SENSORIAL TECHNIQUES OF ODOUR MEASUREMENTS – A RELATIONSHIP BETWEEN ODOUR CONCENTRATION AND ODOUR INTENSITY FOR A SELECTED WASTE MANAGEMENT FACILITY

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Abstract

Sensory analyses are one of the most frequently used odour research methods that allow establishing the most important odour characteristics, i.e. odour concentration and odour intensity, characterised by a high degree of interrelationship. During an11-month study odour concentration and intensity were measured at selected mechanical-biological solid municipal waste treatment plant at 35 measuring locations to assess the degree of correlation between those two parameters. Commonly used Weber-Fechner law was applied to assess the correlation. Results indicate a high degree of correlation between odour concentration and intensity, for example, R^2 valued for two different approaches at 0.87, and 0.95, while Pearson's r valued at 0.93, and 0.97. Following the results this proves that odour concentration and odour intensity could potentially be used interchangeably for odour assessment. However, applying Weber-Fechner law for prediction of odour concentration based on odour intensity measurements gives imprecise results. Such approach could be potentially applied when limited measurements of odour concentration are available as determination of odour intensity that could be performed even by Facility employees.

Keywords: field olfactometry, odour concentration, odour intensity, waste management, Weber-Fechner law

1. Introduction

Odours can be described with the use of a variety of measurement techniques, including analytical techniques and sensory methods (Brattoli et al., 2011; Bax, Sironi

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and Capelli, 2020; Jońca *et al.*, 2022). Analytical techniques (such as chemical analysis, gas chromatography or gas sensors) provide information about the concentration of specific substances/odorants, while sensory methods give information about the entire sensation caused by a mixture of different substances contained in the air (Muñoz *et al.*, 2010; Conti, Guarino and Bacenetti, 2020). Sensory methods allow using the human sense of smell to detect odours and describe them as they are perceived by humans (Muñoz et al., 2010; Brattoli et al., 2011). Quantitative analysis can be provided by coupling the human nose with external instruments, such as dynamic and field olfactometers, to determine the odour concentration of air samples or in ambient air. Human nose alone may be used to perform parametric measurements and allows describing parameters such as, for example, odour character, odour intensity and hedonic tone (Brattoli et al., 2011; Jońca et al., 2022). Odour concentration and odour intensity are two parameters that show a high degree of interrelationship, and can be considered one of the most important properties of odours when it comes to sensory assessment (Zhang et al., 2002; Jiang, Coffey and Toohey, 2006; Ubeda et al., 2013). Odour concentration, according to European Standard EN13725:2007 (Polish Committee for Standardization, 2007) is defined as the amount of European odour unit per cubic meter of gas in standard conditions, while odour itself is an organoleptic feature perceived by the human sense of smell when smelling certain volatile compound. Therefore, odour concentration can be seen as the strength of odour, while odour intensity is the magnitude of that strength (Jiang, Coffey and Toohey, 2006; Brattoli et al., 2011; Brancher et al., 2017). As the odour concentration is described as ou_E/m^3 or ou/m^3, odour intensity is expressed as a verbal description assigned to a numerical scale (Jiang, Coffey and Toohey, 2006) and is related to odour concentration (Zhang *et al.*, 2002). The relationship between these two parameters can be described by the Weber-Fechner law (Zhang et al., 2002; Jiang, Coffey and Toohey, 2006; Brancher et al., 2017; Bian, Gong and Suffet, 2021; Li et al., 2021), which states that the relationship of psychological perceived intensity and physical feature like odour concentration could be derived as a linear function. As different criteria could be used for odour measurements, different schemes of odour monitoring may be applied. One of the most commonly used approach is the use of dynamic olfactometry to determine odour concentrations at emission sources, and next a calculation of the emission values used as an input for odour dispersion modelling to assess the impact of odour sources (Brancher et al., 2017; Bax, Sironi and Capelli, 2020). This particular approach is one of the most cost-demanding as it incorporates different steps to obtain a final assessment (Brattoli et al., 2011). Another approach to assess odour impact is to use CICOP dimensions or FIDOL factors (Brancher et al., 2017; Guillot, Trousset and Daclin, 2022). The CICOP is the acronym for Concentration, Intensity, Character, Offensiveness and Persistency, while FIDOL is the acronym for Frequency, Intensity, Duration, Offensiveness and Location. The first one combines both analytical and sensory methods, as the concentration parameter may concern both odours measured by e.g. through dynamic olfactometry, and odorants measured by e.g. gas chromatography

(Brancher et al., 2017). The second one is focused more on the simple, descriptive part of odours (Guillot, Trousset and Daclin, 2022). Parametric measurements are considered as less-cost demanding methods as they do not or barely require any additional measuring devices (Brattoli et al., 2011). Various literature sources show that odour intensity and odour concentration measured by field olfactometry are parameters commonly used during different research focusing on odour measurements. The authors (Wiśniewska, Kulig and Lelicińska-Serafin, 2019, 2020b, 2020a) carried out a series of measurements regarding among others odour concentration and odour intensity evaluation at different biogas plants located in Poland. Authors (Sówka et al., 2017) used odour intensity coupled with odour character to assess the air quality in terms of odour nuisance considering different odour sources. In (Kitson et al., 2019), the authors have used a field olfactometer to assess odour intensity at a selected urban area. As waste management is one of the biggest sources of environmental odours (Pawnuk et al., 2022) and waste facilities could emit odours at different stages (Wiśniewska, Kulig and Lelicińska-Serafin, 2019, 2020b, 2020a) there is a need for fast, low-cost and reliable tools for odour quality assessment. Establishing odour concentrations by the means of field olfactometry and describing the odours by their intensity is a straightforward task; those methods can be considered low-cost and can be used in a relatively short time without need for time-consuming training (Brattoli et al., 2011; Fisher et al., 2018; Kitson et al., 2019). Those methods seem to be appealing, especially when considering multipoint measurements. The scope of the work is to find the relationship between odour concentration determined by the means of field olfactometry and odour intensity during an 11-month study at a selected mechanical biological municipal waste treatment plant, covering 35 different measuring points. On the basis of the obtained results comprising 35 measurement points in an 11-month period, 290 measurements of odour concentration and odour intensity were obtained. On this basis, the assessment of the strength correlation between odour intensity and odour concentration and the determination of the Weber-Fechner relation was provided. The main scientific scope is to find whether it is possible to accurately predict odour concentration based on the Weber-Fechner law and to check whether an accurate odour assessment can be carried out without determining odour concentrations. At such a scale, no recent literature is available regarding the aforementioned topics, especially given mechanical biological waste treatment plants in Poland. In the case of limited measurement possibilities, establishing the correlation between odour concentration and intensity can be an extremely useful tool from the point of view of managers of waste management plants. Taking into account the applicability of the Weber-Fechner law, odour intensity can potentially be used to determine odour concentrations. These measurements could be performed, for example, by plant employees after appropriate training. The above-mentioned correlates show great application potential for managers of waste management facilities, especially during so-called odour episodes. Therefore conducting research covering a wide range of measurement points and a wide time range is extremely important.

