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Comprehensive approach to monitoring and managing odour impacts from biowaste treatment facilities

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ABSTRACT

This study presented the results of three measurement campaigns (July 4th, 5th, and 9th 2024) conducted at a biogas plant to assess odour emissions using both instrumental and sensory methods. Odour concentrations, intensity, hedonic tone, and detection frequency were analysed alongside gas concentrations of hydrogen sulphide (H_2S), ammonia (NH_3), and total volatile organic compounds (tVOCs). The highest emissions were consistently recorded at the waste sorting area, with peak odour values exceeding 1300 ou/m^3 and elevated gas concentrations (up to 0.7 ppm H_2S, 4 ppm NH_3, and 15 ppm tVOCs). Moderate levels were observed in composting and digestate handling zones, while background and administrative areas exhibited negligible values. The results from electronic noses and gas sensors showed strong agreement with sensory panel evaluations, confirming the dominant role of raw waste handling in odour nuisance. The use of the Odour Air Quality Index (OAQI) enabled an integrated interpretation of multidimensional data. Across all campaigns, it consistently classified the sorting hall as very poor, placed the composting and digestate zones in the moderate band, and clearly captured day-to-day variability driven by wind conditions. These findings underscore the value of combining real-time instrumental monitoring with trained panel assessments to guide odour mitigation strategies in biowaste treatment facilities.

Keywords: odour monitoring, biogas plant, electronic nose, field olfactometry, VOCs, ammonia, hydrogen sulphide.

INTRODUCTION

Odour emissions from biowaste treatment facilities frequently pose an environmental challenge for nearby communities. These installations release complex mixtures of volatile organic compounds (VOCs), inorganic volatiles, and volatile sulphur compounds (VSCs) that contribute to nuisance and may entail health concerns [1, 2]. Complaints are common, particularly where technologies are less advanced or where materials are processed or stored in open systems, which amplifies exposure pathways [2, 3]. Although concentrations of individual compounds often remain below toxicological thresholds, their irritant properties can elicit sensory discomfort as well as psychosomatic reactions, and even physical symptoms [2, 4] Taken together, this evidence underscores the need for effective, site-specific odour-management strategies.

Assessment of odour impacts at biowaste treatment plants draws on a set of complementary methods, each with a specific role, strengths, and limitations. Field sensory surveys

and dynamic olfactometry are the principal approaches. Field olfactometry (dilution-to-threshold ratio D/T, e.g., Nasal Ranger) provides immediate in-situ readings for screening and complaint response, but results are affected by human variability and therefore require trained operators [5, 6]. As an on-site technique, D/T is well suited to rapid source identification and short-term ranking of impacts, whereas dynamic olfactometry (EN 13725) [7] yields standardised odour concentrations (ou_E/m^3) under controlled conditions, useful for compliance assessment and abatement design, yet it is not appropriate for continuous monitoring [6, 8, 9]. Analytical methods (e.g., GC–MS) identify key odorants, but mixture effects and very low odour thresholds mean that chemistry alone may not capture perceived nuisance. Electronic noses, based on sensor arrays and pattern recognition, offer high-frequency, continuous signals and reduce reliance on panels, while demanding rigorous calibration, maintenance, as well as the use of appropriate computational algorithms to ensure stability and accuracy under varying environmental conditions [5, 10]. Finally, dispersion and meteorological modelling (e.g., CALPUFF) links emissions to receptor exposure for planning and regulatory appraisal, though outcomes remain sensitive to input data quality and modelling assumptions [11].

Comparing multiple odour assessment results collected using different approaches, including sensory perception scales and instrumental measurements, can be challenging, as each method captures different dimensions of odour impact. To address this, various frameworks have been proposed to integrate multidimensional odour data into a single, interpretable indicator. One widely referenced example is the FIDOL framework, which combines frequency, intensity, duration, offensiveness, and location to characterise odour impacts [12, 13]. While FIDOL provides a systematic way to describe odour nuisance, it is best suited for long-term monitoring programmes requiring extensive datasets collected under diverse meteorological and seasonal conditions. For short-term field campaigns more flexible, multi-parameter indices are recommended [14 – 17].

Odour management in biowaste treatment facilities should be based on an integrated, BAT-aligned (Best Available Techniques) approach in which monitoring, forecasting, and abatement are tightly coupled [18 – 21]. At its core is an Odour Management Plan comprising: an inventory and prioritisation of sources, a selection of technical and organisational controls, intervention thresholds, and continuous oversight, including the use of dynamic olfactometry. On the engineering side, priorities are the enclosure/ hermetisation of process units, the effective capture and ventilation, and the subsequent air treatment, e.g. in biofilters and wet scrubbers.

A comprehensive assessment of odour nuisance was conducted at a full-scale biowaste treatment facility in south-western France across three measurement campaigns. A combined approach was applied, which includes: continuous electronic-nose monitoring, field olfactometry (D/T), and field sensory assessments (odour intensity, I; hedonic tone, H; detection frequency, F). The results were consolidated into a unified Odour Air Quality Index (OAQI), enabling spatiotemporal comparisons and identification of hotspots at key process units.

MATERIALS AND METHODS

Characteristics of the studied facility

The investigated facility is located in the south-western region of France and specialises in the recycling of organic waste and biowaste. Its operations include composting, wood recycling, collection of green and organic waste, as well as biogas production through anaerobic digestion. The composting process is carried out on two dedicated outdoor platforms. Incoming green waste undergoes a visual inspection to remove undesired materials, such as plastics or other foreign objects. After inspection, the material is shredded using a mobile hammer mill and arranged into windrows, where it is composted for approximately four weeks. During the active composting phase, process temperatures range between 50 °C and 75 °C, enabling both hygienisation and the destruction of weed seeds. The piles are regularly irrigated using recirculated leachate collected from the composting process. Following this stage, the material enters the maturation phase, carried out in a windrow system where temperatures gradually decrease and stabilise at ambient levels. During this transition, thermophilic microorganisms are replaced by mesophilic ones, resulting in a stable compost

product. Once matured, the compost is screened using sieves of various mesh sizes, and depending on the granulometry, it is allocated for different purposes: fractions of 0–40 mm are used in agriculture, 0–25 mm for landscaping, 0–10 mm for horticulture, and 20–40 mm for mulching or as biofilter media. The facility also operates an anaerobic digestion system for biogas production, primarily processing organic material sourced from large and medium-sized retailers, as well as animal by-products. The feedstock includes category 3 materials (milk, meat, eggs, fish) and category 2 inputs (manure and slurry). Before digestion, the material undergoes deconditioning, hygienisation, and homogenisation, after which it is processed in sealed anaerobic silos. The resulting biogas is composed mainly of methane (CH_4) and carbon dioxide (CO_2). The generated methane is then used in a combined heat and power (CHP) engine to produce electricity and heat for on-site operations and potential grid distribution.

The facility is surrounded predominantly by agricultural fields and scattered rural housing. To minimise odour nuisance, green buffer zones and tree belts have been introduced along the boundaries closest to residential areas. The spatial layout of the facility, including the main processing zones and odour measurement points, is presented in Figure 1.

