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DOCTORAL THESIS

Assessment of different odor monitoring strategies in waste management

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CONTENTS

Ilość wytwarzanych odpadów komunalnych, w tym ilość zebranych odpadów w formie odpadów zmieszanych zawierających wysoki udział frakcji organicznej jest jednym z głównym powodów powstających uciążliwości zapachowych w szeroko rozumianej gospodarce odpadami. Gospodarka odpadami sama w sobie jest procesem ciągłym i wieloetapowym, na których to może dochodzić do uwalniania znaczących ilości substancji zapachowo czynnych. Wśród etapów gospodarki odpadami jakie mogą powodować uciążliwości zapachowe wyróżniamy między innymi ich zbiórkę, transport, przeładunek w stacjach przeładunkowych bądź ich zagospodarowanie w mechaniczno-biologicznych zakładach przetwarzania odpadów, w zakładach termicznego przekształcania odpadów bądź na składowiskach odpadów. Zakłady mechaniczno-biologicznego przetwarzania odpadów są szczególnym miejscem gdzie następuje wysoka intensyfikacja różnych procesów mogących emitować odory do środowiska. Monitoring źródeł emisji odorów jest procesem trudnym i czasochłonnym, jednak niezwykle koniecznym co wskazują m.in. *Najlepsze dostępne techniki w odniesieniu do przetwarzania odpadów*. Mówią one o konieczności wdrażania planów zarządzania odorami, które to obejmują m.in. programy identyfikacji źródeł zapachów i mające na celu określenie ich zmienności. Dobór odpowiedniej metody jest zadaniem kluczowym.

W pracy przedstawiono charakterystykę 5 wybranych strategii monitoringu odorów w kontekście ich aplikacyjności w planach zarządzania odorami na terenie 3 wybranych obiektów gospodarki komunalnej. Celem pracy było, m.in.: określenie przydatności wybranych strategii monitoringu odorów w skali krótko i długo terminowej; określenie zmienności emisji z wybranych procesów i instalacji zlokalizowanych na terenie badanych obiektów; przeprowadzenie analizy wpływu podstawowych parametrów odpadów i warunków meteorologicznych na wybrane źródła emisji odorów; określenie wpływu zmienności emisji z wybranych procesów na zasięg oddziaływania zapachowego wybranego obiektu gospodarki komunalnej.

W celu realizacji badań określono 5 strategii monitoringu odorów, obejmujących m.in. pomiary z wykorzystaniem olfaktometrii terenowej i olfaktometrii dynamicznej, pomiary parametryczne z wykorzystaniem oceny intensywności odorów, pomiary lotnych związków organicznych oraz dwie metody obliczeniowe, tj. metodę ważonych odwrotnych odległości i system CALMET/CALPUFF. Badania przeprowadzono w latach 2021/2022 na terenie 3 wybranych zakładów mechaniczno-biologicznego przetwarzania odpadów.

Na podstawie przeprowadzonych badań wykazano przydatność każdej z zastosowanych technik pomiarowych i obliczeniowych w monitoringu odorów w określonym zakresie. Dzięki zastosowaniu pomiarów z wykorzystaniem olfaktometrii terenowej, pomiarów intensywności zapachowej oraz pomiarów lotnych związków organicznych możliwe jest oszacowanie zmienności emisji odorów w badanych źródłach oraz wskazanie najbardziej problematycznych obszarów pod względem emisji odorów i substancji odorotwórczych na terenie wybranych obiektów. Wykorzystana metoda interpolacji danych przestrzennych pozwala na uzyskanie poprawnych, jednak obarczonych pewnym błędem statystycznym rozkładów stężeń, które to również mogą posłużyć do wyznaczania obszarów najbardziej odorogennych i opisu zmienności przestrzennej odorów. Zastosowany system CALMET/CALPUFF w połączeniu z odpowiednio dobranym wskaźnikami emisji i zdefiniowaną zmiennością, pozwolił na uzyskanie potencjalnego zasięgu oddziaływania badanego obiektu. Przeprowadzone analizy oraz obliczenia wskazują na znaczny wpływ zmienności emisji odorów na określenie zasięgu ich rozprzestrzeniania i uzyskane rezultaty z zastosowaniem modeli dyspersji. Dzięki zastosowanym metodom badawczym można wnioskować na temat zmienności emisji odorów i metody te mogą być integralną częścią planów zarządzania odorami zgodnie z *Najlepszymi dostępnymi technikami*.

ABSTRACT

The amount of municipal waste generated, including the amount of collected waste in the form of mixed waste containing a high proportion of organic fraction, is one of the main reasons for the occurrence of olfactory nuisances in the broadly understood waste management. Waste management itself is a continuous and multi-stage process, during which significant amounts of odorous substances can be released. Among the stages of waste management that may cause olfactory nuisances, we can distinguish, among others, their collection, transport, transshipment at transfer stations, or processing in mechanical-biological waste treatment plants, in thermal waste treatment plants or at waste landfills. Mechanical-biological waste treatment plants are a particular place where there is a high intensification of various processes that can emit odors into the environment. Monitoring of odor emission sources is a difficult and time-consuming process, but extremely necessary as indicated by, among others, the *Best Available Techniques conclusions for waste treatment*. They indicates the necessity to implement odor management plans, which include programs for identifying odor sources and aimed at determining their variability. The selection of an appropriate method is a key task.

In the study, characteristics of 5 selected odor monitoring strategies in the context of their applicability in odor management plans. The aim of the study was, among others: to determine the usefulness of selected odor monitoring strategies for short- and long-term purposes; to determine the variability of emissions from selected processes and installations located on the premises of the studied facilities; to conduct an analysis of the influence of basic waste parameters and meteorological conditions on selected odor emission sources; to determine influence of the variability of odor emissions from selected processes on the range of odor impact of the selected waste management plant.

To carry out the research, 5 odor monitoring strategies were selected, including measurements using field olfactometry and dynamic olfactometry, parametric measurements using odor intensity, measurements of volatile organic compounds, and two computational methods, i.e. the inverse distance weighted interpolation method, and the CALMET/CALPUFF system. A series of measurements were conducted in 2021/2022 at 3 selected mechanical-biological municipal waste treatment plants.

Based on the conducted research, the usefulness of each of the applied measurement and computational techniques in odor monitoring was assessed. By using measurements with field olfactometry, odor intensity measurements, and measurements of volatile organic compounds,

it is possible to estimate the variability of odor emissions in the studied sources and to indicate the most problematic areas in terms of odor emissions and odor-producing substances within the selected facilities. The utilized method of spatial data interpolation allows for obtaining correct, albeit with some statistical error, concentration distributions, which can also be used to determine the most odorogenic areas and describe the spatial variability of odors. The applied CALMET/CALPUFF system, combined with properly selected emission factors and defined odor emission variability, allowed for obtaining the potential range of impact of the studied facility. The results indicate a significant influence of the detail of the considered variability of odor emissions on their dispersion with the use of CALMET/CALPUFF system. The applied research methods can be used to drawn about the variability of odor emissions, these methods can be an integral part of odor management plans in accordance with Best Available Techniques.

1 INTRODUCTION

1.1 THE BACKGROUND OF THE RESEARCH PROBLEM

Odors are one of the many air pollutants that can directly affect the environment and the lives of the inhabitants of today's societies. According to various literature studies, over the last years, odors become one of the most important aspects that concerns many communities, not only at the local scale, but also on a much larger scale including state agencies, as well as offices such as the European Union [1–7]. Excessive emission of odor compounds that have a direct effect on residents are associated with their complaints to authorities, making odors not only an environmental problem but also an economic and social one [7–10]. Prolonged exposure of residents to odors can lead to a situation of odor nuisance and health problems [4,6,11,12]. Nonetheless, these effects are typically regarded as not highly harmful, and tend to create more of psychical annoyance than causing severe health issues [4,13,14]. However, excessive exposure to odors may lead to symptoms such as headaches, nausea, increase in stress levels, sleeplessness, eye and nose irritation, respiratory problems [7,15].

The presence of odors in the environment is usually linked with the functioning of communities and their existence. Waste management (including solid and liquid waste), industrial activities, and agriculture and animal husbandry are considered as three main sources of odors in the environment [7,16,17]. The increase in urbanization, the growth of cities and societies mean that waste management facilities, industrial facilities or activities related to agriculture and animal husbandry are closer to residential clusters, and thus contribute to increased complaints about their activities, especially taking into account the emission of odors. Waste management facilities, as well as single processes and steps of waste management, have a considerable effect on the environment. It involves the release of different substances into the water, ground, and atmosphere [18]. Waste management itself is linked with emission of many various air pollutants into the atmosphere, including dust, bioaerosols, methane, carbon dioxide, carbon monoxide, nitrogen oxides, and volatile organic compounds, and odors [11,18,19]. It is the emission of odors that is one of the main causes of complaints regarding the operation of waste management facilities [1–3,5,7,20,21]. The issue of odor nuisance originating from the impact of broadly understood waste management is crucial environmental problem. The living habits of people, the necessity to fulfill living needs, and the existence of people in general lead to the production of substantial amount of waste in various phases of individual and societal development, especially when considering the amount of municipal waste generated. Regarding

the diverse nature of communities, considering both local and global perspectives, managing and controlling over the municipal waste generated by individual countries, cities, or particular regions becomes a complex challenge. Due to the growing trends of waste generation, both on the scale of individual countries as well as taking into account the global scale, waste management is highly topical issue [2,6,12,19]. For example, in Poland in 2021 the amount of municipal waste generated was at the level of 13,673 Gg. An increase of approximately 36% compared to 2010 can be observed in the case of municipal waste generated [22]. Waste management is inherently a multi-stage process, during which odors can be released at nearly every stage. The main reason of odor emissions from waste management is the presence of organic waste fraction in municipal waste, especially in mixed municipal waste stream [23,24]. It is the organic fractions that are the main cause of odor emissions, which are a direct result of the biological decomposition of these fractions [2,19]. During the whole mixed municipal waste management chain, organic fraction is present at almost every phase of waste management, starting from waste collection from individuals, waste transportation, waste transfer at transfer stations, and processing of waste at mechanical-biological waste treatment plants, thermal processing of waste, and waste disposal at landfills [25–32]. From the perspective of waste management facilities, mechanical-biological waste treatment plants are considered as the most important ones, due of the diversity of odor sources inside their boundaries. Modern mechanical-biological waste treatment plants carry out different processes related to processing of different waste fractions, including mixed waste. Among them, we can distinguish, for example, mechanical sorting of waste, biological processing using aerobic and anaerobic conditions, waste storage, refused-derived fuel production, management of leachates and all other activities related to waste management at the premises of mechanical-biological facilities [30,33–36]. A variety of mechanical-biological waste processing plants, various unit processes, the difference in the amount of received waste, and the difference in waste composition, making the odor problem much more complicated and difficult to handle. Statistical data [22,37] shows that 144 mechanical-biological waste treatment plants were operating in Poland in 2021, and every single one could be considered as a possible source of odors. However, in order to confirm odor emissions from such objects, it is necessary to support this with a reliable assessment based on various measurement and calculation tools.

The variety of measurement techniques available to describe odors, including two main groups: analytical techniques and sensory methods [13,38,39]. The first group are focused on the qualitative and quantitative analysis of substances that causes the response of human

olfactory system when exposed to those substances, i.e. analytical techniques allows to determine which substances and in what concentration are present in the air [40,41]. Among analytical techniques, the most important are gas chromatography coupled with mass spectrometry, single gas sensors or sensors arrays in the form of electronic noses [39,42,43]. Despite the high accuracy of analytical methods, they are considered as relatively complicated and they do not allows to assess odors in the way that humans can perceive them. They gives information about specific odor substances but not about the whole sensation caused by them. Therefore, the most useful method oof odor assessment belongs to the group of sensory analyses, where human nose is treated as a measuring device. These methods allow for an assessment consistent with the perception of odors by humans [38,40,44]. Quantitative analysis of odors with the use of sensory techniques is possible by coupling the human nose with external devices. Two main methods can be used for the quantitative analysis – field olfactometry, and dynamic olfactometry, which allow the determination of odor concentration [38,39]. Using human nose alone is utilized to perform parametric measurements and allows to describe parameters such as, for example, odor character, odor intensity, and hedonic tone [38,39]. In addition to the tools mentioned above, various computational and modeling methods can be used in odor studies. The calculation results obtained with the help of such tools can be used to determine the potential impact range of waste management plants, thus allowing the identification of potential areas exposed to odor nuisance. The most commonly used are odor dispersion modellings [45,46], and some of the available literature indicates a potential use of interpolation methods in odor research [47,48].

The measurement methods indicated above allow obtaining various information on odors and odor-producing substances. They have a wide range of applications, they can be used as potential methods of identifying odor emission sources, as tools to characterize given odor sources, and as a tools to assess the extent of odor emissions. Selecting an appropriate measurement method is crucial to assess the emissions of odors and odor-generating substances from municipal waste management facilities. Legal regulations are an undoubted issue related to the problem of odors in waste management. Different approaches are adopted around the world when it comes to odor regulations, the selection of appropriate odor impact criteria for the assessment purposes, and odor prevention methods [49,50]. At the European level, conclusions of the Best Available Techniques for waste treatment, are one of the most important findings about odor prevention and measures actions aimed towards possible odor monitoring strategies [51]. Among different measures, BAT 10 directly indicates the need for periodic

monitoring of odor emissions using EN or ISO and other standards (like EN 13725 [52]) when the EN standards are not available. BAT 34 determines the emission levels for selected substances in the case of emissions to air from mechanical-biological waste treatment processes, including odor concentration, ammonia concentration, and total volatile organic compounds concentration. One particular BAT conclusion is highly interesting from the perspective of odor monitoring, namely BAT 12. This indicates the need to create odor management plans, which, according to the document itself, should include [51]:

- *a protocol containing actions and timelines;*
- *a protocol for conducting odor monitoring as set out in BAT 10;*
- *a protocol for response to identified odor incidents;*
- *an odor prevention and reduction programme to identify sources; to characterize contribution of sources; and to implement prevention and/or reduction measures.*

The programs indicated in the last sub-item, aimed at identifying odor sources and assessing their share in emissions, are a kind of gateway that allows the use of various measurement methods and strategies. Measurements using field olfactometry, determination of odor intensity, measurements using dynamic olfactometry, the use of a gas sensors - many of those could be adopted for such tasks. Therefore, a comprehensive assessment of commonly used methods for the needs of odor management plans, should be provided, especially in the terms of short and long-term monitoring.

1.2 RESEARCH OBJECTIVES AND MAIN HYPOTHESIS

The main objectives of the doctoral dissertation were:

- assessment of the suitability of selected odor monitoring strategies for short and long-term purposes;
- determining the variability of odor emissions from selected processes or installations located on the premises of a selected waste management facilities;
- conducting an analysis of the temporal and spatial variability of odor concentrations, odor intensity, and volatile organic compounds in the area of selected waste management facilities alongside with an assessment of their correlation;

- and evaluation of the influence of the variability of odor emissions from selected sources on the range of odor impact of selected waste management plant.

For research purposes, the following theses were put forward:

1) *Assessment of the impact of waste management facilities characterized by the presence of sources with variable odor emissions over time and space requires the simultaneous application of measurement and computational methods.*

2) *One of the methods that allows for characterizing sources of odor emissions is field olfactometry, whose application enables the determination of the temporal and spatial variability of odors within waste management facilities.*

3) *Analyses of the relationships between the concentration of odors obtained through field olfactometry and parametric measurements (odor intensity) and the concentrations of volatile organic compounds can play a significant role in the effective management of the odor quality of air in waste management facilities.*

4) *Emission measurements combined with modeling tools allow to estimate the range of odor impact of waste management facilities. Nevertheless, to ensure the proper quality of modeling results, a highly standardized parameterization of odor emission variability is necessary.*

5) *The degree of variability of odor emissions has a significant influence on the potential odor impact of waste management facilities.*

1.3 THE CONCEPT OF THE WORK AND ITS STRUCTURE

The work includes two main parts. The first part concerns the literature review of the issues regarding the characteristics of the waste management system on the example of Poland, the characteristics of odor emissions from waste management facilities, the literature review on the methods of odor monitoring, including description of computational methods, and the review of legal solutions related to odors. The second part of the work is the research part. This part describes the research methodology used to achieve the intended research objectives and to confirm the hypotheses. The main research part focuses on assessing the usefulness of 5 selected odor monitoring strategies at selected mechanical-biological waste treatment plants.

In order to achieve the intended objectives of the work and to prove the theses, a series of measurements was performed using various odor monitoring strategies on three selected municipal waste management facilities, belonging to the group of mechanical-biological municipal waste treatment facilities. Two groups of tools were used in the work, these were measuring tools, and computational and modeling tools. In the case of the measurement tools, the focus was on measurements using field olfactometry, odor intensity measurements and on the measurements of volatile organic compounds. In the modeling and computational part, the method of spatial interpolation of data obtained by the means of field olfactometry and modeling of the odor dispersion from a selected waste management plant were used. Due to the tools used during the research phase, 5 main odor monitoring strategies can be distinguished. Figure 1 presents selected odor monitoring strategies with the main measurement or modeling tool assigned to them.
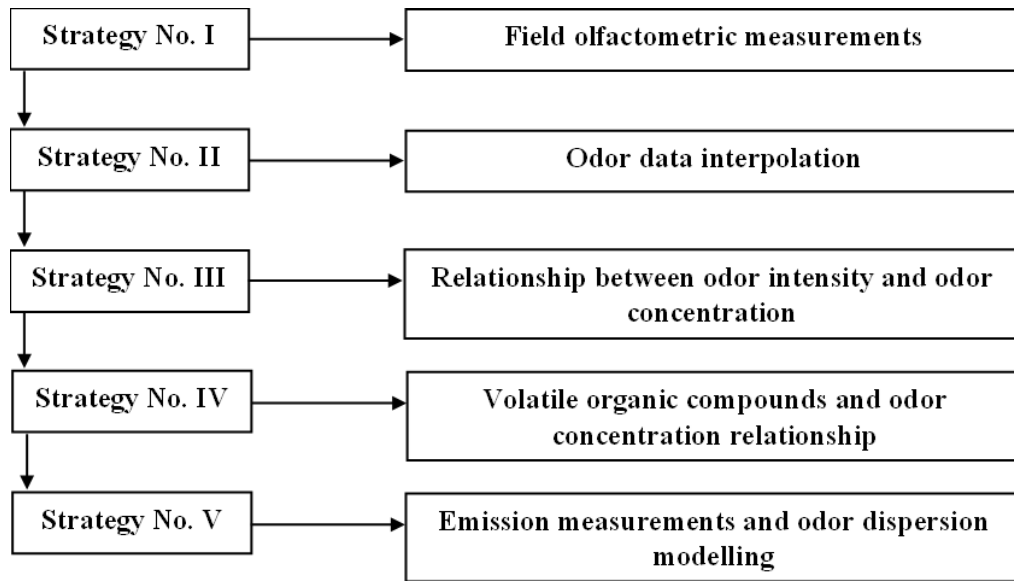
Figure 1. Selected odor monitoring strategies with the main measurement or modeling tool used in particular strategy.

Strategy No. I focus on a series of measurements using field olfactometry carried out at one of the three selected mechanical-biological waste treatment plant. The main goal of Strategy No. I was the assessment of the usefulness of field olfactometry in identifying odor emission sources and determining their variability in given sources in the context of annual measurement series. In addition, due to the measurement of meteorological conditions, an assessment of the degree of correlation between the odor concentration measured by field olfactometry and the basic meteorological parameters, such as temperature, humidity, wind speed and direction was provided. The use of field olfactometry in such studies is an extremely interesting aspect, especially considering the Best Available Techniques for waste treatment [51,53]. Odor management plans, indicated in BAT12 [51,53], should provide, among many others measures to reduce or prevent odor emissions, an odor sources identification programs. Therefore, a complex assessment for field olfactometry measurements for the implementation in such a programs, should be provided.

Strategy No. II covers the use of previous olfactometric measurements in algorithms of simple methods of spatial data interpolation on the example of the inverse distance weighted method. From the point of view of the management of municipal management plants, obtaining the correct spatial distribution of odors based on olfactometric measurements should be prioritized, when it comes to odor management. These distributions can be used similarly to the olfactometric measurements themselves to identify key odor sources and areas with the greatest

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potential of exposure to odor emissions. As field olfactometry itself, spatial data interpolation methods, could be incorporated into waste management plans as a key elements for odor management at waste management facilities [51,53]. As only few literature studies about the use of interpolation methods in odor research are available, for example [47,54,55], more emphasis should be put in those tools and assessment of usefulness in odor source identification should be provided.

Strategy No. III is about determining the relationship between odor concentration measured by field olfactometry and odor intensity. Measurements of odor intensity were performed in the same manner as for Strategy No. I and included the same measurement points at Facility #1. Literature reports indicating a high degree of correlation between odor concentration and odor intensity [56–58] which suggest the possibility of replacing olfactometric measurements with measurements of odor intensity, and thus reducing the complexity of odor monitoring. Therefore, the assessment of parametric measurement with the use of intensity measurements was provided.

Strategy No. IV concerns sensor measurements of volatile organic compounds at selected 3 waste management plants. It allows to assess the usefulness of odorant measurements using non-specific gas sensor methods in odor monitoring in comparison with odor concentrations measured by the means of field olfactometry. Some literature sources indicates the existence of high correlation between odor concentration and the concentration of specific odorants [59–61]. Therefore, the use of Strategy no. IV, could provide information on the potential use of volatile organic compounds measurements to identify the sources of the odors and odor generating-substances, and to determine their variability depending on the source.

Previous strategies have focused on monitoring of the odors within the boundaries of selected facilities. Strategy No. 5 implements emission measurements using a dynamic olfactometry to model the dispersion of odors and thus to assess the potential impact of odor emission source beyond the boundaries of facilities. As a main modelling tool – the CALMET/CALPUFF system was used. During this research step, two modeling scenarios were adopted, based on the degree of complexity of the variability of odor emissions from the modeled sources. Odor dispersion modeling is crucial for odor research at receptor points. During the implementation of Strategy No. V, a different levels of odor emission variability were considered to assess the potential impact. Main role of the Strategy No. V is to provide a

feedback about the impact of assumed variability of odor emission on the results of odor distribution modeling.

2 MUNICIPAL SOLID WASTE MANAGEMENT: A SIGNIFICANT SOURCE OF ODORS

2.1 WASTE MANAGEMENT AS MULTI-STAGE PROCESS

As mentioned in the Introduction section (*Chapter 1.1*) of this study, waste management is a continuous process that involves multiple stages. These processes include collection of a specific fraction of waste in households or containers located in the vicinity of housing estates, collection of waste by authorized entities, transport of collected waste to waste transfer stations or directly to facilities for their processing and disposal [25–32]. Figure 2 shows a simplified diagram of waste management chain including main waste management steps. Regarding odor emissions, waste management is one of the most complicated odor sources. Gathering information about specific waste management systems and gathering the information on emissions of odorous substances is one of the main tasks in mitigating and managing them. Therefore the characterization of waste management system in Poland and characterization of different steps waste management in terms of odor-generating emissions are provided.
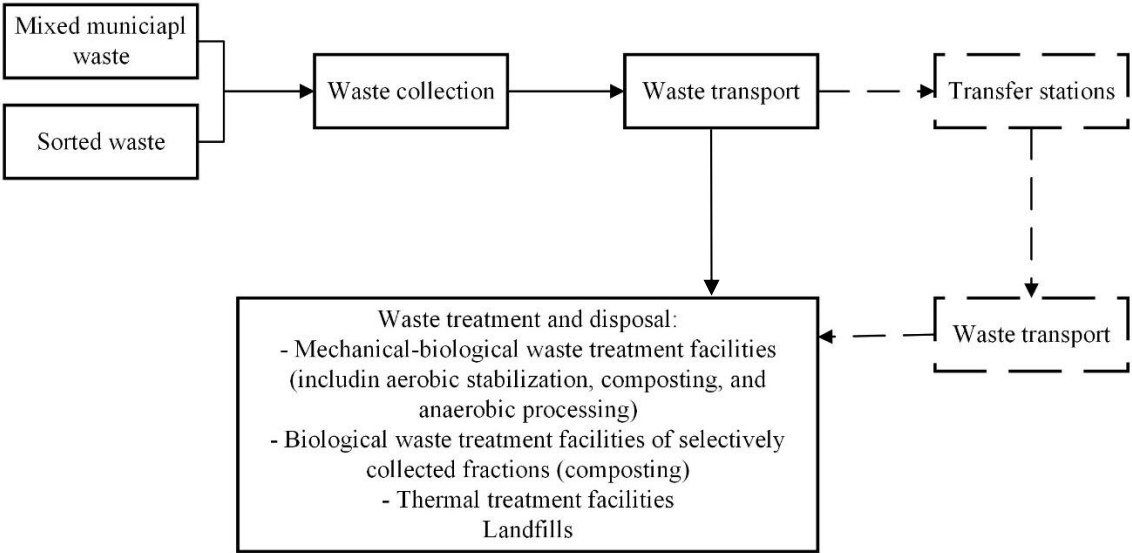
Figure 2. Simplified waste management chain, based on [37,62,63], steps related to waste transfer station are optional.

2.2 OVERVIEW OF MUNICIPAL SOLID WASTE MANAGEMENT IN POLAND

2.2.1 Waste stream in Poland over the last decade

Based on the data released by Statistics Poland in 2021 [22], an estimated total of 121,385 Gg of waste was produced. This amount account for both industrial and municipal waste, of which industrial waste accounted for approx. 88.74% of the total generated waste (107,712 Gg), and municipal waste accounted for remaining 11.26% (approx. 13,673 Gg). *Chapter 1.1* highlights that municipal waste management is a prominent source of odors. Therefore, the further analysis is exclusively centered on municipal waste. Figure 3 depicts the fluctuations in the quantities of municipal waste generated.
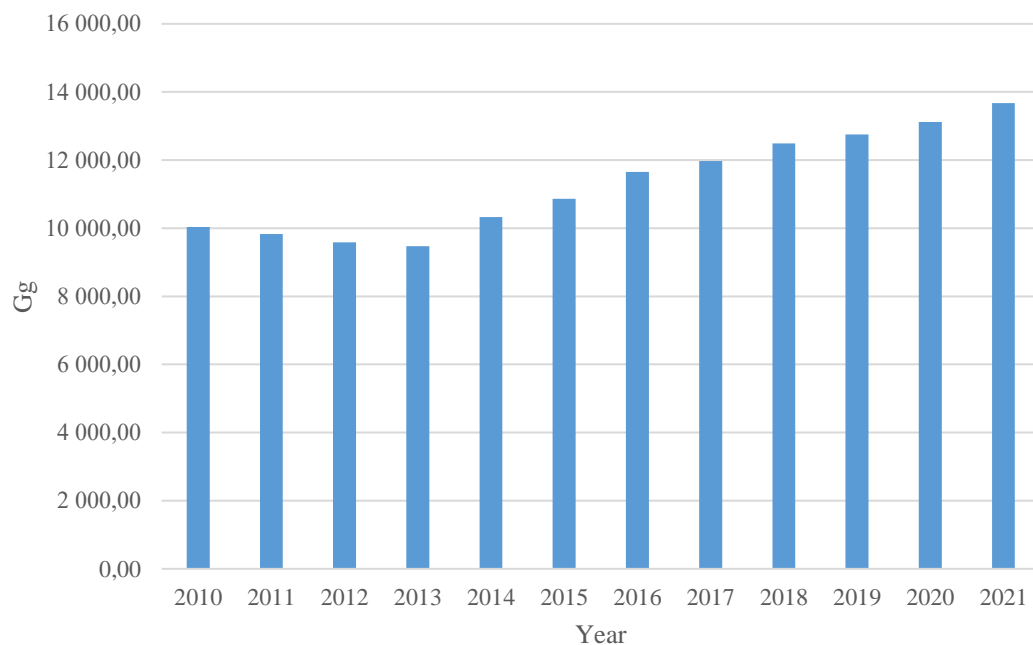
Figure 3. Mass of municipal waste (in Gg) collected in Poland over the years 2010–2021 [22].

The data presented in Figure 3 provide information about municipal waste from 2010 to 2021. In 2010, the annual volume of municipal waste generated was 10,040.11 Gg. From 2011 to 2013, there was a decrease in the amount of waste generated. The decrease compared to 2010 was approximately 2.1% in 2011, 4.6% in 2012, and 5.6% in 2013. However, since 2014, there has been a noticeable increase in the generation of municipal waste. In comparison to 2010, the amount of waste generated increased by 2.9% in 2014, 8.2% in 2015, 16.1% in 2016, 19.2% in 2017, 24.4% in 2018, 27.0% in 2019, and 30.6% in 2020. In 2021, it experienced a further

increase of 36.2% compared to 2010, reaching a total of 13,673.58 Gg. It is important to note that the provided quantitative data encompass both waste generated in households and waste generated from other sources. According to the definition of municipal waste applied in Polish legislation, the composition of waste generated from these other sources is similar to that of municipal waste (as defined in the Act of 14 December 2012 on waste [64]). The data indicate a rising tendency in municipal waste generation over recent years. Figure 4 depicts the quantity of municipal waste generated over years 2010 to 2021 by voivodships [22]. The data reveal that the overall pattern in the volume of waste generated in distinct voivodships aligns with the pattern shown in Figure 3. Between 2011 and 2013, the volume of waste generated slightly decreased exhibiting minor fluctuations. In the span of 2014 to 2021, mirroring the national scenario, there was an escalation in waste production relative to the year 2010.
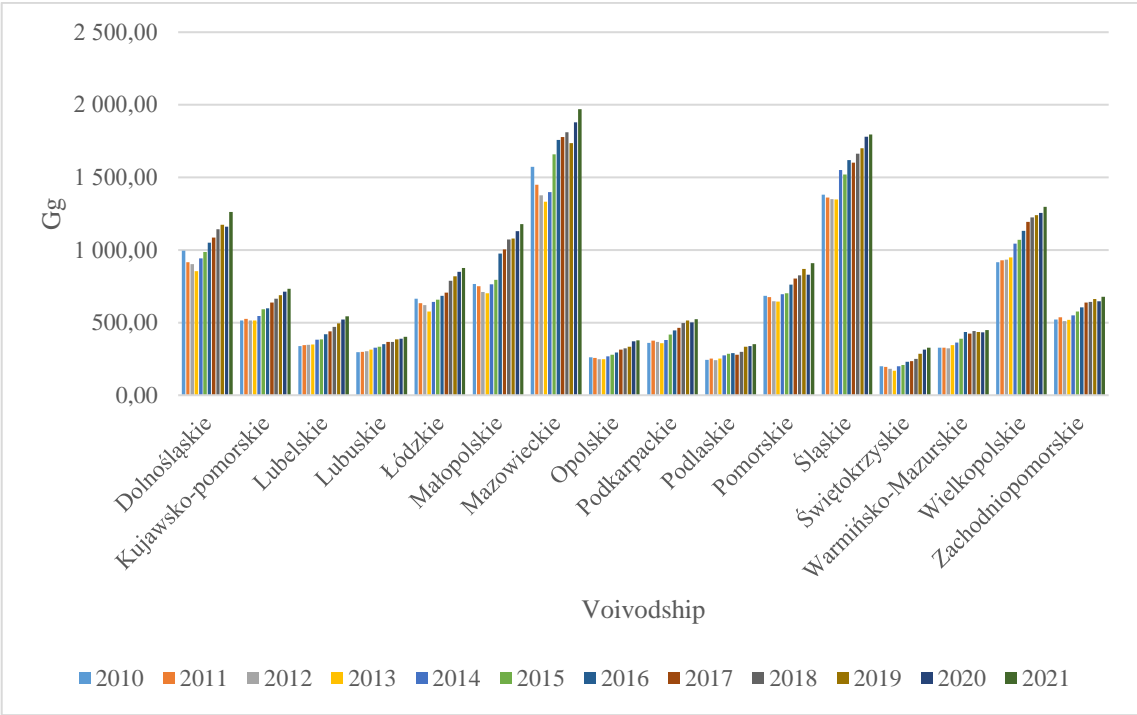
Figure 4. Mass of municipal waste (in Gg) collected in individual voivodships over the years 2010–2021 [22].

Figure 4 showcases the data which distinctly pinpoint the four principal voivodships that account for the highest amount of generated waste. These voivodships are, respectively, Mazowieckie, Śląskie, Wielkopolskie, and Dolnośląskie. In 2021, the Mazowieckie voivodship produced 1,970.63 Gg of municipal waste, followed by the Śląskie voivodship with 1,795.02 Gg, the Wielkopolskie voivodship with 1,296.60 Gg, and the Dolnośląskie voivodship with 1,261.84 Gg. In comparison with 2010, similar upward trend in municipal waste generation

can be observed. Starting from 2010 amount of generated municipal waste increased in aforementioned viovodships by 25.31% in Mazowieckie, 31.06% in Śląskie, 41.70% in Wielkopolskie, and 26.89% in Dolnośląskie. Various factors could contribute to these elevated levels of waste generation, including the population size or the residents' lifestyle within these voivodships. It is notable that Mazowieckie, Śląskie, and Wielkopolskie are the most densely populated voivodships in Poland, with Dolnośląskie ranking as the fourth. The voivodships that exhibited the lowest quantities of waste generation are: Świętokrzyskie (328.34 Gg), Podlaskie (350.73 Gg), Opolskie (378.27 Gg), and Lubuskie (403.19 Gg). These voivodships are characterized by having the smallest populations within Poland.
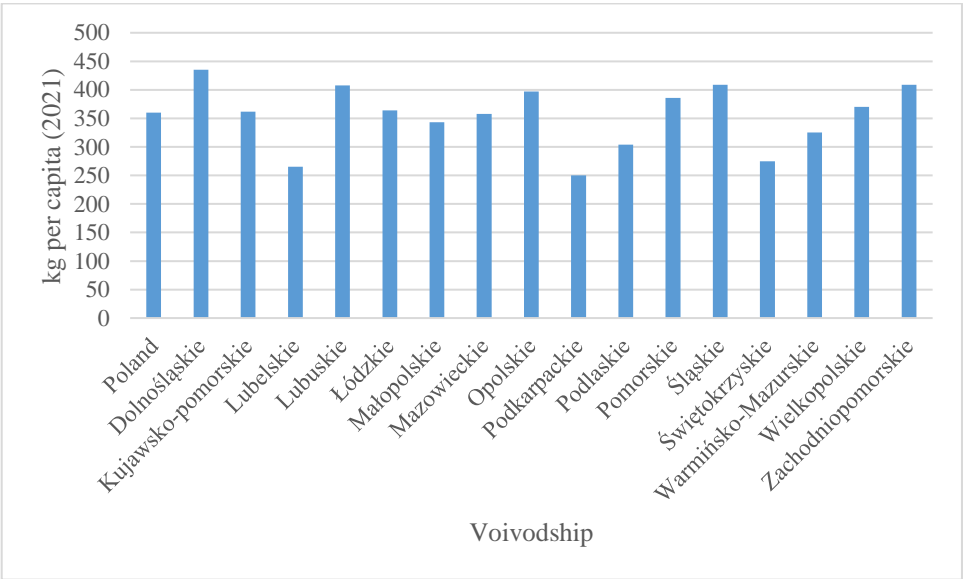
Figure 5. Mass of generated waste (kg) per capita in 2021 [22].