2. Methods and Materials

2.1. Facility description

The research was carried out at a mechanical-biological solid municipal waste treatment plant in Poland with a maximum capacity of yearly processed waste equal up to 106 00 Mg. The Facility consists of two main parts: the mechanical part and the biological one. The biological treatment of waste is carried out in two main processes: aerobic treatment (composting, aerobic stabilization) and anaerobic digestion (methane fermentation). In addition, the selected MBT plant has an active landfill quarter, a RDF production line, leachate tanks, as well as all necessary components required for its uninterrupted, highly standardized and environmentally friendly operating conditions. 35 measuring points were selected for measurements. Measuring points were selected for each place that could emit

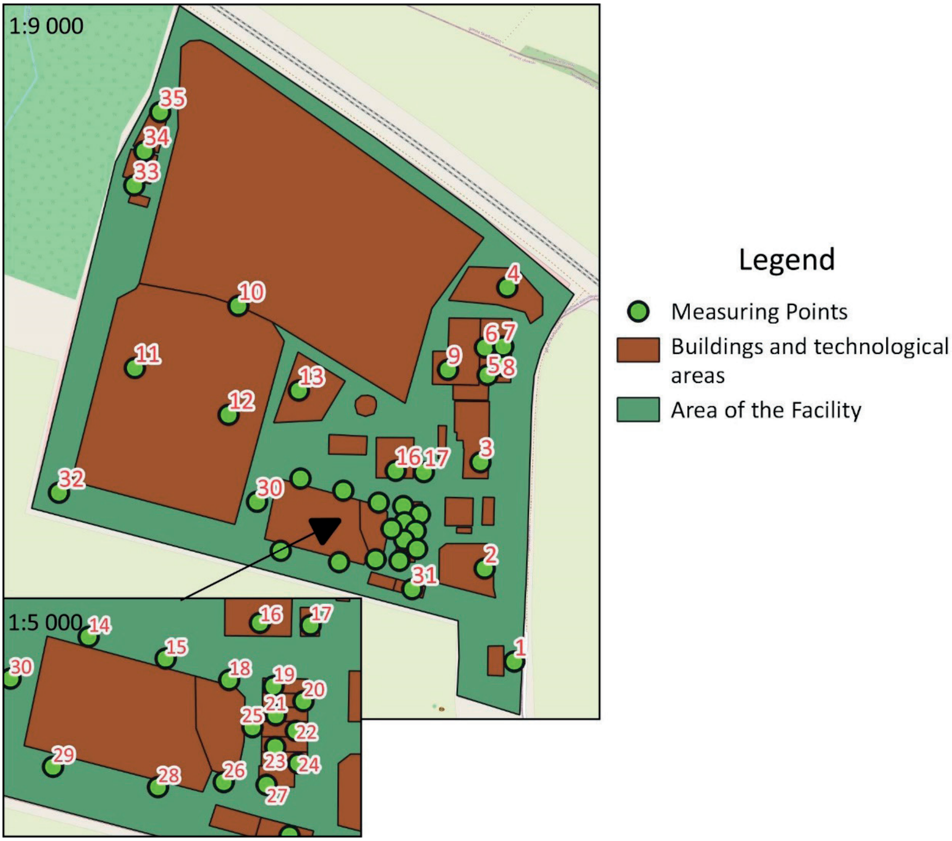

Figure 1. Measuring points at the Facility (made with the QGIS software, based on data provided by OpenStreetMap)

odours or be under the direct influence of other odour sources. Before commencing the measurement series, several site visits were conducted at the investigated facility to become familiarized with its working conditions. Due to the nature of the plant, the multitude of odour sources and their spatial distribution, the measurement points are located in an irregular grid. The number of measurement points was limited due to the constraints of the field olfactometry method used for establishing odour concentrations. Points coverage can be considered as representative for the studied Facility. They include both points located inside technological buildings and outside buildings. Figure 1 shows the location of each measuring point located at the Facility.

The description of the measurement points is as follows: 1 – administrative building; 2 – technical area; 3 – RDF preparation and storage building; 4 – selective waste storage area; 5 – sorting hall; 6 – sorting cabin 1; 7 – sorting cabin 2; 8 – sorting hall (1st step of waste sorting); 9 – waste reception hall; 10 – landfill site entrance; 11, 12–landfill site; 13 – bulky waste processing and storage area; 14, 15, 28, 29 – aerobic stabilization area; 16 – anaerobic processes technical building; 17 – biofilter (anaerobic processes); 16 – anaerobic processes technical building; 18, 26 – green waste storage area; 19–24 – bioreactors; 25 – between aerobic stabilization chambers and green waste storage area; 27 – biofilter (aerobic processes); 30 – between landfill site and aerobic stabilization; 31 – leachate tank for biological processes; 32 – facility border; 33–35– landfill leachate tanks.