Measurement campaigns

Three field measurement campaigns were conducted on July 4th, 5th, and 9th 2024 at the investigated facility to assess the spatial and temporal variability of odour emissions under different operational and meteorological conditions. The measurements were carried out at ten designated locations, covering both the main processing zones and control points. These included: 1 – the background reference site, 2 – the administrative building, 3 – composting platform 1, 4 – composting platform 2, 5 – the composting leachate collection area, 6 – the location next to the biofilter, 7 – the waste sorting area, 8 – the space between the digestate tanks, 9 – the waste reception hall, and 10 – one of the digestate tanks.

At each location, field sensory odour assessments were performed to determine odour intensity, frequency of occurrence, and hedonic tone. In addition, field olfactometry measurements were conducted using a portable olfactometer, and continuous monitoring was performed with an electronic nose system. The combined use of these complementary techniques enabled a comprehensive evaluation of odour emissions across the facility. A detailed description of the applied methodologies, equipment, and measurement protocols is provided in section – odour measurement methods.

Figure 1. Odour measurement locations across the biowaste treatment facility

Odour measurement methods

Field sensory odour assessment

Field sensory odour assessments were conducted during each measurement campaign to evaluate the perceived odour nuisance at the designated locations. The assessments were performed by a trained team of field inspectors, whose olfactory sensitivity was verified using the reference substance (n-butanol) in accordance with the EN 13725 standard [7]. The measurements were carried out in accordance with the VDI 3940 guidelines [22], which define standardised procedures for field odour assessments. At each measurement point, three parameters were determined: odour intensity (I), hedonic tone (H), and odour frequency (F). Odour intensity (I) was assessed using a six-point scale ranging from 0 (no detectable odour) to 6 (extremely strong odour). The hedonic tone (H) was evaluated on an eight-point bipolar scale, from -4 (extremely unpleasant odour) through 0 (neutral perception) to +4 (extremely pleasant odour). The odour frequency (F) represents the fraction of time during which odours were perceived at a given location, expressed as a value between 0 and 1.

Each individual measurement at a single point lasted 10 minutes. During this period, each field inspector evaluated the surrounding air in 10-second intervals, resulting in 60 individual odour assessments per measurement cycle. For every 10-second interval, only a single inhalation was performed, and the identified odour or the absence of any noticeable odour was recorded in a standardised measurement protocol. The percentage odour frequency (F) was calculated as the ratio of the number of intervals in which odours were detected to the total number of intervals during the 10-minute cycle.

Field olfactometry

The field olfactometry measurements were performed during each campaign at the same ten locations where sensory odour assessments were conducted, using a portable field olfactometer (Nasal Ranger®, St. Croix Sensory Inc., Stillwater, MN, USA). The device operates based on the dilution-to-threshold ratio (D/T) principle, mixing odorous ambient air with filtered air purified through activated-carbon filters. It consists of two separate air paths: one connected to an adjustable orifice that regulates the intake of odorous air and the other delivering purified air. The operator used a fitted mask, breathing at a controlled rate guided by LED indicators integrated into the device.

During the investigations, two Nasal Ranger field olfactometers were used, each equipped with a 12-position control dial containing six blank positions and six active D/T ratio settings. The first device included ratios of 500, 400, 300, 200, 100, and 60, while the second device provided ratios of 60, 30, 15, 7, 4, and 2. The D/T ratio represents the proportion of filtered air mixed with ambient air at the point where the odour becomes just perceptible to the field inspector. The obtained D/T values were subsequently converted into odour concentrations (C_{OT}), expressed in odour units per cubic metre (ou/m³), based on calibration data provided by the manufacturer and following the approach described by Pawnuk et al. [23].

Sensory data analysis

To enable a direct and quantitative comparison between the sensory field assessments and the instrumental data from the electronic nose, a dedicated Odour Air Quality Index (OAQI) was developed. This index integrates four key parameters measured during the campaigns into a single, standardised metric: odour concentration (C_{OT}) obtained from field olfactometry, and three sensory-derived indicators – odour frequency (F), intensity (I), and hedonic tone (H) (Sections 2.3.1–2.3.2).

The OAQI was calculated using the following formula [17]:

$$AQI = \left(\begin{array}{c} \alpha \cdot \left(\frac{C_{OT}}{C_{OT(max)}} \right) + \beta \cdot \left(\frac{F}{F_{(max)}} \right) + \\ +\gamma \cdot \left(\frac{I}{I_{(max)}} \right) - \delta \cdot \left(\frac{H}{H_{(max)}} \right) \end{array} \right) \cdot 100 \quad (1)$$

where: C_{OT} – odour concentration from field olfactometry, ou/m³, F – odour detection frequency, I – odour intensity, H – hedonic tone, $C_{OT(max)}$ = 550 ou/m³, F_{max} = 1, I_{max} = 6, H_{max} = 4.

The weighting coefficients were determined empirically through an iterative optimisation process based on the data collected at four different waste treatment facilities. The final weights were set as: α = 0.3 for C_{OT}, β = 0.3 for F, γ = 0.3 for I, and δ = 0.1 for H.

The resulting OAQI values were classified into five odour air quality levels (Table 1), ranging from very good (OAQI ≤ 20) to very poor (OAQI

> 80), enabling consistent interpretation of sensory results across campaigns and supporting their comparison with instrumental measurements.

Electronic nose

The main instrument used for on-site measurements was an electronic nose (e-nose), designed to provide continuous information on odour concentration and dynamics in real time. The device incorporates a gas sensing array mounted inside a 0.25 L measurement chamber, where a micropump ensures a constant airflow of 0.5 L/min. Two gas inlets, controlled by solenoid valves, allow switching between zero air and the odorous sample, both equipped with filters to protect against moisture and particulate matter. The array combines up to eight metal oxide semiconductor (MOS) sensors (custom made and Figaro Engineering Inc., Osaka, Japan), two electrochemical sensors for hydrogen sulphide (H_2S-A4) and ammonia (NH_3-AF), and one photo-ionisation detector for total volatile organic compounds (PID-AH2, Alphasense, UK). Temperature and humidity sensors were also integrated into the chamber to stabilise sensor performance.

The e-nose was trained and validated. A total of 40 air samples, including blanks, were collected during five field campaigns and subsequently exposed to both undiluted and diluted versions of the collected samples using a pre-dilution system (Olfasense GmbH, Kiel, Germany), which ensured stable conditions with a variability of less than 5%. Two fixed dilution factors were applied (1:9 and 1:93), and an additional dilution level of 1:837 was obtained by sequentially diluting the 1:93 sample at the 1:9 ratio. This approach expanded the dataset from the initial 40 to a total of 69 samples. Each exposure phase lasted 5 minutes, followed by a 15-minute purge with zero air to restore baseline conditions. The same samples were analysed with dynamic olfactometry. This reference method provided the ground truth data that enabled the e-nose to learn the relationship between sensor responses and odour concentrations. As a result, the device is capable of directly predicting odour concentration in odour units per cubic meter (ou/m^3). Data analysis was performed using the Random Forest algorithm, which provided robust predictive performance.