Following the data of Statistics Poland [22], the average quantity of municipal waste generated per person in Poland in 2021 was 360 kg. In contrast, the European Union's average valued at 530 kg [65], positioning Poland as the second-lowest waste-producing country in Europe on a per-capita basis in 2021. Figure 5 indicates that, within Poland in 2021, Dolnośląskie voivodship took the lead in per-capita waste generation with 435 kg. The western regions of Poland, specifically the voivodships of Dolnośląskie (435 kg), Śląskie and Zachodniopomorskie (both 409 kg), and Lubuskie (408 kg), are responsible for the highest per-capita waste generation. This can be attributed to a larger proportion of their populations residing in urban areas (particularly 76.6% in Śląskie and 68.4% in Dolnośląskie), a relatively higher GDP per capita in western Poland, and a distinct consumption pattern that aligns with a western lifestyle.

2.2.2 Fractional composition of waste

The most recent official information regarding waste composition in Poland, as presented in the National Waste Management Plan 2022 [66], is based on analyses conducted between 2008 and 2010. Since then, only several seasonal studies have been prepared, aimed at examining the fractional composition of municipal waste. This includes the assessment of both separately collected and mixed waste streams, which have served as the foundation for estimating the composition of municipal [67,68]. This information has been compiled and juxtaposed with the data from 2008-2010, which was utilized for the NWMP 2022 [66], and is illustrated in Figure 6.
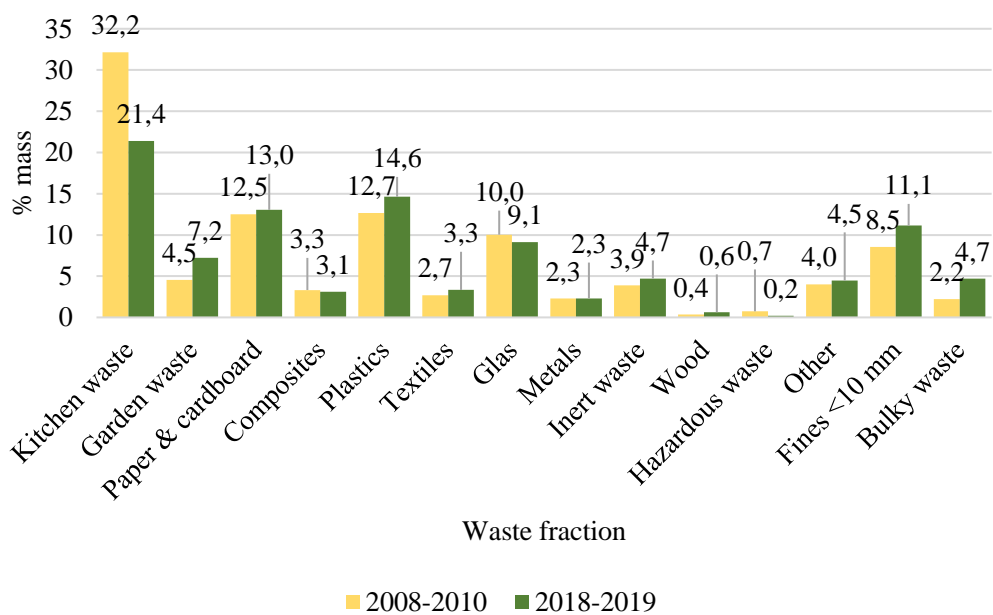
Figure 6. Composition of municipal waste in Poland, based on [67,68].

An analysis of Figure 6 reveals a shift in the composition of municipal waste from a higher proportion of kitchen waste to an increased presence of recyclable materials, such as plastics, paper and cardboard, and textiles. There is a notable decrease in the percentage of kitchen waste, from 32.2% to 21.4%, which could potentially be attributed to a transition in lifestyles from traditional cooking to the consumption of ready-made meals. Interestingly, there has been a rise in the fines content, which is often associated with individual heating systems that rely on solid fuels and the ashes they produce.

However, majority of municipal waste continues to be collected as mixed waste. In 2021, 8,234 Gg, equivalent to approximately 60% of the total municipal waste generated that

year, was collected as mixed waste. The composition analyses of mixed municipal waste have been instrumental in shaping various investment projects, and have been disclosed in the course of tender processes [69–72]. Figure 7 shows the average composition of mixed municipal waste, as derived from the aforementioned studies. The primary component is kitchen and garden waste, which accounts for 32.7% of the total weight and is the main cause of odor issues during waste collection, transportation, and processing phases. Other degradable components encompass paper and cardboard (10.7%), as well as fines < 10 mm (10.1%).
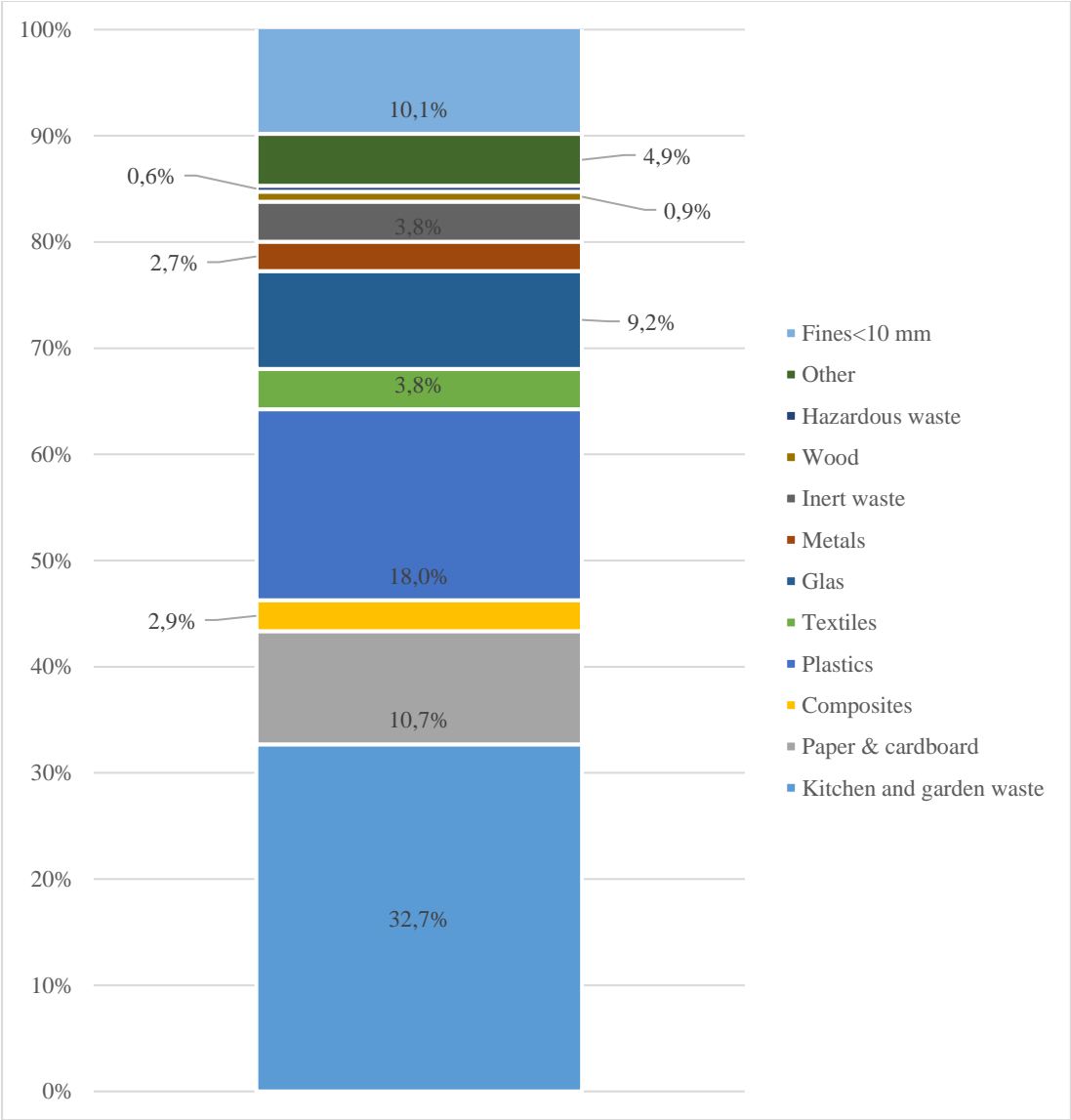
Figure 7. Mixed municipal waste composition, based on [69–72].

2.2.3 Municipal waste management in Poland by different treatment methods

For effective waste management through recycling, composting, or fermentation, it is necessary to carry out a selective collection of municipal waste. Based on the information provided by Statistics Poland [22], the quantity of selectively collected municipal waste in Poland was 5,440 Gg, making up 39.78% of the total municipal waste generated. Mixed municipal waste comprised 60.22% of the total (8,234 Gg). Statistics Poland's reports [73] points out that there has been a notable change in the composition of selectively collected waste over time. In 2005, a study indicated that the selectively collected waste mainly included paper and cardboard (32.4%), glass (33.60%), plastics (14.0%), metals (2.40%), bulky waste (11.60%), and other materials (6.0%). As time progressed, this composition witnessed significant change. In 2010, biodegradable waste emerged as an additional category, constituting 21.1% of the total. In 2021, the composition of selectively collected municipal waste in Poland was as follows: paper and cardboard (10.1%), glass (14.40%), plastics (9.60%), metals (0.20%), bulky waste (13.80%), biodegradable waste (33.9%), and other materials (18.80%).

Figure 8 depicts the proportions of municipal waste subjected to various treatment methods between 2004 and 2021, relying on Poland's statistical data from [22]. Recycling data is only accessible from 2013 onwards. Substantial advancements in waste treatment since 2013 can be observed, which corresponds to a significant overhaul of the municipal waste management system. This reform, initiated on July 1st, 2013, transitioned the responsibility for waste management from private companies to municipalities. In 2012, the Polish government officially established recycling goals for paper, glass, metal, and plastics through legislation (Regulation of the Minister of the Environment of 29 May 2012 on the levels of recycling, preparation for re-use and recovery by other methods of certain fractions of municipal waste (Journal of Laws of 2012, item 645)) [74]. This legislative action catalyzed an increase in material recycling, alongside the growth of energy recovery from high-calorific waste fractions, known as RDF (refuse derived fuel), primarily via co-incineration in the cement industry. These innovations led to a decrease in waste landfilling, dropping from 9,194 Gg in 2004 to 5,296 Gg in 2021. However, a reversal in this trend is evident from 2017, with landfilling rates increasing between 2017 and 2019, and only a slight decline in 2020 can be observed, followed by a rise in 2021.
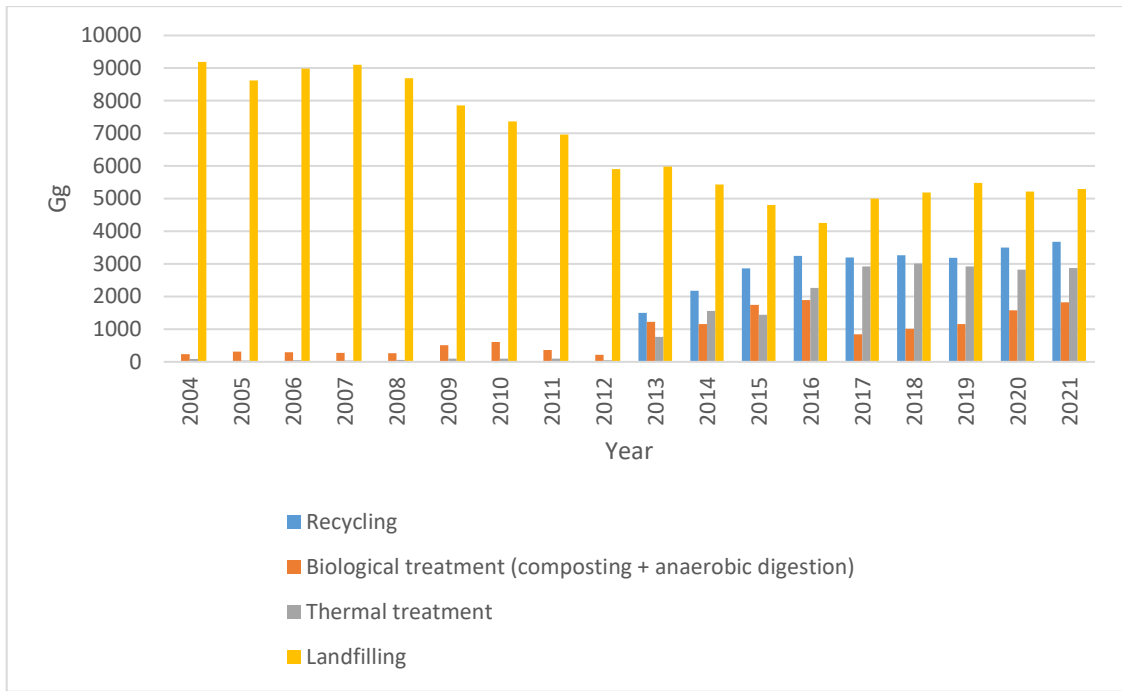
Figure 8. Municipal waste treatment in the years 204-2021, based on [22].

Table 1 shows the numerical data from Statistics Poland concerning the management of municipal waste produced between 2017 and 2021 [22]. Five primary streams of municipal waste were identified according to their treatment methods, which are linked to the waste hierarchy set by the European Directive on waste [75] and integrated into Polish law through the Act of 14 December 2012 on waste (Journal of Laws of 2020, item 797) [64]. These streams include the mass of municipal waste designated for recycling, the mass of municipal waste designated for composting or fermentation, the mass of municipal waste designated for incineration with energy recovery, the mass of municipal waste designated for incineration without energy recovery, and the mass of municipal waste designated for landfilling. In 2021, the mass of municipal waste directed for recycling was 3,681 Gg, making up 26.92% of the overall municipal waste generated, showing an upward trend compared to prior years. The amount of collected municipal waste treated through composting or fermentation in 2021 was 3,681 Gg, comprising 13.34% of the total municipal waste generated. This data indicates a rising trend in waste designated for composting or fermentation since year 2017. Municipal waste sent for incineration with energy recovery amounted to 2,702 Gg in 2021 (19.76% of the total municipal waste generated. The amount of waste incinerated without energy recovery stood at a mere 171 Gg in 2021, accounting for 1.25% of the total, with a decreasing trend since 2017. Lastly, the weight of municipal waste sent to landfills was 5,296 Gg in 2021, making up 38.73% of the total. Here, an increase was noted in 2018 and 2019 relative to 2017, followed

by a decrease in 2020 and an increase in 2021. In summary, the aggregate weight of municipal waste directed towards recovery processes, such as recycling, composting or fermentation, and thermal processing with energy recovery, was 8,207 Gg in 2021 (60.02% of the total waste generated). 5,467 Gg - representing 39.98% of the total municipal waste generated was dispatched for disposal processes (landfilling or incineration without energy recovery). Contrasting the evaluated data with the waste hierarchy, it is evident that despite some improvements, there is an adverse trend in waste management in Poland, especially when considering the volume of waste being handled through less desirable methods such as disposal and landfilling.

Analyzing individual voivodships, the general trend mirrors the data depicted in Figure 4. The provinces of Śląskie, Mazowieckie, Dolnośląskie, and Wielkopolskie led in the mass of waste designated for recycling in 2021, whereas Świętokrzyskie, Opolskie, Podlaskie, and Lubuskie had the smallest volumes. In 2021, the provinces of Śląskie, Mazowieckie, Wielkopolskie, and Małopolskie had the highest amount of waste directed for composting or fermentation, while Świętokrzyskie, Podkarpackie, Podlaskie, and Warmińsko-Mazurskie had the lowest. The mass of municipal waste designated for thermal treatment with energy recovery in 2021 was predominant in Wielkopolskie, Małopolskie, Mazowieckie, and Kujawsko-Pomorskie voivodships, where waste incineration plants are located. Regarding the mass of municipal waste designated for landfilling in 2021, Mazowieckie, Śląskie, Dolnośląskie, and Łódzkie viovodships were at the forefront, while Podlaskie, Warmińsko-Mazurskie, Lubelskie, and Lubuskie had the least amount of waste landfilled.

Table 1. Management of municipal waste by the type of its management, produced between 2017 and 2021 [22].

Region	Mass of municipal waste for recycling					Mass of municipal waste for composting or fermentation					Mass of municipal waste for incineration with energy recovery					Mass of municipal waste for incineration without energy recovery					Mass of municipal waste for landfilling				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
	Gg																								
Poland	3199	3269	3192	3499	3681	848	1012	1153	1578	1824	2724	2822	2742	2656	2702	198	191	179	166	171	5000	5191	5487	5218	5296
Dolnośląskie	362	391	367	395	442	71	74	89	122	149	104	101	92	103	107	11	10	11	0.01	0.02	538	567	614	539	564
Kujawsko-pomorskie	144	167	142	159	157	66	72	78	102	113	152	130	147	216	245	10	0.26	0.21	0.25	0.21	266	297	323	236	218
Lubelskie	79	96	113	136	138	28	37	49	66	86	122	132	127	140	148	5	0.0	0.0	0.02	0.04	206	205	206	181	171
Lbuskie	78	72	73	99	103	29	31	37	42	53	46	52	78	59	65	25	17	20	21	8	188	194	177	168	175
Łódzkie	203	185	134	222	217	58	82	114	117	121	56	60	61	63	125	0.0	0.0	0.0	0.01	0.01	389	461	510	449	413
Małopolskie	254	257	239	313	307	76	94	113	134	152	401	346	289	271	288	67	59	69	82	81	207	318	369	331	349
Mazowieckie	411	381	439	527	489	101	111	90	212	256	530	580	417	355	286	49	53	38	20	17	685	687	753	764	922
Opolskie	82	79	94	72	87	28	32	35	48	54	63	63	47	60	50	0.0	0.0	0.0	0.0	0.0	140	149	157	191	187
Podkarpackie	90	89	95	115	126	16	18	23	31	41	158	157	138	124	122	14	14	13	13	7	184	219	246	219	228
Podlaskie	55	66	75	95	98	16	21	25	40	44	99	122	129	109	139	0.0	0.0	0.02	0	4	109	90	105	95	66
Pomorskie	164	160	172	191	231	87	91	103	138	142	243	154	167	145	123	3	7	10	12	48	307	416	418	344	366
Śląskie	682	698	660	539	578	109	170	184	229	261	98	128	155	188	180	14	31	18	2	6	698	637	685	823	770
Świętokrzyskie	58	64	70	69	81	8	7	11	16	20	24	23	18	18	23	0.03	0.02	1	15	0.0	144	156	186	197	204
Warmińsko-mazurskie	82	84	87	132	141	18	24	24	37	47	127	109	116	88	106	1	0.01	0.0	0.4	0.01	195	225	208	175	154
Wielkopolskie	265	310	259	287	319	97	103	124	173	201	381	427	474	489	456	0.1	0.1	0.1	0.1	0.1	451	383	384	306	320
Zachodniopomorskie	189	172	173	148	166	40	44	55	71	85	118	240	287	228	238	0.0	0.0	0.01	0.0	0.0	291	187	148	199	188

2.2.4 Waste management infrastructure

Appropriate and specialized infrastructure plays a crucial role in managing municipal waste effectively. Such infrastructures include composting plants, biogas plants, waste incineration plants, waste landfills, and mechanical-biological waste treatment plants. In Poland, it is mandatory to pre-process all municipal waste before it is ultimately disposed. For example, by waste deposition in landfill [64]. This pre-treatment is carried out in either mechanical-biological waste treatment plants or waste incinerators. As reported by the Marshal Offices (data for 2021), there were 174 mechanical-biological wase treatment facilities holding the required permits to process mixed municipal waste, alongside 8 incinerators that can handle either mixed municipal waste or sorting residues (Figure 9, Figure 11) [68]. 8 out of these mechanical-biological waste treatment facilities employ the anaerobic digestion process as a part of the biological treatment of mixed municipal waste [76]. Statistics Poland has reported that in the year 2020, there were 271 operational municipal landfills in the country (Figure 10), and 265 in 2021 [22]. However, data from Marshal Offices (data for 2021) indicates that only 163 of these qualify as municipal landfills, meaning that they are authorized to handle pre-processed municipal waste or sorted residues [68]. A noticeable trend of decreasing numbers of active landfills was observed between 2010 and 2021. In 2010, Statistics Poland reported a total of 633 municipal waste landfills [12]. Since that time, 368 landfills have been closed. Despite this reduction, landfilling continues to be a prevalent method for managing municipal waste. The separately collected biowaste is treated in 220 installations (Figure 11), of which 144 are located together with mechanical-biological waste treatment plants (data from 2021) [68]. Only one anaerobic digestion plant for separately collected biowaste is operated and two more are under construction.
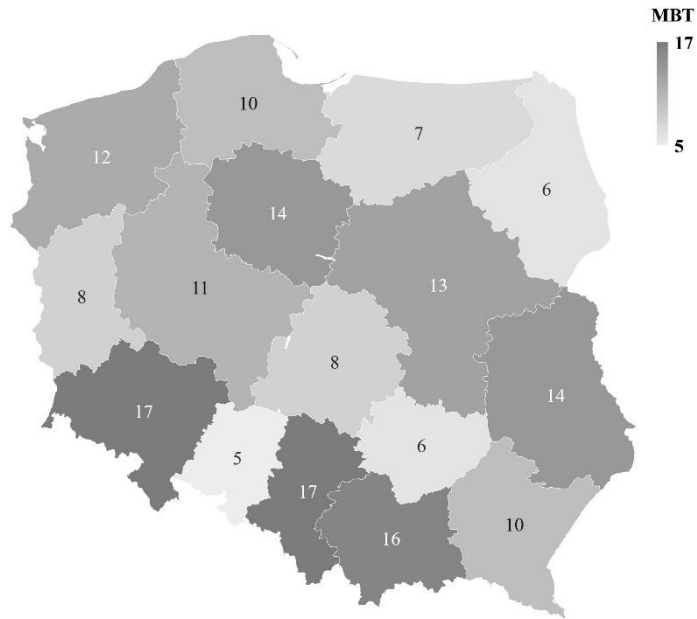
Figure 9. The number of the mechanical-biological treatment installations within the borders of individual voivodeships, elaboration based on [68].
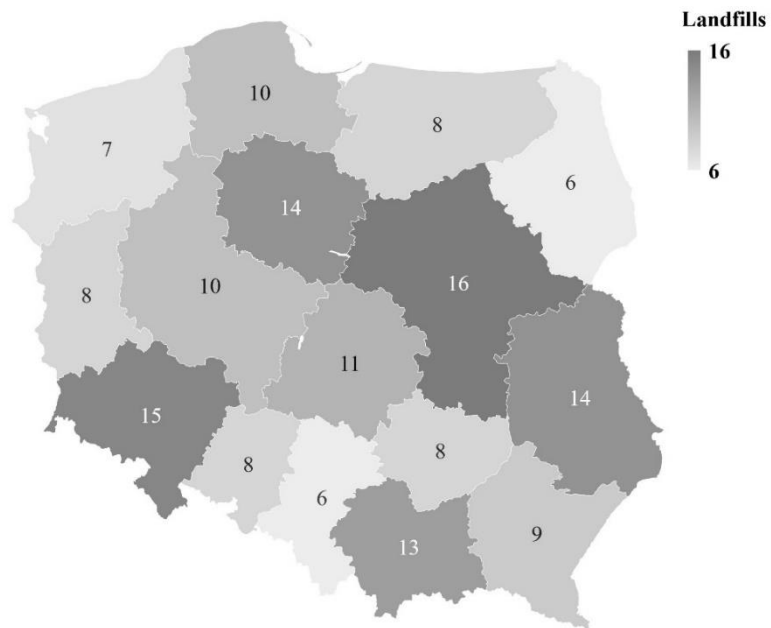

Figure 10. The number of the landfills within the borders of individual voivodeships, elaboration based on [68].
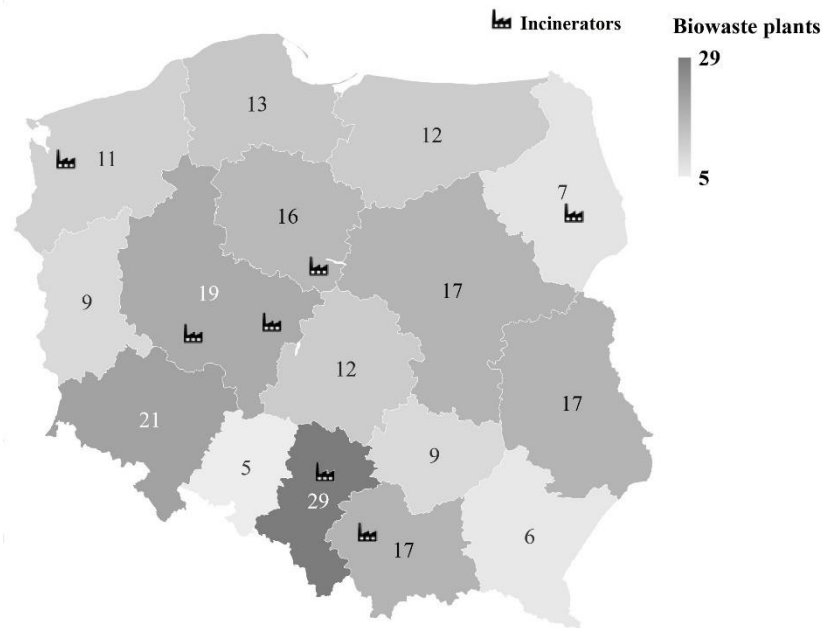
Figure 11. The number of the biowaste plants for separately collected biowaste and the location of waste incinerators within the borders of individual voivodeships, elaboration based on [68].

2.3 ODOR AND ODORANT EMISSIONS FORM MUNICIPAL WASTE MANAGEMENT

2.3.1 Waste collection and transport

The collection of waste at the places of its production, for example, in waste containers in residential areas, as well as waste collection and transport processes by responsible entities, are considered as first stages of waste management [3,26,77–79]. The release of substances that produce odors during these steps mainly occurs due to the initial decomposition stage of organic matter contained in the municipal waste [3,26,77,78]. Several factors, including ambient temperature, waste composition, and the duration of waste storage in containers significantly influence emissions related to waste collection and transportation [78]. These factors can change depending on the waste collection methods and regions from which waste is collected [3].

Multiple studies have been conducted in the area of emissions of odor-generating substances during the initial phases of waste management, which include the collection and transportation of waste. Study by [3], simulated the initial decomposition of organic matter in municipal waste with varying levels of easily biodegradable organic matter content (15%, 45%,

and 60%). Throughout the study, 43 different volatile organic compounds were detected and categorized into five groups: sulfur compounds, aromatics, halogenated compounds, hydrocarbons, and oxygenated compounds. Among the samples with 45% and 60% organic content, the highest emission was from oxygenated compounds, with ethanol being the dominant component. The average concentration of ethanol was 17.23 ppm. The researchers measured the odor concentration using the dimensionless c_o unit. Methyl sulfide, ethanol, dimethyl disulfide, and ethyl acetate were identified as the primary odorants. In the case of waste containing 60% organic material, methyl sulfide exhibited the highest c_o value of 162.72, the second one was ethanol (66.19), third - ethyl acetate (9.19), and last one - dimethyl disulfide (6.41). In the samples with 45% organic material, ethanol had the highest c_o value of 56.95. For samples with 15% organic content, dimethyl disulfide was the most prominent with a c_o value of 56.03, followed by methyl sulfide (3.15), whereas ethanol was ranked sixth with a c_o value of 0.33. The study's findings suggest that the quantity of easily biodegradable organic material was a key determinant in the emissions of volatile organic compounds. For instance, the average emission of volatile organic compounds was 50.72 ppm for samples with 60% organic content, and 37.66 ppm for those with 45% organic content. In summary, the authors of the study concluded that the content of organic matter is a key factor influencing the emission of odor-generating substances [3].

In another study [77], the authors examined samples collected from, among others, waste bins situated in residential areas. The study was designed to identify specific odor-generating compounds and to measure the concentration of odors, which was expressed in dimensionless units (as previous study). The substances that were identified were categorized into several groups: ammonia (NH_3), sulfide compounds, aromatic compounds, oxygenated compounds, halogenated compounds, and alkanes. The main compounds detected as emissions from the waste containers were methyl mercaptan, ammonia (NH_3), dimethyl disulfide, acrolein, dimethyl sulfide, methacrolein, benzene, toluene, ethylbenzene, and m,p-xylene. The concentration of ammonia was observed to be in the range of 912.3 ± 106.8 meter $\mu g/m^3$, while sulfide compounds had a concentration of 15.6 ± 9.2 $\mu g/m^3$. The concentration of halogenated compounds was recorded at level of 220.2 ± 192.1 $\mu g/m^3$, and the concentration of alkanes was 5.9 ± 1.7 $\mu g/m^3$. The study also reported the dimensionless odor concentration, according to Chinese emission standards, which was found to be below 20. This is indicative of relatively low odor levels. Additionally, the study included an assessment of the environmental impact of the odors emitted near residential areas, comparing it to the impact of odors near transfer

stations and a landfill site. The findings showed that the odors emitted from waste containers located in residential areas had the least environmental impact compared to the other locations.

In the study cited as [78], the authors simulated the initial decomposition of organic waste throughout prepared waste sample that contained a mixture of easily biodegradable, biodegradable, and non-biodegradable components. During the study, they identified 52 odorous substances and classified them into seven principal categories: saturated hydrocarbons, unsaturated hydrocarbons, aromatic compounds, halogenated compounds, oxygenated compounds, sulfur compounds, and terpenes. The findings of the study highlighted that, in the majority of cases, ethanol had the highest concentration (379.85 ± 409.57 ppm, approx. 80 % of the sample composition was ethanol) among the emitted substances, similar to the results in study [3]. The substance with the second-highest concentration was propylene, which is part of the unsaturated hydrocarbons category, with an average concentration of around 13%, or 67.18 ± 79.86 ppm. The data from study [78] also demonstrated that the emissions of odor-causing substances varied over time and with temperature changes. The emission of odorants was substantially lower at a temperature of 5°C compared to emissions observed at 30°C. When the temperature increased from 5°C to 30°C, the proportion of ethanol in the total odor-producing substances identified changed from approximately 22.30% to 70.01%. Furthermore, in the span of time from 6 hours to 24 hours, the percentage of ethanol rose from 40.1% to 82.9%.

Authors of [26] focused on research of odorants dispersion during waste transportation and used substances such as ethanol, dimethyl disulphide, and methylene chloride for dispersion modelling. Another study [79] found a total of 40 volatile organic compounds that were emitted from waste containers. These compounds were categorized into five groups: terpenes, alkanes, sulfur compounds, aromatic compounds, and hydrocarbons. The study analyzed emissions from different types of waste containers, including those for mixed waste, kitchen waste, and other types of waste. The research was conducted over the course of a year and took into account the variations across the four temperature seasons. The findings indicated that containers for mixed waste were predominantly responsible for the highest emissions of volatile organic compounds. Additionally, it was observed that summer was the season during which the emission of volatile organic compounds from mixed waste containers was at its peak.

2.3.2 Waste transfer stations

Waste transfer stations are another component in the waste management system, taking into account the emission of odor-causing substances and their mixtures that manifest as odors

[77,80–82]. These stations act as temporary storage facilities for waste, especially in cases where the final waste management site, such as a landfill or a mechanical-biological waste treatment plant, is located at a considerable distance from the point of waste collection, which makes direct transportation economically impractical due to high cost of transportation without waste reloading [83,84]. It is important to note that incorporating transfer stations into waste management chain is an optional strategy within waste management systems.

In an analysis of odor emissions from a waste transfer station, the authors of study [77] identified ammonia, acrolein, methyl mercaptan, methacrolein, dimethyl disulfide, benzene, toluene, dimethyl sulfide, m, p-xylene, and propanal as the main odor-generating substances. These substances were categorized into groups including sulfide compounds, aromatic compounds, oxygenated compounds, halogenated compounds, and alkanes. The authors examined four different locations within the transfer station and found that the waste discharge area had the highest odor concentration - approximately 442 in dimensionless units (as per Chinese emission standards). This was followed by the waste compaction area with an odor concentration of around 300, the leachate tank with approximately 120, and the plant boundary which had a concentration below 20. An evaluation of the environmental impact indicated that the odor emissions from transfer stations were intermediate between those from residential waste containers and landfills. However, it's noteworthy that the environmental impact of the transfer stations was significantly less than that of the landfill.

In study [28], the authors identified a total of 76 different odorants at waste transfer station. These compounds were classified into six categories: saturated hydrocarbons, unsaturated hydrocarbons, aromatic hydrocarbons, sulfur compounds, oxygenated compounds, and halogenated hydrocarbons. Among these compounds, ethanol was found to be the most prevalent with an average concentration of 7.14 mg/m³ (oxygenated compounds category). Additionally, dimethyl disulfide and methyl mercaptan, both of which belong to the sulfur compounds category, were identified as significant contributors, with concentrations of 4.63×10^{-2} mg/m³ and 3.45×10^{-4} mg/m³ respectively.

In study [82], the authors identified 76 different odorants emitted from waste transfer station. These compounds were categorized into seven groups: sulfur compounds, oxygenated compounds, aromatic compounds, terpenes, halogenated compounds, saturated hydrocarbons, and unsaturated hydrocarbons. According to the results obtained by the authors, the substances that were recognized and had the highest odor impact were methane thiol, hydrogen sulfide,

ethanol, dimethyl disulfide, and dimethyl sulfide. Among these, ethanol was found to have the highest concentration, measuring 15.6 ± 9.2 μg/m³. However, methane thiol was identified as the most dominant odor-generating substance, due to its extremely low odor detection threshold, which is 0.00007 ppm.

In their study conducted at a waste transfer station, the authors cited as [81] identified several substances as the primary contributors to odor generation. These substances included methyl mercaptan, hydrogen sulfide, acetaldehyde, acetic acid, butyric acid, and terpenes.

2.3.3 Mechanical-biological waste treatment

Mechanical-biological waste treatment plants are considered as one of the most significant sources of odor emissions into the atmosphere. Various studies have indicated that the operations of mechanical-biological treatment plants are associated with the release of odors and odor-generating substances into the air [29,30,33–35,59,61,76,85–92]. The core activities of mechanical-biological waste treatment plants are focused around the handling of mixed municipal waste, and they are recognized as critical components within waste management systems [89]. Within those, the treatment of mixed municipal waste is carried out in two principal phases [33,61,86,92].

- 1st stage - mechanical preparation of waste for biological processes.
- 2nd stage - biological decomposition of waste under aerobic (composting) or anaerobic (fermentation) conditions followed by aerobic stabilization of fermentation residues.