2.2. Measuring methods

For every measuring point a sensory evaluation was performed. Two main methods of sensory analysis were used for the research, including quantitative analysis and parametric measurements. For the quantitative analysis, odour concentrations were established with the use of a portable field olfactometer NasalRanger by St. Croix Sensory, Inc (St. Croix Sensory, 2023a). The device allowed fast in-situ measurements. The working principles of the selected field olfactometer are based on dilution to threshold ratio (D/T) and its main role is to dilute ambient air which may be contaminated with odours with clean air filtered by pair of active carbon filters and to determine the D/T ratio at which odours can be detected (Laor, Parker and Pagé, 2014; Pawnuk, Sówka and Naddeo, 2023; St. Croix Sensory, 2023a). The used olfactometer allowed establishing 6 different D/T ratios: 60, 30, 15, 7, 4, 2. By identifying the particular D/T ratio at which odors were detectable and comparting it to the setting where they were non-detectable, it is possible to determine the odor concentration which is expressed as a geometric mean of those two D/T readings The calculations were made in accordance with formulas provided in available research (Barczak and Kulig, 2017; Byliński et al., 2017; Kulig and Szyłak-Szydłowski, 2019; Wiśniewska, Kulig and Lelicińska-Serafin, 2020a). The used device and the methodology for odour concentration determination allowed establishing 7 different concentrations values: 0 ou/m^3; 3.87 ou/m^3; 6.32 ou/m^3;

11.31 ou/m^3; 22.27 ou/m^3; 43.49 ou/m^3; 78.49 ou/m^3. 0 ou/m^3 was adopted for every point where odour concentration was under the detection threshold of the used field olfactometer (less than 2 D/T or respectively less than 3.87 ou/m^3). The accuracy of measurements with the use of NasalRanger field olfactometer is ± 10%. Parametric measurements were focused on the determination of odour intensity. For the description of odour intensity, a 7-point scale was used based on the German standard VDI 3882. The scale of odour intensity measurement is shown in Table 1.

Table 1. Intensity numerical scale and its verbal description used in parametric measurements

Verbal, descriptive scale	Numerical scale
Not perceptible	0
Very weak	1
Weak	2
Distinct	3
Strong	4
Very strong	5
Extremely strong	6

The measurements were carried out during 11 measurement days over 11 months. The dates of measuring days are as follows: 18/11/2021; 14/12/2021; 28/01/2022; 23/03/2022; 29/04/2022; 13/05/2022; 27/06/2022; 26/07/2022; 28/08/2022; 15/09/2022; 13/10/2022. As it was stated above, the measurement series covered 35 points at the Facility. However, mostly due to technological reasons (i.e. bioreactors were closed, the sorting hall was not operating on the given measuring day) or due to the meteorological conditions it was not possible to establish such parameters in every desired point. A total of 291 measurements (pairs of odour concentration-intensity) were considered.

For the compiled data regarding odour concentration odour intensity Weber-Fechner law was applied, which describes the dependency between the perceived psychological intensity and physical features like concentration. The Weber-Fechner law can be described with the equation below (eq. 1).

$$I = a \cdot \log(C) + b \qquad (1)$$

where:

I – is odour intensity,

C – is odour concentration (ou/m^3),

a,b – are Weber-Fechner constants (a – is the slope of the regression line, b – is the intercept).

The OriginPro software by OriginLab Corporation was used for data processing and analysis for this paper. The software has been used for tasks such as data curation acquisition or executing statistical tests (the Shapiro-Wilk test, determination of Spearman coefficient, and determination of linear correlation)

3. Data analysis and results

3.1. Characteristics of odour concentrations and odour intensity during the given measuring period

Figure 2 and Figure 3 show average odour concentrations (later as c_{od}) and intensity values (later referred to as i_{od}) in a given measuring month. The N of points, which were used to plot Fig. 2 and Fig. 3 is as follows: 32 (18/11/2021), 11 (14/12/2021), 17 (28/01/2022), 31 (23/03/2022), 28 (29/04/2022), 26 (13/05/2022), 26 (27/06/2022), 26 (26/07/2022), 31 (28/08/2022), 28 (15/09/2022), 35 (13/10/2022). An analysis of average odour concentrations (Fig. 2) shows that the highest average measured c_{od} was recorded during October 2022 (41.33 ou/m^3), while the lowest one in December 2021 (9.66 ou/m^3). In most cases, the average c_{od} for a given measuring month is higher than 20 ou/m^3, but for December 2021 and January 2022, it was below that (9.66 ou/m^3 and 11.34 ou/m^3 respectively). A similar pattern can be observed in the case of average intensity values in a given measuring month (Fig. 3). The highest average i_{od} was found during October 2022 (4.06) and the

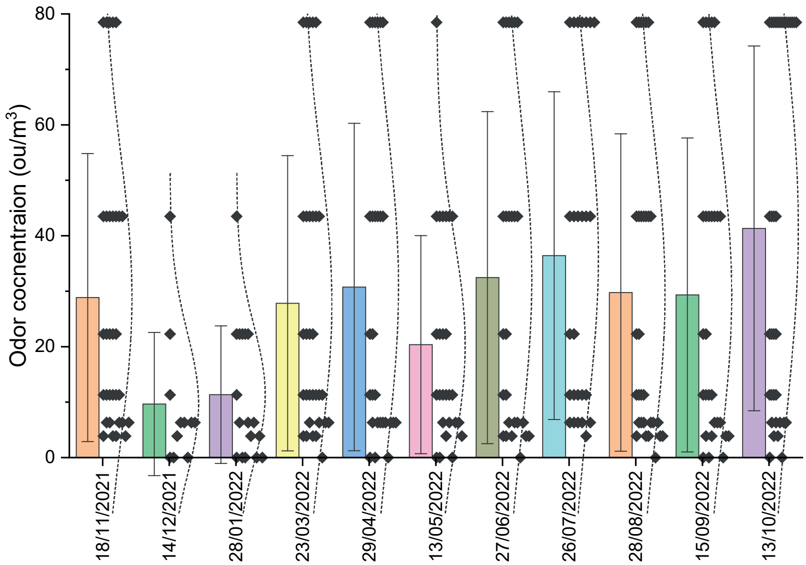

Figure 2. Average odour concentration in a given measuring month ± 1 standard deviation with plotted measured concentrations and distribution line