An important feature of this configuration is that the H_2S, NH_3 and PID sensors integrated into the e-nose array perform a dual role. On one hand, they act as part of the overall sensor matrix, contributing to odour pattern recognition in the same way as MOS sensors. On the other hand, they serve as selective analysers, providing direct quantitative information on hydrogen sulphide, ammonia, and total volatile organic compounds (tVOCs). Calibration of these sensors was carried out using certified standard gases (0.5 ppm H_2S, 5 ppm NH_3, and 50 ppm isobutane for tVOCs). This dual functionality enhances the versatility of the e-nose, allowing it to provide both an integrated measure of odour concentration and detailed insights into the levels of specific odorants responsible for odour nuisance.

RESULTS AND DISCUSSION

Sensory odour assessment results

The results of the measurements conducted on July 4th 2024 are presented in Figure 2. The data show pronounced spatial variability in odour concentration across the measurement points within the facility. At the reference locations (background and administrative building), odour concentration (COT) values were close to zero, and odour intensity was 0.00 and 0.08

Table 1. Odour Air Quality Index (OAQI) categories and descriptions

OAQI range	OAQI	Description
0–20	Very good	Odours are undetectable or occur very rarely, are of low intensity, and/or have a neutral/pleasant hedonic quality.
21–40	Good	Odours are rarely detectable, have moderate intensity, and usually have a neutral hedonic quality.
41–60	Moderate	Odours occur more frequently, are detectable with moderate intensity, and may have a neutral or slightly unpleasant hedonic quality.
61–80	Poor	Odours are frequently detectable, have high intensity, and usually have an unpleasant hedonic quality.
81–100	Very poor	Odours are very frequently detectable, are very intense, and have a distinctly unpleasant hedonic quality

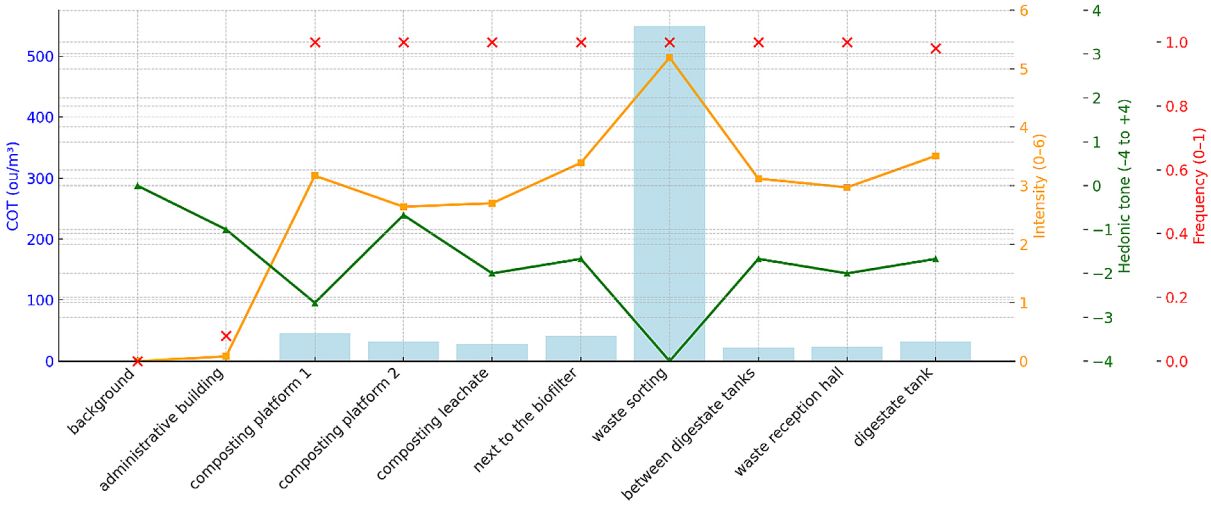

Figure 2. Sensory results on July 4th 2024

ou/m³, respectively. A neutral hedonic tone and low detection frequency yielded OAQI values of 0.00 and 5.30, corresponding to the "very good" category. Substantially higher values were recorded in the areas associated with technological processes. On the composting platforms, at the leachate collection tank, near the biofilter, in the waste reception hall, at the digestate tank, and at the location between the digestate tanks, odour concentration ranged from 21.8 to 45.8 ou/m³, with mean intensities of 2.6–3.5. Hedonic tone values at these points ranged from −0.67 to −2.67, indicating odours from slightly to distinctly unpleasant. The corresponding OAQI values (46.65–53.38) classified these locations as "moderate." The highest values for all parameters were observed in the waste sorting area, identified as the main source of odour emissions. Here, the odour concentration reached 549 ou/m³, which corresponds to the maximum measurable range of the olfactometer. The intensity was 5.19, and the hedonic tone −4.00, indicating odours judged unequivocally as very unpleasant. The OAQI value of 95.90 placed this point in the "very poor" category.

During the second measurement campaign, conducted on July 5th 2024, clearly higher odour metrics were recorded compared with the first day of the study. The meteorological conditions on the measurement day were characterised by higher temperatures and stronger winds than during the previous campaign, which may have favoured both an intensification of odour emissions and their faster dispersion within the facility. The results are presented in Figure 3.

The highest odour concentrations were again recorded in the waste sorting area (549 ou/m³) and in the vicinity of the biofilter (252.33 ou/m³). It is noteworthy that the biofilter is located immediately adjacent to the sorting hall, which influenced odour perception at that sampling point. Elevated COT values were also obtained in the waste reception hall (209.00 ou/m³), indicating a substantial accumulation of odorants at these locations. The same points also exhibited the greatest odour intensities (exceeding 4 on the six-point scale) and very low hedonic tone values (from −2.33 to −4.00), unequivocally confirming the predominance of unpleasant, negatively perceived odours. On both composting platforms, moderate odour concentrations were recorded (60.50 ou/m³ and 21.00 ou/m³); however, the values on Platform 1 were noticeably higher, which may indicate more intensive biological activity in this part of the installation. A similar pattern was observed around the digestate tanks (14.67 ou/m³) and in the compost leachate area (28.43 ou/m³), where the indicators were consistent with moderate odour nuisance. At the reference points – the background site and the administrative building – all parameters remained very low (COT ≤ 0.67 ou/m³, I ≤ 0.39), confirming that odour impacts at these locations were negligible.

The third measurement campaign was conducted on July 9th 2024. Compared with the previous days, meteorological conditions featured moderate temperatures and very strong winds, which may have markedly affected the recorded values. The high wind speed promoted the dispersion of odorants in the air, resulting in lower