By integrating mechanical and biological methods, the volume of waste directed to landfills is substantially reduced, and valuable components of the waste stream, such as ferrous and non-ferrous metals, are recovered for potential reuse. Additionally, mechanical-biological treatment procedures yield products like refuse-derived fuel or biogas, which can be used for the energy needs of the facility [76,86].

In a study conducted by [93] regarding the emissions of odorous substances at selected mechanical-biological waste treatment plant, the technological process was broken down into four stages: pre-mechanical treatment, pre-biological treatment, post-mechanical treatment, and post-biological treatment. Throughout these processes, 75 gaseous substances were identified and categorized into nine groups: nitrogen compounds, sulfur compounds, carbonyls, alcohols, aromatics, alkanes, alkenes, terpenes, and volatile fatty acids. The study highlighted acetic acid,

butyric acid, valeric acid, isovaleric acid, and dimethyl sulfide as the major odor-generating substances. During the pre-mechanical treatment phase, the concentrations of the gaseous substances were found to vary between 64 to 175 ppm based on the sampling location. In the pre-biological treatment stage, the concentrations ranged from 132 to 317 ppm, with the peak concentration of 317 ppm recorded on the seventh day amid the aerobic process. For the post-mechanical treatment phase, the concentrations were in the range of 91 to 119 ppm, depending on the measuring point, while in the post-biological treatment phase, the concentrations ranged from 128 to 185 ppm. The study concluded that acetic acid, butyric acid, valeric acid, isovaleric acid, and dimethyl sulfide were the chief substances responsible for odor generation.

The researchers in [29,30,34,61,76,92] conducted studies on the emission of odorants and odors from six mechanical-biological waste treatment plants in Poland, each equipped with a installation for the anaerobic decomposition, also known as fermentation, of the organic matter present in mixed municipal waste. The conducted research primarily involved the analysis of substances such as volatile organic compounds (with measured values averaging in the tens ppm), ammonia (also averaging in the tens of ppm), hydrogen sulfide (typically not exceeding a few ppm), dimethyl sulfide, and methyl mercaptan (usually below one ppm). Additionally, the concentration of odors was analyzed using field olfactometry. Among the sources considered within the studied mechanical-biological waste treatment plants, the authors identified various areas of odor emissions including waste storage areas, mechanical waste treatment process, areas of preparation of waste for fermentation, sites for the dewatering of digestate, the aerobic stabilization phase, and surfaces of biofilters.

2.3.4 Landfilling

As detailed in the *Chapter 2.2.4* Poland predominantly uses landfilling as the main method of municipal waste management. In 2021, 38.73% of all municipal waste produced was landfilled. This volume of landfilled waste necessitates an adequate number of landfills. Despite a continuous decrease in the number of landfills (*Chapter 2.2.4*), 265 active municipal landfills existed in Poland in 2021. The operation of municipal landfills negatively impacts the environment, primarily through air pollution, numerous studies discuss these issues [11,18,19,27,32,46,77,80,94–107].

The primary cause of odor-emitting substances from landfills is the deposited municipal waste itself undergoing three main processes: biodegradation of deposited organic waste, direct volatilization of different compounds contained in deposited waste mass, and biological or

chemical reactions between deposited waste and reaction products [32]. The decomposition of deposited waste begins under aerobic conditions and shifts to anaerobic conditions as oxygen gets consumed. As results of various reactions, the landfill gas is emitted comprising methane, carbon dioxide, and trace substances responsible for the emission of odors [32]. Deposited waste mass at the landfill is not the only source of odor emissions, landfill leachate tanks or landfill degassing wells could contribute to odor emissions [94].

The authors of [80] identified six main categories of substances that generate odors emanating from a waste landfill and composting facility: alkanes, oxygenated compounds, sulfide compounds, aromatic compounds, halogenated compounds, and ammonia. Within these groups, the principal substances contributing to odor pollution in the landfill were identified as hydrogen sulfide (averaging up to 129 ppb), benzene (averaging up to 291 ppb), ammonia (averaging up to 1132 ppb), ethyl acetate (averaging up to 1292 ppb), ethylbenzene (averaging up to 143 ppb), ethyl disulfide (averaging up to 216 ppb), p-ethyltoluene (averaging up to 18 ppb), n-hexane (averaging up to 54 ppb), 1,2-dichlorobenzene (averaging up to 22 ppb), and trichloroethylene (averaging up to 0.4 ppb). The study revealed that the odor impact of the landfill being evaluated was significantly lower compared to that of the waste composting plant.

Authors of [106] identified a total of 63 substances emitted from a waste treatment plant that employed three primary technologies: fermentation, ecobiological-mechanical treatment, and waste disposal. These substances were categorized into six groups: halogenated compounds, sulfur compounds, alkanes, alkenes, aromatic compounds, and oxygenated compounds. The primary substances responsible for generating odors at the facility included methanethiol (ranging from 15,136 to 29,087 μg/m³), dimethyl sulfide (ranging from 36,847 to 43,307 μg/m³), dimethyl disulfide (ranging from 2,945 to 4,561 μg/m³), carbon disulfide (ranging from 2,385 to 4,928 μg/m³), as well as styrene, m-xylene, 4-ethyltoluene, ethylbenzene, 2-hexyl ketone, and n-hexane.

In another study by [94] a total of 35 substances that generate odors were identified and classified into six categories: aromatic compounds, sulfur compounds, oxygenated compounds, amines, fatty acids, and ammonia. The highest concentrations of the identified substances in the landfill area were recorded for styrene (up to 555 ppb), toluene (up to 46 ppb), xylene (up to 279 ppb for p-xylene and up to 125 ppb for m-xylene), acetone (up to 139 ppb), methanol (up to 58 ppb), n-butanone (up to 77 ppb), n-butylaldehyde (up to 241 ppb), acetic acid (up to 2,250 ppb), dimethyl sulfide (up to 78 ppb), dimethyl disulfide (up to 121 ppb), and ammonia

(up to 70,000 ppb). It was noted that concentrations differed based on the location of the sampling site.

2.3.5   Thermal treatment

Waste incineration plants represent another type of facilities that could potentially emit odors and odor-generating substances. These plants serve to effectively reduce waste mass through thermal treatment. Due to the nature of these facilities[28,106], potential sources of odorant emissions might be vehicles delivering waste to the facility and the waste storage site (storage bunker)[28,105]. For waste incineration plants, primary emission sources includes mainly stack emissions. These emissions encompass substances like dust, sulfur oxides, hydrochloric acid, nitrogen oxides, dioxins, furans, ammonia, carbon monoxide, volatile organic compounds, and heavy metals such as Cd, Hg, Pb [108–111]. The waste fed to incineration plants is typically in the early stages of biodegradation, which suggests that the primary emissions of odor-generating substances might be similar to those from waste collection and transportation.

Authors of [31] identified 75 volatile compounds with an average concentration of 33,129.25 $\mu g/m^3$ emitted from waste incineration plants in their research. They studied sources such as a storage bunker (70 compounds, 53,305.83 $\mu g/m^3$), waste unloading site (72 compounds, 72,053.89 $\mu g/m^3$), and the background level in the incinerator (48 compounds, 1,607.19 $\mu g/m^3$). The researchers noted the highest substance concentration at the waste unloading site. The researchers compared the concentrations from the waste incineration plant with those from the transfer station and landfill, with the waste incineration plant exhibiting the highest values. Hydrocarbons and oxygenated compounds constituted the most substantial portion of the identified volatile organic compounds. The identified substances were categorized as halogenated compounds, terpenes, hydrocarbons, oxygenated compounds, aromatic compounds, and sulfur compounds. In conclusion, waste incineration plants are significant sources of a variety of emissions, including those that cause odors, highlighting the importance of monitoring and managing these emissions to minimize their impact on the environment.

3 ODOR MONITORING STRATEGIES

3.1 MEASUREMENT METHODS OF ODORS AND ODORANTS

3.1.1 Classification of used methods in odor research

The measurement techniques available to describe odors include two main groups: analytical techniques and sensory methods [13,38,39]. Characterizing odors is a complex task. Finding straightforward answers to questions regarding "what" and "how" in odor research can be challenging. According to EN 13725 standard [52] odor is an organoleptic feature perceived by the human sense of smell when smelling certain volatile compound. As the air that humans inhale is considered as a mixture, thus odors are considered as mixture of substances known as odorants. They stimulate the human olfactory system, resulting in the perception of specific smells when exposed to them [41,52]. The precise definition of odors is crucial when discussing odor problems. Odors can be described as a whole sensation resulting from mixtures, sensation caused by specific substances (odorants) or even by a single odorant. Odorants primarily belong to the category of volatile organic compounds, although certain inorganic substances such as hydrogen sulfide or ammonia can also induce a feedback from the human olfactory system [40,41,112,113]. The choice of a suitable method for qualitative and quantitative evaluation of odors depends on which part of the definition is being emphasized, reflecting the approach to defining odors. Analytical techniques, such as chemical analysis, gas chromatography, and gas sensors, offer insights into the concentration of specific substances or odorants [40,41]. Sensory methods provide information about the overall sensation resulting from the combination of various substances present in the air [38,40]. Sensory methods utilizes the human sense of smell to detect odors and describe them in accordance with how they are perceived by humans, human nose is treated as a detector/sensor [38,40,44]. Sensory methods allows to characterize basic odor properties, i.e. odor character, odor intensity, hedonic tone, and odor concentration. Quantitative analysis of odor can be achieved by combining the human nose with external instruments like dynamic and field olfactometers. This allows for the determination of odor concentration in air samples or ambient air. Utilizing the human nose alone is used for parametric measurements and facilitates the description of parameters such as odor character, odor intensity, and hedonic tone [38,39].

3.1.2 Basic odor properties

Odor character, odor intensity, and hedonic tone are considered to be one of the basic characteristics of odors and belongs to the group of parametric measurements [38,39]. Parametric measurements are considered as less-cost demanding methods as they do not or barely require any additional measuring devices [38].

Among the three basic parameters, odor intensity seems to be one of the most important. To properly define odor intensity it is needed to define odor concentration. Odor concentration according to European Standard EN 3725 [52] is defined as the amount of European odor unit per cubic meter of gas in standard conditions, while odor itself is an organoleptic feature perceived by the human sense of smell when smelling certain volatile compound. Therefore, odor concentration can be seen as the strength of odor, while odor intensity is the magnitude of that strength [38,49,56]. As the odor concentration is described as ou_E/m^3 or ou/m^3, odor intensity is expressed as a verbal description assigned to a numerical scale [56] and it is related to odor concentration [58]. The relationship between these two parameters can be described by the Weber-Fechner law [49,56,58,114,115], which states that the relationship of psychological perceived intensity and physical feature like odor concentration could be derived as a log-linear function. Various literature shows that odor intensity is one of the most commonly used parameters during different research focusing on odor measurements, examples can be found in [48,59,92,116].

Determining the odor character parameters, consists mainly in verbally articulating one's sensory experience related to the sensed odor., i.e. it consists in stating that the perceptible smell is, for example, the smell of sewage or the smell of processed municipal waste [38]. Example of the use of odor character parameter can be found in [48]

Hedonic quality allows a qualitative characterization of the perceived odors. Hedonic tone measures the degree to which an odor is pleasant or unpleasant, and is assessed using a scale that ranges from -4 (extremely unpleasant) to +4 (extremely pleasant), with zero indicating a neutral odor that is neither pleasant nor unpleasant. [38,39,117]. Hedonic tone seems to be important parameter for the description of annoyance as it is strongly connected with the way that humans perceive odors. In general, the more unpleasant an odor is, the greater the likelihood of it being considered an annoying [15,117]. Despite its potential usefulness, hedonic tone is rarely used.

3.1.3 Dynamic olfactometry

The dynamic olfactometry method is considered as the most advanced sensorial technique used in odor concentration determination. It follows the European standard EN 13725 [52] and enables the measurement of odor concentration in the air, which is expressed as ou_E/m^3 (European odor units per cubic meter). The dynamic olfactometry method works by exposing a group of panelists to odor samples taken directly from emission sources that are diluted with odorless air in specific and precise ratios. Its working principles are based on dilution to threshold ratio. Odor concentration determined by the means of dynamic olfactometry method is expressed as a number of dilutions required to bring odors samples to their threshold where 50% of the population are able to detect odors [13,38,40,41]. The samples are presented to the panelist in a decreasing dilutions series until the moment, when panelists are able to sense odors. Summarizing – odor concentration determined by the dynamic olfactometry method, tells how many times during the test, the odor samples have to be diluted to reach the detection threshold for analyzed samples. The dynamic olfactometry method employs a device known as a dynamic olfactometer, which performs multiple functions including diluting the odor samples, presenting them in a series of dilutions to the panelists in the form of an air stream, and is responsible for communication between the panelists and the device itself. An example of such a device is the TO8 dynamic olfactometer by ECOMA, which can be seen in Figure 12.

Figure 12. Dynamic olfactometer T08 by ECOMA.

The YES/NO method is widely used in dynamic olfactometric measurements. During the measurements with YES/NO method, panelist are exposed to either clean, odorless air or odor contaminated air diluted with odorless air at specific ratios. Their role is to provide feedback about the presence of odors in presented air stream [40]. As said before, odor samples are presented in and decreasing series of dilution, i.e. at the beginning of the measurement the odor sample is highly diluted (for example, the sample is diluted 70,000 times), and at the end the odor sample reach low dilutions (for example, 2 times). Starting with the initial dilution, each subsequent dilution is twice as small, i.e. 1st dilution – 70.000 times, 2nd – 35.000 times, and so on. The measurement is considered complete when all panelists, twice in a row, find the presence of odor in the presented air, thus the odor detection threshold is established. Odor detection threshold is calculated as the geometric mean of the first positive response (dilution step at which odors were detectable) and the last negative response to odor (dilution step, before panelists were able to detect odors). Before panelists can assess odor samples, they undergo a pre-tests with the reference substance (n-butanol) to determine whether they meet the required standards specified in EN 13725 standard [52]. The olfactory system of the panelists should be characterized by average sensitivity, which is assessed through tests with the reference substance (n-butanol) [40,52]. The odor concentration is considered more as a dimensionless quantity rather than a physical unit. By following the methodology described above, it is expressed as ou/m^3 [38]. If the odor concentration is presented as ou_E/m^3, it means that the measurement was carried out in accordance with the EN 13725 standard [52]. It is important to note that ou_E/m^3 is calibrated to the reference gas (n-butanol), therefore 1 ou_E/m^3 corresponds to the olfactory sensation caused by 123 µg of reference substance dissolved in 1 cubic meter of air [52,118].

Despite being standardized, the dynamic olfactometry method possesses certain disadvantages. Firstly, it is limited to determining odor concentrations only at the sources of their emission. EN 13725 [52] does not extend to measuring odors in ambient air beyond the odor sources [13]. Additionally, it is unsuitable for determining low odor concentrations [40,41,119,120]. Continuous measurements are not possible as samples must be collected from the emission source and transported to the laboratory for odor concentration determination [13,41]. Moreover, dynamic olfactometry is considered as one of the most expensive odor monitoring method [40].

The dynamic olfactometry is widely used in literature studies, mostly as a method of determining the odor concentration for the purposes of odor dispersion modelling. Some of the examples can be found in [26,46,104,119,121,122].

3.1.4 Field olfactometry

The field olfactometry is another example of widely used odor measuring method. It is designed to give the possibility to determine the odor concentrations in in-situ measurements in the ambient air [38,40,119]. In opposition to dynamic olfactometric measurements, which are designed to determine the odor concentrations at samples taken directly from odor emission sources, field olfactometry could be used in real-time in-situ measurements. It could be used around problematic areas directly or indirectly exposed to or affected by odors [13,38,112,123]. A device called a field olfactometer is used in this method. Essentially, it is a portable olfactometer with the capability of being operated by a single person [118]. An example of such a device is the Nasal Ranger field olfactometer manufactured by St. Croix Sensory, Inc [124]. Figure 13 shows the aforementioned device.
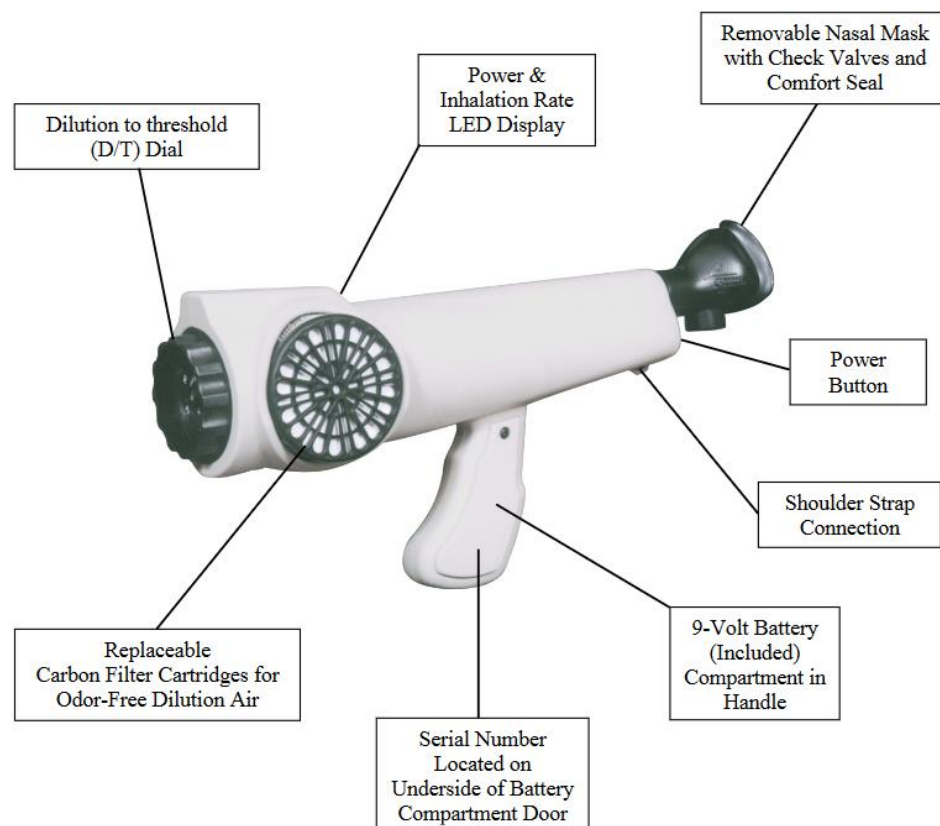

Figure 13. Nasal Ranger by St. Croix Sensory, Inc. (source: Manufacturer Device Manual [124]).

Similar to the dynamic olfactometry method, Nasal Ranger operates on the same principles, and employs the dilution to threshold ratio as a method of odor quantification [118]. However, field olfactometry allows the expression of odor concentration in odor units per cubic meter (ou/m^3), not as European odor unit per cubic meter (ou$_E$/m^3) as the EN 13725 [52] standard does not apply to the field olfactometry method [13,39,125].

Utilizing the field olfactometry methods, it is possible to overcome shortcomings of the dynamic olfactometry method. Based on literature, field olfactometry appears to be more proficient in determining lower odor concentrations [39,40,120]. As previously mentioned, it is well-suited for in-situ measurements, its portability allows to cover much larger area with measurements regarding odor concentrations. They can serve as alternatives during field inspections or as supplementary measurement tools, which makes it possible to extend the range of research [119].

Field olfactometry has a broad spectrum of applications, available literature shows numerous areas in which field olfactometry can be utilized. For instance, one study utilized field olfactometry method in conducting an ecological audit of a former excavation pit that had been repurposed as a waste disposal site [125]. In this study, the authors used a field olfactometer to measure odors, and chemical sensors to measure specific odorants at a chosen research location. Another study [126] used field olfactometric measurements to investigate potential odor nuisance in urban areas characterized by the presence of multiple source of odors. By utilizing field olfactometric measurements, authors have been able to point out areas that were affected by odors from specific sources. The assessment of odor emissions linked to diverse manure management technologies, with the use of field olfactometry, was provided by authors of [127]. Other literature sources indicates that field olfactometry is applicable in evaluating odor quality in the animal feeding and husbandry sectors [47,128]. It can be used as odor sources identifying tool before measurements with the use of DO method [129].

The assessment of odors associated with generally understood waste management in its various forms, including management of both solid and liquid waste, is a key application area of field olfactometry method. For instance, authors of [120] employed data gathered with the use of field olfactometry as input for modeling the dispersion of odors. Another study used field olfactometry to measure odor concentrations at selected biogas facilities located in Poland [34,92]. Authors of used field olfactometry to measure odor concentrations at various steps of wastewater treatment process [130,131], while in other study authors used field olfactometry

to compare odor air quality at wastewater treatment plant before and after its modernization [132]. Waste management is a multi-step process, and as shown in the *Chapter 2*, and odors can be emitted at nearly every stage due to the substantial amount of organic waste in mixed municipal waste stream. The diversity of odor sources within the boundaries of waste management facilities makes them a subject of interest for the field olfactometry technique.

3.1.5 Analytical techniques – gas chromatography coupled with mass spectrometry

As said above, analytical methods allow for the identification and determination of concentrations of specific substances that contributes to the to the whole sensation caused by inhaled air mixture. Their application enables the determination of the composition of the odorous mixture and precise quantification of chemical compounds present in it [40,41].

The most commonly used analytical method for identification and quantification of odorants is gas chromatography combined with mass spectrometry (GC-MS). Gas chromatography consists in separating the compounds contained in the mixture due to their affinity for the filling of the column through which the analyzed substances flow [13,133,134]. This method can be used as a basic tool to determine the composition of odor emission. However, it does not provide any information on the overall perception of odor samples, which according to the definition of odors, is the result of the overall olfactory effect of the individual components of the mixture [13,52]. Finding the relationship between individual odorants and their potential odor concentration is a difficult and complicated task. One method to do such a thing is to calculate an odor activity value (eq. 1) which is defined as the sum of ratios of between the concentration of each odorant contained in mixture to its odor detection threshold [13,39]. Odor activity value can also be calculated for a single odorant.

$$odor\ activity\ value\ = \sum_{i=1}^{n} \frac{C_i}{OT_i} \tag{1}$$

where:

C_i – concentration of i-odorant (mg/m^3),

OT_i – odor detection threshold of i-odorant (mg/ou),

odor activity value – odor activity value of analyzed mixture (ou/m^3).

One of the disadvantages of calculating the potential odor concentration using the odor activity value is that for complex odor mixtures it is not always possible to clearly relate the

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olfactory impact of specific odorant to its chemical concentration, therefore the calculated odor activity value can be relatively imprecise. Another factor that can lead to imprecise results is the challenge in obtaining trustworthy odor threshold values, as they can vary significantly over different literature sources [13,39].

Analytical techniques, especially gas chromatography couples with mass spectrometry is widely used in different literature studies regarding emissions of odorant in broadly understood waste management, examples can be found in [8,134]. In many cases, the literature studied presented in *Chapter 2.3,* as a basic method of qualification and quantification of odorant emission at studied cases, used the gas chromatography method.

3.1.6 Gas sensors

The identification of odorous substances can be accomplished using gas sensors. The costs associated with the use of sensors are significantly lower than in the case of, for example, chromatographic methods [125,135]. They allow for a real-time data acquisition of concentration of measured gases in proximity to the sensor. They are distinguished by their compact size, lightweight nature, and minimal power consumption [39].

Specific sensors can be used to determine a specific, single substance in the analyzed air. In some cases, when the problem of odor pollution is primarily attributed to the presence of a single substance, specific sensors prove to be exceptionally useful [13]. Ammonia and hydrogen sulfide concentrations are frequently measured in odor monitoring and by many literature sources they are treated as reference substances when it comes to odor pollution [39,51,136]. Specific sensors are commonly used in cases like this. A wide range of scientific studies are available regarding their use in the study of odor compounds in waste management, examples can be found in [30,34,59,61]. Authors of those studies used specific sensors to determine the concentration of hydrogen sulfide, ammonia, and methyl mercaptan. Chemical analysis using specific sensors can be used for determining both emission and immission values of concentrations. In cases where the odor problem is directly correlated with the presence of one specific odorant, the measured analytical concentration with the use of a specific sensors can be used to estimate the odor concentration by calculating the odor activity value [13,39].

Non-specific sensors, like Photoionization Detectors (PID), can be employed as instrumental assessment method in cases where the issue of odors is associated, for example, with the presence of volatile organic compounds [13]. These detectors work by ionizing the

organic compounds found in the gas being analyzed with the use of ultraviolet lamp. They give information about the concentration levels of all compounds that can be ionized within the sample. The analytical chamber comprises two plates between which a voltage difference is applied. As ionized by-products are produced, a current is generated and recorded. The intensity of this current is a direct measure of the number of ionized molecules. The main disadvantage of this method is the lack of information about the odor properties of substances that were in the analyzed air mixture. The problem is similar to those presented in the gas chromatography chapter [13,39]. Measurements of volatile organic compounds with the PID sensors were in the aim of recent studies regarding odors emitted form municipal waste management facilities [30,34,59,61].

The use of sensor arrays and electronic nose in odor assessment is one of the most advances techniques based on gas sensors [39,137–140]. They are based on the use of matrices of various sensors, both specific and non-specific, to collect comprehensive information about the analyzed mixture of odorous substances. Such an approach allows for a more detailed examination of the sample than in the case of single sensors. By applying proper training of these devices, using appropriate statistical, modeling, and predictive tools, and by collecting a sufficient database of odor samples, it is also possible to obtain information about the potential concentration of odors. These methods are continuously being developed and have gained significant popularity over the past few years.

3.2   COMPUTATIONAL METHODS IN ODOR RESEARCH

3.2.1   Odor dispersion modelling

Odor dispersion modelling is widely used as a tool to assess the potential impact of odor-emitting facilities [26,46,104,119,121,122]. By applying different mathematical approach to simulate the dispersion of odors, a spatial distribution of odors at receptor points (in most cases - residential areas) can be calculated and thus it allows to assess the potential impact on residents. Odor dispersion models usually combines meteorological, topographical and emission data to calculate the spatial distribution of odors at analyzed areas. Models usually differ in the degree of sophistication in parameterizing individual input data, i.e., meteorological, topographical, and emission parameters. There are numerous methods for mathematically modeling the dispersion of odor pollutants in the atmosphere. By the

mathematical foundations, three primary type of models are prominent in pollution dispersion modeling. These are Gaussian, Lagrangian, and Eulerian models respectively.

When it comes to modeling the dispersion of odor pollution in the atmosphere, Gaussian models are regarded as the simplest and most cost-effective tools. These models operate under the assumption that the pollution plume spreading from the source remains unchanged over time (the flow is homogeneous and constant) [119,121,141,142]. Therefore, they are so-called stationary plume models. Their fast computation time makes them the one of the quickest models for simulating pollution transport in the atmosphere. This efficiency is achieved as these models primarily solve a simple equations to compute the concentration levels at receptor locations, which is computationally inexpensive and can be executed on most computers. However, Gaussian models have notable drawbacks. Under stationary conditions or in low wind speeds, they tend to underperform and cannot provide reliable results. Additionally, the complex topography is a crucial parameter for these models [119,142]. In advanced Gaussian models, the influence of complex terrain and turbulence effects are taken into account and parameterized through relevant coefficients to enhance the accuracy of simulation results [119]. Initially, Gaussian models were developed to simulate the dispersion of pollutants from point sources, but they soon evolved to be applicable to surface, linear, and volume sources as well [143]. Due to the limitations of Gaussian models, which assume that both the emitted plume and meteorological conditions are constant over time, they are typically employed for estimating average annual and hourly concentrations of pollutants [143]. There is a variety of models that employ the Gaussian approach to predict the concentration of odor pollution at receptor points, including SCREEN3, ISCST3, ISC-PRIME, TAPM, and AODM. Among these, AERMOD is one of the most commonly used.

Lagrangian models employ a more sophisticated methodology compared to Gaussian models, and are often referred to as particle models. When predicting the dispersion of pollutants in the atmosphere, these models compute the pathways of virtual particles over short time spans within a designated wind field and a three-dimensional field of turbulence. The particles in this context symbolize a specific quantity of pollutants. The dispersion of pollutants in Lagrangian models integrates both stochastic effects (turbulence), and deterministic factors, which include the wind field and buoyancy. The motion of the computational particles is assumed to be random, which results in Lagrangian models being computationally demanding and resource-intensive [119,142–144]. Lagrangian models are also capable of functioning in

conditions with low wind or in calm conditions [46]. Additionally, there are hybrid models that incorporate both Lagrangian and Gaussian approaches, known as puff models. Puff models characterize the dispersion of pollutants using clouds or puffs with a fixed volume. The concentration levels within these puffs are determined by the Gaussian method, while the paths they follow are determined by the Lagrangian approach. One known example of a puff model is CALPUFF, a tool that has garnered global usage for environmental and scientific applications. CALPUFF can simulate the dispersion of odors originating from point, area, and volume sources. In order to simulate odor dispersion, it is crucial to acquire data including emission rates, meteorological information, and topographical data. Much like Gaussian models, CALPUFF can be employed to assess the range of odor impacts from various sources such as animal by-product processing facilities, landfills, waste and residue treatment and incineration plants, or food waste composting sites [120,122,145–147].

Eulerian models stand out as the most sophisticated in terms of mathematical basis. They are often referred to as grid models or 3-D models, a terminology that stems from the fact that the dispersion calculations of pollutants are performed within a three-dimensional domain that is partitioned into distinct cells or grids [26,143]. Eulerian models employ numerical methods to solve dispersion equations for turbulent flows generated by wind, and they compute the average concentration of pollutants within a particular 3D domain. The odor concentrations at receptor points are calculated by applying a specific initial and boundary conditions. One of the strengths of Eulerian models is that they are able to obtain more accurate representation of pollution in both space and time. Eulerian models are versatile and can be applied to small-scale scenarios as well as on a global scale. Within these models, concentrations of pollutants are determined for individual spatial cells, and they are especially effective under unstable atmospheric conditions. However, a significant disadvantage of Eulerian models is their requirement for substantial computational resources, which leads to higher costs associated with their utilization [119,142]. These models are primarily deployed to simulate the dispersion of various kinds of pollutants on a global scale, such as ozone. Nonetheless, literature indicates that they can be readily adapted for local-scale applications. One such tool that employs the Eulerian approach is ModOdour [26,143], which can be used to simulate odor dispersion from waste landfills and other waste management facilities. This exemplifies the adaptability and applicability of Eulerian models in tackling specific environmental challenges.

3.2.2 Spatial interpolation

The most advanced tools for spatial analysis involving Geographic Information Systems are instruments for surface modeling using spatial interpolation [148,149]. These can be natural, anthropogenic, physical, or abstract surfaces. The basis of interpolation is an approximation, which involves determining a function (eq. 2) for predefined values (eq. 3) that are distributed in a discrete manner, allowing for the determination of the interpolated value of a given feature at any point in space [150–152].

$$z = f(x, y) \tag{2}$$

$$z(x, y) \tag{3}$$

Spatial data interpolation directly draws from the so-called Tobler's Law [153]. It states that objects that are closer to each other, both in time and space, are more strongly connected than those that are further apart. Interpolation of data related spatially involves, among other things, converting point measurement data, which carry known information, value, or characteristics, into quantitative or qualitative data in neighboring locations/points where the studied value was previously unknown. In this way, point data are transformed into a continuous surface [148,149]. Both qualitative and quantitative characteristics can be subjected to interpolation. Spatial analysis using these methods is applied in situations where, for various reasons, whether technical, financial, or due to a lack of sufficient time, it was not possible to conduct an adequate number of measurements covering the desired research area. In the case of data interpolation methods, two groups of methods are distinguished. These are deterministic methods and geostatistical methods [154], respectively. Inverse distance weighted method is a widely used deterministic technique for interpolating environmental data [150,155,156], while kriging techniques are represents the wide group of commonly used geostatistical interpolation methods [153,156]. Some of the available studies address the topic of using spatial interpolation methods in the issue of odors, examples can be found in [47,54,55]. The topics of the issues addressed include determining the range of odor impact, identifying sources of odor emissions, and assessing the odor quality of the air around odor-emitting facilities. As most sensory methods involve assessing the odor at a given point, which does not allow for continuous, spatial monitoring, spatial interpolation methods seem to be an exceptionally useful tool in odor studies, especially considering the possibilities of identifying sources as well as their spatial and temporal variability.

Polish legislation lacks explicit legal regulations specifically targeting odor emissions from waste management facilities. Only a few general regulations linked to odor emissions are available. The Act of 14 December 2012 on waste (Journal of Laws of 2020, item 797)[64] defining in Chapter 1, Section II that waste management must be executed in a way that prevents nuisance caused by noise and odors. Furthermore, The Act of 27 April 2001 Environmental Protection Law (Journal of Laws 2001 No. 62 item 627)[157] allows for the establishment of regulations in scenarios where emission standards and permissible levels of substances in the air are undefined. Consequently, this Act opens the possibility for the establishment of specific reference values for odors in the air through regulation, as well as methods to evaluate air quality and the frequency or averaging periods of odorants' measurements [157]. These areas remain untouched by regulation. Another notable document within Polish legislation that specifically addresses odor emissions is the Regulation of the Minister of the Environment of 30 April 2013 on waste landfills (Journal of Laws 2013 item 523) [158]. This regulation states that landfills should be surrounded by a green belt of at least 10 meters in width to mitigate the risks linked to landfill operation, including the emission of odors [158]. In February 27, 2009, a Draft Law titled "Law on the prevention of odour nuisance" was introduced [159]. This proposed legislation outlined protocols for situations where odor nuisances are induced by business operations. It also elaborated on methods for assessing the quality of air in terms of odors, such as employing field measurement or odor dispersion modeling, and established odor concentration levels in the air for computational methods like odor dispersion modelling. Within this Draft Law [159], 1 ou/m^3 was established as the reference value for odor concentration in the air, and permissible frequencies for exceeding 1 ou/m^3 were defined, depending on the land use. However, this draft did not evolve into a formal Act.

It's important to note that in Poland, in addition to national regulations, European standards also apply due to the country's membership in the European Union. In 2018, the Best Available Techniques (BAT) Reference Document for Waste Treatment, also known as the BREF Document, was introduced to European Union members [53]. Alongside it, an annex in the form of an Implementing Decision by the European Union Commission, which established BAT conclusions for waste treatment, was presented [51]. These documents have been

assimilated into the Environmental Protection Law of April 27, 2001 (Journal of Laws 2001 No. 62 item 627) and are now applicable to waste management facilities in Poland [157].