lowest one was in December 2021 (2.27). In the case of the remaining measurement months, the average odour intensity is higher than 3.0. The average values of odour concentrations and intensities shown in Figures 2 and 3 suggest the existence of a relationship between these parameters. Therefore, further analysis is needed to determine this correlation. In addition, data shown in Figure 2 and Figure 3 suggest the existence of a seasonality for the data, i.e. higher odour concentrations are associated with higher temperatures in a given season. However, the authors' considerations on this subject can be found in (Pawnuk, Sówka and Naddeo, 2023). The obtained results indicate that there is no relationship or a weak one may be observed between the meteorological conditions and odour concentrations in this case.

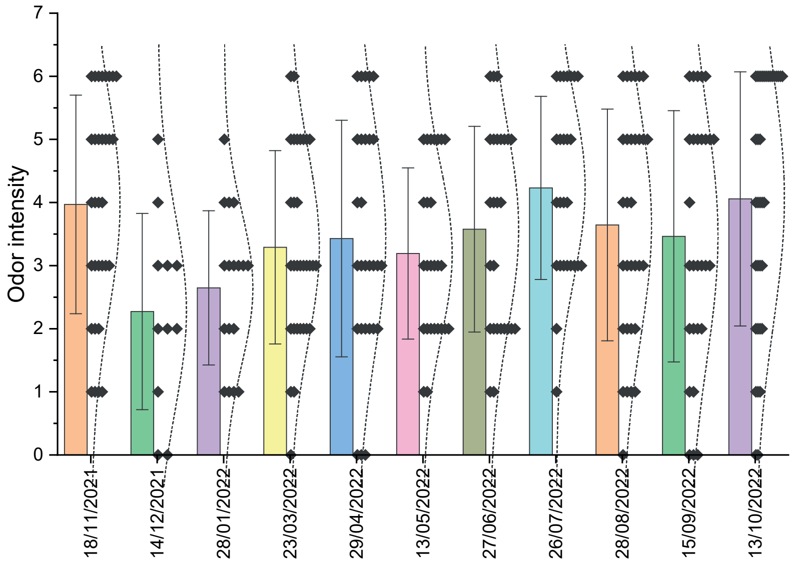

Figure 3. Average odour intensity in a given measuring month ± 1 standard deviation with plotted measured intensity and distribution line

Since monthly data are presented in Figures 2 and 3, the average values of the measured parameters for individual measurement points based on the entire measurement period (11-months) are shown in Figure 4. Figure 4A shows average odour concentrations for the whole measured period, while Figure 4B shows average odour intensity (for detailed information about points location and description see Chapter 2.2).

The highest average odour concentrations can be found around the biological processing area at the Facility (aerobic stabilization area, green waste storage, bioreactors, anaerobic processing technological building). The average c_{od} ranges from 35.02 ou/m^3 up to 78.49 ou/m^3. A similar situation is in the case of average intensity values. For the biological processing area, the average i_{od} is in the range of 4.3 up to 6.0. A total of 16 measuring points are scattered around that area.

Figure 4. Average odour concentration (A) and average odour intensity (B) for each measuring point located at Facility, based on a 11-month measuring period

In addition, the point located at the leachate tank for biological processes is characterized by average c_{od} and i_{od} of 24.33 ou/m^3 and 4.0 respectively. Outside the biological part of the Facility, only one point is characterized by such a high odour concentration and intensity located in the waste reception hall (c_{od} – 40.62 ou/m^3, i_{od} – 5.3). The rest of the measuring points are characterized by average c_{od} below 35 ou/m^3 and i_{od} below 4.0. The second highest average odour concentrations can be found around the landfill area and inside RDF preparation and storage building, two points located directly at landfill site valued at 33.16 ou/m^3 (i_{od} 4.0) and 27.32 ou/m^3 (i_{od} 3.7) respectively and the RDF building valued at 19.12 ou/m^3 (i_{od} 3.6.). The landfill entrance is valued at 16.82 ou/m^3 (i_{od} 3.0). Average odour concentration at bulky waste processing and storage area is valued at 12.5 ou/m^3 (i_{od} 2.7). The rest of the measuring points are characterized by much lower average odour concentrations (below 10 ou/m^3) and odour intensity (below 3.0). Sorting hall ranges from 3.87 ou/m^3 up to 9.17 ou/m^3 for average c_{od} and from 1.0 up to 3.0 for average i_{od}. Points located around landfill leachate tanks range from 6.57 ou/m^3 (i_{od} 2.2) up to 7.58 ou/m^3 (i_{od} 2.4). Selective waste storage is valued at 6.52 ou/m^3 (i_{od} 2.2). Biofilter for aerobic processes is valued at 6.44 ou/m^3 (i_{od} 2.2), while the biofilter for aerobic processes at 9.17 ou/m^3 (i_{od} 2.4). Points located in the technical area, administrative building, and the Facility corner are valued at 4.69 ou/m^3 (i_{od} 2.09), 2.44 ou/m^3 (i_{od} 1.09), and 0.70 ou/m^3 (i_{od} 0.55) respectively.

Based on the measurement results, values of average odour concentration and odour intensity for each potential odour sources were provided in table 2.