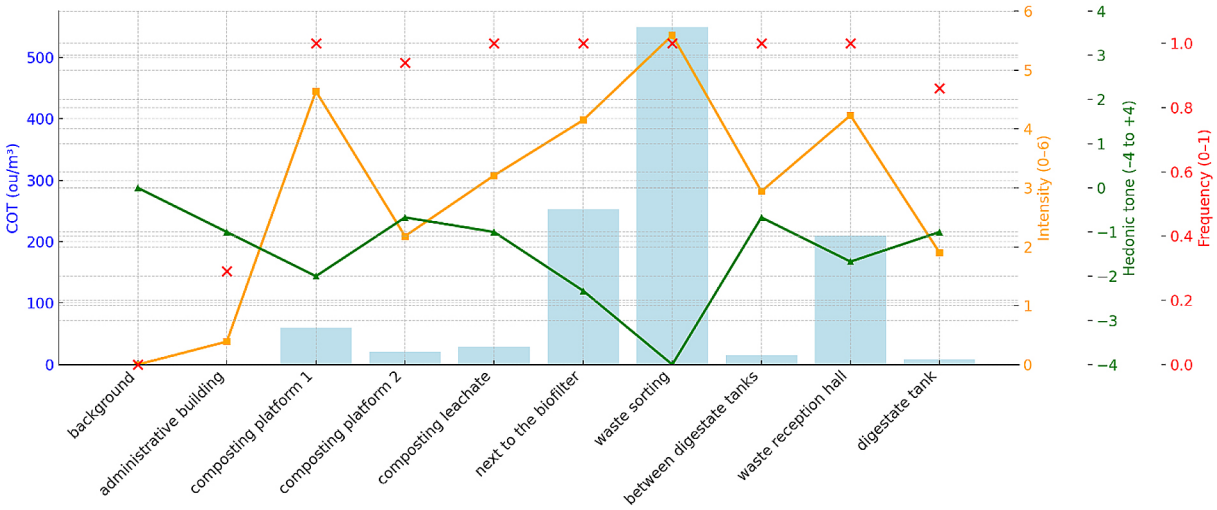

Figure 3. Sensory results on July 5th 2024

concentrations at some points than during the second campaign, while simultaneously potentially transporting nuisance odours across the facility. The results are presented in Figure 4.

As in the previous campaigns, the highest odour concentrations were recorded in the waste sorting area (449.67 ou/m³), accompanied by very high odour intensity (I = 4.80) and the lowest hedonic values (H = −4.00), indicating a decidedly unpleasant character of the emitted odours. Compared with July 5th 2024, the values at this point were lower by almost 100 ou/m³, which can be attributed to strong ventilation of the area. Moderately elevated concentrations were obtained at Composting Platform 1 (51.17 ou/m³) and in the compost leachate area (51.17 ou/m³), where odour intensities reached I = 4.35 and I = 4.43, respectively, and hedonic tone indicated clearly unpleasant odours (H ≈ −1.33 to −1.67). In the waste reception hall (62.83 ou/m³), both moderate concentrations and a markedly reduced hedonic tone (H = −2.00) were observed, confirming that this area remains one of the significant sources of odour nuisance. Lower concentrations, below 15 ou/m³, were recorded near the biofilter (12.00 ou/m³) and around the digestate tanks (3.83 ou/m³). At these locations, the results point to moderate-to-low odour nuisance, consistent with the expected dilution under strong ventilation. The lowest parameter values were again observed at the reference points – the background site (COT = 1.00 ou/m³) and the administrative building (COT = 6.67 ou/m³) – where odour intensity was very low (I ≤ 2.04) and the hedonic tone indicated an essentially neutral perception. The comparatively higher readings at these points arose from plume dispersion across the site.

The aggregated results from the three measurement campaigns conducted on July 4th, 5th, and 9th 2024 enabled the identification of local hotspots of odour nuisance within the facility (Figure 5). The Odour Air Quality Index (OAQI), integrating odour concentration, intensity, detection frequency, and hedonic quality, provided a concise appraisal of the odour situation and allowed comparison of results obtained under differing meteorological conditions.

The analysis showed that the waste sorting area (point 7) remained the dominant source of odour nuisance across all campaigns, with OAQI values persistently at the highest level, invariably classifying this location as "very poor" (OAQI > 90). Elevated index values were also observed near the biofilter (point 6) and in the waste reception hall (point 9), where OAQI mainly fell within the "poor" to "moderate" range, depending on atmospheric conditions. A second group comprised moderately burdensome locations – the composting platforms (points 3 and 4) and the digestate tank (point 10) – for which OAQI fluctuated between "moderate" (41–60) and "good" (21–40). Inter-day variability at these points was particularly pronounced, indicating that their potential impact on the surroundings is strongly modulated by meteorology and the intensity of ongoing process operations. By contrast, the reference points – the background site (point 1) and the administrative building (point 2) – consistently exhibited low OAQI values (< 20), confirming no material influence of plant processes at these locations.

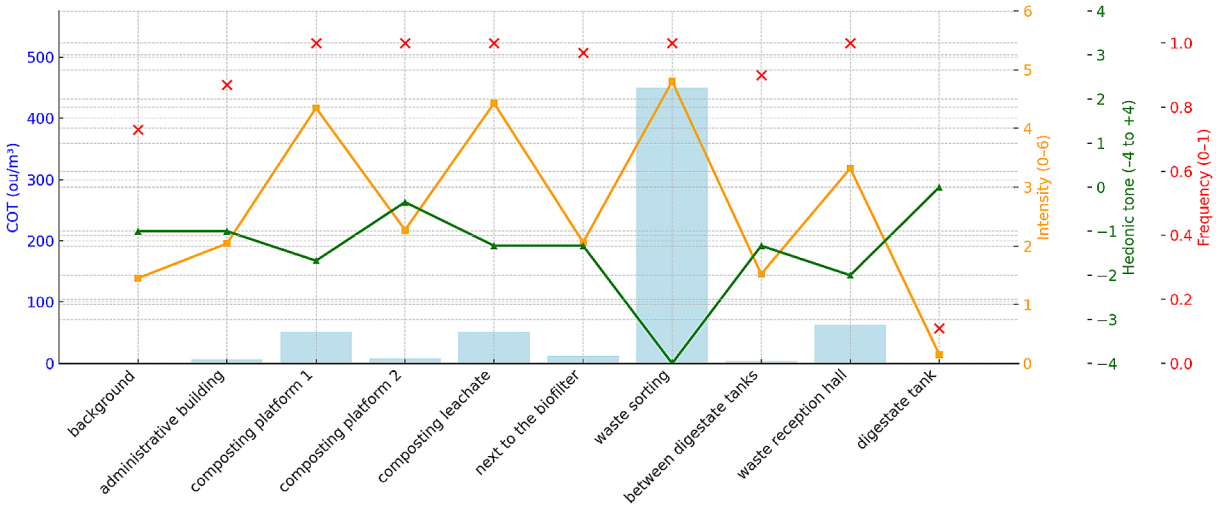

Figure 4. Sensory results on July 9th 2024

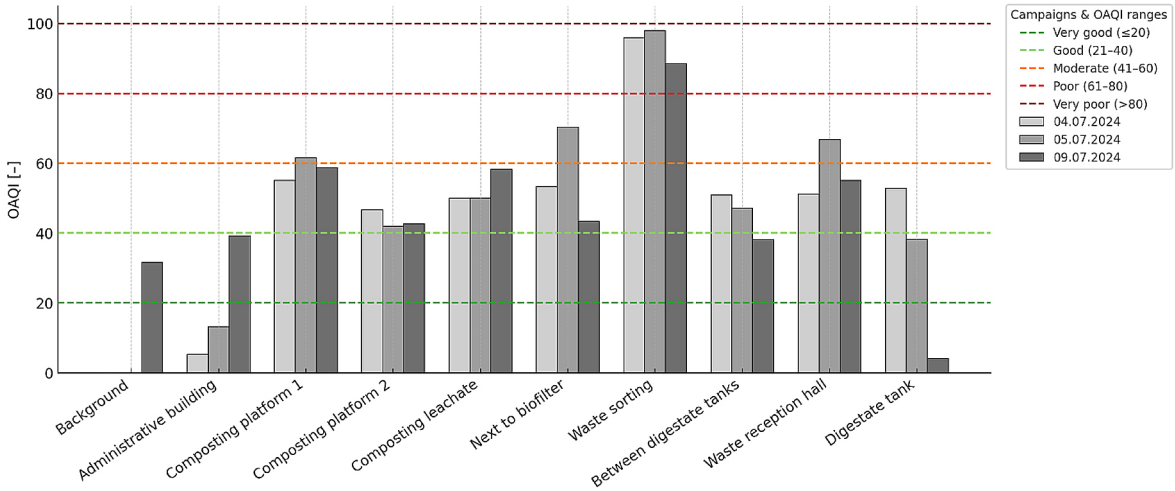

Figure 5. Odour Air Quality Index (OAQI) by sampling location for the three field campaigns