The BREF Document [53] is a culmination of information exchange between European Union member states, relevant industries, non-governmental organizations focusing on environmental protection, and the European Commission. It encompasses widely employed techniques, current emission levels, and technologies deemed optimal within the waste management sector. The European Union Commission Implementing Decision establishing conclusions on best available techniques (BAT) for waste treatment [51] is the second European document, incorporated into Polish law, which summarizes different measures to mitigate odor emissions. It draws from the BREF Document, summarizing the best available techniques regarding waste treatment, and offering detailed insights into these techniques. The BAT conclusions are not prescriptive and allow the use of alternative techniques, only if comparable environmental protection standards are achievable. Moreover, BAT conclusions do not focus only on description of technologies for reducing odor emissions but also outline a series of non-technological actions to enhance environmental performance by waste management facilities [51]. Some of the most important conclusions from the perspective of odor problem are summarized below. BAT 1 advocates for the implementation of an environmental management system that includes management involvement, defining environmental policies, implementing procedures, efficiency checks, corrective measures, and considerations of environmental impacts associated with facility decommissioning at the final stage of its operation. BAT 2 outlines activities for improving environmental performance by implementing proper waste characterization procedures, proper waste pre-collection and collection procedures, tracking systems, development of waste quality management systems. BAT 10 indicates the importance of regular odor emissions monitoring using EN, ISO, or other standards when EN standards are not accessible. BAT 12 discusses odor management plans, which should include protocols containing actions, timelines, odor monitoring based on BAT 10, response protocols for odor incidents, and programs to prevent and mitigate odor episodes. BAT 13 and 14 list actions aimed at preventing or reducing odor emissions, such as minimizing waste storage times, employing chemical waste treatments, optimizing aerobic waste treatment, limiting the number of diffuse sources, and employing equipment with high integrity, limiting the dispersion of odors, collecting and processing diffuse emissions through the use enclosed devices or buildings, maintaining proper pressure in them, directing emissions to emission reduction systems. The BAT conclusions also provide recommendations for specific waste treatment

processes, such as aerobic waste treatment, anaerobic waste treatment, and mechanical-biological treatment processes.

From the perspective of worldwide regulations adopted by specific countries a high diversity of different standards regarding odors can be found [49,50]. Over the years, these regulations have changed significantly and continue to evolve. Particular attention should be paid to the diverse criteria related to the assessment of the odor impact of facilities that may emit odors. Despite the diversity of regulations, a commonly used approach is the assessment of exceedances of a given odor threshold values at the receptors on an annual scale by applying mathematical modelling. As stated above, in Poland, aforementioned draft law regarding the prevention of odor nuisance [159] proposed as a reference value for the threshold of odor detection at the receptor points the value of 1 ou/m^3, and the permissible value of exceedances of that value at the level of 3% of hours per year (262 h). By applying different values of aforementioned parameters, the possible odor impact could vary significantly. Authors of [129] applied 1 ou/m^3 as a permissible value of odors in the air at receptor points with the frequency of exceedance of that value set at 3% on an annual scale (based on the polish draft law) and values of 5 ou/m^3 and 2% (Dutch guidelines) respectively for the purposes of odor dispersion modelling from selected agricultural plant. The results shows a significant difference between those two approaches.

5   SUMMARY OF THE LITERATURE REVIEW

From the conducted literature review, the following conclusions can be drawn:

- The waste management sector is an important source of odor emissions into the environment. The complexity of the waste management chain makes controlling of the generated odors a challenging task. Odors can originate from the very first stages of waste management, such as during collection in household containers, and continue until the waste reaches its final facilities of its management. The final disposal sites in the form of mechanical-biological waste treatment plants are one of the most complicated sources of odor emissions in the entire waste management chain. Various processes that can emit odors are intensified within these facilities, ranging from waste storage, sorting, aerobic and anaerobic treatment, to landfilling. Each of these sources can contribute to odor emissions. Considering the multitude of sources and the degree of their spatial dispersion

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within boundaries the mechanical-biological waste treatment plants, describing them, taking into account temporal and spatial variability, is a complex task.

- Inconsistent and imprecise regulations at the national level, as well as the lack of specific regulations at a unified European level, mean that control over odor emissions, especially in the case of waste management, is not regulated to any extent. The conclusions of the Best Available Techniques for waste treatment indicate, among other things, the need to introduce so-called odor management plans, which cover methods of monitoring of odors that would allow for the determination of emission variability at the sources. This opens up a wide range of possibilities for the application of various tools for this purpose.

- In the available literature, there are many measurement and modeling tools that can potentially be used in odor management plans in accordance with the Best Available Techniques for waste treatment. Among the measurement tools, field olfactometry can be distinguished, which is used to determine odor concentrations, together with parametric measurements of basic odor characteristics such as odor character, odor intensity, or hedonic quality, and the measurements using sensors, both specific and nonspecific, to determine the concentrations of individual odorants or their mixtures. The most popular modeling tools are those used for modeling the dispersion of pollutants in the air in order to determine the range of odor impact of the facilities under study. Additionally, literature sources indicate the use of interpolation methods in odor studies.

- Each of the methods mentioned above may be used as a potentially separate odor monitoring strategy in waste management, which may find potential application in odor management plans. For this reason, it is necessary to evaluate each of the methods used in odor studies in terms of this application and their usefulness for long-term and short-term monitoring.

6 METHODOLOGY

6.1 CHARACTERISTICS OF ADOPTED ODOR MONITORING STRATEGIES FOR RESEARCH PURPOSES

In order to achieve assumed objectives of the work, i.e.:

- assessment of the suitability of selected odor monitoring strategies for short and long-term purposes;

- determining the variability of odor emissions from selected processes or installations located on the premises of a selected waste management facilities;

- conducting an analysis of the temporal and spatial variability of odor concentrations, odor intensity, and volatile organic compounds in the area of selected waste management facilities alongside with an assessment of their correlation;

- and evaluation of the influence of the variability of odor emissions from selected processes in the seasonal cycle on the range of odor impact of selected waste management plant,

5 main strategies of odor monitoring were considered. All measurements related to the implementation of the assumptions of the work were made at 3 different municipal waste management plants (Facility #1, Facility #2, Facility #3), whose main method of processing municipal waste was mechanical-biological waste treatment. Facility #1 was the main research object in the whole study. As indicated in the *Chapter 1.3*, considered odor monitoring strategies are:

- Strategy No. I based on field olfactometric measurements,

- Strategy No. II considering the methods of spatial data interpolation, with the use of inverse distance weighted interpolation method,

- Strategy No. III based on odor intensity measurements and its relation to odor concentration,

- Strategy No. IV based on volatile organic compounds measurements and its relation to odor concentration,

- and Strategy No. V based on odor dispersion modelling.

The scope of work related to the implementation of research on individual strategies is presented below. Characteristics of selected Facilities is provided in *Chapter 6.2*, while basics principles of selected measuring techniques, their potential application in odor research, and characteristics of used devices are provided in *Chapter 3.2, Chapter 3.3, Chapters 6.2-6.5*, respectively.

6.1.1 Strategy No. I

The research scope of the Strategy No. I consists of a series of odor concentration measurements utilizing the field olfactometry technique at the premises of Facility #1. The scheme of research flow is presented in the Figure 14.
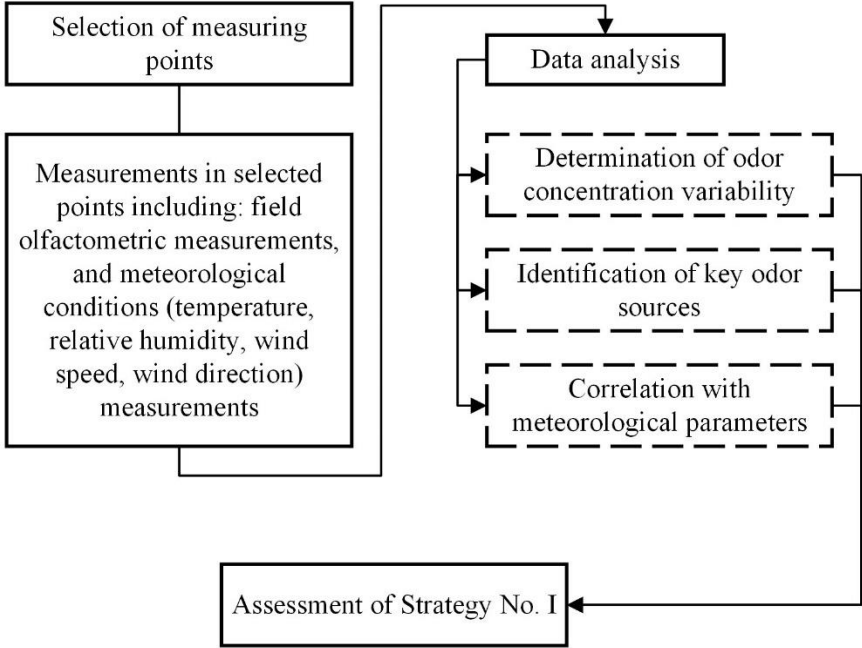

Figure 14. The research flow of the Strategy No. I.

The first step was the determination of measuring points. 35 measuring points were selected at the area of selected Facility #1. 22 out of 35 measuring points were located in the open air, and the remaining 13 were located inside of the technological buildings. Measurement points included places that could be a potential source of odors or could be directly affected by them. They were considered as a representative for the whole Facility. The measuring points in the open air include, among others, the administrative building and technological area, selective waste storage area, bulky waste storage area, 3 point located around active landfill site, points scattered around aerobic stabilization area and green waste storage area, 2 biolfilters, biological leachate tank and landfill leachate tanks. Points located inside technological buildings include, among others, RDF preparation and storage building, waste sorting hall, waste reception hall, anaerobic processing technological building, and bioreactors for aerobic treatment. For the exact location of measuring points and the description of Facility #1 see *Chapter 6.2.1*.

The main research method for the realization of Strategy No. I was field olfactometry using Nasal Ranger device by St. Croix Sensory, Inc. In every measuring points odor

concentration was determined with the field olfactometry method. The methodology of concentration determination using olfactometers, together with the specification of used field olfactometer, is presented in *Chapter 6.3.1*. Besides odor concentration, meteorological parameters such as temperature, humidity, wind direction and its speed were monitored as well. The measuring campaign at the Facility #1 span over the one year duration, starting in November 2021, and ending in October 2022. The measurement series includes 11 measurement days for the mentioned period. 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. The primary objective of this strategy was to assess the variability of odor concentrations at a chosen Facility. This involved identifying the processes that are responsible for the highest odor emissions, identifying the most problematic areas, and the assessment of influence of meteorological conditions on the measured odor concentrations.

6.1.2   Strategy No. II

The research steps for the realization of Strategy No. II are shown in Figure 15. For this strategy, 22 measuring points located in the open air in the premises of Facility #1 were selected. Those points were used as an input data for the inverse distance weighted interpolation method. By implementing the calculation methodology of inverse distance weighted method, spatial distribution of odor concentrations were obtained. The description of inverse distance weighted method is provided in *Chapter 6.5.1*. Together with odor distribution calculations, a cross-validation of obtained data was provided. The evaluation of the obtained spatial distributions was carried out based on the cross-validation results, namely the Mean Error and Root Mean Square Error parameters. The final assessment of the usefulness of selected interpolation method for odor sources identification was provided by coupling the results of graphical spatial distribution and cross-validation results.
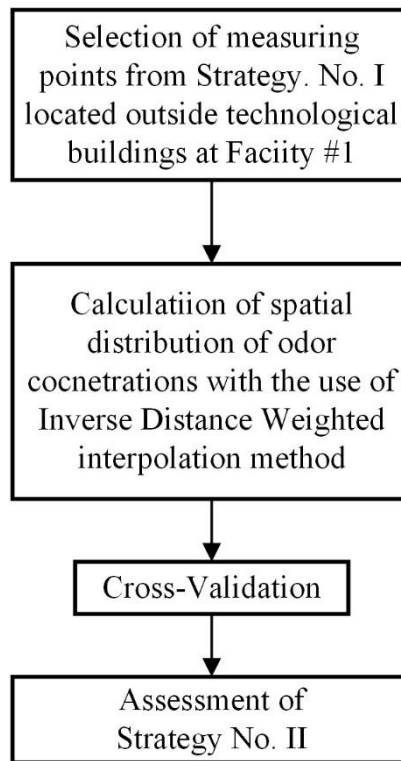
```
┌─────────────────────────┐
│   Selection of measuring │
│   points from Strategy. No. I │
│  located outside technological │
│   buildings at Faciity #1 │
└─────────────────────────┘
            │
            ▼
┌─────────────────────────┐
│   Calculatiion of spatial │
│   distribution of odor   │
│  cocnetrations with the use of │
│  Inverse Distance Weighted │
│   interpolation method   │
└─────────────────────────┘
            │
            ▼
    ┌─────────────────┐
    │ Cross-Validation │
    └─────────────────┘
            │
            ▼
    ┌─────────────────┐
    │   Assessment of  │
    │  Strategy No. II │
    └─────────────────┘
```

Figure 15. Research steps used for the implementation of Strategy No. II.

6.1.3 Strategy No. III

The measurements of odor intensity to determine the correlation between odor intensity and odor concentrations for the implementation of Strategy No. III were carried out simultaneously with olfactometric measurements used for the realization of Strategy No. I and Strategy No. II. Research steps used for the implementation of Strategy No. III are shown in the Figure 16. The main scope of the Strategy No. III was to find the degree of correlation between odor intensity and odor concentration. The Weber-Fechner Law was used to evaluate its applicability for calculating odor concentrations based on intensity values. At the end, the usefulness of parametric measurements on the basis of odor intensity in the identification of odor sources and the assessment of emission variability based on the odor intensity parameter was assessed. The information about odor intensity scale, Weber-Fechner Law, and the data categorization for the purposes of correlation assessment are provided in *Chapter 6.3.2*. The measuring campaign span over the same duration as in the case of Strategy No. I.
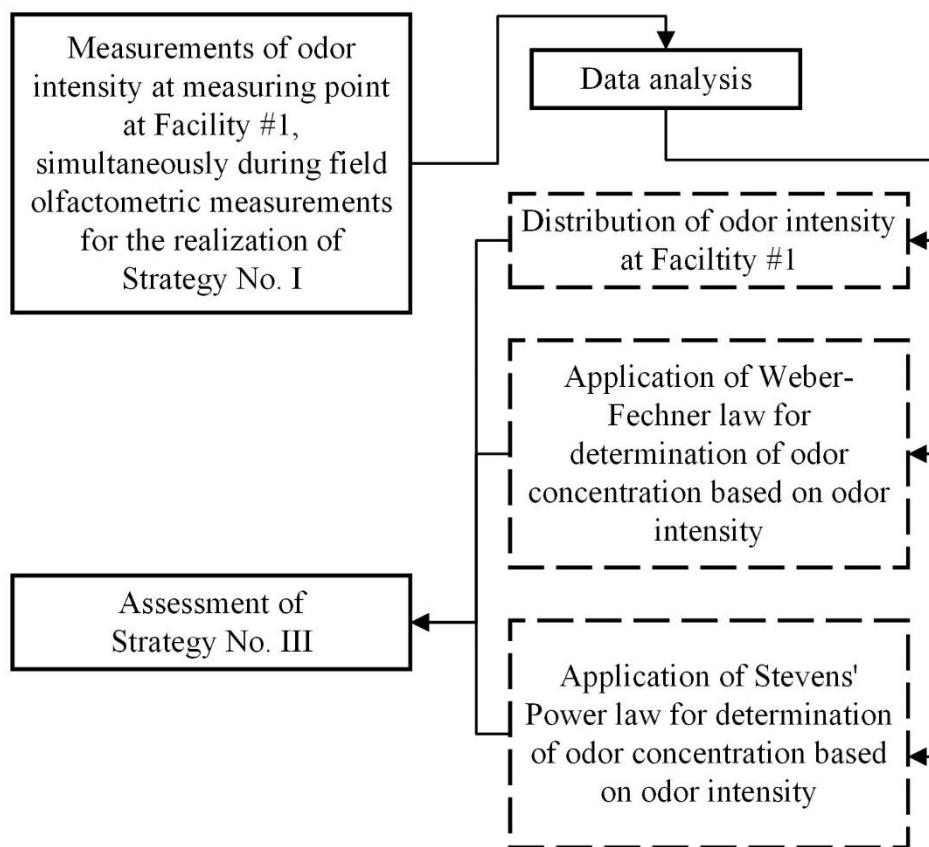
Figure 16. Research steps used for the purposes of realization of Strategy No. III.

6.1.4 Strategy No. IV

To assess the correlation between volatile organic compounds and odor concentration measured by field olfactometry method, and to assess the usefulness of such a measurements in odor monitoring, a different measuring campaign was carried out. Research scheme is provided in Figure 17. In the case of Strategy No. IV, three different waste management facilities were considered. First measuring object was the Facility #1 used for realization of pervious strategies, the second one was Facility #2, and the third one was Facility #3, which are described in *Chapter 6.2.1 – 6.2.3*. Volatile organic compounds measurement at Facility #1 were carried out in following dates: 13.10.2022, 17.02.2023 in the same measuring points as in the case of Strategy No. I. Measurements at Facility #2 were provided only once, in the 23.11.2022, covering 21 measuring points. 16 were located outside technological buildings and 5 of them inside technological buildings. Facility #1 and Facility #2 are characterized by a high degree of similarity in terms of technological processes used. In the case of Facility #3, measurements were carried out in two different days, 24.10.2022 and 02.11.2022. In this case, measuring campaign covers 26 measuring points. Only 2 of them were located inside. Facility

#3 is characterized by different technological processes and technological regime. Full description of measuring points and selected Facilities see *Chapter 6.2*. The selection of points at Facility #2 and Facility #3 was dictated by places that may emit or be directly influenced by other odor sources, same as in the case of Facility #1. The choice of measuring points was considered as representative for selected Facilities.
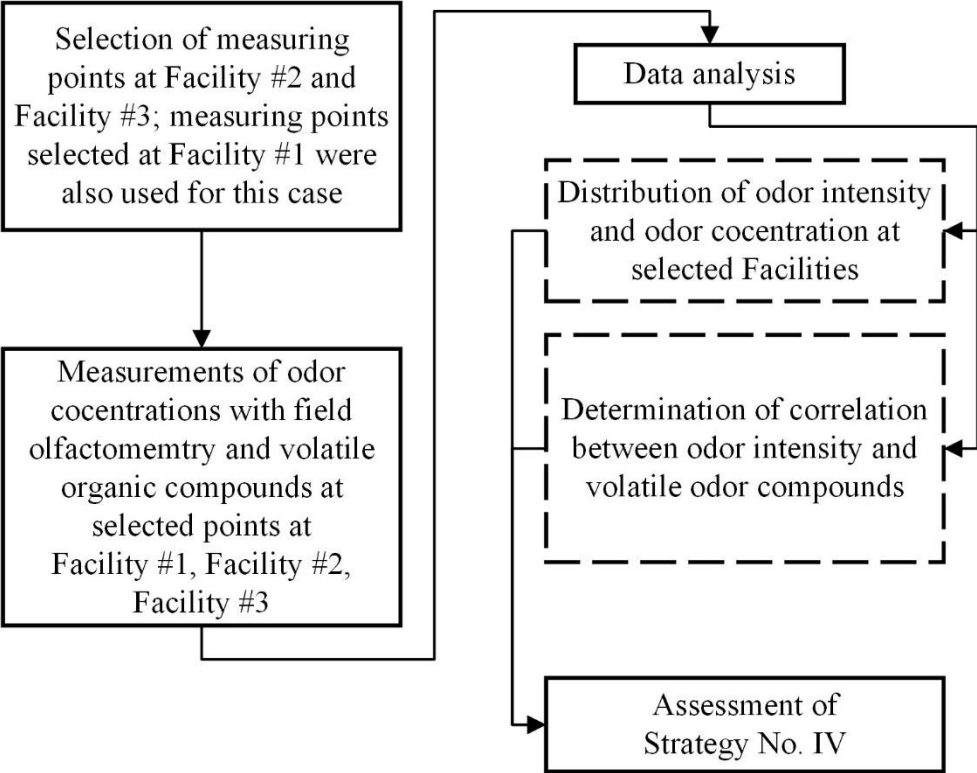
Figure 17. Research flow of Strategy No. IV.

6.1.5 Strategy No. V

Strategy No. V was used to characterize the extent of possible odor impact of selected Facility. For this purposes a Facility #1 was considered and a 10 different odor sources were included in odor dispersion modelling. Those include, among others, green waste storage area, aerobic stabilization area, biofilter for aerobic processes, biofilter for anaerobic processes, landfill area, two landfill leachate tanks, biological leachate tank, and fans located at the top of waste sorting hall (5) and waste reception hall (4). The location selected odor sources and locations of sampling points is provided in *Chapter 6.2.1*. 79 total of samples were collected with the use of ventilated sampling hood. The methodology of the whole sampling process is shown in *Chapter 6.3.4*, together with the description of odor concentration determination. On the basis of determining odor concentration, the emission factors were calculated for each

source. Two modelling scenarios were considered. First scenario was based on the assumption that emissions from sources are constant over time. Therefore no emission variability was considered. For the second scenario different levels of emission variability for each source was assumed. In addition, simple diffusion coefficients, based on the assumption that substances such as hydrogen sulfide and ammonia are emitted in selected sources, were included in the variability. The CALMET/CALPUFF system was used for odor dispersion modelling, which is described in *Chapter 6.5.2*. Figure 18 shows the research flow of Strategy No. V
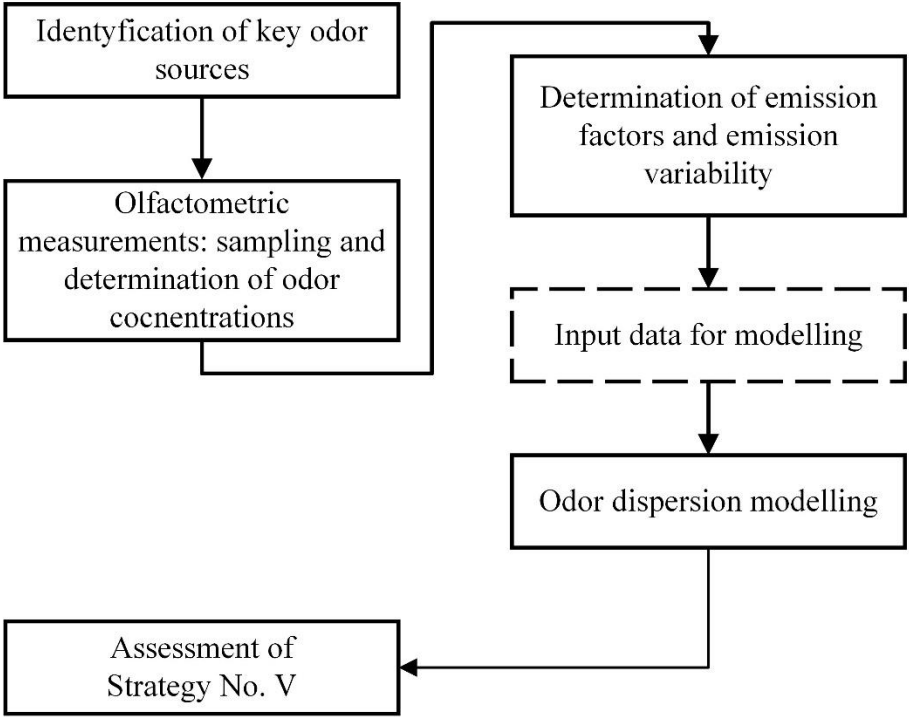
Figure 18. Research flow of Strategy No. V.

6.2 CHARACTERISTICS OF SELECTED WASTE MANAGEMENT FACILITIES

6.2.1 Facility #1

The first plant that was the object of research was the mechanical-biological waste treatment plant (Facility #1) located in the Dolnośląskie voivodship (south-western Poland). The maximum capacity of the Facility 1# is up to 106,000 Mg/year. The main stream of waste delivered to the plant is municipal waste. The treatment of mixed municipal waste takes place in two main parts of the Facility. First one is the mechanical part. The processing capacity of mechanical is up to 65,000 Mg/year for mixed municipal waste and up to 15,000 Mg/year for nonmixed waste. The main section of the mechanical part is a sorting hall with a series of

conveyors, sieves, and separators that allows for the separation of individual waste fractions (e.g. ferrous metals, non-ferrous metals, different types of plastics, paper, cardboard, and so forth). Two sorting cabins are integrated into the sorting line for manual sorting of waste stream. Mixed waste is collected in a separate waste reception hall, from where it is fed to the sorting line. Separators and a sieve located in the aerobic stabilization area also belong to the mechanical part of the Facility.

The second part of Facility #1 is the biological part, with waste processing capability of 31,000 Mg/year. The biological part consists of two main processes, therefore two main technological lines are present. The first is anaerobic digestion, where up to 31,000 Mg of waste using methane fermentation is processed yearly. As an input for anaerobic digestion, a fraction of 0-60 mm separated from mixed waste in the mechanical part is used. Anaerobic digestion is carried out in two digester with an operative volume of 1,200 m^3 each. Anaerobic treatment can be supplied by using fats, kitchen and restaurant waste, which is stored in standalone tanks. The resulting biogas partially covers the plant's demand for heat and energy, therefore a biogas preparation unit is built into the aerobic digestion installation, as well as a cogeneration and cooling units. To mitigate the potential odorous emissions a biofilter with a scrubber is integrated into the whole system to discharge the processed, odor polluted air.

The second installation at the biological part of the Facility #1 is the installation for aerobic waste treatment. Six sealed bioreactors are the foundations of aerobic treatment. Each equipped with an aeration system, a sprinkler system, and leachate drainage. Three main processes are carried out in bioreactors, depending on the Facility's need and processing capacity. They are: aerobic stabilization, composting, and biological drying respectively.

Up to 27,000 Mg of organic fraction after the anaerobic digestion is processed yearly in the 5 bioreactors. In the sixth bioreactor, up to 6,000 Mg yearly of selectively collected biowaste and other biowaste are handled in the form of composting process. Depending on the processing capacity and needs of the plant, other fractions of biodegradable waste can be processed in bioreactors. All of the bioreactors are connected to the second biofilter (separated from the first one) integrated with the scrubber by ventilation system in order to reduce potential odorous emissions. After aerobic waste processing the material undergoes maturation stage at maturation yard in the open air, where stabilizate and compost cleaning area is present.

Figure 19 shows a schematic map of the Facility #1 with marked main installations and areas of interest.

Facility #1
Scale: 1:9500

A - Administrative buulding
B - Technical area
C - RDF preparation and storage building
D - Waste reception hall
E - Waste sorting hall
F - Selective waste storage area
G - Active landfill
H - Landfill leachate tanks
I - Bulky waste processing and storage area
J - Anaerobic digestors

K - Fermentation technical building
L - Biofilter for anaerobic processes
M - Aerobic bioreactors (6x)
N - Maturing yard for composting and aerobic stabilization
O - Biofilter for aerobic processes
P - Tank for biological leachates
R - Reclaimed closed landfill area
S - Biogas tank

Figure 19. Map of Facility #1 with marked main installations and areas of interest.

In addition, the production of refused-derived fuel with the up to 20,000 Mg yearly is carried out at the Facility #1. Three landfill quarters (two decommissioned, one under ongoing exploitation with a maximum volume of approx. 27,000 m^3). The plant has necessary separate storage places, technological areas and all necessary equipment for its environmental friendly and uninterrupted operations.

Facility #1 was used for the purposes of implementation of Strategy No. I, II, III, IV, and V. Figure 20 shows measuring points determined at the selected Facility #1 for the purposes of Strategies I-IV. Selected measuring points represent potential sources of odors and odorous compounds emission, as well as points that could be affected by emissions from different sources. Overall, 35 points were selected at Facility #1. 22 out of 35 are located outside, in the open air, scattered around Facility#1 area. 13 out of 35 are located inside technological buildings. The following measuring points (Figure 19) were used for the purposes of field olfactometric measurements, inverse distance weighted interpolation, determination of odor intensity-odor concentration relationship, and for the purposes of volatile organic compounds measurements. In addition, Facility #1 was used for the implementation of Strategy No. V. i.e., was used as a sources of emission data for odor dispersion modelling. The points from which samples were taken for determining the odor concentration using dynamic olfactometry are shown in Figure 21.

Facility #1

Scale: 1:9500

● Measuring points 1
▭ Facility borders

Scale: 1:4500

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 - Landfill site 1st point
12 - Landfill site 2nd point
13 - Bulky waste processing and storage area
14 - Aerobic stabilisation area 1st point
15 - Aerobic stabilisation area 2nd point
16 - Anaerobic processes technical building
17 - Biofilter (anaerobic processes)
18 - Green waste storange area 1st point

16 - Anaerobic processes technical building
17 - Biofilter (anaerobic processes)
18 - Green waste storange area 1st point
19 - 24 - Bioreactosr 1-6
25 - Between aerobic stabilisation chambers and green waste storage area
26 - Green waste storage area 2nd point
27 - Biofilter (aerobic processes)
28 - Aerobic stabilisation site 3rd point
29 - Aerobic stabilisation site 4th point
30 - Between landfill site and aerobic stabilisation
31 - Leachate tank for biological processes
32 - Facility border
33 - Landfill leachate tank 1st point
34 - Landfill leachate tank 2nd point
35 - Landfill leachate tank 3rd point

Figure 20. Location of measuring points at Facility #1.

64
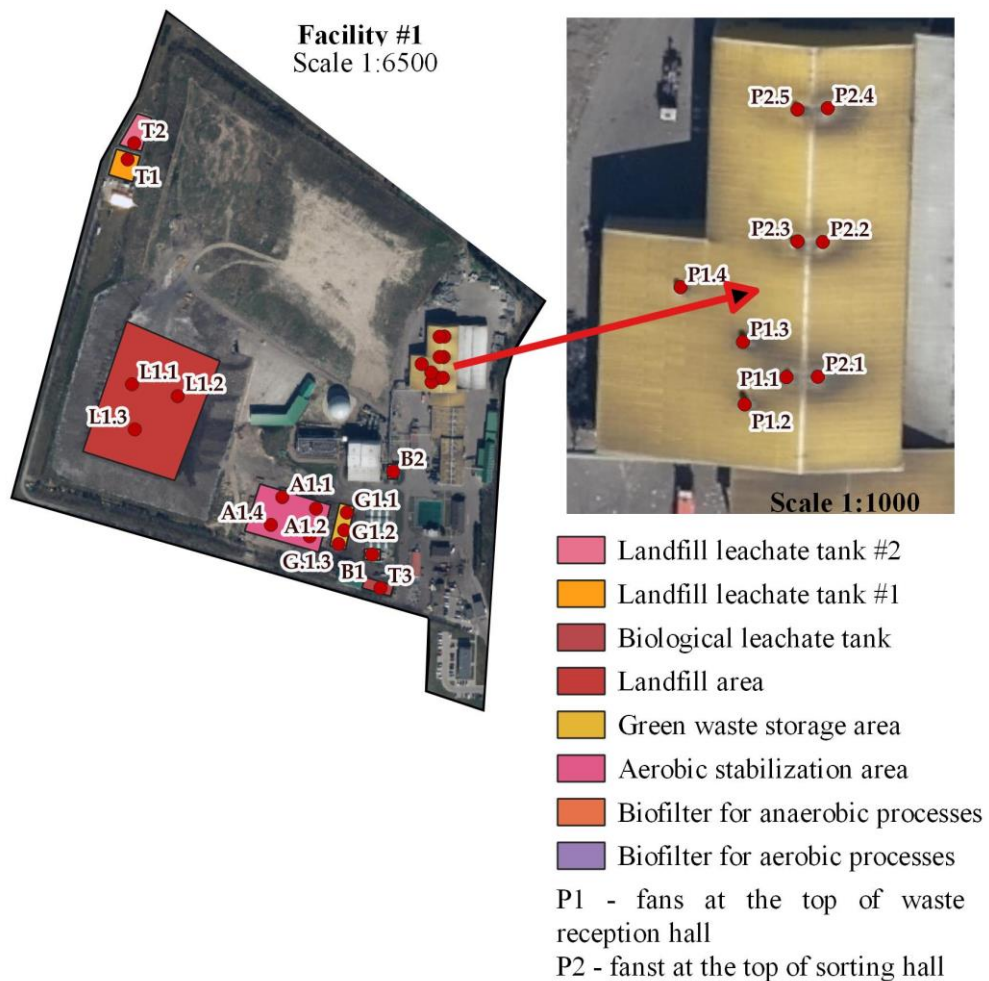
Figure 21. Selected odor sources used in odor dispersion modelling with the use of CALMET/CALPUFF system (Strategy No. V) together with location of sampling points for dynamic olfactometric measurements.

6.2.2 Facility #2

The second Facility used for the research purposes is also a mechanical-biological waste processing plant. The Facility #2 operates in the field of processing, disposal and collection of waste, including mixed municipal waste, which is similar to Facility #2. Two main parts can be distinguished within the plant boundary: "the new part" where the main waste processing takes place and "the old part" of the plant. Installations where ongoing main activities related to the processing, disposal and collection of waste are carried out under the integrated permit obtained by the Facility #2 are listed below:

- installation for mechanical-biological treatment of unsorted (mixed) municipal including:

- mechanical processing of municipal waste at mechanical part of Facility #2,
  - biological waste treatment by the means of aerobic stabilization and anaerobic digestion (methane fermentation),
- sorting line for processing (sorting and cleaning) selectively collected municipal waste,
- composting plant for biowaste constituting municipal waste and other biodegradable waste,
- bulky waste processing line,
- point of selective collection of municipal waste for residents,
- non-hazardous and non-inert waste landfill (for municipal waste).

When it comes to "the old part" of the Facility, there are: a small sorting plant for selectively collected waste, crusher for construction waste, processing of mixed post-renovation waste, collection of problematic waste, for example, collection of electronic waste. Figure 22 shows a schematic map of the Facility #2 with marked main installations and areas of interest.