Table 2. Average values of odour concentration and odour intensity together with standard deviation for sources in the Facility

Odour source	Average odour concentration	Standard deviation	Average odour intensity	Standard deviation
	ou/m^3	ou/m^3	-	-
Bioreactors	76.43	8.49	6.00	0.00
Anaerobic processes technical building	57.49	18.07	5.30	0.48
Aerobic stabilisation area	56.07	22.34	5.18	0.80
Green waste storage area	51.78	25.06	4.95	1.05
Waste reception	40.62	16.65	4.90	0.74
Landfill	25.77	16.71	3.57	0.97
Leachate tank for biological processes	24.33	20.41	4.00	0.89
RDF preparation and storage	19.12	21.14	3.60	0.97
Bulky waste processing area	12.50	5.54	2.70	0.82
Biofilter (aerobic processes)	9.17	5.31	2.40	0.52
Landfill leachate tanks	7.08	2.78	2.30	0.75
Waste sorting	7.06	8.51	2.14	1.17
Selective waste storage area	6.52	6.66	2.20	1.48
Biofilter (anaerobic processes)	6.44	3.26	2.00	0.67

The obtained results indicate that the values of odour concentration and odour intensity are strongly correlated with the location of measuring points and the proximity of potential odour-generating sources. The highest odour concentrations and odour intensities can be found in the biological part of the Facility, especially inside bioreactors, anaerobic processes technical building, around waste stabilization, green waste storage area or the waste reception hall. Much lower values can be observed in the mechanical part of the Facility. Mid-range of average c_{od} and i_{od} values was ascertained at the landfill and near the leachate tank for biological processes and RDF preparation and storage building. The lowest range of measured values has been recorded at the mechanical part of the Facility (sorting hall), around landfill leachate tanks, selective waste storage area and around biofilters. A big difference between c_{od} and i_{od} is between biofilters and the source of the process air that goes into them. For example, biofilter for aerobic processes gather the air from inside of bioreactors, which were characterized by the highest values of c_{od} and i_{od}, and the biofilter itself is characterized by one of the lowest, with a similar pattern observed for the biofilter for anaerobic processes. Those results point to a potential use of field olfactometric measurements in the assessment of working conditions of biofilters by measuring the odour concentrations at the odour source and at the inlet of biofilters.

As indicated by the results of measurements of odour concentrations and odour intensity at the Facility, the monthly averages, point averages from the entire measurement period and averages for specific sources show a high degree of correlation between odour concentration and odour intensity. To determine the degree of correlation between these parameters, statistical analyses were conducted in chapters 3.2 and 3.3.

3.2. Odour concentration-odour intensity relationship analysis

To determine the odour concentration-odour intensity relationship, the odour data was categorized based on odour concentration and intensity scale. To each odour concentration (7 steps, from 0 ou/m^3 up to 78.49 ou/m^3) an odour intensity value was assigned (7 point scale). The theoretical scatterplot is shown in Figure 5 (on the left). The data categorization is as follows: odour concentration: 0 ou/m^3 – intensity scale: 0; 3.87 ou/m^3 – 1; 6.32 ou/m^3 – 2; 11.31 ou/m^3 – 3; 22.27 ou/m^3 – 4; 43.49 ou/m^3 – 5; 78.49 ou/m^3 – 6. The plotted theoretical scatterplot indicates the existence of a logarithmic relationship between odour concentration and intensity. This was an expected outcome as the intervals between odour concentrations measured by the means of field olfactometry are not equal and as the concentration increases, the range between successive concentrations increases, while the intensity scale remains linear. The experimental scatterplot was derived from data compiled during the measuring campaign (Fig. 5 (on the right)).

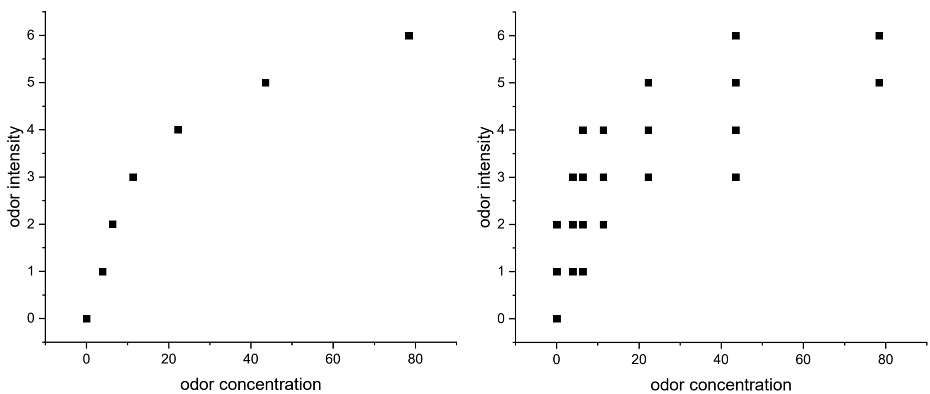

Figure 5. Odour concentration and intensity scatterplots: theoretical (on the left) and experimental (on the right)

One particular phenomenon can be observed by plotting the measured odour concentrations and odour intensity. The obtained results indicate that for the given odour concentration, the odour intensity values assume different values. Data categorization of measured values is not as straightforward as theoretical data binding. The frequency of occurrence of a given measured odour intensity relative to a given measured odour concentration is provided in Table 3.

Table 3. The frequency of occurrence of a given measured odour intensity relative to a given measured odour concentration

c_{od}	N count	%	Intensity						
			0	1	2	3	4	5	6
0	22	7.56	**4.12**	2.75	0.69	0	0	0	0
3.87	30	10.31	0	**5.50**	4.47	0.34	0	0	0
6.32	51	17.53	0	0.34	**10.31**	6.19	0.69	0	0
11.31	43	14.78	0	0	2.06	**10.31**	2.41	0	0
22.27	33	11.34	0	0	0	4.12	**5.50**	1.72	0
43.49	57	19.59	0	0	0	0.69	2.75	**15.12**	1.03
78.49	55	18.90	0	0	0	0	0	2.75	**16.15**
Sum	291	100	4.12	8.59	17.53	21.65	11.34	19.59	17.18
			%						