Comparison of the campaigns indicates a strong dependence on weather. During the second campaign (July 5th 2024), conducted under higher temperatures and stronger winds, clear increases in odour concentrations and OAQI were recorded in the sorting area, near the biofilter, and in the reception hall. In the third campaign (July 9th 2024), despite moderate temperatures, very strong winds likely enhanced dispersion, resulting in reduced OAQI values at several points relative to the previous measurement day.

Instrumental analyses of odorous samples

Figure 6 presents the odour concentration (measured with the SENSODOR e-nose), and the concentrations of H_2S, NH_3, and tVOCs (determined with electrochemical sensors and PID detector) at different locations of the biogas plant on July4th 2024.

During the measurements of odour concentration, clear fluctuations were observed across the different sampling points. The background concentration was negligible (close to 0 ou/m³). The highest odour concentration was recorded at point 7 (waste sorting), reaching values close to 900 ou/m³. Elevated concentrations were also present at points 4 and 6 (composting platform), with levels above 500 ou/m³. Most of the other measurement locations showed values between 200–400 ou/m³. The H_2S concentration exhibited distinct peaks throughout the measurement period. The baseline remained close to zero, while the highest peak was observed at point 7, reaching approximately

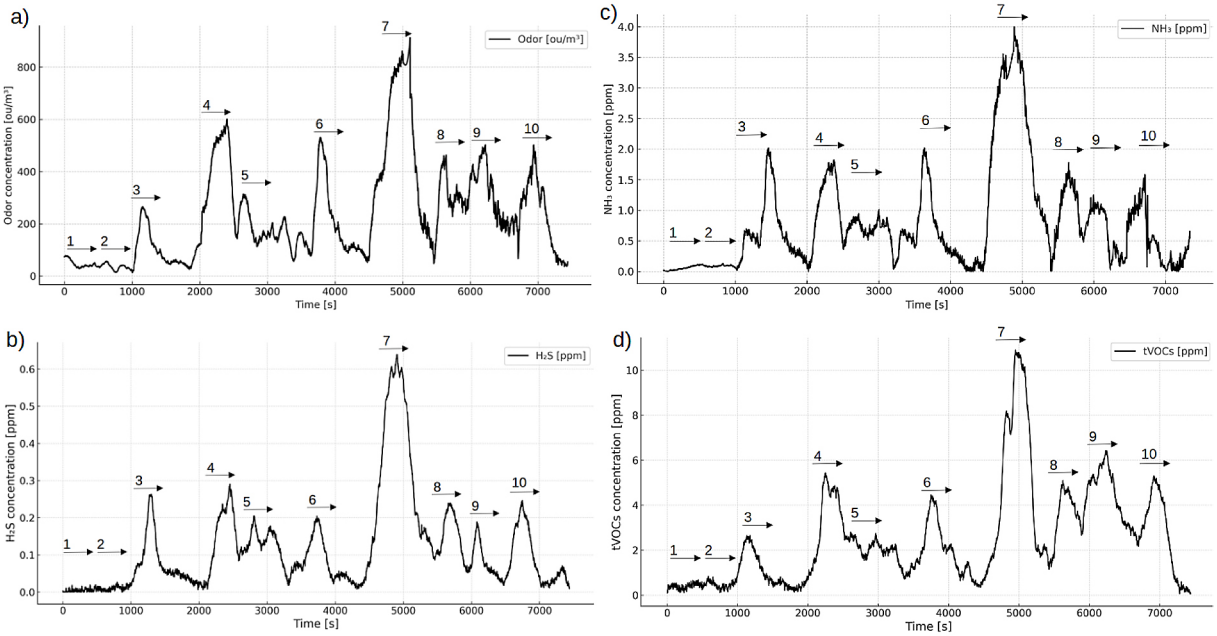

Figure 6. The odour concentration (a), and the concentrations of H_2S (b), NH_3 (c), and tVOCs (d) measured at different locations of the biogas plant. July 4th 2024

0.6 ppm. Additional peaks of 0.2–0.3 ppm were detected at points 3, 4, 5, 6, 8, and 10. This indicates localised emissions, strongly correlated with odour peaks.

The ammonia levels were more variable, with concentrations ranging from below 0.5 ppm in the background to as high as 3.8 ppm at point 7. Several intermediate peaks were also observed (2.0–2.5 ppm at points 3, 4, and 6). This confirms ammonia as a significant contributor to odour emissions, especially near waste sorting and composting activities. The tVOCs showed a similar dynamic profile to odour concentration. The baseline was low, but concentrations rapidly increased, reaching a maximum of about 11 ppm at point 7. Additional peaks of 4–6 ppm were registered at points 4, 6, 8, and 9. This highlights a strong correlation between tVOCs and odour nuisance. The sensory panel results indicate that odour perception was rated from "very good" (background, administrative building) to "very poor" at waste sorting (point 7). Moderate odour nuisance was reported at most other points (composting platforms, leachate tank, digestate areas). These subjective assessments correlate well with the instrumental measurements, confirming that the highest odour concentrations coincided with elevated H_2S, NH_3, and tVOCs levels, particularly at point 7.

Figure 7 presents the odour concentration (measured with the SENSODOR e-nose), and the concentrations of H_2S, NH_3, and tVOCs (determined with electrochemical sensors and PID detector) at different locations of the biogas plant on July 5th 2024.

The odour concentration measurements at the biogas plant on July 5th show clear spatial variation. The lowest values were recorded at the background (point 1) and administrative building (point 2) and thus only marginally influenced by processing activities. Another low-odour area was point 10, located near stabilised digestate. Moderate odour levels, ranging between 300 and 600 ou/m^3, were found at the composting leachate (point 4), composting platform (point 5), biofilter vicinity (point 6), and digestate handling area (point 8). Higher values were measured at point 3 (700 ou/m^3) and point 9 (> 1000 ou/m^3). The most pronounced odour emissions were recorded at point 7, where the concentration exceeded 1300 ou/m^3, indicating fresh waste handling as the main odour source.