Facility #2

Scale: 1:11000
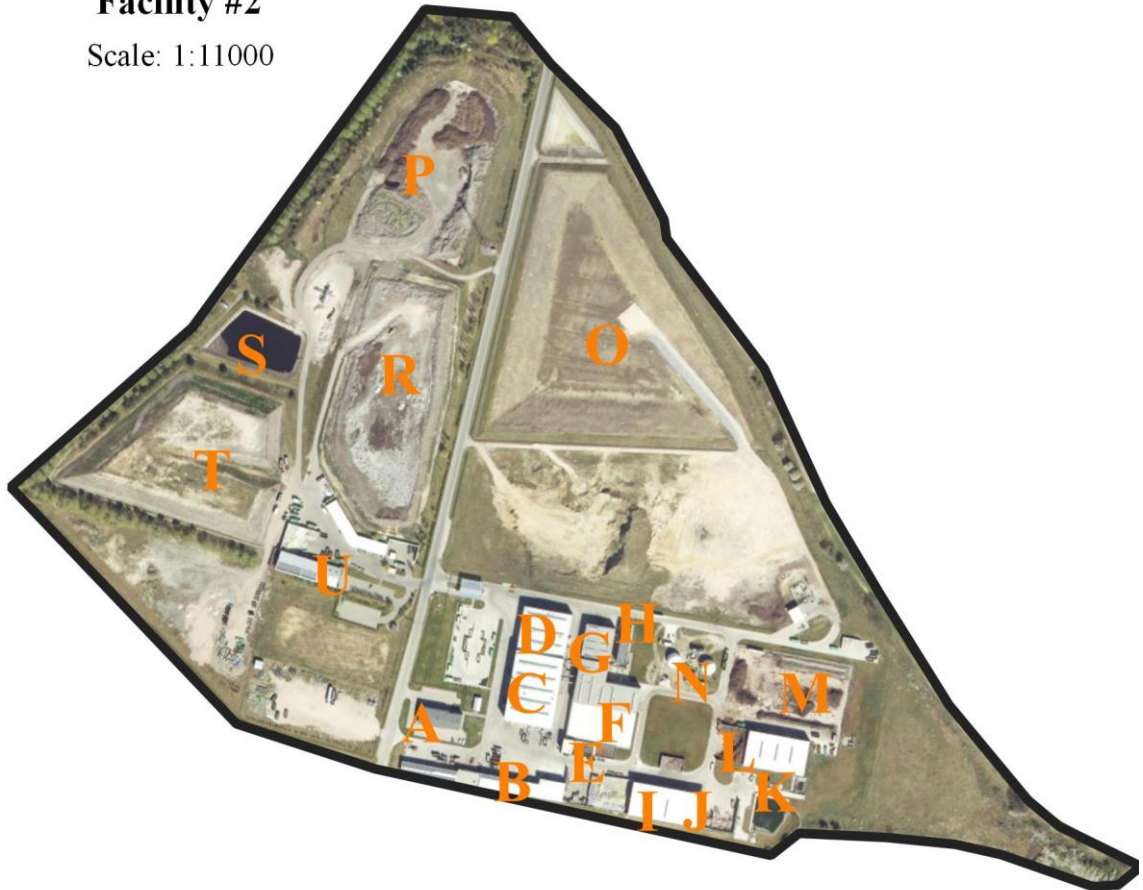
A - Administrative building
B - Sorted waste storage area
C - Sorting hall
D - Waste reception hall
E - Biofilter
F - Hall for aerobic processes
G - Waste reception hall for anaerobic processes
H - Anaerobic digestor
I - RDF storage
J - Bulky waste processing area
K - Wastewater treatment plant
L - Green waste storage area

M - Maturin yard
N - Biogas tank
O - Landfill area
P - Reclaimed landfill area
R - Closed landfill area
S - Leachate tank
T - Photovoltaic farm
U - Small sorting plant

Figure 22. Map of Facility #2 with marked main installations and areas of interest

Similar to Facility #1, the second plant in the mechanical part has a separate sorting hall with a series of conveyors, sieves, and separators that allows for the separation of individual waste fractions, and a separate waste reception hall. In the contrast with the Facility #1, the aerobic processes are carried out in bioreactors located inside a hall, providing double encapsulation of the process. The waste gas stream is discharged into the biofilter coupled with

an acid scrubber. Facility #2 has separate digestor for anaerobic digestion process and a separate hall for waste reception used in that process. Maturation of the compost material and stabilizate is carried out in the open air. The plant has all necessary equipment for its uninterrupted and highly standardized operation. Facility #1 and Facility #2 have a high degree of connection in the technologies used and show an equally high standard of municipal waste processing.

Facility #2 was used for the purposes of implementation of Strategy No. IV. Figure 23 shows measuring points determined at the selected Facility #2. Selected measuring points represent potential sources of odor and odor compounds emission, as well as points that could be affected by emissions from different sources. Most of the measurement points are located in the open air (16), only a few are located inside technological buildings (these are points number 4, 5, 6, 8 and 9 – located in sorting hall, waste reception halls, and aerobic treatment hall).

Facility #2
Scale: 1:15000

● Measuring points
▢ Facility borders

1 - Administrative building
2 - Selective waste storage area
3 - Entrance to sorting hall
4 - Beginning of the sorting line
5 - Waste reception hall
6 - In the middle of the sorting line
7 - Biofilter
8 - Aerobic stabilization hall
9 - Waste reception hall for anaerobic processes
10 - RDF storage
11 - Bulky waste storage
12 - Wastewater pretreatment plant
13 - Green waste storage

14 - Waste stabilization yard after aerobic processes
15 - Waste stabilization yard after anaerobic processes
16 - Landfill site
17 - Reclaimed landfill site
18 - Closed landfill site
19 - Leachate tank
20 - Photovoltaic farm
21 - Technical yard

Figure 23. Location of measuring points at Facility #2.

6.2.3 Facility #3

The third Facility used for the research purposes, like its predecessors, is also categorized as a mechanical-biological waste treatment plant. As part of Facility #3, the following installations and activities are carried out:

- mechanical and manual processing of mixed municipal waste
- mechanical and manual processing of waste other than mixed municipal waste,
- biological treatment of a biodegradable fraction of at least 0-80 mm separated from mixed municipal waste,
- biological processing of selected types of biodegradable waste other than the separated from mixed municipal waste,
- biological processing of selectively collected green waste and other biowaste, together with other biodegradable waste,
- collection of municipal and industrial waste,
- processing (disassembly) of bulky waste,

with the possibility of development of around 320,000 Mg of waste per year. The Facility #3 provides external services regarding the renovation of degraded areas.

Mechanical-biological treatment of waste is carried out in two main installations. An installation for mechanical and manual processing of waste and consists of:

- recovery of unsorted (mixed) municipal waste aimed at separation of specific fractions that can be used for material or energy purposes and separation of the biological fraction requiring further biological processing,
- recovery of waste other than mixed municipal waste for preparation them for recovery purposes.

Maximum capacity of the installation for mechanical-manual processing of waste is 160,000 Mg/year. The installation is located in the technological hall where waste crusher, sieve for separating fractions of 0-80 mm and fractions above are located, as well as sorting cabin, magnetic separator and control room. Screen for separation of fractions 0-20 mm and above and magnetic separator are located outside of the hall. Installation for the biological treatment of waste, consisting of "closed part" (closed tunnels acting as bioreactors), and an "open" part (maturation yard) and relies on:

- disposal of the biodegradable fraction of at least 0-80 mm separated from mixed municipal waste,
- disposal of selected types of biodegradable waste other than separated from mixed municipal waste,
- recovery of selectively collected green waste and other biowaste, including others biodegradable waste,
- recovery of other biodegradable waste than selectively collected green and other biowaste.

The maximum capacity of the installation for the biological treatment of waste is 75,000 Mg/year.

Facility #3 is significantly different from Facility #1 and Facility #2. The main difference is in the biological treatment of waste. Facility #1 and Facility #2 process waste under aerobic and anaerobic conditions, while Facility #3 rely only on aerobic waste processing. In facility #3 biological treatment is carried out in closed, plastic tunnels filled with biodegradable matter with sprinkler systems, leachate collection and aeration systems located inside the tunnel. Tunnels are located outside, in the open air. Maturation stage is carried out in open air like in the case of Facility #1 and Facility #2. It is worth noting that Facility #3 does not have its own landfill.

Figure 24 shows a schematic map of the Facility #3 with marked main installations and areas of interest.

Facility #3

Scale: 1:5000
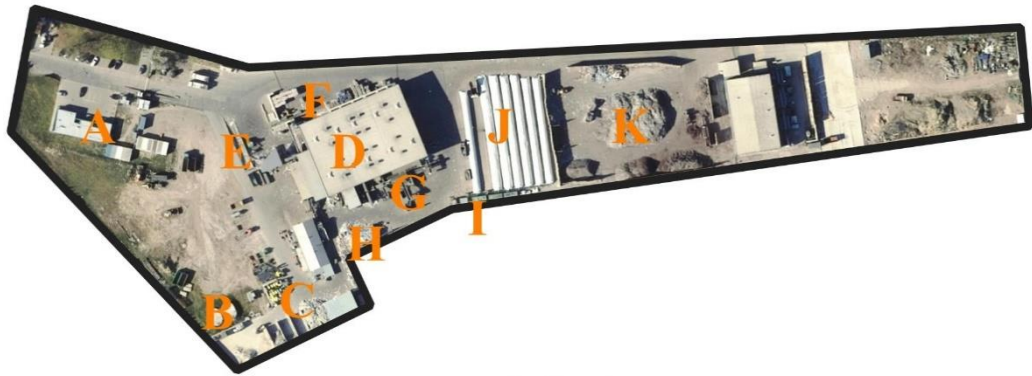
A - Administrative building
B - Leachate tanks
C - Selective waste storage area
D - Mixed municipal waste and green waste reception hall and sorting hal
E - Beginning of the sorting line (waste feed) and temporary mixed waste storage

F - Sorted waste storage area
G - RDF production
H - Mixed waste storage area
I - Biofilters foor aerobic treatment processes
J - Bioreactors in the form of closed, plastic tunnel
K - Waste storage area (Mixed municipal waste, shredded municipal waste, RDF, intert waste, bulky waste)

Figure 24. Map of Facility #3 with marked main installations and areas of interest.

Similar to Facility #2, Facility #3 was used for the purposes of implementation of Strategy No. IV. Figure 25 shows measuring points determined at the selected Facility #2. Selected measuring points represent potential sources of odors and odorous compounds emission, as well as points that could be affected by emissions from different sources. Similar to Facility #2, most of the measurement points are located in the open air (24), only two points are located inside buildings, i.e. points number 12, and 13 are located inside waste reception hall.

Facility #3

Scale: 1:6700

● Measuring points

▭ Facility borders

1 - Administrative building
2 - Leachate tanks
3 - Selective waste storage area
    1st point
4 - Selective waste storage area
    2nd point
5 - West entrance to waste reception
    and sorting hall
6 - Mixed waste storage
    (waste loading area to sorting line)
7 - Facility corner (sorted waste
    storage area)
8 - Facility corner
9 - East entrance to waste reception
    and sorting hall
10 - Shredded waste unloading area
11 - Mixed waste storage
12 - Green waste storage
13 - Mixed waste storage

14 - North-west corner of biological
    processing area
15 - Middle of the biological processing
    area
16 - North-east corner of biological
    processing area 17 - South-west
corner of biological
    processing area
18 - South-east corner of biological
    processing area
19 - RDF storage
20 - Shreded mixed waste storage
21 - Composted material storage
22 - Shreded mixed waste storage
23 - Mixed waste storage
24 - Bulky waste storage
25 - Mixed waste storage
26 - Mixed waste storage

Figure 25. Location of measuring points at Facility #3.

6.3 OVERVIEW OF EMPLOYED MEASUREMENT METHODS AND THEIR APPLICATION IN RESEARCH

6.3.1 Determination of odor concentration by the means of field olfactometry

The Nasal Ranger device by St. Croix Sensory, Inc. [124] was used in the odor concentration measurements. It is a portable field olfactometer that allows to measure odor concentrations in-situ. The basic operating principles of the chosen field olfactometer are based in the concept of the dilution to threshold ratio. Its main purpose is to combine odor contaminated air with clean, filtered through pair of activated-carbon filter at given specific ratios. It is equipped with two integrated airflow paths. The air in first path goes through an

orifice located in the front panel of the device called D/T dial. In the second path, the air goes through pair of filters located on either side of the olfactometer. By turning the D/T dial it is possible to change the orifice size, hence it is possible to control the volume of odor contaminated air that enters the device. The used field olfactometer is presented in Figure 26.

Figure 26. The used field olfactometer Nasal Ranger (on the left) manufactured by St. Croix Sensory, Inc., and the D/T dial of used field olfactometer (on the right).

The basic technical parameters of the device, according to the manufacturer's information, are presented below [124]:

- standard D/T ratios: 2, 4, 7, 15, 30, and 60,
- higher D/T ratios are available: 60, 100, 200, 300, 400, 500, as well as customized ones,
- Accuracy: +/- 5/10% after calibration (depending on selected D/T dial),
- Inhalation rate: 16-20 liters per minute,
- Temperatures operating range: 0-40 °C.

The dilution to threshold ratio is given by an equation 4 and it mirrors the number of dilutions required to make the odor contaminated air nondetectable.

$$\frac{D}{T} = \frac{Volume\ of\ filtered\ air}{Volume\ of\ odorous\ air} \qquad (4)$$

The standard D/T dial (Figure 26) features 12 settings, of which 6 are blank positions (where only filtered air passes through the device) and the remaining 6 are D/T positions (60, 30, 15, 7, 4, and 2). To perform accurate measurements using the selected olfactometer, the operator must secure the mask of the field olfactometer snugly over the nose and commence breathing at an airflow rate of 16-20 liters per minute. The LEDs positioned at the top section

of the device indicate the rate of inhalation. The operator starts at the blank position between D/T 60 and D/T 2, then starts to breathe at required rate of inhalation for 2 minutes. After 2 minutes, the operator has to switch to the highest D/T ratio (when operating standard D/T dial, the highest is 60) and has to breathe two times at required inhalation rate, after that the operator has to switch to next blank position, breathe for two minutes. Then he has to ask himself if he was able to sense odors in given D/T position. If so, the measurement is considered complete (D/T =< 60), if not, the operator continues the measurement by going to the next D/T value. The measurement ends when the odors are detected at the given D/T setting. If no odors are detected by the operator at any setting then the concentration is considered to be below the detection threshold of the device. Comprehensive guidelines on how to use the olfactometer can be found on the manufacturer's website [124].

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, expressed as ou/m³. In the study, the calculations for odor concentration were carried out utilizing the following formulas provided below (eq. 5, 6, 7, 8). The formulas are fundamentally derived from the operating principles of the field olfactometer and are similar to the computation of odor concentration through dynamic olfactometry method [52]. These formulas have been employed in prior studies by various researchers [59,60,92,131,132].

$$Z_{YES} = (D/T)_{YES} + 1 \tag{5}$$

Z_{YES} – the dilution ratio at which the odor was detectable during the measurement, $(D/T)_{YES}$ – the dilution ratio when the odor was detected for the first time,

$$Z_{NO} = (D/T)_{NO} + 1 \tag{6}$$

Z_{NO} – the dilution ratio at which the odor was undetectable during the measurement, $(D/T)_{NO}$ – the dilution ratio when the odor was undetected just before the $(D/T)_{YES,}$

$$Z_{ITE} = \sqrt{Z_{YES} * Z_{NO}} \tag{7}$$

Z_{ITE} – assessment of individual threshold, expressed as dilution ratio,

$$Z_{ITE} = C_{od} \tag{8}$$

c_{od} – odor concentration, ou/m³.

Those equations were used for determining the odor concentration for the purposes of implementation of Strategy No. I, II, III, and IV, for each measuring points where field olfactometry was used. The field olfactometric measurements were carried out at the premises of Facility #1, Facility #2, and Facility #3. The location of individual measuring points for each strategy are provided in *Chapter 6.2*. The odor concentration in each point was calculated as Z_{ITE}. During the measurements, the standard D/T dial was used with D/T ratios equals to 60, 30, 15, 7, 4, and 2, thus it was possible to determine odor concentrations equals to 78.49, 43.49, 22.27, 11.31, 6.32, 3.87 ou/m^3.

6.3.2 Odor intensity as an example of parametric measurements

For the measurements of odor intensity, the 7-point scale was used based on the German standard VDI 3882 [160]. The scale of odor intensity used in measurement is shown in Table 2.

Table 2. Intensity numerical scale and its verbal description used in parametric measurements, according to VDI 3882 [160].

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

To determine the odor concentration-odor intensity relationship the odor data was categorized based on odor concentration and intensity scale. To each odor concentration (7 steps, from 0 ou/m^3 up to 78.49 ou/m^3) an odor intensity value was assigned (7 point scale). The theoretical scatterplot regarding data categorization is shown in Figure 27. The data categorization is as follows: odor 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.
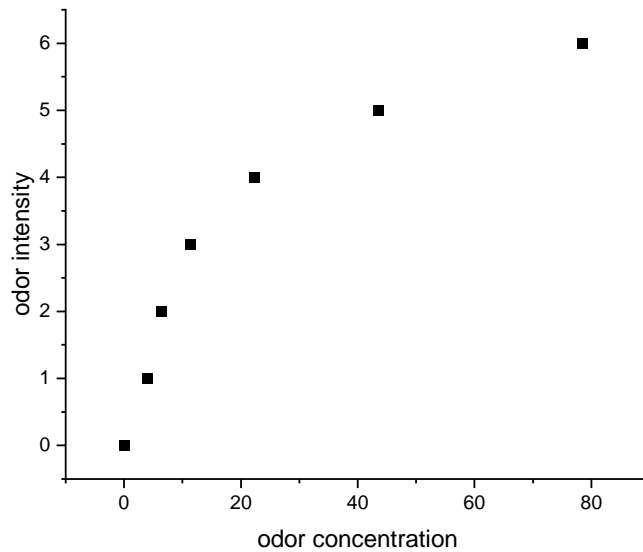
Figure 27. A theoretical scatter plot for proposed data categorization.

Plotted theoretical scatterplot indicates the existence of a logarithmic relationship between odor concentration and intensity. It was expected outcome as the intervals between odor concentrations measured by the means of field olfactometry are not equal and as the concentration increases, the range between successive concentrations increases, while intensity scale remains linear.

In order to classify data with assumed data categorization at measuring points where odor concentrations were determined as below the detection threshold, the values were changed to 0.00 ou/m^3.

For gathered data regarding odor concentration and odor intensity, the Weber-Fechner law was applied, which describes the dependency between perceived psychological intensity and physical features like concentration. The Weber-Fechner law can be described with the equation above (eq. 9).

$$I = a * \log(C) + b \tag{9}$$

where:

I – is odor intensity,

C – is odor concentration (ou/m^3),

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

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6.3.3 Volatile organic compounds measurements

Volatile Organic Compounds measurements were carried out with the use of a MiniRae Lite (PGM-7300 model) portable handheld Volatile Organic Compound monitor by RAE Systems. The used device is shown in the Figure 28. Volatile organic compounds were measured using a photoionization sensor (PID). The used sensor operate by detecting compounds that undergo ionization as a result of exposure to radiation emitted by an ultraviolet lamp. The ionization energy of these compounds is lower than the energy of photons emitted from ultraviolet lamp. The ionization products are recorded by an electrometer. The used sensor is not a selective one, hence, it provides information about the total amount of volatile organic compounds contained in analyzed air.

Figure 28. MiniRae Lite (PGM-7300 model) by RAE Systems.

The specification of used device for volatile organic compounds measurements is provided below:

- Used sensor: Photoionization sensor (PID) with standard 10.6eV lamp;
- Purpose: Direct readings of Volatile Organic Compounds as ppm by volume
- Measuring range: 0 to 999.9 ppm with the resolution of 0.1 ppm with the response time (T90) < 3 seconds; 1,000 to 5,000 ppm with the resolution of 1 ppm with the response time (T90) < 3 seconds;
- Operating temperatures: -20 to 50 °C;
- Operating humidity: 0 up to 95% of relative humidity;
- Integrated internal sampling pump with flow rate at 400 ml/min;

6.3.4 Dynamic olfactometry – sampling and determination of odor concentration.

The first step in determining the emission values of odor concentrations in the studied sources (see *Chapter 6.2.1* for the exact location of sources and measurement points) was to conduct a sampling campaign. The sampling campaign lasted from November 2021 to August 2022. During this period, 79 odor samples were collected from the studied odor emission sources. The whole sampling campaign was carried out at the premises of Facility #1. 8 main sources of odor emissions were chose, among others, two biofilter, active landfill, green waste storage area, aerobic stabilization area, two landfill leachate tanks and biological leachate tank

Due to the nature of the sources, i.e. these were surface sources, the sampling kit consisted of the following elements (which can be seen in Figure 29):

- CSD30 vacuum sampler (Olfasense GmbH, Germany, 2018) with regulated sampling time of 5, 10, 15, and 30 minutes;
- ventilated sampling hood (approx. dimension 1030 mm x 530 mm x 250 mm) with forced air flow (Ecoma GmbH, Germany, 2007) with adjustable flow fan, carbon filter, and battery;
- PTFE plastic bags to which sampled air was collected;
- elements of sampling kit were connected with Teflon pipes;
- in the case of leachate tanks, a special float was used to keep the sampling hood on the surface.

Figure 29. Sampling kit used for samples collection from area sources: biofilter on the left, landfill leachate tank on the right.

The entire sample collection kit was built from materials that do not absorb odors and do not emit them. Each sampling bag underwent a preconditioning process for around 2 minutes prior to being used for air sampling. Each sample was collected over 10 minutes period, sampling time at the CSD vacuum sampler was set to 10 minutes. This setting made it possible to obtain average concentration values and to avoid momentary emission peaks.

After collecting the samples, they were transported to the olfactory testing laboratory and analyzed to determine odor concentrations using dynamic olfactometry, within a 24-hours' time frame. The determination of odor concentrations in the collected samples was conducted using dynamic olfactometry, employing the YES/NO method as outlined EN 13725 standard [52].The determination of odor concentrations was performed using a TO8 4-station olfactometer by Ecoma GmbH. The measurement team was comprised of four evaluators and one operator. Each member of the team went through a proper training with n-butanol, which is the reference substance, in accordance with the 13725 standard [52]. The odor concentrations that were identified in each sample were expressed in European odor units per cubic meter (ou_E/m^3). The results of olfactometric measurements were directly used for determination of odor emission factors, which were used in the further odor dispersion modeling. During the entire period from collection to completion of olfactometric determinations, the samples were stored under stable conditions in order to limit the influence of external variables on the sample.

6.4 WEATHER DATA MEASUREMENTS

During the measurements aimed at implementing Strategies No. I and No. II, weather conditions were monitored. The meteorological data was gathered using a Testo 410-2 portable handheld weather station, which is presented in Figure 30. As per the specifications provided by the manufacturer, this device is capable of measuring temperatures ranging from -10°C to 50°C with a resolution of 0.1°C. Additionally, it can measure relative humidity from 0% to 100%, and offers a precision of 2.5% for humidity levels between 5% and 95%, with a resolution of 0.1%. The device also measures wind speed within the range of 0.4 to 20 m/s with a precision of 0.2 m/s plus 2% of the measured value, and it offers a resolution of 0.1 m/s. The recorded data encompassed ambient temperature (in °C), relative humidity (in percentage), wind speed (in m/s), and wind direction. Meteorological data was measured at the approx. height of 1.8 meters. The direction of the wind was measured with a high approximation, as the portable weather station did not allow for wind direction measurement. The meteorological data

was collected at the same locations where odor concentrations were assessed using a field olfactometer.

Figure 30. Testo 410-2 handheld weather station used for meteorological conditions measurements.

6.5 SELECTED DATA MODELLING METHODS

6.5.1 Inverse distance weighted interpolation method

For the implementation of Strategy No. II, the inverse distance weighted method of data interpolation was used. It was used for the purposes of obtaining spatial distribution of odors at the premises of Facility #1 for points located outside of the technological buildings. The selected method allows for obtaining information about odor concentrations at locations outside defined measuring points, i.e. at locations not covered by measurements. Inverse distance weighted method is a widely used deterministic technique for interpolating environmental data by utilizing following formulas (eq. 10, 11) [150,155]:

$$u(x,y) = \frac{\sum_{n=1}^{N} \frac{u_n(x_n, y_n)}{d_n}}{\sum_{n=1}^{N} \frac{1}{d_n}}$$

(10)

$$d_n = \sqrt{((x - x_n)^2 + (y - y_n)^2)^i} \tag{11}$$

where: N - number of unknown locations,

$u(x, y)$ – calculated values at unknown locations,

d_n – distance between analyzed points,

i – exponential function, by standard equal to 2.

The chosen method allows for interpolation from known values at specific, measured locations to estimate values at unknown locations; as a result, a continuous surface representation of the selected phenomena can be generated. The fundamental premise is that points in closer proximity to each other have a higher correlation compared to those further apart [156]. The values at unknown locations are computed as a weighted average of the measurements from known points [155]. In alignment with this core premise, the interpolated values are influenced more significantly by the nearby known locations/measured points, with this influence diminishing with distance. To closer known values are assigned higher weights [155,156]. The power function (eq. 11) allows for manipulation of the extent to which known locations influence the interpolated values [156,161]. For the research purposes, ArcGIS Pro software with integrated Geostatistical Wizard tool was used for interpolating field olfactometry data.

In order to evaluate the effectiveness of the inverse distance weighted interpolation method, cross-validation was employed. The primary objective was to examine the extent to which the data derived through the selected interpolation method aligns with the input data that was utilized for the interpolation process. The leave-one-out technique was adopted for cross-validation, in which a single data point is excluded from the dataset, and the value at that specific location is then estimated using the remaining data points. Comparing the measured and predicted values enables the derivation of parameters that can be used for the purposes of validation of interpolation [152,162]. The built-in cross-validation tool in ArcGIS Pro was utilized for this purpose. ArcGIS Pro software facilitates the analysis of two parameters specific to the inverse distance weighted method: the mean error (eq. 12), and the root mean square error (eq. 13). The power function (eq. 11) was optimized using the built-in Geostatistical Wizard in order to achieve the lowest possible cross-validation outcomes.

$$Mean\ Error = \frac{1}{n}\sum_{i=1}^{n} I_i - O_i \tag{12}$$

$$Root\ Mean\ Square\ Error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(I_i - O_i)^2} \tag{13}$$

where:

I_i – predicted values,

O_i – measured values,

n – number of samples.

The Mean Error parameter offers insights into the average error during cross-validation. Ideally, it should be as close to zero as possible. If the Mean Error value is greater than zero, it implies that the model tends to overestimate values, if it is lower than zero, the models tends to underestimate values [162]. The Root Mean Square Error parameter is a measure of the accuracy of the interpolation model. The lower the RMSE, the better as it indicates that the predicted values are closer to the actual measured values. It provides information on the extent of deviation between predicted and measured values [162].

6.5.2 Odor dispersion modelling – CALMET/CALPUFF system

The used tool for modeling the dispersion of odors form selected sources at Facility #1 was CALMET/CALPUFF system developed by Exponent, Inc [163,164]. According to the CALPUFF use guide [164], CALPUFF model is a non-steady-state Lagrangian Gaussian puff dispersion model, which can take into account time varying and space varying meteorological conditions when simulating the dispersion of pollutants. One of its most important components is the CALMET [164]meteorological preprocessor, which allows for the incorporation of three-dimensional fields of meteorological data that can be calculated on the basis of external models such as the Weather Research & Forecasting Model (WRF) [165]. CALMET/CALPUFF modeling system can be used to simulate the dispersion of pollutants from different sources, including point, line, volume and area sources. The model takes into account the detailed information about terrain (heights) and its cover. It can be used for areas with dimensions from tens of meters to several hundred kilometers. Figure 31 shows the modelling scheme of used CALMET/CALPUFF system.
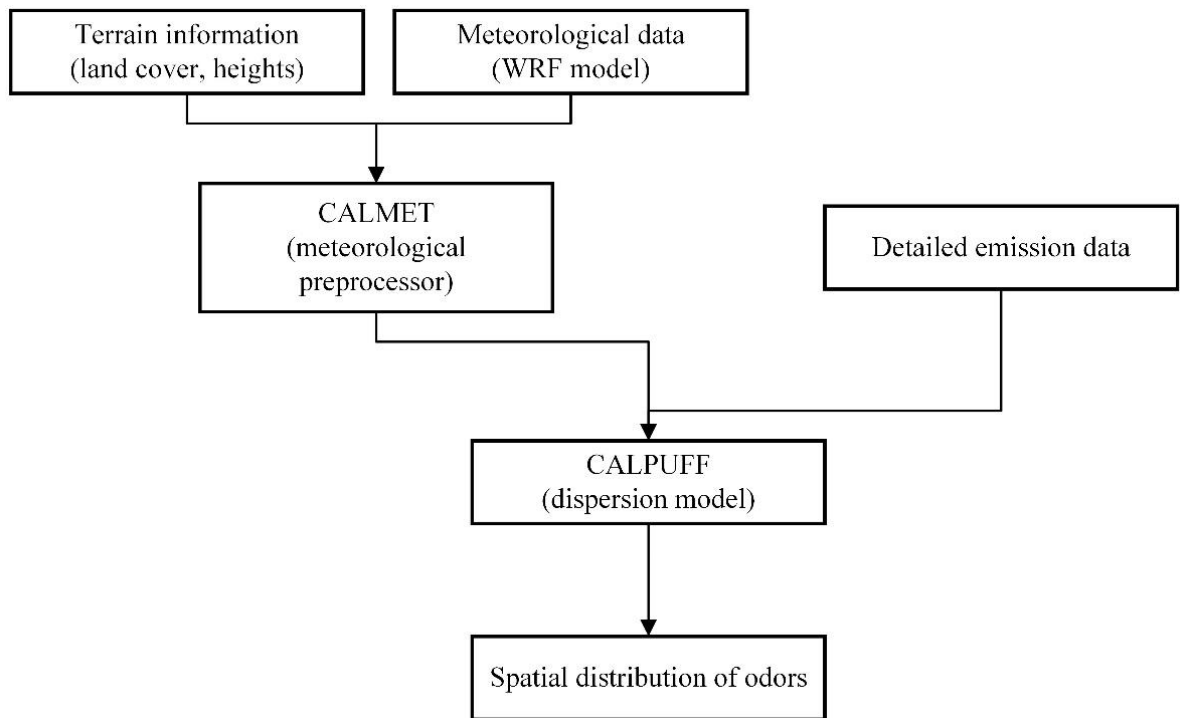
Figure 31. CALMET/CALPUFF system workflow scheme [164].

The part of the CALMET/CALPUFF modeling system responsible for preparing primary terrain information and meteorological data for input to the CALPUFF model is the CALMET preprocessor [163,164]. Meteorological calculations take place on a user-defined grid that covers the analyzed area of odor dispersion modeling. The user also defines the size of the grid cell, which depends on the scale of the study area. It is necessary to prepare the following for input to the preprocessor:

- appropriate terrain information, containing topography along with land use in classes specified according to the model instruction,
- meteorological input data, which includes:
  - on the surface: wind speed, wind direction, air temperature, relative humidity of the air, precipitation amount (snow or rain), which enters the model in two ways – as precipitation code (solid or liquid precipitation) and quantitatively, cloud cover, base of low clouds in feet above sea level, pressure;
  - at pressure levels: geopotential height, wind speed, wind direction, temperature, relative humidity.

Based on the aforementioned input data, CALMET [163,164] creates two- or three-dimensional meteorological fields of certain parameters necessary for pollution dispersion calculations, while other parameters are assigned to locations (e.g., meteorological stations) for which the input data was defined. Three-dimensional fields are created for temperature and wind components. Parameters such as: atmospheric stability class, Monin-Obukhov length, inversion layer height, friction velocity, convective velocity, and precipitation index are recorded in the form of a two-dimensional field. Values for temperature, air density, shortwave radiation, relative humidity, and precipitation code are recorded at specific locations.

In the calculations, data from the global meteorological model WRF [165]was used as the source of basic meteorological information. This model can provide meteorological data for both classical second-generation dispersion models as well as for photochemical models. It is a mesoscale numerical dynamic model with data assimilation - designed for simulating and forecasting atmospheric circulation. As input data, it uses information from the publicly available NCEP/NCAR Reanalysis project, which incorporates all measurement information from ground-based, meteorological, and precipitation measurement networks, as well as data from soundings and satellite observations.

CALPUFF is an advanced Gaussian second-generation puff model [163,164]. It is highly sensitive to the spatial characteristics of the environment and the variability of the meteorological field. It has built-in modules that allow, among other things, to take into account the transport of pollutants over water bodies and the influence of large water reservoirs (seas), building washout, dry and wet deposition, simple chemical transformations, pollutant dispersion in complex terrain, and consideration of boundary conditions.

In the CALMET/CALPUFF model, hourly time series are used at each stage of processing, calculated for each grid cell or receptor. This means that in each grid cell (receptor), hourly time series of meteorological parameters and pollutant concentrations are defined. These series are then saved to output files and can be processed multiple times, and after processing, they are visualized in a GIS environment.

7.1   STRATEGY NO. 1 – FIELD OLFACTOMETRIC MEASUREMENTS

7.1.1   Results of field olfactometric measurements outside technological buildings

Table 3 presents the results of field olfactometric measurements for measuring points within the Facility #1, excluding those situated inside the technological buildings. For the first measurement point (point no. 1), which is in proximity to the administrative building, the odor concentration vary between 3.87 ou/m^3 and 11.31 ou/m^3. The peak value of 11.31 ou/m^3 was recorded in July 2022. Throughout the five-month measurement period, the odor concentration remained under the detection threshold of the field olfactometry method.

The point no. 2, a technical area designated for the parking and maintenance of facility vehicles, is characterized by odor concentrations varying between 3.87 ou/m^3 and 11.31 ou/m^3. The maximum value of 11.31 ou/m^3 was recorded only once, during the final month of measurement (October 2022). In two months, December 2021 and May 2022, the measured odor concentrations were below the detection threshold.

The highest values at point no. 4 (selective waste storage) reached 22.27 ou/m^3 In October 2022, and 11.31 ou/m^3 in November 2021. During December 2021, January 2022, April 2022, and September 2022, odor concentrations were below the detection threshold. In the remaining measuring months, the concentrations were consistently measured at level of 6.32 ou/m^3.

Measuring points numbered 10, 11, and 12 were situated in close proximity to the landfill site, where point no. 10 is located near the entrance, while point no. 11 and point no. 12 are directly located on the landfill site. The range of odor concentrations at point no. 10 vary from 6.32 ou/m^3 to 43.49 ou/m^3. The peak concentration of 43.49 ou/m^3 was observed in July 2022, while the lowest concentrations, measured at 6.32 ou/m^3, were recorded in January 2022 and September 2022. In December 2022, the odor concentration was under the detection threshold of the Nasal Ranger device. A similar situation in December took place at points 11, 12, 13, 14, 15, 17, 18, 25, 26, and 32. For point no. 11, the odor concentration is in the range of 3.87 ou/m^3 up to 43.49 ou/m^3. Throughout the majority of the measurement period, the odor concentration was either equal to or exceeded 22.27 ou/m^3. In January 2022, the odor concentration was at its lowest at point no. 11 and valued at 3.87 ou/m^3. Point no. 12 shows a

similar trend, with concentrations ranging from 6.32 ou/m^3 to 78.49 ou/m^3. The lowest value was recorded in January 2022 (6.32 ou/m^3), while the highest was in July 2022 (78.49 ou/m^3). For the remaining measuring months, concentrations were within the range of 22.27 ou/m^3 to 43.49 ou/m^3.

The area designated for bulky waste storage (point no. 13) was characterized by odor concentrations varying between 6.32 ou/m^3 and 22.27 ou/m^3. The peak concentrations were recorded in January 2022 and August 2022. The lowest concentrations, at the level of 6.32 ou/m^3, was observed in November 2021 and April 2022. During the rest of the measuring period, the odor concentrations remained constant level of 11.31 ou/m^3.

Points no. 14, 15, 28, and 29 are scattered around the aerobic stabilization area. General trend for this particular location shows that odor concentration is at the highest level of measuring range of selected field olfactometer, with only a few exceptions. Most of the time, the odor concentrations vary between 43.49 ou/m^3 and 78.49 ou/m^3. Concentrations at the level of 22.27 ou/m^3 were measured in April 2022 at point no. 14, and in May 2022 at point no. 29. December 2021 and January 2022 were months where the odor concentrations diverged significantly from those in the rest of the measurement series. As previously stated, the odor concentration at points no. 14, 15, and 28 in December 2022 was below the detection threshold. At points no. 28 and 29, the odor concentration was notably lower at 6.32 ou/m^3 compared to other months. In January 2022, the odor concentration across the whole aerobic stabilization area was below the detection threshold.