Overall, 291 pairs of c_{od}-intensity were used for this particular study. An analysis of the frequency of occurrence of a given odour concentration has shown that in 57 measuring points throughout the whole measuring period the odour concentration was 43.49 ou/m^3, and it was the most frequently measured value (19.59 % of all values). The second one was 78.93 ou/m^3 (18.90 %), the third one - 6.32 ou/m^3 (17.53 %), the fourth one - 11.31 ou/m^3 (14.78%), the fifth one-22.27 ou/m^3, the sixth - 3.87 ou/m^3, and the seventh, the lowest, was 0 ou/m^3, which was measured in 7.56 % of all cases. As can be observed for c_{od} 0 ou/m^3 intensity values range from 0 to 2, for 3.87 ou/m^3 from 1 up to 3, for 6.32 ou/m^3 from 1 up to 4, for 11.31 ou/m^3 from 2 up to 4, for 22.27 ou/m^3 from 3 up to 5, for 43.49 ou/m^3 from 3 up to 6, and for 78.49 ou/m^3 from 5 up to 6. However, when considering the percentage of occurrence of a given intensity value in a given odour concentration, the "right" intensity value, following theoretical assumptions of data categorization, is the most common one. For example, for the c_{od} 0 ou/m^3 the most frequently occurring value (by percentage) of intensity is 0. The same situation can be observed for the rest of the odour concentrations.

To assess the statistical relationship between odour concentration and odour intensity statistical tests were performed. Figures 2 and 3, in addition to the average concentration and intensity, also show the distribution line for the measured data.

An analysis of the graphical distributions indicates that some of them are not normally distributed, which may affect the selection of the correlation method. Therefore, the Shapiro-Wilk test was carried out to assess the distribution of data. The hypothesis for the Shapiro-Wilk tests is as follows:

- H_0: data is normally distributed if the p-value is higher than 0.05
- H_1: data is not normally distributed if the p-value is lower than 0.05

The results of the Shapiro-Wilk test show that in the case of odour concentration, the data are not normally distributed for every measuring day (the p-value is less than 0.05 in every case, and the H_0 is rejected). When it comes to odour intensity, the p-value is higher than 0.05 on the given measuring days: 14/12/2021, 28/01/2022, and 23/03/2023, which means that the data are normally distributed. However, for the rest of the measurement days, the p-value was less than 0.05 and the data are not normally distributed. When performing the Shapiro-Wilk test for the whole data set, the hypothesis for data normality is not confirmed. Consequently, the Spearman's correlation coefficient was chosen to assess the c_{od}-i_{od} relationship. The Spearman's r_s for monthly relationship evaluation is provided in Table 4.

Table 4. Monthly values of r_s for c_{od}-i_{od} correlation

	Measurement date										
	18/11/2021	14/12/2021	28/01/2022	23/03/2022	29/04/2022	13/05/2022	27/06/2022	26/07/2022	28/08/2022	15/09/2022	13/10/2022
r_s	0.93	0.87	0.88	0.90	0.97	0.89	0.94	0.97	0.99	0.99	0.99

A high degree of monotonic correlation can be observed only for two measuring days (14/12/2021, and 28/01/2022) r_s is lower than 0.90. In addition to the whole data set (291 pairs of c_{od} and i_{od}) r_s valued at 0.95 and shows a high degree of relationship between measured odour data.

3.3. Application of the Weber-Fechner Law

The Spearman correlation coefficient assessed the monotonic, not necessarily linear relationship. To assess the linear correlation of data, the Weber-Fechner law (eq. 1) was applied and the linear correlation according to the aforementioned law is presented in Figure 6.

The linear function derived from the data can be described as (eq. 2):

$$I = (3.18 \pm 0.07) \cdot \log(c_{od}) - (0.30 \pm 0.10) \quad (2)$$

where:

I – odour intensity,
c_{od} – odour concentration (ou/m^3),
(3.18±0.07) – Weber-Fechner constant (slope of regression line),
(0.30±0.10) – Weber-Fechner constant (intercept).

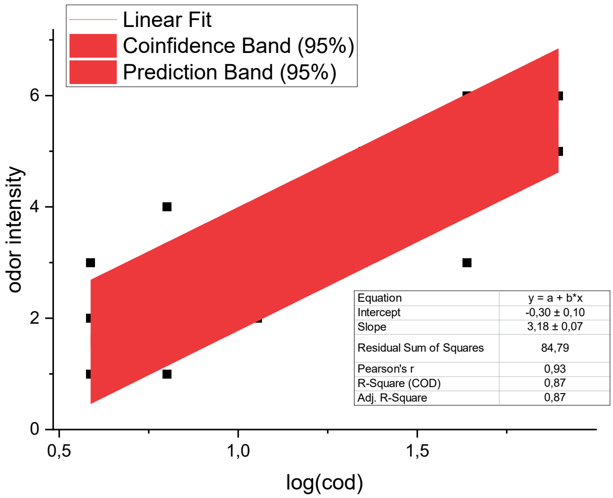

Figure 6. Application of Weber-Fechner law – linear correlation of log(c_{od}) and odour intensity based on 269 pairs of odour concentration and intensity measurements, pairs where cod valued at 0 ou/m^3 were removed

The linear relationship, obtained by applying the Weber-Fechner law, is characterized by a high coefficient of determination R^2 0.8711. Pearson's r is 0.93, which is similar to Spearman's r_s (0.95). Both coefficients confirm the high degree of correlation between odour concentration and odour intensity.

By converting the equation of the Weber-Fechner law (eq. 1, eq. 2) to the form of (eq. 3) it is possible to determine the odour concentration based on the measured odour intensity value.

$$c_{od} = 10^{\left(\frac{I-b}{a}\right)} \quad (3)$$

where:

c_{od} –odour concentration (ou/m^3),
I –odour intensity,
a – Weber-Fechner constant (slope of regression line (3.18±0.07)),
b – Weber-Fechner constant (intercept (0.30±0.10))

An assessment of the ability to predict odour concentrations using the Weber-Fechner law derived from measurements carried out on the Facility based on intensity is shown in Table 5.