The distribution of hydrogen sulphide (H_2S) follows a similar pattern. Background and administrative locations showed negligible values, close to zero. Moderate H_2S concentrations (0.2–0.3 ppm) were observed at points 4–6 and 8, consistent with partially decomposed organic matter. Peaks were recorded at point 3 (0.6 ppm) and point 9 (0.6 ppm), while the highest H_2S level occurred at point 7, reaching 0.7 ppm. Ammonia

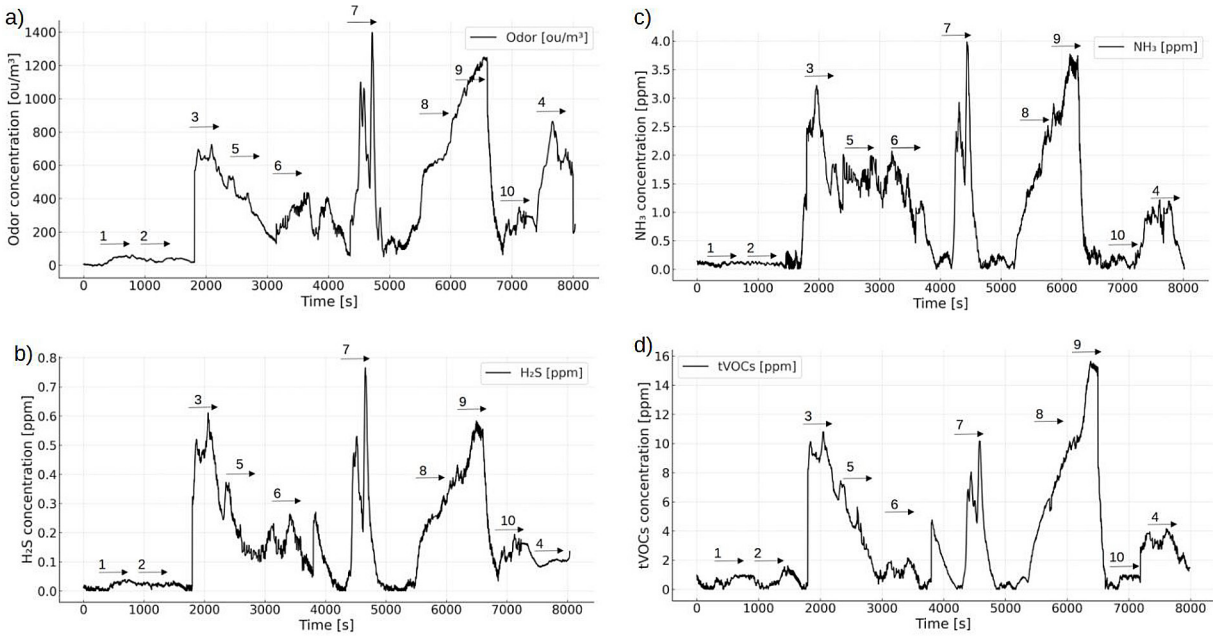

Figure 7. The odour concentration (a), and the concentrations of H_2S (b), NH_3 (c), and tVOCs (d) measured at different locations of the biogas plant. July 5th 2024

(NH_3) concentrations were also lowest at points 1, 2, and 10 (< 0.5 ppm). Moderate levels between 1 and 2 ppm appeared at points 4 – 6 and 8, reflecting nitrogen release from composting and digestate. At point 3, NH_3 rose to about 3 ppm, while the highest values were again observed at points 7 and 9, where concentrations exceeded 3 ppm. The distribution of total volatile organic compounds (tVOCs) confirms the odour trends. Background and administrative sites registered 2 ppm, and point 10 remained below 3 ppm. Intermediate values (4–6 ppm) occurred at points 4 – 6 and 8. Point 3 showed elevated concentrations (10 ppm), while the strongest peaks were observed at point 9 (15 ppm) and point 7 (12 ppm), clearly associated with raw waste handling.

The instrumental results correspond well with sensory odour assessments made by trained panelists. The locations rated as "very good" (points 1 and 2) and "good" (point 10) match the lowest measured concentrations of odours and gases. "Moderate" assessments (points 4, 5, 6, and 8) are consistent with the intermediate odour and gas levels observed. The sites classified as "Poor" (points 3, 6, and 9) coincide with elevated instrumental readings, particularly for odour and NH_3. The only location rated as "very poor" (point 7) also exhibited the highest odour concentration and gas peaks, confirming it as the main source of odour nuisance at the plant. This alignment highlights that H_2S, NH_3, and tVOCs are key contributors to the odour profile and validates both instrumental and sensory methods.

Figure 8 presents odour concentration (measured with the SENSODOR e-nose), and concentrations of H_2S, NH_3, tVOCs (determined with electrochemical sensors and PID detector) at different locations of the biogas plant on July 9th 2024.

The odour concentration measurements at the biogas plant show a clear spatial pattern, with the lowest values recorded at the background location and the administrative building, indicating minimal influence from processing activities in these areas. Moderate odour levels were found near the composting platform, composting leachate, the area next to the biofilter, the waste reception hall, and digestate handling points such as the digestate tank and the space between digestate tanks. The highest odour concentration, exceeding 1000 ou/m^3, was recorded at the waste sorting area, where fresh, untreated organic waste is handled. This stage of processing releases the most intense odours, originating from both anaerobic and aerobic degradation processes. Elevated values were also observed at the composting platform, reflecting strong emissions during active organic matter decomposition.

This odour distribution aligns closely with the gas concentration patterns for tVOCs, H_2S, and NH_3. The waste sorting area, which showed the

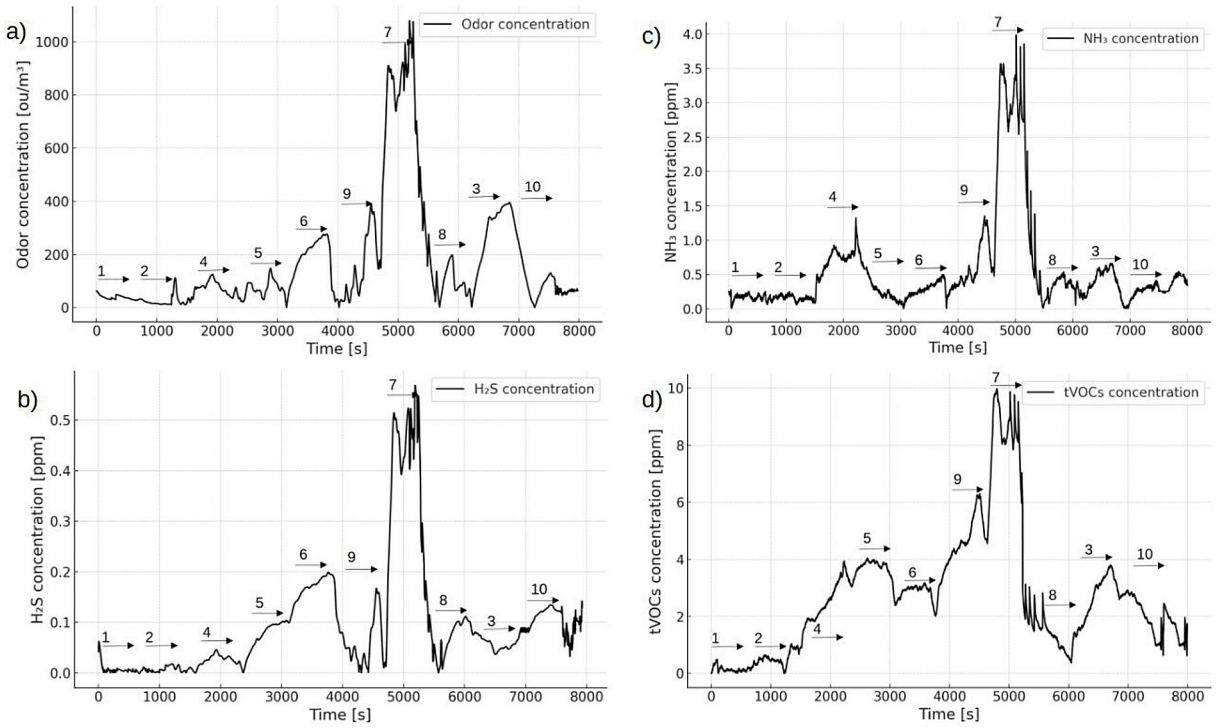

Figure 8. Odour concentration (a), and concentrations of H_2S (b), NH_3, (c) tVOCs d) measured at different locations of the biogas plant. July 9th 2024