Green waste storage area (points no. 18, 26) is characterized by similar trend to the aerobic stabilization area. In December 2021, the odor concentrations for both points were below the detection threshold. The lowest odor concentration at point 18 was measured during January 2022 (3.87 ou/m^3), the second lowest was recorded in May 2022 (11.31 ou/m^3). The rest of the measurement period is characterized by the odor concentrations at point 18 in the range of 43.49 ou/m^3 and 78.49 ou/m^3. As for point no. 26, the lowest concentrations were measured in January 2022 and May 2022 (22.27 ou/m^3), while during the remainder of the measurement series, the odor concentrations ranged from 43.49 ou/m^3 to 78.49 ou/m^3.

Measuring point no. 25 located between the aerobic stabilization chambers and the green waste storage area shows a similar trend to those mentioned above (measured odor concentrations were in the range of 22.27 ou/m^3 up to 78.49 ou/m^3.

Point no. 17 (biofilter for anaerobic processes) and point no. 27 (biofilter for aerobic processes), despite their close proximity to green waste storage area and aerobic stabilization area, are characterized by much lower values of odor concentrations in comparison to those located in their vicinity.

Four measurement points were located in the vicinity of the leachate tanks. Point no. 31 was located near a tank designated for biological processes, while points no. 33, 34, and 35 were adjacent to two tanks for landfill leachates. Among all the points near the leachate tanks, the biological leachate tank (point no. 31) shows the highest odor concentrations. The peak odor concentration was recorded in November 2021, amounting to 78.49 ou/m^3, the second highest was measured in December 2021 (43.49 ou/m^3). Following that, the concentration levels have fluctuated between 11.31 ou/m^3 and 22.27 ou/m^3, in the rest of the measuring series. This particular point is unique as it was the only point where it was possible to measure odor concentration in all measuring months. Regarding points no. 33, 34, and 35, the odor concentrations typically varied between 3.87 ou/m^3 and 11.31 ou/m^3, with an exception in February 2022 when the odor concentration was below detection level of used field olfactometer

Table 3. Results of field olfactometric measurements excluding points located inside technological buildings, these points were considered during the implementation of Strategy No. II.

Point number	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
1	3.87	*	*	3.87	*	*	3.87	11.31	3.87	*	*
2	6.32	*	6.32	3.87	6.32	*	3.87	6.32	6.32	3.87	11.31
4	11.31	*	*	6.32	*	6.32	6.32	6.32	6.32	*	22.27
10	11.31	*	6.32	22.27	11.31	11.31	22.27	43.49	22.27	6.32	11.31
11	22.27	*	3.87	43.49	43.49	22.27	43.49	43.49	43.49	22.27	43.49
12	11.31	*	6.32	22.27	22.27	22.27	43.49	78.49	22.27	22.27	22.27
13	6.32	*	22.27	11.31	6.32	11.31	11.31	22.27	11.31	11.31	11.31
14	43.49	*	*	43.49	22.27	43.49	78.49	78.49	78.49	43.49	78.49
15	43.49	*	*	78.49	78.49	43.49	78.49	78.49	43.49	78.49	78.49
17	11.31	*	*	11.31	6.32	6.32	6.32	6.32	6.32	6.32	3.87
18	78.49	*	3.87	43.49	43.49	11.31	78.49	78.49	78.49	43.49	43.49
25	78.49	*	22.27	78.49	78.49	43.49	43.49	78.49	78.49	43.49	78.49
26	43.49	*	22.27	78.49	43.49	22.27	43.49	43.49	78.49	78.49	78.49
27	22.27	3.87	*	6.32	6.32	11.31	6.32	11.31	11.31	6.32	6.32
28	43.49	6.32	*	43.49	43.49	43.49	78.49	78.49	43.49	78.49	78.49
29	43.49	6.32	*	43.49	78.49	22.27	78.49	43.49	43.49	43.49	78.49
30	22.27	22.27	*	22.27	43.49	43.49	43.49	43.49	43.49	43.49	22.27
31	78.49	43.49	22.27	11.31	11.31	11.31	22.27	22.27	11.31	11.31	22.27
32	3.87	*	*	*	*	*	*	3.87	*	*	*
33	11.31	6.32	*	6.32	6.32	6.32	6.32	6.32	6.32	3.87	6.32
34	11.31	6.32	*	11.31	6.32	6.32	3.87	11.31	3.87	3.87	6.32
35	6.32	11.31	*	6.32	6.32	3.87	3.87	11.31	3.87	11.31	11.31

*below the detection threshold of Nasal Ranger field olfactometer

Table 4. Results of field olfactometric measurements inside technological buildings.

Point number	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
3	22.27	**	11.31	11.31	11.31	11.31	11.31	11.31	11.31	11.31	78.49
5	6.32	**	**	11.31	6.32	3.87	3.87	6.32	6.32	3.87	43.49
6	3.87	***	***	3.87	***	***	***	***	3.87	***	6.32
7	3.87	***	***	3.87	***	***	***	***	3.87	***	3.87
8	6.32	***	***	11.31	***	***	***	***	6.32	***	6.32
9	22.27	**	22.27	22.27	43.49	43.49	43.49	78.49	43.49	43.49	43.49
16	43.49	**	43.49	43.49	78.49	78.49	78.49	43.49	43.49	43.49	78.49
19	43.49	*	*	78.49	*	*	*	*	*	*	78.49
20	78.49	*	*	78.49	*	*	*	*	78.49	*	78.49
21	*	*	*	*	*	*	*	*	*	*	78.49
22	78.49	*	*	*	78.49	*	*	*	78.49	78.49	78.49
23	*	*	*	*	78.49	*	*	*	*	78.49	78.49
24	*	*	*	*	*	*	*	*	*	*	78.49

*bioreactors were closed

** below the detection threshold of Nasal Ranger field olfactometer

*** the sorting line was stopped/not operational during the measurements

7.1.2 Results of field olfactometric measurements inside technological buildings

Table 4 contains results of field olfactometric measurements carried out inside technological buildings.

The lowest concentrations during the first measuring month (November 2021) were measured within the sorting hall, at points no. 5, 6, 7, and 8. The most lowest concentrations, at the levels of 3.87 ou/m^3, were observed in sorting cabins 1 (point no. 6) and 2 (point no. 7). The points no. 5 and 8 (at the central area of the sorting hall and near the starting point of the sorting line) valued at 6.32 ou/m^3. In the waste reception hall, the concentration was measured at the level of 22.27 ou/m^3, comparable to point no. 3 (RDF preparation and storage building). The concentration in the technical building dedicated to anaerobic processes, as well as within Bioreactor 1, valued at be 43.49 ou/m^3. The highest concentrations were observed within bioreactors 2 and 4 (78.49 ou/m^3). The rest of the bioreactors were not operational on the day the measurements were taken, hence data could not be collected from these points.

In the second month of the measuring series, December 2021, determining the odor concentrations at the chosen measurement points was not possible as all the of readings were below the detection threshold of the field olfactometer Nasal Ranger. Moreover, all the bioreactors were non-operational at the time, making it impossible to determine the odor concentrations inside them.

In January 2022, it was possible to measure the odor concentrations only in 3 measuring points: inside the technical building for anaerobic processes (point no. 16), which was 43.49 ou/m^3, within the waste reception hall (point no. 9) - 22.27 ou/m^3, and in the RDF preparation and storage building (point no. 3) - 11.31 ou/m^3.

Throughout the entire measurement series, the lowest concentrations within the technological buildings were recorded in the waste sorting hall, specifically in sorting cabins 1 and 2 (point no. 6 and 7), with a value of 3.87 ou/m^3. The highest concentration observed in this area reached 6.32 ou/m^3. The concentrations in the middle part of the sorting hall and near the beginning of the sorting line were slightly higher, reaching up to 11.31 ou/m^3.

In January 2022, the odor concentration in the RDF preparation and storage building was measured at 11.31 ou/m^3, which was lower than what was recorded in November 2021. This concentration remained stable until October 2022, when it reached 78.49 ou/m^3. Between March 2022 and July 2022, the sorting line was not operational during the time when

measurements were conducted, making it impossible to determine the odor concentrations inside the sorting cabins. In July, the odor concentration for sorting cabins 1 and 2 (points no. 6 and 7) was consistent with the levels recorded in March 2022 and November 2021.

In September, the sorting line was again inactive on the day that measurements were taken. On October 2022, there was an observed increase in concentration within sorting cabin 1 (point no. 6), and valued at 6.32 ou/m^3, which was higher than in preceding months, while sorting cabin 2 (point no. 7) recorded a stable concentration of 3.87 ou/m^3. Between April and July, the concentration at the center of the sorting line varied from 3.87 ou/m^3 to 6.32 ou/m^3. However, the concentration at the beginning of the sorting line could not be measured during this period as the line was not operational. A notable increase in odor concentration was captured in the middle of the sorting hall on October 2022 and the odor concentration valued at the level of 43.49 ou/m^3, while at the beginning of the sorting line odor concentration was at the level of 6.32 ou/m^3.

In March 2022, the odor concentration in waste reception hall (point no. 9) reached 22.27 ou/m^3. The concentration in the waste reception hall remained consistent at 43.49 ou/m^3 until the end of the measurement series, with an exception in July 2022 when it reached 78.49 ou/m^3. The concentration within the technical building for the anaerobic processes varied between 43.49 ou/m^3 and 78.49 ou/m^3 from March to October. Almost throughout the entire measurement series, the concentrations inside the bioreactors were consistently at 78.49 ou/m^3, with the exception of Bioreactor 1 in November 2021, where the concentration was measured at 43.49 ou/m^3.

7.1.3 Variability of odor concentrations at Facility #1

During the research, in most measurement points, the variability of odor concentrations was relatively low. Table 5 summarizes basic statistics about odor variability in 35 measured points, including average values of odor concentration, standard deviation, median, and maximum and minimum values of recorded odor concentrations. As said above, some of the measuring points were characterized by odor concentration below the detection threshold of used Nasal Ranger field olfactometer, therefore the number of successful measurements during the whole campaign is provided, as well as number of missing measurements. In addition, in some points it was impossible to measure due to different operating modes of some sources, for example, during the most of the measuring days the waste sorting line was stopped or the

bioreactors were closed. Summary statistics are based solely on measurement points where a specific odor concentration has been measured and determined.

Table 5. Summary statistics of odor concentration measurements at Facility #1.

Point number	N of measurements	N of missing measurements	Mean	Standard Deviation	Minimum	Median	Maximum
1	5	6	5.36	3.33	3.87	3.87	11.31
2	9	2	6.06	2.30	3.87	6.32	11.31
3	10	1	19.12	21.14	11.31	11.31	78.49
4	7	4	9.31	6.01	6.32	6.32	22.27
5	9	2	10.19	12.70	3.87	6.32	43.49
6	4	7	4.48	1.23	3.87	3.87	6.32
7	4	7	3.87	0.00	3.87	3.87	3.87
8	4	7	7.57	2.50	6.32	6.32	11.31
9	10	1	40.62	16.65	22.27	43.49	78.49
10	10	1	16.82	11.27	6.32	11.31	43.49
11	10	1	33.16	14.35	3.87	43.49	43.49
12	10	1	27.32	20.36	6.32	22.27	78.49
13	10	1	12.50	5.54	6.32	11.31	22.27
14	9	2	56.69	21.74	22.27	43.49	78.49
15	9	2	66.82	17.50	43.49	78.49	78.49
16	10	1	57.49	18.07	43.49	43.49	78.49
17	9	2	7.16	2.49	3.87	6.32	11.31
18	10	1	50.31	27.97	3.87	43.49	78.49
19	3	8	66.82	20.21	43.49	78.49	78.49
20	4	7	78.49	0.00	78.49	78.49	78.49
21	1	10	78.49	--	78.49	78.49	78.49
22	5	6	78.49	0.00	78.49	78.49	78.49
23	3	8	78.49	0.00	78.49	78.49	78.49
24	1	10	78.49	--	78.49	78.49	78.49
25	10	1	62.37	21.70	22.27	78.49	78.49
26	10	1	53.25	23.21	22.27	43.49	78.49
27	10	1	9.17	5.31	3.87	6.32	22.27
28	10	1	53.77	24.09	6.32	43.49	78.49
29	10	1	48.15	24.24	6.32	43.49	78.49
30	10	1	35.00	10.96	22.27	43.49	43.49
31	11	0	24.33	20.41	11.31	22.27	78.49
32	2	9	3.87	0.00	3.87	3.87	3.87
33	10	1	6.57	1.83	3.87	6.32	11.31
34	10	1	7.08	3.11	3.87	6.32	11.31
35	10	1	7.58	3.36	3.87	6.32	11.31

The Figure 32 shows an average distribution of odor concentration based on the whole measuring period at the premises of Facility #1.
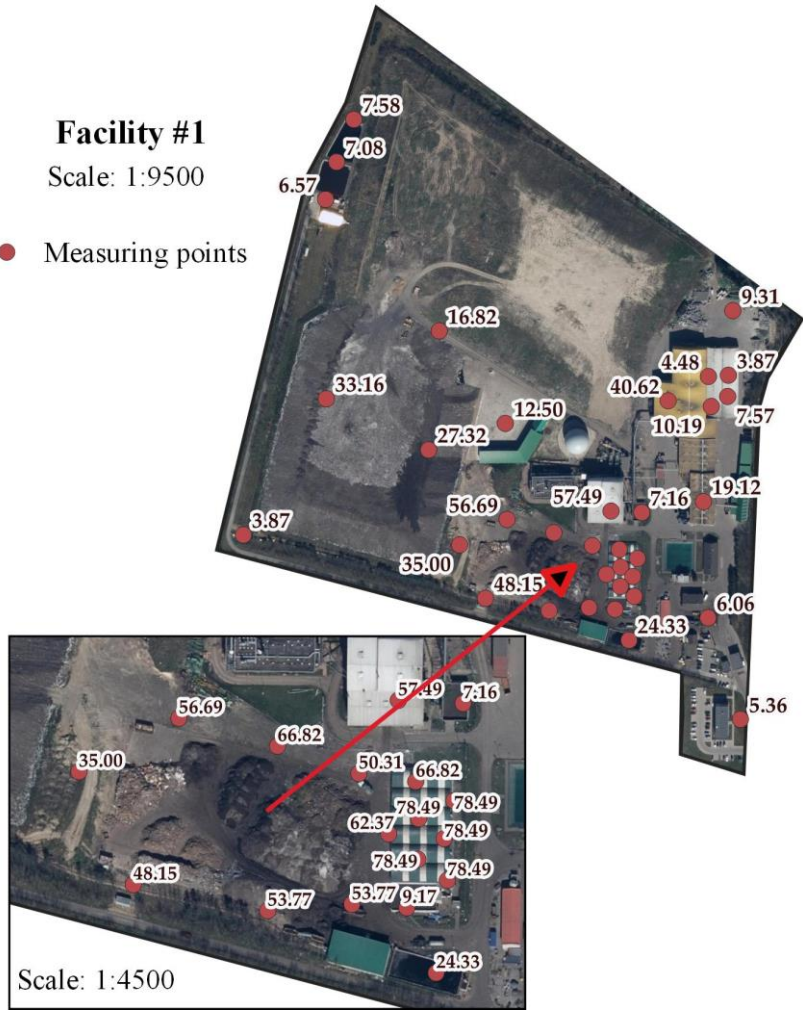
Figure 32. Distribution of average odor concentration based on the whole measuring series.

The highest average odor concentrations can be found around the biological processing area at the Facility #1 (aerobic stabilization area, green waste storage, bioreactors, anaerobic processing technological building). The average odor concentration in that area ranges from 35.00 ou/m^3 up to 78.49 ou/m^3. A total of 16 measuring points are scattered around that area. In addition, the point located at the leachate tank for biological processes is characterized by average odor concentration of 24.33 ou/m^3. Waste reception hall is characterized by average odor concentration of 40.62 ou/m^3. The rest of the measuring points are characterized by average odor concentration below 35 ou/m^3. Another high average odor concentrations can be found around the landfill area, two points located directly at landfill site valued at 33.16 ou/m^3

and 27.32 ou/m^3. Landfill entrance valued at 16.82 ou/m^3. RDF building valued at 19.12 ou/m^3. The rest of the measuring points are characterized by much lower average odor concentrations (below 15 ou/m^3). Sorting hall ranges from 3.87 ou/m^3 up to 10.19 ou/m^3. Points located around landfill leachate tanks range from 6.57 ou/m^3 up to 7.58 ou/m^3. Selective waste storage valued at 9.31 ou/m^3. Biofilter for aerobic processes valued at 9.17 ou/m^3, while biofilter for anaerobic processes valued at 9.17 ou/m^3. Points located at the technical area, administrative building, and the Facility corner are valued at 6.06 ou/m^3, 36 ou/m^3, and 3.87 ou/m^3 respectively.

Based on the measurement results values of average odor concentration (based on all measuring points scattered around each odor source) for each potential odor sources were provided in Table 6.

Table 6. Average values of odor concentration and odor intensity for sources in the analyzed Facility.

Odor source	Average odor concentration
-	ou/m^3
Bioreactors	76.43
Anaerobic processes technical building	57.49
Aerobic stabilization area	56.07
Green waste storage area	51.78
Waste reception	40.62
Landfill	25.77
Leachate tank for biological processes	24.33
RDF preparation and storage	19.12
Bulky waste processing area	12.50
Biofilter (aerobic processes)	9.17
Waste sorting	7.39
Biofilter (anaerobic processes)	7.16
Landfill leachate tanks	7.08
Selective waste storage area	6.52

As obtained results indicate that the values of odor concentration correlated with the location of measuring points and the proximity of potential odor-generating sources. The highest odor concentrations can be found in the biological part of the Facility, especially inside bioreactors, anaerobic processes technical building, around waste stabilization area, green waste storage area, or waste reception hall, where fresh mixed waste are delivered. Much lower values can be found in the mechanical part of the Facility. Mid-range of average odor concentration values can be found at the landfill and near the leachate tank for biological

processes and inside RDF preparation and storage building. The lowest range of measured values can be found at the mechanical part of the Facility (sorting hall), around landfill leachate tanks, selective waste storage area, and around biofilters. A high difference between odor concentrations can be found 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 odor concentrations, and the biofilter itself is characterized by one of the lowest, similar pattern can be found for the biofilter for anaerobic processes. Those results show a potential use of field olfactometric measurements in the assessment of the working conditions of biofilters by measuring the odor concentrations at the odor source and at the inlet of biofilters.

7.1.4 Relationship between odor concentrations and meteorological conditions

Figure 33 shows the average distribution of odor concentration over the measuring period.
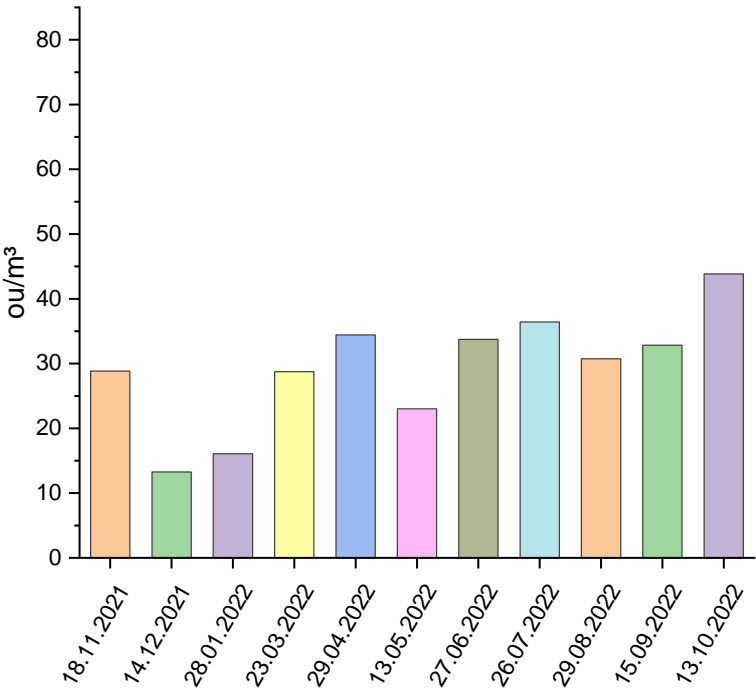
Figure 33. Average odor concentrations during measuring period.

The average odor concentration for each measuring day is: 28.85 (18.11.2021), 13.28 (14.12.2021), 16.07 (28.01.2022), 28.75 (23.03.2022), 34.44 (29.04.2022), 23.02 (13.05.2022), 33.75 (27.06.2022), 36.42 (26.07.2022), 30.75 (29.08.2022), 32.84 (15.09.2022), 43.83

(13.10.2022) ou/m^3, respectively. The expected result of the measurements was a clear seasonality in the average odor concentrations, however, as shown in Figure 33 there is no clear seasonality in the averages for the entire Facility in a given months. Only two months seem to have some seasonality, December 2021 and January 2022, respectively, as they are characterized by the lowest average concentrations during the whole measuring period. However, more sophisticated analysis assess the variability over the entire measurement period, especially when considering temperature and humidity, is provided below.

Figures 1 and 2 show the average values of temperature and humidity for individual measuring days. Figure 34 illustrates the average temperature (°C), accompanied by the minimum and maximum values measured on each measuring day.
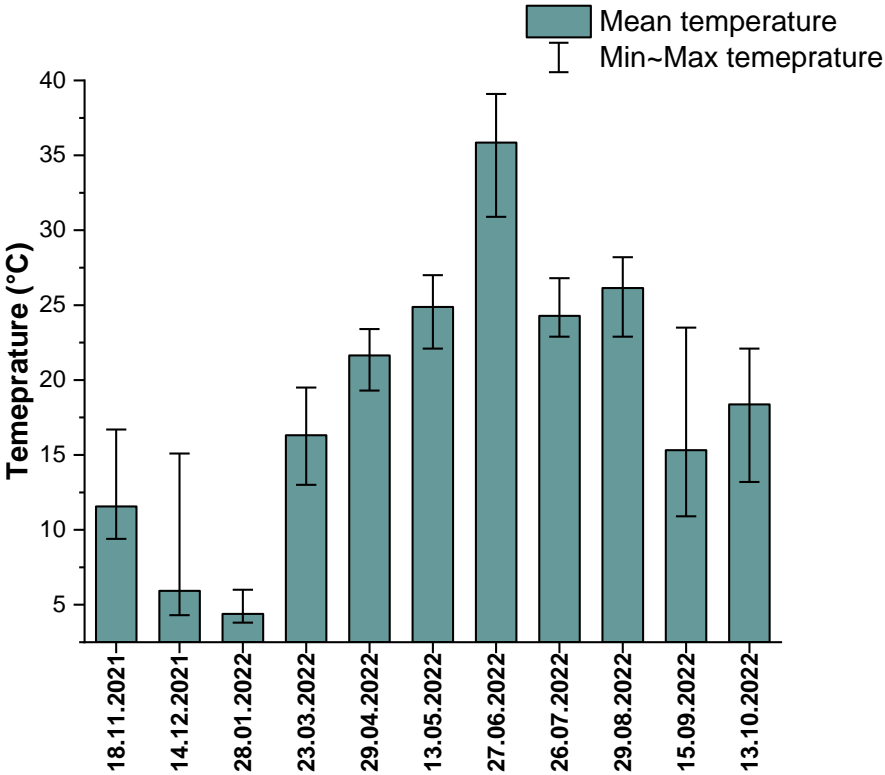
Figure 34. Average values of temperature for individual measuring days.

The measuring series started in November, during which the average temperature was 11.56°C. In the subsequent two months, December and January, there was a decline in the average temperatures, registering 5.92°C and 4.38°C respectively. Measurements carried out in December and January are characterized by the lowest average temperatures measured during each measuring day. From March through June, there was a noticeable rising trend in the

average temperatures. Specifically, the average temperatures were 16.31°C in March, 21.64°C in April, 24.89°C in May, and significantly higher temperature was recorded at the level of 35.85°C in June. The peak temperature in the whole series was recorded in June. In July, the average temperature slightly dropped to 24.28°C, followed by a mild increase to 26.14°C in August. September and October showed cooler averages at 15.32°C and 18.37°C, respectively. As the measurements spanned across 12 months, the data exhibited seasonality. The winter months were marked by the lowest temperatures, while summer months had the highest. Spring and autumn months had intermediate temperature values. However, when comparing the average temperatures and average odor concentrations measured during each measuring days, there is no clear correlation between studied data. Figure 35 shows average temperatures and average odor concentrations in each measuring days. By analyzing the results shown in Figure 35, it can be concluded that no particular pattern between average odor concentration and average temperatures can be observed, for example, the highest average temperature was recorded during 27.06.2022 (35.85°C) with an average odor concentration at the level of 36.42 ou/m^3, while the highest odor concentration was recorded during 13.10.2022 (43.83 ou/m^3), whit an average temperature of 18.37 °C.
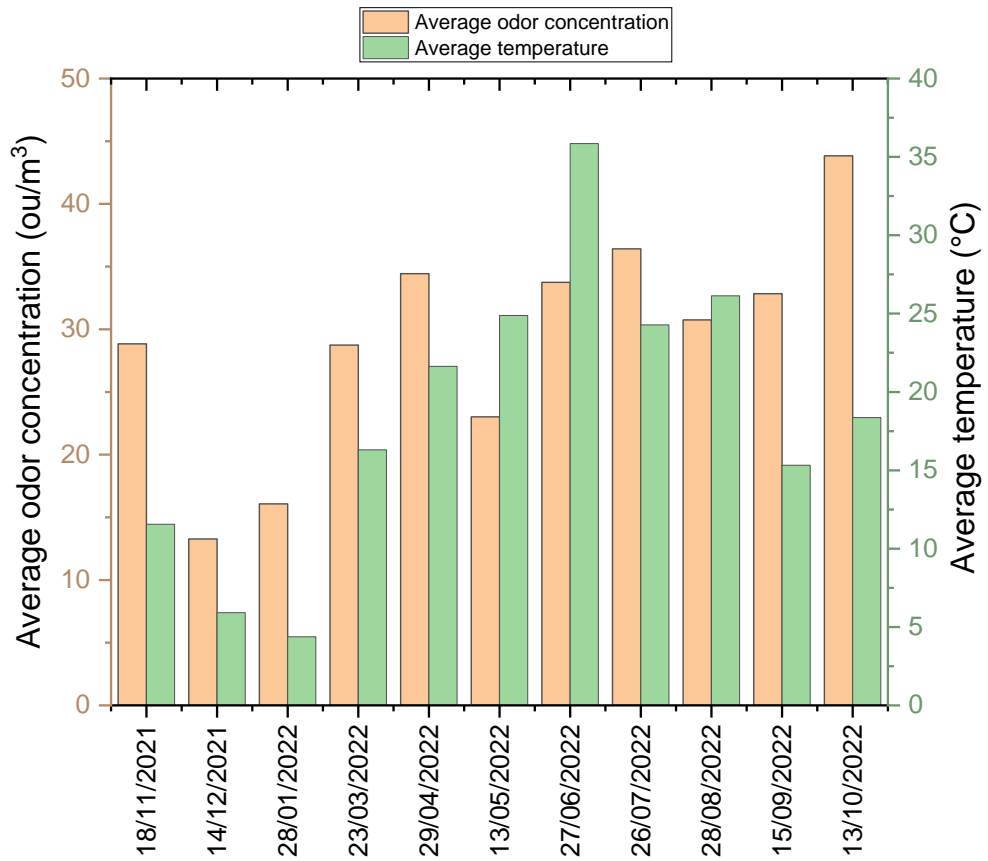
Figure 35. The average temperatures and average odor concentrations measured during each measuring days

Figure 36 shows the average relative humidity (% RH), along with the highest and lowest values noted on each day of measurement. During the measurements in November, an average relative humidity of 68.07% was measured. December experienced an increase in measured relative humidity, with an average of 92.72%, which was the highest average value in the entire dataset.
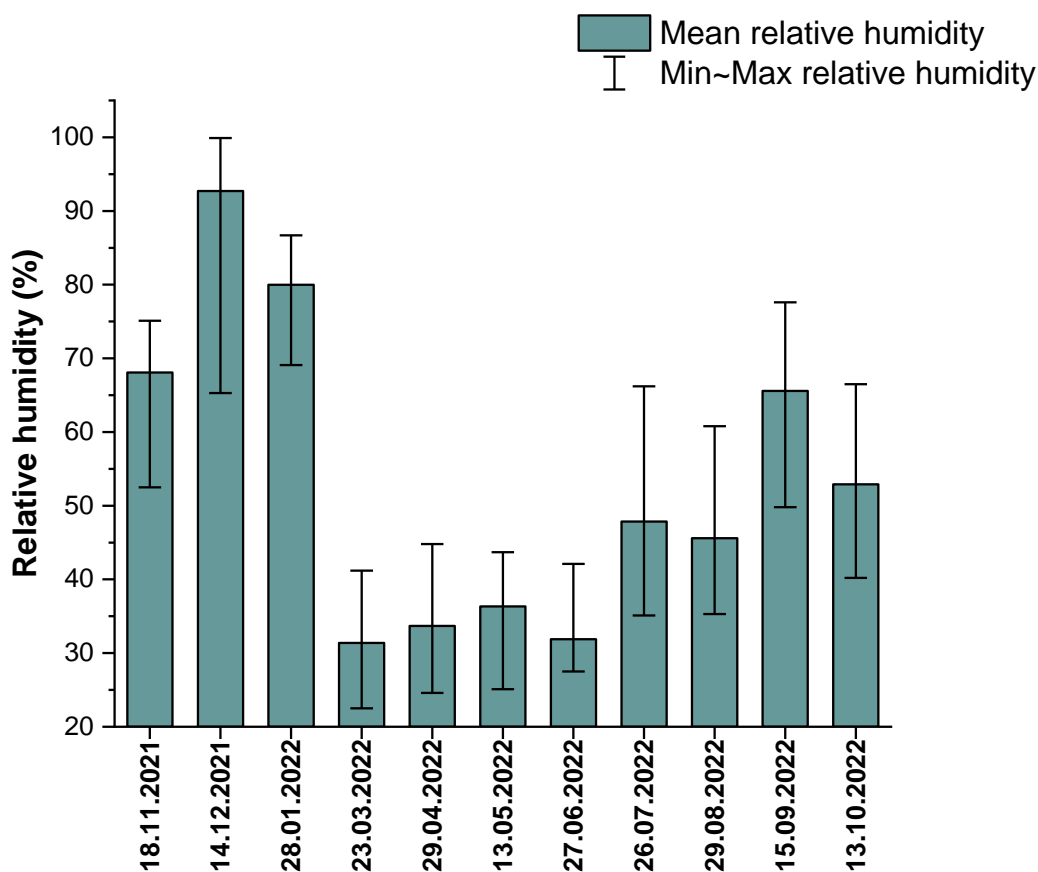
Figure 36. Average values of humidity for individual measuring days.

In contrast, from March to June, there was a substantial decline in average humidity. The average values were 31.37% in March, 33.67% in April, 36.33% in May, and 31.89% in June. June had the lowest average humidity across the measuring series. Moving on to July, the average humidity was 47.85%, and in August it was slightly lower at 45.59%. In September, there was an increase to 65.58%, and in October, the average humidity was 52.91%. As in the case of average temperatures, average humidity exhibits partial seasonality. However, when comparing values of odor concentration and humidity, similar pattern can be observed as in the case of odor concentration and temperature, which is shown in Figure 35 By analyzing the results shown in Figure 37, it can be concluded that no particular pattern between average odor concentration and average humidity can be observed similar to the previous case, without a few exceptions. For example, the highest values of average relative humidity were recorded during 14.12.2021 (92.72% RH) and 28.01.2022 (79.99% RH), with average odor concentrations in those days equals to 13.28 ou/m^3 and 16.07 ou/m^3, respectively. Those values were the highest average values of relative humidity and the lowest values of odor concentrations during the

whole measuring period. However, when considering the rest of the measuring days, no particular pattern can be found.
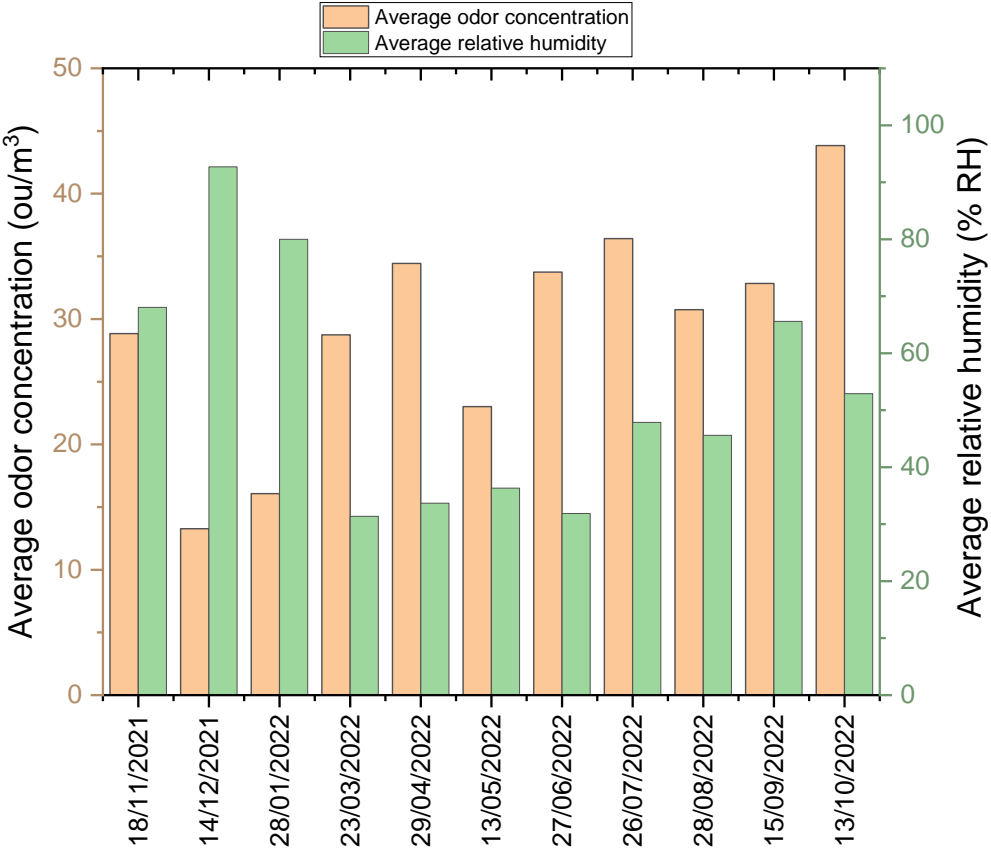
Figure 37. The average humidity and average odor concentrations measured during each measuring days.