When comparing odour concentrations obtained with the use of Weber-Fechner law to reference values of odour concentrations that can be determined with the field olfactometry method, it can be seen that predicted odour concentrations differ from reference values. The biggest difference can be observed for both ends of the odour concentration range, i.e. when predicting c_{od} for intensity 1 the predicted c_{od} is equal to 2.55 ou/m^3, which is 34.0% lower than the reference value

Table 5. Assessment of Weber-Fechner law in the prediction of odour concentrations based on intensity

-	Predicted odour concentration	95% Lower Confidence Interval	95% Upper confidence Interval	Predicted odour concentration	95% Lower Confidence Interval	95% Upper confidence Interval	Ref. value
Intensity	ou/m^3			% difference			ou/m^3
0	1.24	1.08	1.42	-	-	-	0
1	2.55	2.23	2.93	-34.00	-42.40	-24.30	3.87
2	5.27	2.35	11.80	-16.70	-62.80	+86.70	6.32
3	10.86	4.86	24.27	-4.00	-57.10	+114.60	11.31
4	22.38	10.02	50.02	+0.50	-55.00	+124.60	22.27
5	46.14	20.63	103.21	+6.10	-52.60	+137.30	43.49
6	95.11	82.99	109.01	+21.20	+5.70	+38.90	78.49

(the value determined by field olfactometry method and following proposed data categorization). For intensity 6, the c_{od} is 21.2 % higher than the reference value. The most accurate results can be observed in the central concentration range, i.e. from 11.31 ou/m^3 to 43.49 ou/m^3.

As with the use of (eq. 3) it is impossible to obtain precise odour concentration results, the behaviour of the Weber-Fechner law of individual measurement points was additionally verified. For each measurement point, the average concentration and average intensity were used (see. Fig 4. For details). On this basis, the linear correlation equation was established. This approach does not eliminate points with an odour concentration of 0 ou/m^3 as the data are averaged. The regression line for this approach is shown in Figure 7.

The linear function derived from the averaged data can be described as (eq. 4):

$$I = (3.14 \pm 0.13) \cdot \log(c_{od}) - (0.30 \pm 0.18) \tag{4}$$

where:
I – odour intensity,
c_{od} – odour concentration (ou/m^3),
(3.14±0.13) – Weber-Fechner constant (slope of regression line),
(0.30±0.18) – Weber-Fechner constant (intercept)

The determination coefficient R^2 is higher than in the case of (eq. 2) and equals to 0.95. The same can be observed for Pearson's r coefficient. It is higher and amounts to 0.97. By adopting (eq. 3) to new values of the regression line (eq. 4) the assessment of the ability to predict odour concentration was performed and is shown in Table 6.

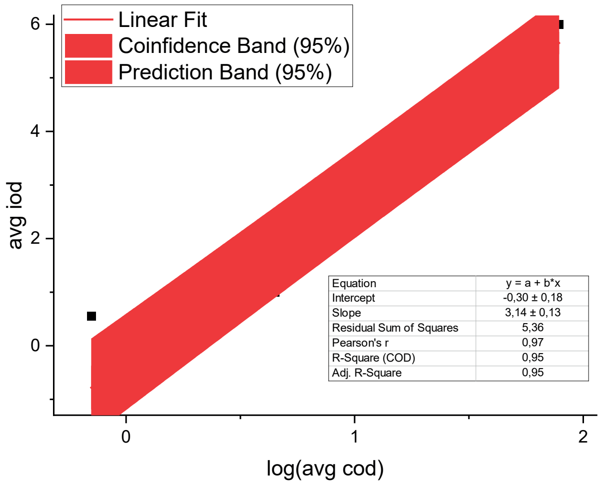

Figure 7. Application of Weber-Fechner law – linear correlation of log(average c_{od}) and average odour intensity. For each of the 35 measurement points, average concentration and intensity values were calculated for the 11-month measurement period

Table 6. Assessment of the Weber-Fechner law in the prediction of odour concentrations based on the intensity for the second approach

-	Predicted odour concentration	95% Lower Confidence Interval	95% Upper confidence Interval	Predicted odour concentration	95% Lower Confidence Interval	95% Upper confidence Interval	Ref. value
Intensity	ou/m³			% difference			ou/m³
0	1.25	0.65	2.40	-	-	-	0
1	2.60	1.38	4.89	-32.90	-64.40	+26.40	3.87
2	5.40	2.91	10.04	-14.50	-54.00	+58.90	6.32
3	11.25	6.1	20.74	-0.50	-46.00	+83.30	11.31
4	23.42	12.73	43.09	-5.10	-42.90	+93.50	22.27
5	48.74	26.37	90.08	12.10	-39.40	+107.10	43.49
6	101.45	78.68	130.79	29.20	+0.20	+66.60	78.49

When comparing the predicted values based on the Weber-Fechner law, it can be concluded that both approaches result in some underestimation or overestimation of the data. Both approaches seem to better handle the central range of odour concentrations (from 11.31 ou/m³ up to 43.49 ou/m³), while values at both ends of the odour concentrations range seem to be drifting away from the reference values.