highest odour levels, also had the highest peaks for all measured gases: tVOCs reached around 10 ppm, H_2S exceeded 0.5 ppm, and NH_3 rose to about 4 ppm. These compounds are well-known contributors to odour nuisance – hydrogen sulphide imparts a strong, unpleasant smell even at very low concentrations, ammonia adds a pungent note from nitrogen-rich material breakdown, and tVOCs encompass a broad range of volatile organic substances with various odour characteristics. Moderate gas concentrations at the composting platform and digestate handling points mirror the moderate odour levels there, confirming that the emissions at these locations are still significant but lower than at raw waste handling stages. In contrast, the background and administrative building consistently showed minimal levels of both odours and gases, illustrating the effectiveness of spatial separation from active processing zones.

Overall, the combined odour and gas data reveal a consistent pattern: areas handling fresh waste emit the highest concentrations of odorous compounds, intermediate processing and storage points produce moderate emissions, and peripheral or non-processing areas remain at baseline levels. This gradient is typical for biogas plants and reflects the progression from untreated organic material toward stabilised outputs.

DISCUSSION

In biowaste treatment facilities, odour emissions are typically dominated by a small number of critical sources. Feedstock composition and process configuration exert a strong influence on odour release [4]. Waste reception and sorting frequently account for the largest share of impacts, as mixed municipal streams liberate volatile organic compounds and ammonia in an uncontrolled manner during unloading and mechanical treatment [24]. This effect is particularly pronounced for food-rich waste, the high biodegradability and moisture of which favour rapid fermentation and peak odour episodes. The reported generation potentials include hydrogen sulphide at 48.4 µg/kg and ammonia at 4742 µg/kg (3933 µg/kg for fruit waste), with rates increasing over the first hours to days (up to ~72 h) and remaining elevated throughout the first 90 days of processing [25]. The scale of these effects is corroborated by field olfactometry at a waste management plant, where odour concentration (after D/T conversion) at the reception/tipping area ranged from 22.27 to 78.49 ou/m^3 across campaigns [23]. Complementary dynamic olfactometry reported mean values of 60.0 ou_E/m^3 in the reception hall and 265.5 ou_E/m^3 in the sorting hall [26].

During composting, forced aeration and windrow turning rapidly release accumulated gases, generating short-lived yet intense emission peaks – particularly where process control is insufficient [27, 28]. The reported odour concentrations range from hundreds to thousands of ou/m^3, depending on the composting phase and operational practices. For freshly formed windrows, values around 750 ou/m^3 have been observed, rising after 2–3 weeks of aeration to 1250–1300 ou/m^3, and in some cases approaching 10 000 ou/m^3 [29, 30]. Other authors report odour peaks exceeding 3000 ou/m^3 during windrow turning and up to 12 000 ou/m^3 during compost screening [31], confirming that short-term operations can dominate local odour impact. Stage-resolved analyses confirm a downward trend: 28 546 ou/m^3 before process onset, decreasing to 4902 ou/m^3 after four weeks and 2569 ou/m^3 after thirteen weeks [32].

In anaerobic digestion (AD) and digestate management, the odour levels exhibit marked variability tied to specific unit operations. During feedstock preparation, field olfactometry indicated 4–78 ou/m^3, whereas digestate dewatering yielded 8–448 ou/m^3 with spikes during loading and mixing [33]. Source-based dynamic olfactometry shows substantially higher concentrations at organised sources. In a study [34] encompassing three facility types – farm-scale biogas plants (Farm), WWTP-integrated AD (Waste Water Treatment Plants - Anaerobic Digester) and regional plants processing agri-food wastes (Territory) – the highest burdens occurred at reception and pre-treatment. Territory sites reached several to tens of thousands of ou_E/m^3 (up to 19 000 ou_E/m^3), while WWTP sites typically ranged from tens to 1446 ou_E/m^3. Raw-material storage emitted from hundreds to a few thousand ou_E/m^3 (Farm: 389–620 ou_E/m^3; WWTP: 560–1250 ou_E/m^3; Territory: 2525–7741 ou_E/m^3). Reactor emissions were generally lower (Farm: < 25–25 ou_E/m^3; WWTP: 40–2244 ou_E/m^3), and phase separation at WWTPs ranged 255–1210 ou_E/Nm^3. In digestate management, the concentrations depended on the phase: liquid storage showed higher ranges (Farm 2200–5650 ou_E/m^3; WWTP 310–620 ou_E/m^3) than solid storage (Farm 140–320 ou_E/m^3; Territory 730–1100 ou_E/m^3). Seasonally, minima occurred in winter. Practically, this highlights the sensitivity of reception/pre-treatment and digestate handling, where enclosure, negative pressure, and high-efficiency treatment of captured air are essential.

In this study, the instrumental results are in strong agreement with the sensory odour assessments conducted in the field using trained panelists. The locations rated as "good" or "very good" in sensory tests – such as the background, administrative building, and some digestate handling points – correspond to the lowest measured concentrations of odours and gases. The sites assessed as "moderate" show matching intermediate levels in both odour units and gas concentrations, typically associated with areas where material is partially stabilised, such as composting platforms, leachate zones, and the biofilter vicinity. The only location classified as "very poor" by the sensory panel, the waste sorting area, also exhibited the highest instrumental readings across all parameters, confirming it as the primary source of odour nuisance at the plant. This strong agreement between sensory perception and measured gas concentrations validates the reliability of both approaches and sets the stage for a deeper analysis of gaseous contributors to odour nuisance.

In addition to sensory results, the measurements of hydrogen sulphide, ammonia, and total volatile organic compounds provided valuable insights into the chemical drivers of odour nuisance at the studied facility. Although the observed concentrations (up to 0.7 ppm H_2S, 4 ppm NH_3, and 15 ppm tVOCs) remained well below toxicological thresholds, their extremely low odour detection limits make them significant contributors to the perceived annoyance. This aligns with previous studies showing that even sub-ppm levels of H_2S and NH_3 can dominate olfactory impressions in waste treatment environments [25, 33]. The measured values also fall within ranges reported for comparable facilities, where H_2S typically varies from 0.1 to 1 ppm, NH_3 from 1 to 10 ppm, and tVOCs from a few to several tens of ppm, depending on feedstock and process stage [33, 34]. In this context, the values observed at the studied site ($\leq$ 0.7 ppm H_2S, $\leq$ 4 ppm NH_3, $\leq$ 15 ppm tVOCs) appear representative and do not indicate any abnormal or uncontrolled emissions. Nevertheless, these concentrations are sufficiently high to generate noticeable odour due to the low sensory thresholds of the compounds.

