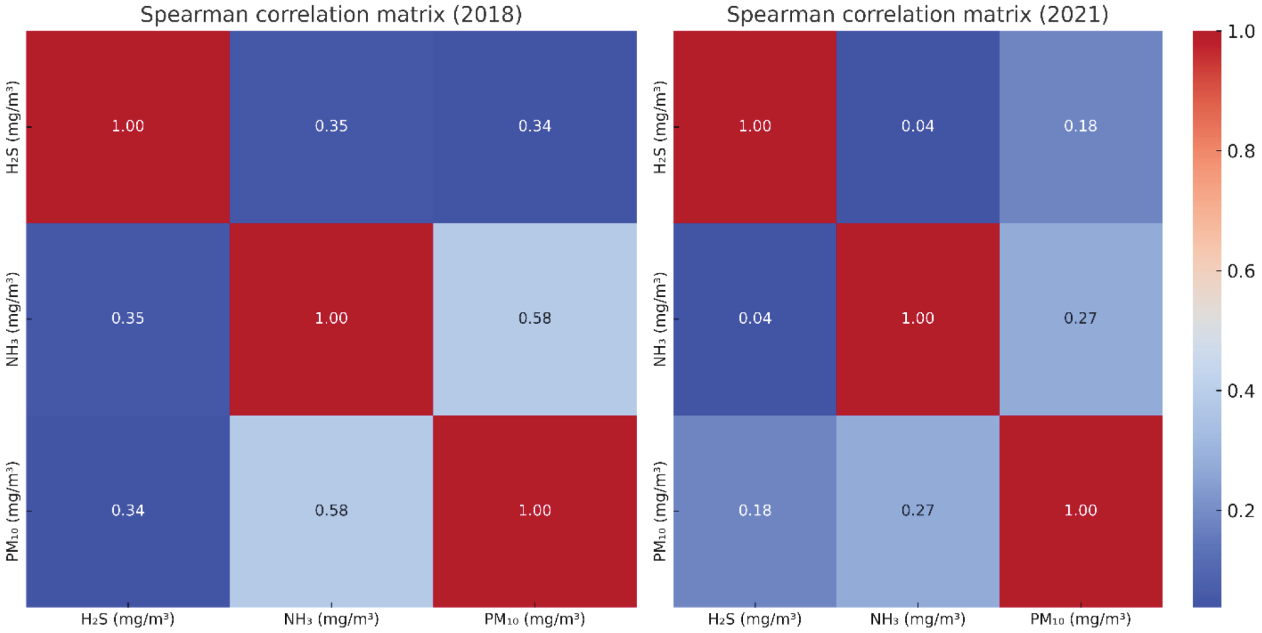

Figure 9 Spearman's rank correlation matrix illustrating the relationships between H_2S, NH_3, and PM_{10} levels measured in ambient air near the WMC Marišćina for the years 2018 and 2021. The colour scale represents the strength and direction of the correlations, with values ranging from -1 (perfect negative correlation) to 1 (perfect positive correlation)

CONCLUSION

In conclusion, while HDPE covers do offer a promising solution for reducing certain landfill emissions, their implementation must be part of a broader, integrated approach to landfill management. This approach should include comprehensive environmental monitoring programmes, consider all potential emissions, and employ adaptive management strategies to ensure that interventions lead to a net positive environmental and health outcome.

A novel strategy in that respect could be the deployment of advanced monitoring technologies such as drones and sensor networks, which could also help identify the sources of increased NH_3 emissions. In addition, future research should focus on understanding the mechanisms which are driving the increase in NH_3 emissions and on developing strategies to mitigate them. This includes exploring potential interactions between different landfill gases and conditions under which they are produced and released. Future research should also investigate long-term effects of HDPE cover on landfill emissions and how they could contribute to broader environmental goals, such as reducing greenhouse gas emissions and improving air quality.

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Učinkovitost pokrova polietilena visoke gustoće (HDPE) u sprječavanju emisija odlagališnih plinova: smanjenje atmosferskih koncentracija H_2S, NH_3 i PM_{10}

U ovom radu analizirali smo učinkovitost primjene pokrova polietilena visoke gustoće (HDPE) u smanjenju emisija sumporovodika (H_2S), amonijaka (NH_3) i lebdećih čestica promjera manjeg od 10 μm (PM_{10}) s odlagališta na području Centra za gospodarenje otpadom Marišćina. U istraživanju smo usporedili podatke o kakvoći zraka prikupljene na mjernoj postaji smještenoj u blizini Centra tijekom 2018. godine, kada HDPE pokrov nije bio instaliran, s podacima iz 2021. godine, nakon ugradnje pokrova. Rezultati pokazuju značajno smanjenje koncentracija H_2S (36,76 %) i PM_{10} (24,18 %), što potvrđuje učinkovitost HDPE pokrova u smanjenju tih specifičnih emisija. Međutim, razine NH_3 neočekivano su porasle 20,48 %, što upućuje na moguće postojanje dodatnih izvora amonijaka u blizini Centra ili na promjene u mikrookolišu samog odlagališta otpada. U radu se ističe važnost primjene HDPE pokrova kao mjere za kontrolu emisija s odlagališta otpada, ali se istodobno upućuje i na potrebu za sveobuhvatnim pristupom upravljanju okolišem kako bi se smanjile emisije svih onečišćujućih tvari u okoliš. Buduća istraživanja trebala bi biti usmjerena na procjenu dugoročnih učinaka HDPE pokrova na emisije s odlagališta, s naglaskom na smanjenje emisija stakleničkih plinova i poboljšanje ukupne kakvoće zraka.

KLJUČNE RIJEČI: amonijak; bioreaktorsko odlagalište; gospodarenje otpadom; kakvoća zraka; lebdeće čestice; sprječavanje onečišćenja; sumporovodik