To explore the degree of correlation between odor concentration and meteorological variables, such as temperature and relative humidity, statistical tests were conducted. Initially, the Shapiro-Wilk (SW) test was utilized to evaluate the distribution of the data [166]. The findings from the normality tests were used of the purposes of selection of an appropriate method for data correlation analysis. Normality tests were executed for odor concentration, temperature, and relative humidity for each measuring day. These tests encompassed the entire dataset, individual measurements in each measuring points at the premises of the Facility #1 were considered. The Shapiro-Wilk test is designed to assess the extent to which the gathered data conforms to a normal distribution [166]. If the p-value is 0.05 or less, the hypothesis of normality for the SW test is rejected. The outcomes of the Shapiro-Wilk tests are presented in the Table 7.

Table 7. Results of the normality test for the whole data set divided on a single measuring days.

Date	Odor concentration			Temperature			Humidity		
	Statistic	p-value	Reject normality?	Statistic	p-value	Reject normality?	Statistic	p-value	Reject normality?
18.11.2021	0.81	<0.05	YES	0.82	<005	YES	0.88	<0.05	YES
14.12.2021	0.70	<0.05	YES	0.60	<0.05	YES	0.72	<0.05	YES
28.01.2022	0.83	<0.05	YES	0.79	<0.05	YES	0.93	>0.05	NO
23.03.2022	0.80	<0.05	YES	0.95	>0.05	NO	0.94	>0.05	NO
29.04.2022	0.80	<0.05	YES	0.89	<0.05	YES	0.97	>0.05	NO
13.05.2022	0.82	<0.05	YES	0.95	>0.05	NO	0.97	>0.05	NO
27.06.2022	0.81	<0.05	YES	0.88	<0.05	YES	0.85	<0.05	YES
26.07.2022	0.81	<0.05	YES	0.95	>0.05	NO	0.94	>0.05	NO
28.08.2022	0.80	<0.05	YES	0.95	>0.05	NO	0.95	>0.05	NO
15.09.2022	0.83	<0.05	YES	0.88	<0.05	YES	0.96	>0.05	NO
13.10.2022	0.77	<0.05	YES	0.95	>0.05	NO	0.99	>0.05	NO

According to the data shown in Table 7, odor concentrations do not follow a normal distribution for each individual day of measurement. In the case of temperature and humidity, the data distribution is mixed. Drawing on the outcomes of the Shapiro-Wilk tests, Spearman's rank correlation coefficient (r_s) was employed to assess the correlation among the data [167]. The r_s test assess the strength and direction of a monotonic relationship between the data sets [168]. The results of the correlation assessment is provided in Table 8.

Table 8. Calculated values of Spearman's coefficients.

	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
	Spearman's correlation coefficient (r_s)										
odor concentration - temperature	-0.11	-0.10	-0.16	0.20	0.07	0.71	0.01	0.32	0.23	0.21	0.09
odor concentration - relative humidity	0.21	0.31	0.28	0.14	-0.10	0.20	0.16	0.64	0.48	0.15	0.29

Upon examining the relationship between odor concentration and temperature shown in Table 8, it is apparent that in the majority of cases, there is either no monotonic correlation or only a weak monotonic correlation between odor concentration and temperature is observed. The most substantial monotonic correlation was calculated for May 2022, where Spearman's rank correlation coefficient is valued at 0.71 (strong correlation). The second-highest r_s value

is noted in July 2022 at 0.32. For the remaining months, r_s values span between -0.1 and 0.2. A similar trend is noticeable when considering the relationship between odor concentration and relative humidity. Though the overall pattern suggests a weak correlation, the r_s values for the odor concentration humidity relationship are generally higher compared to those for the odor concentration-temperature relationship. The peak r_s values were recorded in July 2022 (0.63) and August 2022 (0.48), while the r_s values for the other measuring days range from -0.1 to 0.3. These findings indicate that in the majority of cases, the measured odor concentrations were not significantly correlated with meteorological factors such as temperature and humidity.

To find relation between average data shown in Figure 35 and Figure 37, an assessment of the degree of correlation was provided for an average values of meteorological parameters in each measuring days in relation with average odor concentrations. The results are provided in Table 9. Three most used correlation coefficients were used. i.e. Pearson coefficient, Spearman coefficient (same as in the previous case), and Kendall coefficient. When it comes to the correlation between average values of odor concentration and temperature, the results indicate positive correlation between these two parameters. However, used parameters shows that the correlation is at the weak to moderate levels. When it comes to the correlation between average values of odor concentration and average values of relative humidity, results indicates that negative correlation can be observed – as the humidity increases, odor concentration levels decreases.

Table 9. Results of the determination of correlation coefficients for the relationship between odor concentration and meteorological parameters.

	Pearson correlation	Spearman correlation	Kendall correlation
odor concentration and temperature	0.58	0.50	0.34
odor concentration and humidity	-0.58	-0.34	-0.236

7.1.5 Results discussion

The recent literature on studies of odor concentration measurements at mechanical-biological waste management plants using field olfactometry is limited, examples can be found in [30,34,59,61,76,92]. In the study [92] authors carried out a measuring campaign in six different mechanical-biological treatment plants, all of which were had the ability to process the mixed waste using anaerobic stabilization method (methane fermentation). The odor

concentrations were measured at locations similar to those in the study under discussion, such as waste storage areas, mechanical parts of the waste treatment processes, fermentation preparation areas within buildings, digestate dewatering sections, oxygen stabilization areas, and biofilters.

The data analysis reveals that odor concentration for waste storage varied between 4 ou/m^3 and 106 ou/m^3 [59,92], comparable to the range of 22.27 ou/m^3 to 78.49 ou/m^3 observed in measurement point no. 9 (waste reception hall) of this study. It's important to note that references [59,92] utilized a field olfactometer equipped with two distinct D/T dials, the second of which allowed for dilutions of 60, 100, 200, 300, 500, leading to a broader range of odor concentrations that could be measured. From the perspective of obtained results it is an important issue because when a D/T dial with lower dilution ranges is employed, there is a possibility of not capturing the actual odor concentration, as the methodology does not permit exceeding a D/T of 60 with a lower dilution range dial, thus potentially underestimating odor concentrations. The current methodology caps the odor concentration at 78.49 ou/m^3, while the actual value might be higher. Consequently, it's recommended to use the high dilution D/T dial simultaneously with low dilution D/T dial for the most accurate results of the assessments.

Odor concentrations in the mechanical sections of the studied facilities ranged from 4 to 11 ou/m^3 [59,92], which is similar to the range of 3.87 to 11.31 ou/m^3 observed in measurement points no. 6, 7, and 8. However, a substantial difference was observed in aerobic stabilization areas, where authors of [59,92] recorded odor concentrations ranging from 4 to 22 ou/m^3, whereas in measurement points no. 14, 15, 28, and 29 of this study, the range was 43.49 ou/m^3 to 78.49 ou/m^3. Study in [34] reported odor concentrations at waste storage and mixed waste storage points ranging from 5 to 12 ou/m^3 (lower than point no. 9 of this study), while odor concentrations at selectively collected waste points were around 7 ou/m^3, similar to point no. 4. Odor concentrations at biofilter surfaces ranged from 2 to 78 ou/m^3 [34,59,76,92], while in measurement points no. 17 and 27, the range was 3.87 to 22.27 ou/m^3. The higher odor concentrations at biofilters might be attributed to nonoptimal operational conditions.

Operational conditions, technological operations, and the type of waste processed are factors that can influence odor emissions and subsequently, the measured odor concentrations [59,92]. For instance, another study [61] examined leachate tanks at two different mechanical-biological waste treatment plants using a different type of portable olfactometer that allowed for a higher range of odor concentration measurements. They found odor concentrations

ranging from 22 to 6,390 ou/m^3, significantly higher than those observed in points no. 31, 33, 34, and 35 of this study. The highest odor concentrations reported were 448 ou/m^3 for digestate dewatering in [92], 106 ou/m^3 for waste storage in [59], and in [34] the highest was in the oxygen stabilization area.

The literature indicates high variability in odor concentrations, despite certain similarities. The question arises whether it's possible to obtain very similar results across different mechanical-biological waste treatment plants. The answer is negative. As literature [23,37] suggests, waste composition continually changes and can vary among communities, cities, or regions. Therefore, the waste processed in mechanical-biological waste treatment plants located in distinct regions could differ, for example, in the content of organic fractions, which means that odor emissions associated with processing of organic waste might vary. Additionally, despite technological similarities, individual mechanical-biological waste treatment facilities could have variations in specific processes, contributing to differences in odor emissions and concentrations.

A review of existing literature reveals varied findings regarding the correlation between odor concentrations and meteorological factors such as temperature and humidity [169]. For instance, the authors of [59] discovered significant correlations between odor concentrations (using the field olfactometry method) and temperature during their study. They also observed some degree of correlation between odor concentration and relative humidity. Nonetheless, the same study [59] reported a Spearman correlation coefficient of 0.306 for the relationship between odor concentration and temperature, which is not indicative of a strong correlation. Recent literature has particularly focused on evaluating the relationship between temperature, relative humidity, and the concentrations of odor-causing substances like volatile organic compounds, hydrogen sulfide, and ammonia [59,61,169]. These studies highlight the existence of correlations and dependencies between odor concentration and odorants as well as the correlation between odorants and meteorological variables like temperature and humidity.

Authors of different literature studies [42,59,76,126,130,132,170] used a field olfactometry method to assess odorous air quality and as a tool for odor monitoring. It is widely confirmed that field olfactometric measurements can be used for such tasks. From the perspective of waste management facilities field olfactometry should be considered one of the first tools to use when handling odor problems and the use of such a tool should be incorporated into odor management plans indicated in Best Available Techniques for waste treatment [171].

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 [52], it does not require complicated measuring equipment and a laboratory, it is easy to perform, low-cost, and does not require complicated training [38,116,172]. Usually, waste management authorities use external laboratories to carry out odor measurements. However, the field olfactometric measurements could be performed even by employees, as the manufacturer provides an Odor Sensitivity Test Kit which can be used to assess the olfactory ability of, for example, employees [173].

7.2 STRATEGY NO. 2 – INTERPOLATION OF ODOR DATA

7.2.1 Spatial distribution of odor data

The spatial distribution of odor concentrations are presented in Figures 38 to 48, representing the results of interpolating the measured points at the premises of Facility #1 during specific measuring days. The spatial distribution of odor concertation at each Figure was divided into 6 classes, in accordance with the measuring range of Nasal Ranger device. In addition, measured values used for interpolation are also provided in each Figure. In the case of Figure 39 and Figure 40 the inverse distance weighted method was not implemented due to the limited quantity of data points where the odor concertation was measured.
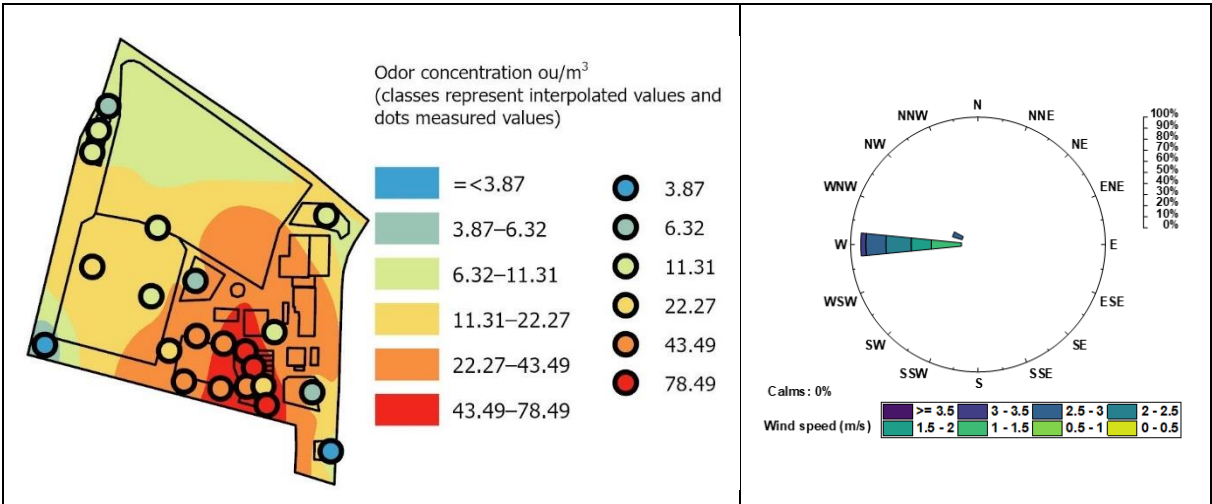
Figure 38. Odor concentration distribution (18.11.2021) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
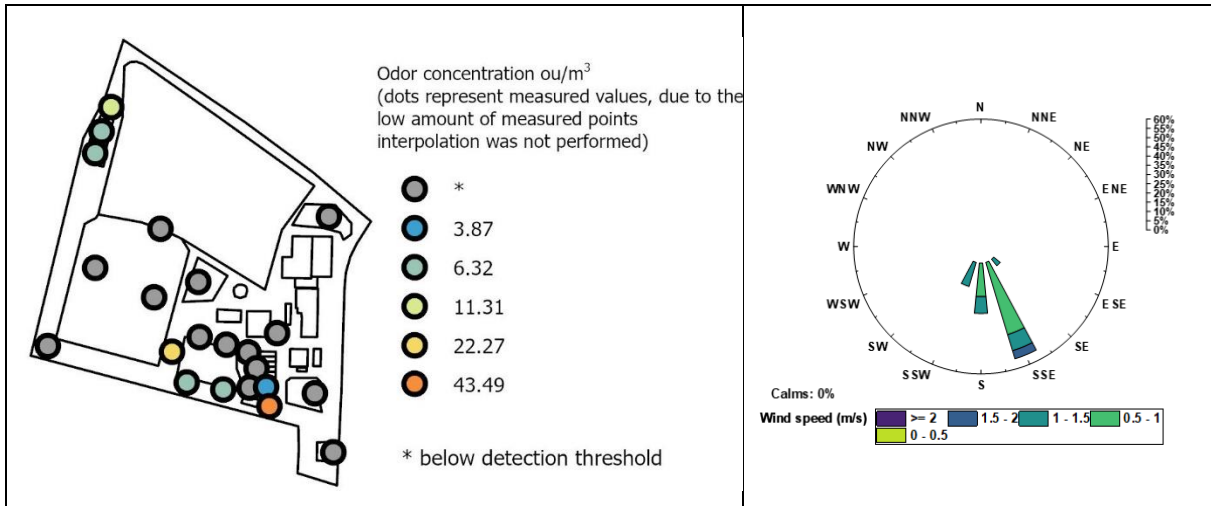
Figure 39. Odor concentration distribution (14.12.2021) within the boundaries of Facility #1 based only on measurement results (on the right), excluding points inside technological buildings. Spatial distribution with the use of inverse distance weighted method was not calculated due to the low number of points where odor concentration was measured above odor detection threshold. Wind rose plotted from the measurements carried out during the given day (on the right).
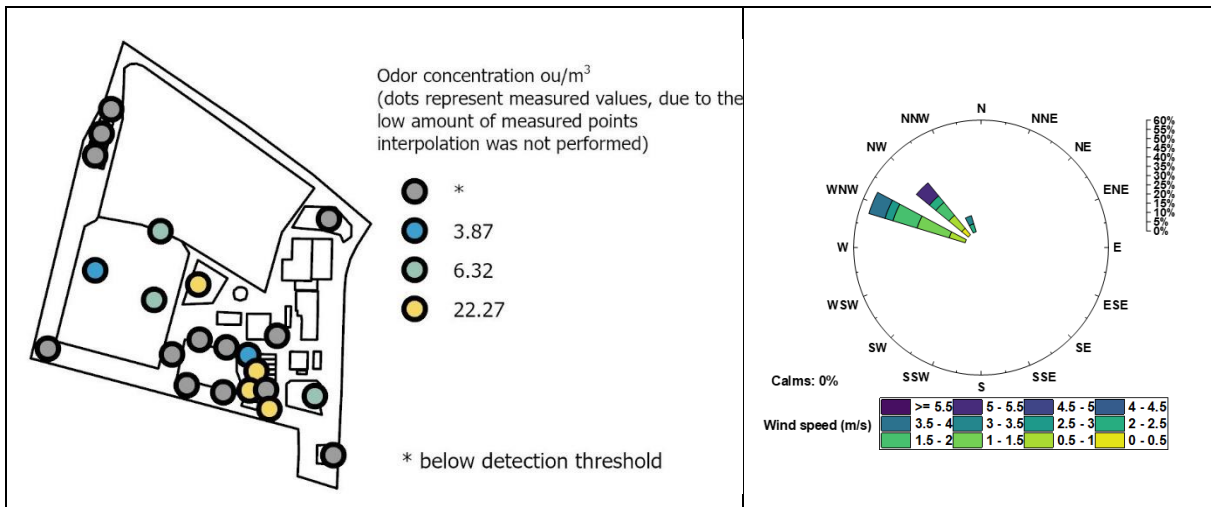
Figure 40. Odor concentration distribution (28.01.2022) within the boundaries of Facility #1 based only on measurement results (on the right), excluding points inside technological buildings. Spatial distribution with the use of inverse distance weighted method was not calculated due to the low number of points where odor concentration was measured above odor detection threshold. Wind rose plotted from the measurements carried out during the given day (on the right).
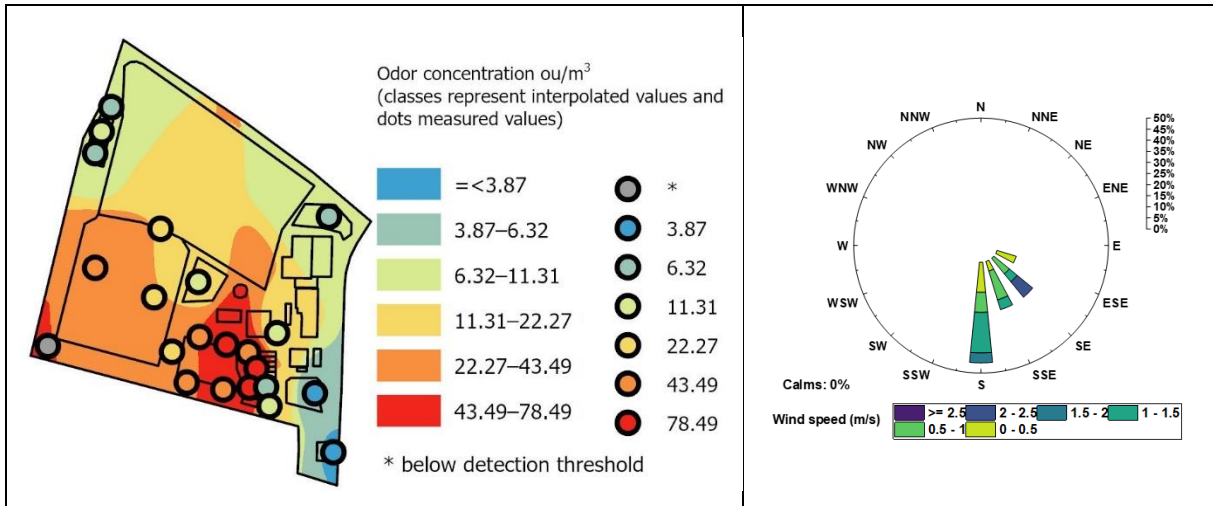
Figure 41. Odor concentration distribution (23.03.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
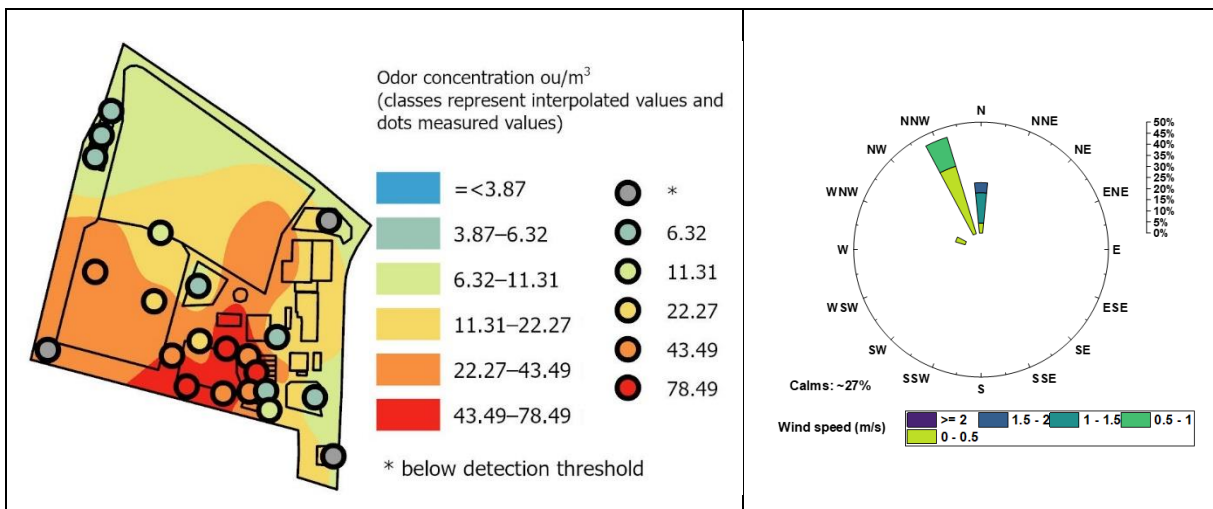
Figure 42. Odor concentration distribution (29.04.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
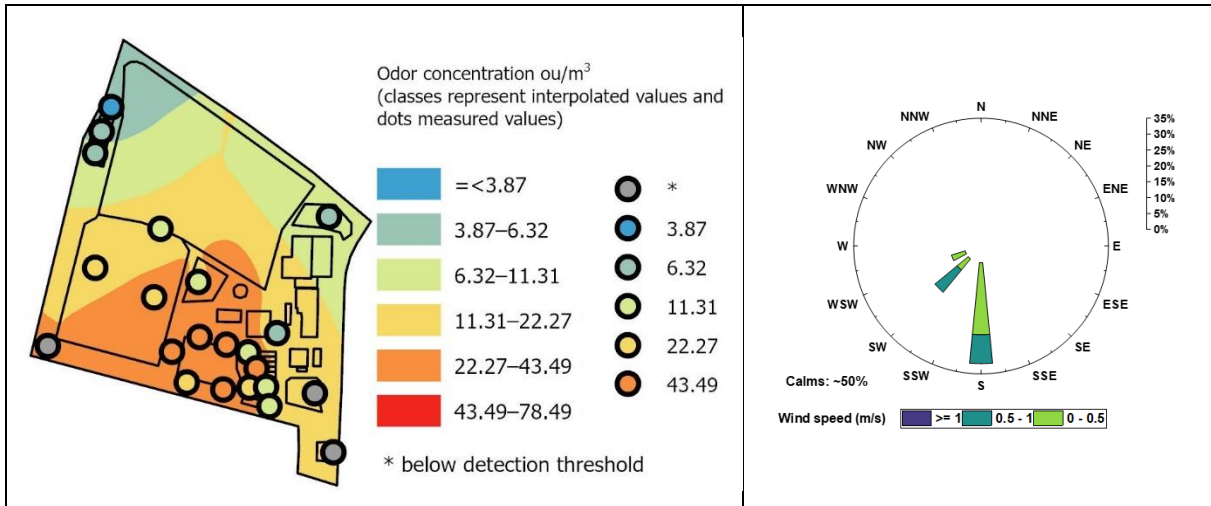
Figure 43. Odor concentration distribution (13.05.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
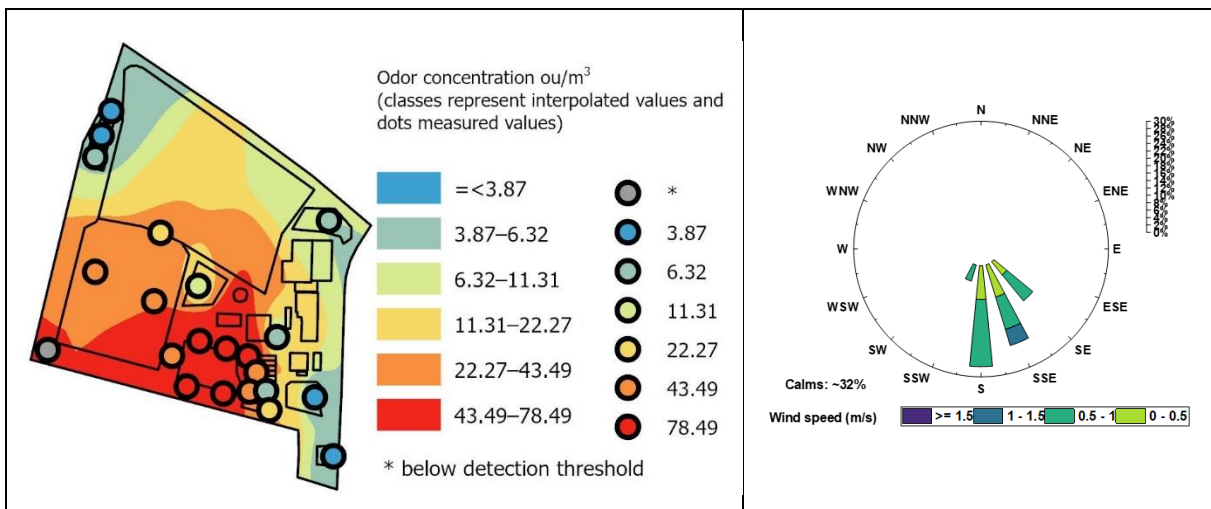
Figure 44. Odor concentration distribution (27.06.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
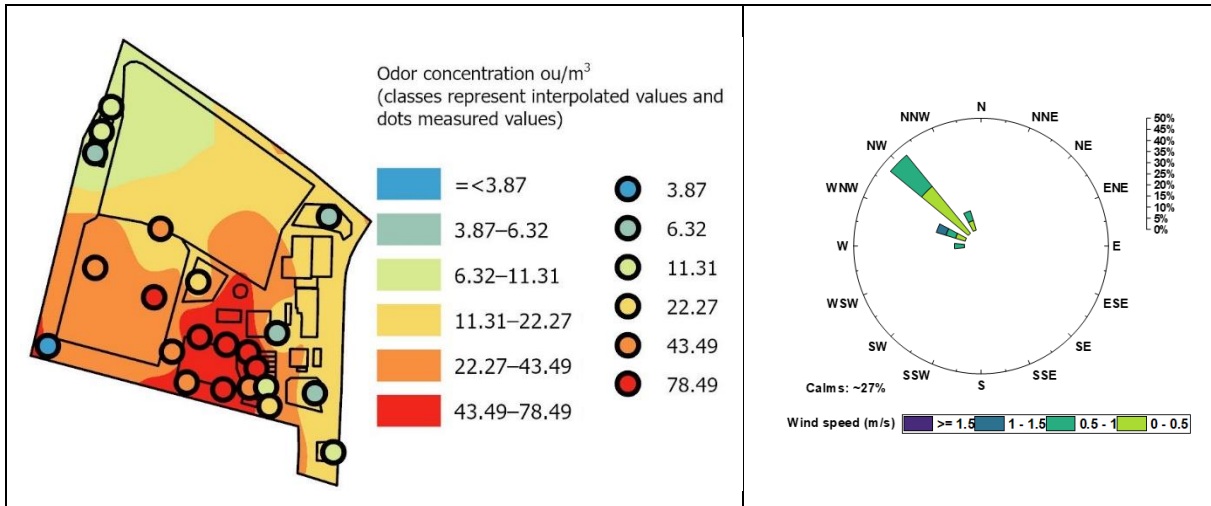
Figure 45. Odor concentration distribution (26.07.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
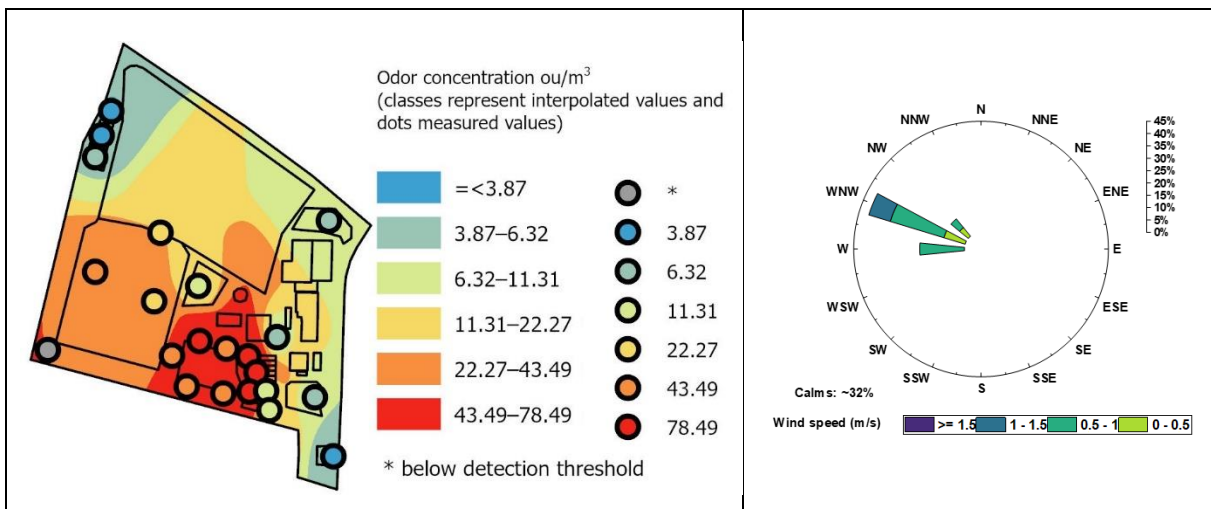
Figure 46. Odor concentration distribution (28.08.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
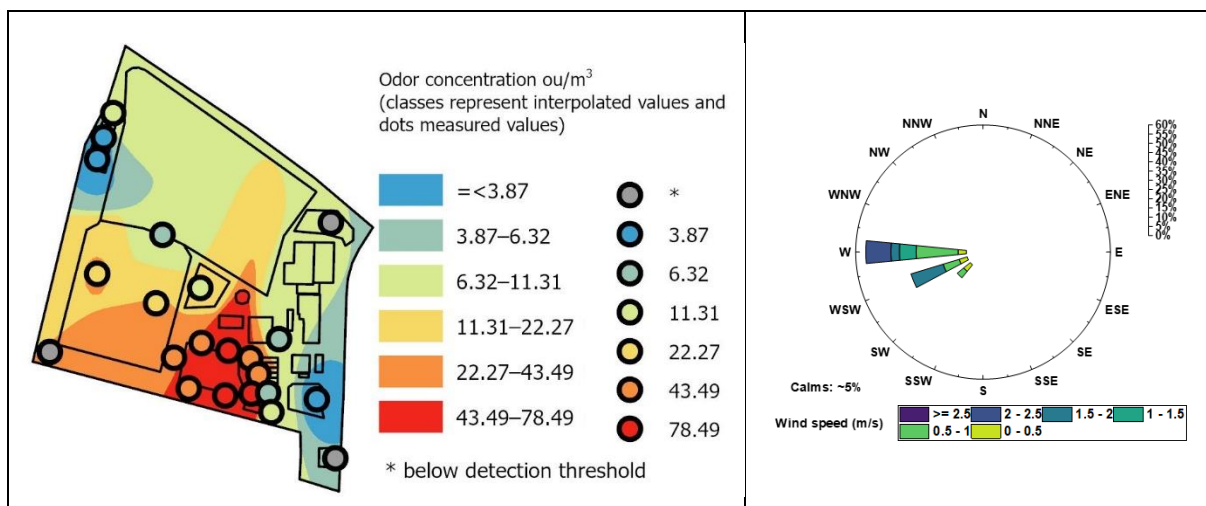
Figure 47. Odor concentration distribution (15.09.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).
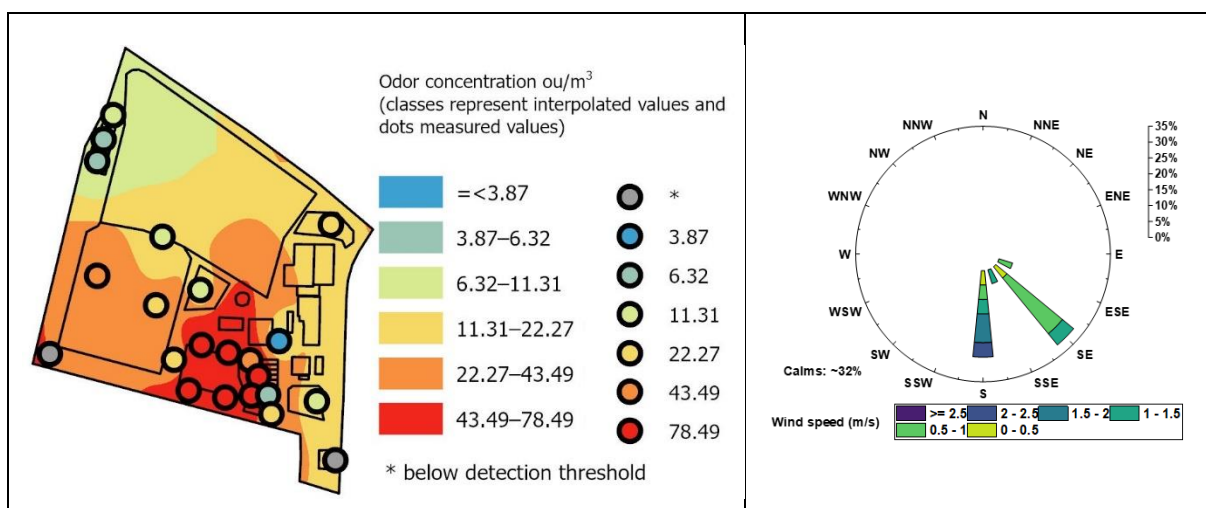
Figure 48. Odor concentration distribution (13.10.2022) within the boundaries of Facility #1 obtained by implementing the inverse distance weighted interpolation method, excluding points located in technological buildings (on the left), and wind rose plotted from the measurements carried out during the given dates (on the right).

7.2.2 Cross-validation results

In the Table 10 the results of cross-validation for obtained spatial distributions are provided. As the considered interpolation method was not performed for 14.12.2021 and 28.01.2022, the table does not present its results for these measurement days.

Table 10. Results of cross-validation for each spatial distribution obtained with the use of inverse distance weighted method.

	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
N of used points	22	-	-	21	19	19	21	22	21	19	20
Mean Error	4.99	-	-	3.61	2.70	1.06	1.69	4.71	5.01	2.16	1.92
Root Mean Square Error	21.88	-	-	21.02	24.03	13.24	20.70	23.06	22.09	17.49	26.70

7.2.3 Results discussion

Upon analyzing the acquired odor concentration distributions for individual measuring days, in conjunction with the cross-validation results, the following observations can be made.

First of all, the cross-validation findings reveal that the Mean Error (eq. 8) is greater than zero in all instances, indicating a tendency of the interpolation formula to over-predict the values. Additionally, the Root Mean Square Error parameter (eq. 9) is relatively high. The minimal RMSE value, which is 13.24, was achieved was achieved for the spatial distribution obtained for 13.05.2022. This implies that, on average, the predicted values deviate by 13.24 ou/m^3 from the actual measured values. The maximum RMSE was computed for 26.70, during which the predicted values exhibited an average deviation of 26.70 ou/m^3.