The spatial distribution of gas concentrations corresponded well with olfactometric and OAQI results, reinforcing the usefulness of these measurements in pinpointing localised nuisance. Moderate levels were recorded at composting platforms and digestate zones, while background

areas showed negligible values. These results suggest that H_2S, NH_3, and VOCs can serve as reliable proxy indicators for odour intensity, providing a valuable complement to sensory and olfactometric methods. From an operational standpoint, gas-specific monitoring can guide targeted mitigation efforts: for example, elevated H_2S may point to the need for better enclosure and sulphur-focused filtration, NH_3 suggests optimising nitrogenous feedstock handling, and tVOC patterns offer data for calibrating electronic noses. When integrated with sensory-based indices, such as OAQI, these chemical indicators contribute to a more robust and responsive odour management framework.

This pattern is consistent with numerous studies highlighting reception and sorting as the principal odour sources in organic waste treatment. The handling of unpackaged food waste, in particular, is known to release large volumes of VOCs and nitrogen- or sulphur-based compounds due to mechanical agitation and the onset of rapid microbial degradation [35, 36]. Field studies conducted at mechanical-biological treatment facilities and anaerobic digestion plants frequently identify waste reception areas and sorting halls as the primary hotspots of odour emissions. Although specific odour concentration values obtained through olfactometric measurements may vary, these locations consistently exhibit the highest levels of odour impact – often significantly greater than those observed in other stages of the treatment process [36, 37]. Interestingly, elevated odour values recorded in the vicinity of the biofilter, despite its role as an abatement unit, can be explained by its close proximity to the sorting hall. The likely cause is the advection of untreated air into this area due to local airflow dynamics rather than any malfunction of the biofilter itself. Improperly ducted ventilation systems or insufficient air capture can result in odorous ”clean zones” adjacent to high-emission sources.

The composting platforms showed moderate odour levels that varied between campaigns, which is expected given the process dynamics of composting. As established in multiple studies, odour emissions during composting are strongly influenced by process phase, temperature, moisture, and aeration method [38]. Odour peaks are particularly pronounced during windrow turning or forced aeration, especially in the early thermophilic stage when microbial activity is at its peak. In this study, the elevated concentrations recorded on Platform 1 suggest a more active or recent composting phase compared to Platform 2, which may have been in a more advanced stabilisation stage. In contrast, the odour levels around the digestate tanks and between digestate zones were generally lower and more stable, consistent with the literature on biogas facilities. While digestate handling – particularly during mixing or dewatering – can occasionally cause brief peaks in odour emissions, properly managed and stabilised digestate tends to have a lower overall impact on ambient odour compared to raw waste [39].

While digestate handling can occasionally cause sharp emission peaks – especially during mixing or dewatering – its overall contribution to ambient odour is typically smaller than that of raw waste [33]. In the present study, the higher gas concentrations observed during warmer or less stable atmospheric conditions (e.g., July 5th) suggest that weather plays a significant role in modulating the release and transport of odorous compounds. Meteorological conditions had a visible impact on odour dispersion across the three campaigns. Higher temperatures and moderate wind speeds were associated with intensified odour concentrations at key emission points, likely due to increased volatilisation rates. Conversely, during the third campaign, very strong winds appeared to reduce local concentrations through enhanced dilution, yet may have contributed to odour perception at locations otherwise unaffected. This dual effect of dispersion – diluting concentrations at source while potentially extending the impact footprint – is well documented in the context of odour nuisance [13].

The use of the OAQI in this study enabled an integrated interpretation of multidimensional odour data. By combining concentration, intensity, hedonic tone, and frequency of detection, OAQI provides a holistic measure of perceived nuisance that aligns with similar composite indices proposed in the literature [40]. This proved particularly valuable in comparing conditions across different meteorological scenarios and for identifying temporal or spatial hotspots with greater clarity than through single-parameter indicators alone. From an operational perspective, the findings confirm the need for targeted odour control at critical emission points – most notably the sorting and reception zones. This includes physical enclosure, active extraction under negative pressure, and high-efficiency treatment using multi-stage systems such as acid scrubbing followed by biofiltration, which are recommended

in BAT conclusions for the sector [18]. Furthermore, dynamic process management, such as scheduling waste unloading or compost turning during meteorologically favourable periods, can reduce off-site impacts, especially under strong wind conditions. Finally, the integration of electronic noses into facility monitoring appears to be a promising approach for real-time odour management. When properly trained and validated, such systems can detect odour fluctuations at a frequency and resolution far beyond manual sampling techniques. However, challenges remain regarding sensor drift, environmental interference, and the need for periodic recalibration [41]. Future research should continue to refine these systems and explore their use in predictive modelling or early warning applications.

In conclusion, the combination of sensory assessments, gas-specific measurements, and continuous odour monitoring allowed for a comprehensive evaluation of odour emissions at the studied biowaste facility. The results confirm known emission patterns for this type of plant but also underscore the importance of local factors, such as meteorology and facility layout, in shaping actual odour impact.

CONCLUSIONS

The instrumental and sensory measurements conducted on July 4th, 5th, and 9th 2024 at the biogas plant consistently demonstrate that the waste sorting area is the primary source of odour nuisance. On all three days, this location exhibited the highest odour concentrations, exceeding 900 ou/m^3 on July 4th, 1300 ou/m^3 on July 5th, and 1000 ou/m^3 on July 9th. These peaks were strongly correlated with elevated levels of hydrogen sulphide, reaching up to 0.7 ppm, ammonia up to 4 ppm, and tVOCs in the range of 10 to 15 ppm, confirming the critical role of untreated waste handling in generating emissions. Other areas, such as the composting platform, composting leachate, digestate handling points, and the biofilter vicinity, showed moderate odour levels, typically between 300 and 600 ou/m^3, with corresponding gas concentrations of 0.2–0.3 ppm H_2S, 1–2 ppm NH_3, and 4–6 ppm tVOCs. These emissions reflect ongoing biological activity, but remain substantially lower than those observed at raw waste reception. Peripheral locations, including the background and the administrative building, consistently recorded negligible values, confirming minimal influence from the plant processing activities in those zones. The sensory assessments by trained panelists were in strong agreement with the instrumental data. The sites classified as "very good" or "good" matched the lowest odour and gas concentrations, while the areas rated as "moderate" coincided with intermediate values. The only location consistently described as "very poor" by the panel was the waste sorting area, which also had the highest measured instrumental values. Taken together, the results from all three measurement campaigns highlight a stable emission pattern, with the waste sorting area generating the highest impact, composting and digestate handling representing moderate impact, and background or administrative areas showing the lowest impact. These findings confirm that hydrogen sulphide, ammonia, and volatile organic compounds are the key contributors to odour emissions and demonstrate that the combination of electronic nose and gas sensors with sensory panels provides a reliable and complementary approach for monitoring odour nuisance at the facility.

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