4. Discussion

Only a few of the recently available papers follow the topic of odour concentration and intensity measurements at waste management facilities, therefore, it is difficult to compare the obtained results. For example, authors (Wiśniewska, Kulig and Lelicińska-Serafin, 2019, 2020a) carried out a series of measurements at different biogas plants processing municipal waste located in Poland regarding odour concentrations measured by field olfactometry and odour intensity. In both works, the authors stated that the highest odour concentrations are related to the place of measurements, i.e. the source of odours at which the measurement was carried out. A similar situation occurs in this study. As indicated by the results obtained in Chapter 3.1, higher concentrations of odours are present in the biological part of the Facility, while lower concentrations are found in areas where organic matter is present in small quantities or where it is present for a relatively short period of time (such as the waste sorting hall). Authors of different literature studies (Barczak and Kulig, 2016; Kulig and Szyłak-Szydłowski, 2019; Wiśniewska, Kulig and Lelicińska-Serafin, 2019, 2020a; Wojnarowska et al., 2020; Dobrzyniewski, Szulczyński and Gębicki, 2022; Kulig, Szyłak-Szydłowski and Wiśniewska, 2022) used a field olfactometry method to assess odorous air quality and as a tool for odour monitoring. It is widely confirmed that field olfactometric measurements can be used for such tasks. From the point of view of waste management facilities field olfactometry should be considered one of the primary tools to use when handling odour problems and the use of such a tool such be incorporated into odour management plans as indicated in Best Available Techniques for waste management (Pawnuk, Sówka and Naddeo, 2023). Particular attention should be paid to the low degree of technical requirements to carry out a correct measurement with the use of field olfactometry. Unlike the standardized method of dynamic olfactometry (Polish Committee for Standardization, 2007), it does not require complicated measuring equipment and a laboratory, it is easy to perform, low-cost and does not require complicated training (Brattoli et al., 2011; Fisher et al., 2018; Kitson et al., 2019). Usually, waste management authorities use external laboratories to carry out odour measurements. However, the field olfactometric measurements could be performed even by employees, as the manufacturer provides an Odour Sensitivity Test Kit which can be used to assess the olfactory ability of, for example, employees (St. Croix Sensory, 2023b).

When comparing odour concentrations and odour intensity a similar pattern can be observed, i.e. the highest odour intensities can be found at the biological part of the Facility, while to lowest occurs near sources at which organic waste is processed in a limited amount or over a short time. A high degree of correlation can be observed, the highest values of c_{od} are accompanied by the highest values of odour intensities. The results of the correlation analysis between odour concentration and odour intensity indicate the existence of a high degree of correlation between these two parameters. By applying the Weber-Fechner law the values of the R^2

coefficients for the presented approaches were 0.87 and 0.95, respectively. Pearson's coefficients were 0.93 and 0.97, respectively, while the determined Spearman coefficient was 0.95 for the entire dataset. No recent available literature provides such a complex approach for the establishing of the possible relationship between these two parameters including multipoint measurements and long-term studies. The authors of (Wiśniewska, Kulig and Lelicińska-Serafin, 2019, 2020a) provide a series of measurements of odour concentrations and intensity at 5 biogas plants processing municipal waste. They ascertained a high correspondence between these two parameters by directly comparing the results of measurements. They also found a certain correspondence between measured values and the location of measurements. However, they did not include any statistical analysis nor they did provide any correlation coefficient. As a high degree of correlation can be observed, it could be concluded that both parameters could be used interchangeably, i.e. instead of odour concentration odour intensity could be used. This offers another potential use of such a parameter for odour assessment by the employees of waste management facilities.

Furthermore, when applying the determined Weber-Fechner law for establishing the odour concentration based on odour intensity, a high data spread can be observed. The obtained concentrations differ from reference values. However, when using a rich data set of measured odour concentrations and odour intensities at selected points, the determination of Weber-Fechner constants could be used as a decision-supporting tool despite its limitations, i.e. inability to accurately calculate concentrations at either end of the measuring range. Establishing odour concentrations based on measured intensity values can be a useful tool when limited field olfactometric measurements are available.

5. Summary

The following conclusions can be derived based on the research:

1. The measured values of odour concentrations and odour intensity indicate the existence of a large dependence between the measured values and the place of measurement. The highest odour concentrations and intensity values occur in the biological part of the Facility, while the lowest ones in the mechanical part and in places where organic waste is absent or present in small amounts.
2. The obtained results of the statistical analysis of measured values of odour concentrations and odour intensity values indicate the existence of a high degree of correlation between these two parameters. The relationship between the perceived psychological intensity and physical feature has been confirmed in the form of the Weber-Fechner law.
3. As a high degree of correlation between odour concentration and intensity is present, these two parameters could potentially be used interchangeably for odour assessment.

4. The application of the Weber-Fechner law and calculated coefficients resulting from linear correlation to predict concentrations based on odour intensity does not allow obtaining precise results. However, due to the situation in which regular measurements of odour concentrations cannot be made, determining the Weber-Fechner correlation for the tested facility and using it to establish the potential odour concentrations may serve as a complementary tool for assessing the odour situation on a given facility using the intensity determined by employees.

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SENSORYCZNE TECHNIKI POMIARU ODORÓW – ZALEŻNOŚĆ MIĘDZY STĘŻENIEM ODORÓW A ICH INTENSYWNOŚCIĄ DLA WYBRANEGO OBIEKTU GOSPODARKI ODPADAMI

Abstrakt

Analizy sensoryczne stanowią jedną z najczęściej stosowanych metod badań odorów, pozwalającą na określenie najważniejszych ich cech, takich jak stężenie i intensywność. W badaniach trwających 11 miesięcy w 35 wyselekcjonowanych punktach pomiarowych prowadzono pomiary stężenia i intensywności odorów na wybranym zakładzie mechaniczno-biologicznego przetwarzania odpadów komunalnych. Celem było zbadanie związku między tymi dwoma parametrami, wykorzystując m.in. prawo Webera-Fechnera. Wyniki wykazały wysoki stopień korelacji między stężeniem a intensywnością zapachu, tj. współczynnik R2 dla dwóch różnych analizowanych podejść wyniósł odpowiednio 0.87 i 0.95, podczas gdy współczynnik korelacji Pearsona wyniósł odpowiednio 0.93 i 0.97. To sugeruje, że zarówno stężenie, jak i intensywność odorów mogą być użytecznymi parametrami do opisu sytuacji zapachowej w badanym obiekcie. Niemniej jednak zastosowanie prawa Webera-Fechnera do przewidywania stężeń odorów na podstawie pomiarów intensywności daje nieprecyzyjne wyniki. Pomimo tego potencjalne zastosowanie takiego podejścia może być korzystne w sytuacjach ograniczonych możliwości pomiarów stężeń odorów, gdyż określenie intensywności odorów może być, po odpowiednim treningu, wykonane nawet przez pracowników zakładu.

Słowa kluczowe: olfaktometria terenowa, stężenie odorów, intensywność odorów, gospodarka odpadami, prawo Webera-Fechnera