The analysis of the spatial distributions shown in Figures 38 through 48 confirms the cross-validation results. In each instance, some of the interpolated values deviate from the measured values and tend to be higher. The difference is most pronounced when examining the lower end of the values. For instance, as illustrated in Figure 38, the measured values at the corners of the Facility #1, specifically, the southeast corner at point no. 1 near the administration building, and the southwest corner at point no. 32, the boundary of the Facility #1, are at the level of 3.87 ou/m^3. However, the predicted values derived through the used interpolation method are in the range from 3.87 ou/m^3 to 6.32 ou/m^3. A similar pattern can be observed in the center of the facility, for example, at point no. 13, situated in the area for bulky waste processing and storage. Here, the measured value is 6.32 ou/m^3, but the interpolated values are in the class range from 6.32 ou/m^3 to 11.31 ou/m^3 and quickly transitions to a range of 11.31 ou/m^3 to 22.27 ou/m^3 can be observed. Such a trend, where the lowest measured values are not

aligned with the predicted values, is a common occurrence in nearly every spatial distribution. Nevertheless, in the case of Figure 41 and Figure 47 some lower measured values are in precise agreement with the respective class of predicted values - Figure 41, at point no. 1, and Figure 47 at points no. 2, 33, and 34.

The most significant issue regarding the interpolation results arises in the measuring days when some of the odor concentrations at the measurement points were below the detection threshold, as observed in Figures 41 through 48. For instance, in Figure 41, at point no. 32 (situated in the bottom left corner of the facility), the measured odor concentration was below the detection threshold of used field olfactometer. However, the interpolated value for that point falls into the highest possible class, ranging from 43.49 ou/m^3 to 78.49 ou/m^3. This greatly overestimates the spatial distribution around that point by almost the entire potential range of odor concentrations.

By comparing the results of odor concentration measurements through field olfactometry with the spatial distribution obtained by adopting the inverse distance weighted method, and considering the wind rose for each measuring days, it is generally not possible to find a relationship between odor distribution and wind patterns. The wind roses shown were constructed using wind data collected at each measurement location over a period of 3-4 hours. However, these wind roses may not fully depict the overall meteorological conditions, as they could be impacted by local factors.

Despite the fact that the inverse distance weighted interpolation method is considered to be easy to use in terms of mathematical approach, it does not require any significant amount of computational power, and is quick to use, it has some disadvantages [150,151]. Notably, the inverse distance weighted method is highly dependent on the spatial arrangement of measurement points (e.g., whether the points are arranged in a uniform grid or placed irregularly, where clustering might be spotted)[151]. In conducted study, regarding the assessment of spatial distribution of odor concentration with the use of inverse distance weighted method, it is apparent that the points are distributed unevenly, with noticeable clustering, especially in the aerobic stabilization area and at the green waste storage area. Additionally, the method is influenced by the number of data points employed and the power value [150,151]. In this study, the power value was optimized for every case by built-in algorithm in ArcGIS software. The optimization was focused in reducing cross-validation errors. To potentially mitigate these errors and attain a higher-quality spatial distribution, it is

recommended to reconfigure the measurement grid. Taking into consideration the tendency towards overestimation of data and the inability to handle cases where the odor concentrations were below the detection threshold of used olfactometer, the appropriateness of the inverse distance weighted method for managing odor concentration data is debatable. Nonetheless, despite the relatively high margin of error, it can still be employed to identify areas affected by odors.

7.3 STRATEGY NO. 3 – ODOR CONCENTRATION AND ODOR INTENSITY RELATIONSHIP

7.3.1 Odor intensity distribution at premises of Facility #1

Figure 49 shows and average odor intensity values for the whole measuring periods. The results are as follows: for the biological processing area, the average odor intensity is in the range of 4.3 up to 6. A total of 16 measuring points are scattered around that area. In addition, the point located at the leachate tank for biological processes is characterized by average odor intensity of 4.0. Outside the biological part of the Facility, only one point is characterized by such a high intensity located in the waste reception hall – 4.9. The rest of the measuring points are characterized by average odor intensity below 4.0. The second highest average values of odor intensity can be found around the landfill area and inside RDF preparation and storage building, two points located directly at landfill site valued at 4.0 and 3.7, while RDF preparation and storage building valued at 3.6. Average odor intensity at landfill entrance was 3.0. Average odor intensity at bulky waste processing and storage area valued at 2.7. Sorting hall ranges from 1.0 up to 3.0 of average odor intensity. Average odor intensity of points located around landfill leachate tanks range from 2.2 up to 2.4. Selective waste storage valued at 2.2. Biofilter for aerobic processes valued 2.2, while biofilter for aerobic processes valued at 2.4 of average odor intensity. Points located at the technical area, administrative building, and the Facility corner are valued at 2.09, 1.09, and 0.55 respectively. The results shown in *Chapter 7.1*, regarding average values of odor concentration at measuring points show a high degree of correlation with average values of odor intensity.

As stated in the Methodology chapter (*Chapter 6.3.2*) some of the values of odor concentration were changed to 0.0 ou/m^3 in order to provide statistical analysis of odor concentration-odor intensity. Therefore, a slightly different values of odor concentrations were obtained in this approach.
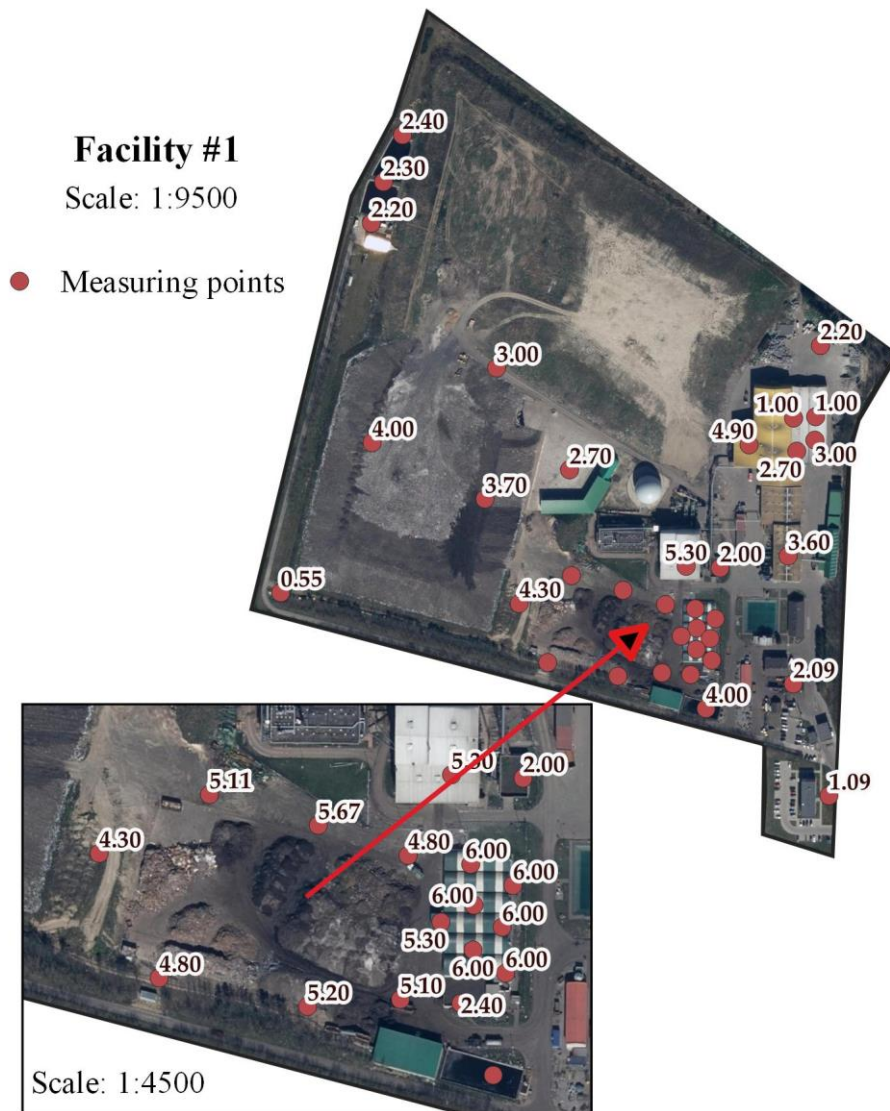
Figure 49. Average odor intensity for each measuring point located at Facility #1
based on 11-month measuring period.

7.3.2 Basic statistical analysis of odor concentration-odor intensity data

To determine the relationship between odor data, i.e. odor concentration and odor intensity, the data was categorized in accordance with the description provided in the *Methodology Chapter*. To each odor concentration, that could be obtained with field olfactometry method (7 steps, ranging from 0 ou/m^3 to 78.49 ou/m^3) an odor intensity level was assigned (7 point reference scale). See *Chapter 6.3.2* for details. As shown in Figure 27 (*Chapter 6.3.2*) there is a clear existence of a logarithmic trend between measured odor parameters, when regarding assumed data categorization. The scatterplot for the data measured during the research campaign is shown in Figure 50.
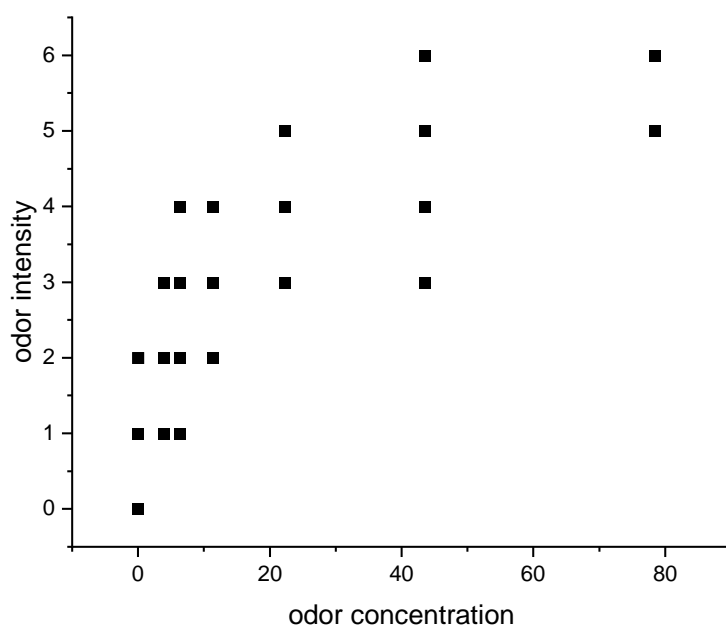
Figure 50. The scatterplot for the data measured during the research campaign.

One particular phenomenon can be observed by measured odor concentrations against measured odor intensity. Obtained results indicate that for a given odor concentration, the odor 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 odor intensity relative to a given measured odor concentration is provided in Table 11.

Table 11. The frequency of occurrence of a given measured odor intensity relative to a given measured odor concentration.

Odor concentration	N count	%	Odor intensity values						
			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	11.31	0	0	0	4.12	**5.50**	1.71	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**
		100	4.12	8.59	17.53	21.65	11.34	19.59	17.18
			%						

Overall, 291 pairs of odor concentration-odor intensity were used for this particular study. Analyzing the frequency of occurrence of a given odor concentration, in 57 measuring points during the whole measuring period the odor 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 %), third - 6.32 ou/m^3 (17.53 %), fourth - 11.31 ou/m^3 (14.78%), fifth - 22.27 ou/m^3, sixth - 3.87 ou/m^3, seventh, the lowest was 0 ou/m^3 which was measured in 7.56 % of all cases. As can be observed for odor concentration of 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 odor concentration, the "right" intensity value, following theoretical assumptions of data categorization, is the most common value. For example, for the odor concentration equals to 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 odor concentrations.

To assess the statistical relationship between odor concentration and odor intensity statistical tests were performed. Previously used Shapiro-Wilk test was performed 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 larger than 0.05
- H_1: data is not normally distributed if the p-value is smaller than 0.05

As stated before (*Chapter 7.1*), in the case of odor concentration, the data is 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 odor intensity, the p-value is greater than 0.05 in the given measuring days: 14.12.2021, 28.01.2022, and 23.03.2023, which means that the data is normally distributed. However, for the rest of the measurement days, the p-value is less than 0.05 and the data is not normally distributed. When performing the Shapiro-Wilk test for the whole data set, the hypothesis for data normality is not confirmed. Due to that reason, Spearman's correlation coefficient was chosen to assess the odor concentration-odor intensity relationship. The Spearman's r_s for odor concentration-odor intensity relationship evaluation is provided in Table 12.

Table 12. Values of r_s coefficient for each measuring days.

	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	0.98	0.98	0.99

High degree of monotonic correlation can be observed, only for three measuring days (14.12.2021, 28.01.2022, and 13.05.2022) r_s is lower than 0.90. In addition for the whole data set (291 pairs of odor concentration and odor intensity) r_s valued at 0.95 and shows a high degree of relationship between measured odor data.

7.3.3 Application of Weber-Fechner law

The Spearman correlation coefficient assessed the monotonic, not necessarily a linear relationship. To assess the linear correlation of data, Weber-Fechner law (eq. 9) was applied and linear correlation according to the aforementioned law is presented in Figure 51.
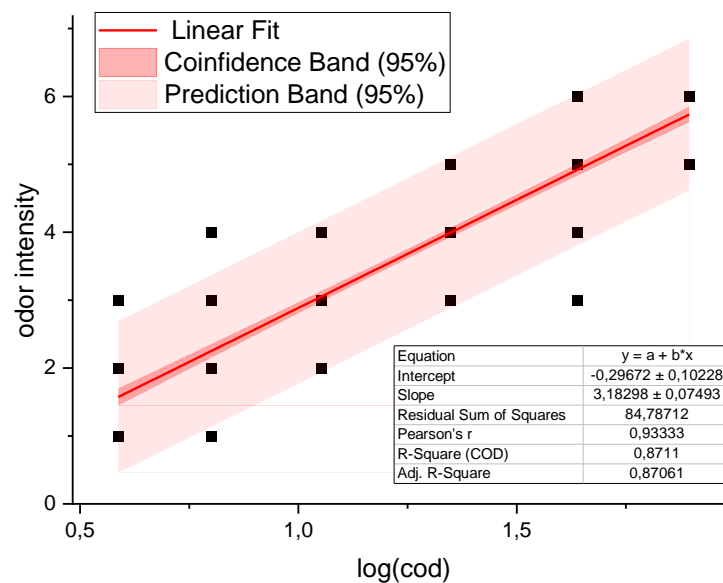
Figure 51. Application of Weber-Fechner law – linear correlation of log(odor concentration) and odor intensity based on 269 pairs of odor concentration and intensity measurements, pairs where odor concentrations valued at 0 ou/m^3 were removed.

The linear function derived from the data can be described as (eq. 14):

$$I = (3.18298 \pm 0.07493) * \log(c_{od}) - (0.29672 \pm 0.10228) \tag{14}$$

where:

I – is odor intensity,

c_{od} – is odor concentration (ou/m^3),

(3.18298 ± 0.07493) – Weber-Fechner constant (slope of regression line),

(0.29672 ± 0.10228) – Weber-Fechner constant (intercept)

The linear relationship, obtained by applying the Weber-Fechner law, is characterized by a high coefficient of determination r^2 0.87. 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 odor concentration and odor intensity.

By converting the equation of Weber-Fechner law (eq. 9, eq. 14) to the form of (eq. 15) it is possible to determine the odor concentration based on the measured odor intensity value.

$$c_{od} = 10^{(\frac{I-a}{b})} \tag{15}$$

where:

c_{od} – is odor concentration (ou/m^3),

I – is odor intensity,

a – Weber-Fechner constant (slope of regression line (3.18298 $\pm$ 0.07493)),

b – Weber-Fechner constant (intercept (0.29672 $\pm$ 0.10228))

The assessment of the ability to predict odor concentrations using the Weber-Fechner law derived from measurements carried out on the tested Facility based on intensity is shown in Table 13.

Table 13. Assessment of Weber-Fechner law in the prediction of odor concentrations based on intensity.

	Predicted odor concentration	95% Lower confidence Interval	95% Upper confidence Interval	Predicted odor 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	-34.0	-42.4	-24.3	3.87
2	5.27	2.35	11.80	-16.7	-62.8	+86.7	6.32
3	10.86	4.86	24.27	-4.0	-57.1	+114.6	11.31
4	22.38	10.02	50.02	+0.5	-55.0	+124.6	22.27
5	46.14	20.63	103.21	+6.1	-52.6	+137.3	43.49
6	95.11	82.99	109.01	+21.2	+5.7	+38.9	78.49

When comparing odor concentrations obtained with the use of Weber-Fechner law to reference values of odor concentrations that can be determined with the field olfactometry method it can be seen that predicted odor concentrations differ from reference values. The biggest difference can be observed for both ends of the odor concentration range, i.e. when predicting odor concentration for intensity 1 the predicted odor concentration is equal to 2.55 ou/m^3, which is 34.0 % smaller from the reference value (the value determined by field olfactometry method and following proposed data categorization). For intensity 6, the odor concentration is 21.2 % higher than the reference value. The most accurate results can be observed in the middle concentration range, i.e. from 11.31 ou/m^3 to 43.49 ou/m^3.

As using (eq. 15), it is impossible to obtain precise odor concentration results, the behavior of the Weber-Fechner law of individual measurement points was additionally checked. 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 determined. This approach does not eliminate points with an odor concentration of 0 ou/m^3 as the data are averaged. The regression line for this approach is shown in Figure 52.
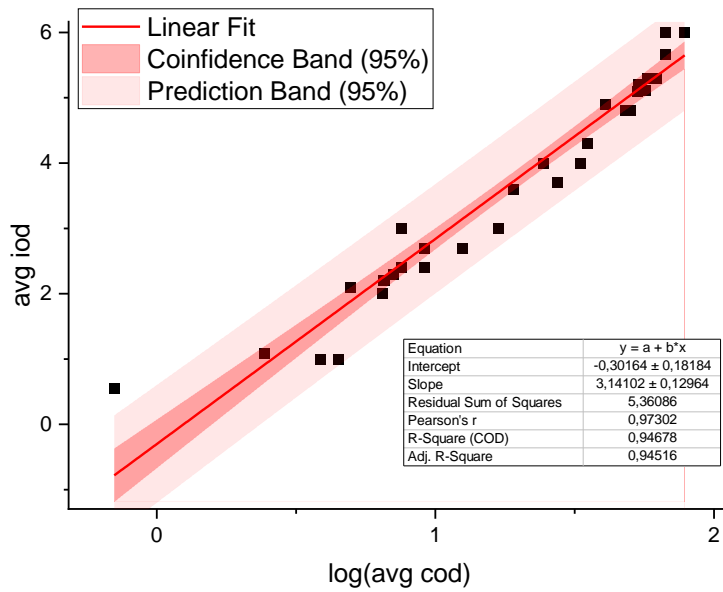
Figure 52. Application of Weber-Fechner law – linear correlation of log(average odor concentration) and average odor intensity. For each of the 35 measurement points, average concentration and intensity values were calculated for the 11-month measurement period.

The linear function derived from the averaged data can be described as (eq. 16):

$$I = (3.14102 \pm 0.12964) * \log(c_{od}) - (0.30164 \pm 0.18184) \qquad (16)$$

where:

I – is odor intensity,

c_{od} – is odor concentration (ou/m^3),

(3.18298 ± 0.07493) – Weber-Fechner constant (slope of regression line),

(0.29672 ± 0.10228) – Weber-Fechner constant (intercept)

The determination coefficient r^2 is higher than in the case of (eq. 14) and is equal to 0.95. The same can be observed for Pearson's r coefficient. It is higher and amounts to 0.97. By adopting (eq. 15) to new values of the regression line (eq. 16) the assessment of the ability to predict odor concentration was performed and is shown in Table 14..

Table 14. Assessment of Weber-Fechner law in the prediction of odor concentrations based on intensity for the second approach.

	Predicted odor concentration	95% Lower confidence Interval	95% Upper confidence Interval	Predicted odor concentration	95% Lower confidence Interval	95% Upper confidence Interval	ref. value
intensity	ou/m^3			% difference			ou/m^3
0	1.25	0.65	2.40	-	-	-	0
1	2.60	1.38	4.89	-32.90	-64.4	+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

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 middle range of odor concentrations (from 11.31 ou/m^3 up to 43.49 ou/m^3), while values at both ends of the odor concentrations range seem to be drifting away from the reference values.

7.3.4 Discussion

When comparing odor concentrations and odor intensity clear pattern can be observed, i.e. the highest odor 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, similar to the distribution of odor concentration A high degree of correlation can be observed between those two parameters, the highest values of odor concentration are accompanied by the highest values of odor intensity. The results of the correlation analysis between odor concentration and odor 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 determining the possible relationship between these two parameters including multipoint measurements and long-term studies. The authors of [59,76] provide a series of measurements of odor concentrations and intensity at 6 biogas plants processing municipal waste. They found

a high correlation between these two parameters by directly comparing the results of measurements. They also found a correlation 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 odor concentration odor intensity can be used. It creates another potential use of such a parameter for odor assessment by the employees of waste management facilities.

In addition, when applying the determined Weber-Fechner law for determining the odor concentration based on odor intensity high data spread can be observed. The obtained concentrations differ from the reference values. However, when using a rich data set of measured odor concentrations and odor 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. Determining the odor concentrations based on measured intensity values can be a useful tool when limited field olfactometric measurements are available.

7.4 STRATEGY NO. 4 – VOLATILE ORGANIC COMPOUNDS MEASUREMENTS

7.4.1 Volatile organic compounds measurements and their correlation with odor concentration

Figures 53, 54, 56, 57, 59 and 60 shows distribution of odor concertation and distribution of volatile organic compounds concentration related to the implementation of Strategy No. IV measured during 5 different measuring days. Figure 53 and 54 focuses on measurements carried out at Facility #1 in 13.10.2022 and 17.02.2023. When it comes to the odor distribution the same situation can be observed as in the case of implementation of Strategy No. I. 13.10.2022 was the same measuring day as in the case of Strategy No. 1, however, the measurements for those two distinct strategies were separated by 2 hours period. The odor distribution does not show any particular different pattern than in the previous case. The highest odor concentration can be found around aerobic stabilization area, waste reception hall and at the landfill. Overall trend did not change. In the case of 17.02.2023 similar situation occurs as in the case of measurements carried out in cold months during the implementation of Strategy No. I. It can be observed that in some of the measuring points the odor concentration was below odor detection threshold, which for this purpose it is treated as 0.00 ou/m^3. Those points are

located outside technological buildings and are scattered around landfill area, leachate tanks and near technological area and administrative building. Overall trend is similar to pattern found in the previous cases, i.e. highest odor concentration are located around biological part of the Facility, the less the organic matter, the less is the odor concentration. When it comes to the distribution of volatile organic compounds in the case of 13.10.2022 it can be observed that the overall pattern is in compliance with odor distribution (Strategy No. I) and odor intensity distribution (Strategy No. II). The highest volatile organic compound concentrations can be found around places where significant amount of organic waste is processed. The highest values of 1.26 ppm and above can be observed inside bioreactors, technical building for anaerobic processes, inside waste reception hall. One particular interesting thing can be observed, the values of 1.26 ppm and above can be found inside waste sorting hall, where odor concentrations are not in the highest possible range. During the measurements in 17.02.2023 the situation regarding volatile organic compounds is significantly different. Despite the fact, that the odor concentration in many points reached mid and high values of ou/m^3, volatile organic compounds stays at relatively low levels in almost the whole area of Facility. Similar situation where the volatile organic compounds are at level of 1.26 ppm and above can be observed in waste sorting area.
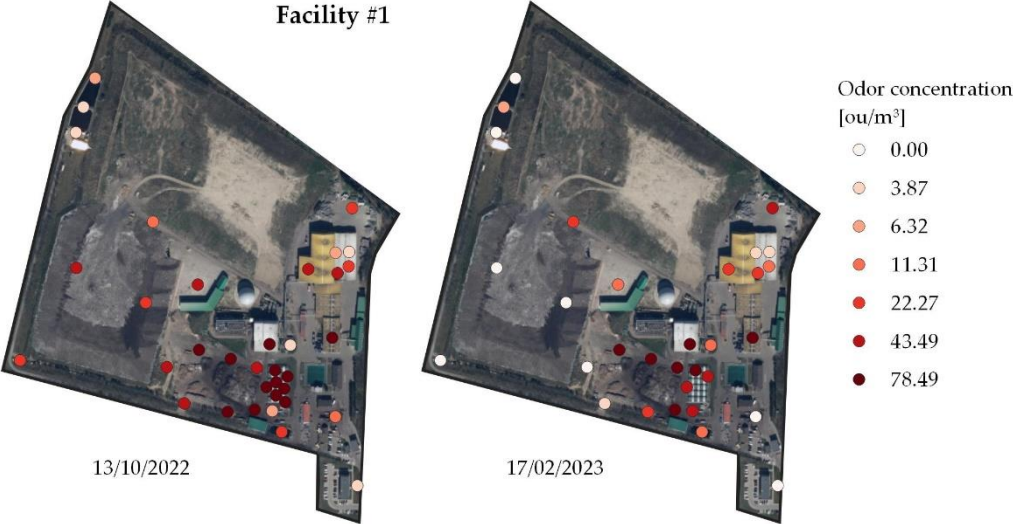
Figure 53. Odor concentration distribution at Facility #1 during measurements for realization of Strategy No. IV.
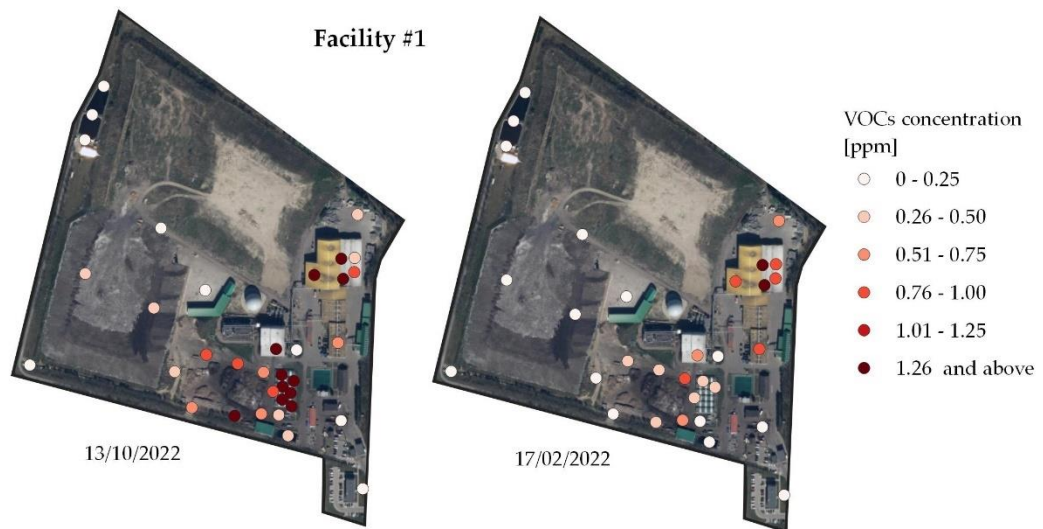
Figure 54. Volatile organic compounds concentration distribution at Facility #1 during measurements for realization of Strategy No. IV.
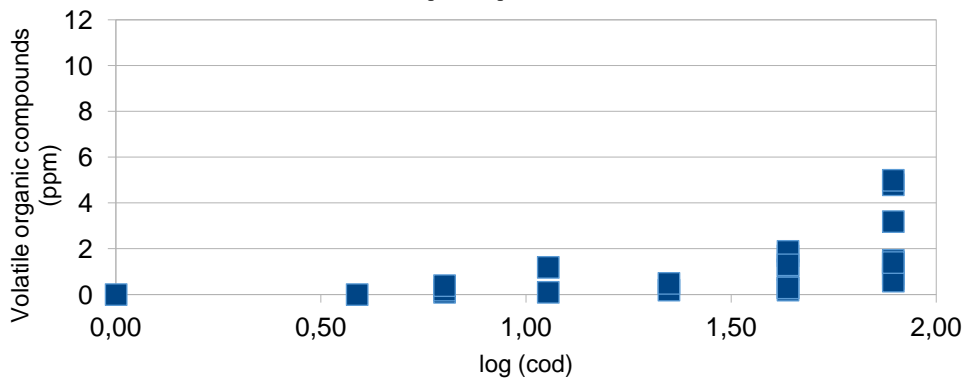
Figure 55 shows the relationship between logarithm of odor concentration and the volatile organic compounds concentration (ppm). It indicate the existence of some degree of correlation between those two parameters. Therefore, further analysis was provided.

13/10/202
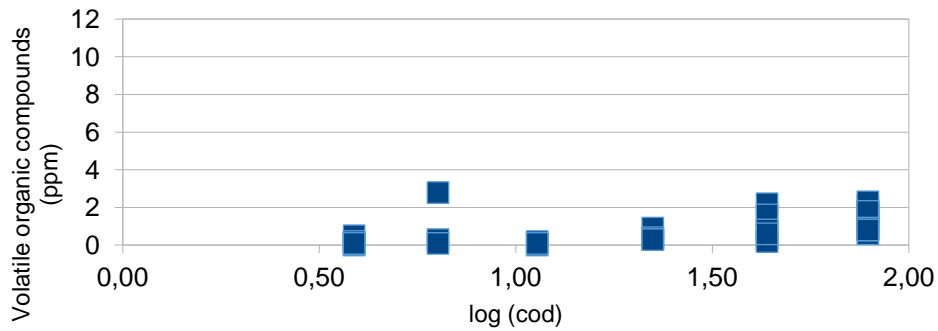
17/02/2022
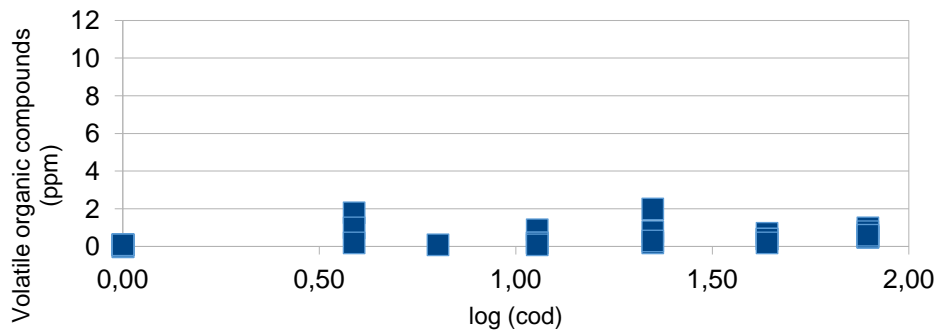
Figure 55. Logarithm of odor concentration plotted against volatile organic compounds concentration in a given measuring days at Facility #1.

The results of measurements carried out in Facility #2 (only one measuring day) shows the existence of a similar pattern in terms of distribution of odor concentration and volatile organic compounds. In the case of Facility #2 (Figure 56) the highest odor concentration can be found inside waste sorting hall and waste reception hall, and inside closed bioreactors in a separate technological hall connected to the waste reception hall for the fermentation process and at the point located near leachate treatment plant. A similar pattern can be found in the distribution of volatile organic compounds (Figure 57). It is worth noting that at in the case of Facility #1, in Facility #2 inside waste sorting hall the volatile organic compounds concentrations exceeded 1.26 ppm. See *Chapter 6.2* for the exact location of the measurement points.
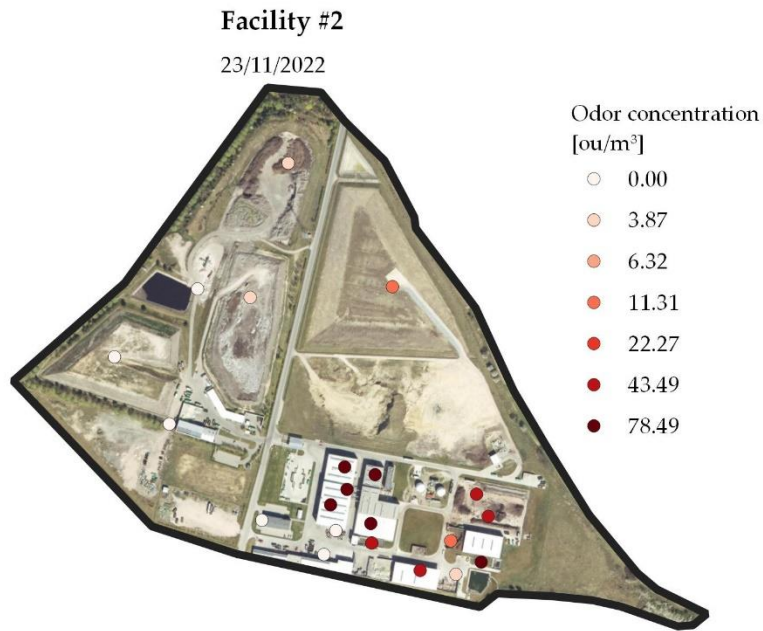
Figure 56. Odor concentration distribution at Facility #2 during measurements for realization of Strategy No. IV.
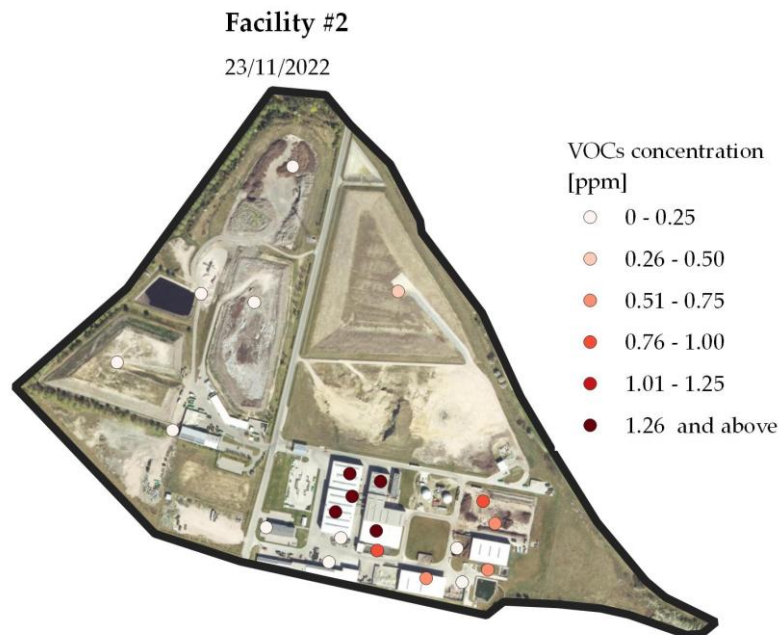
Figure 57. Volatile organic compounds concentration distribution at Facility #2 during measurements for realization of Strategy No. IV.

By analyzing the values of logarithm of odor concentrations and volatile organic compounds concentrations an interesting pattern can be observed (Figure 58). When the

logarithm of odor concentrations reached a certain point, which was equal to odor concentration at the level of 78.49 ou/m^3, the volatile organic compounds concentrations keep increasing. This pattern could be observed at Facility #1 in the case of 13.10.2022, however, it was not that clear as in the case of Facility #2. This particular result may indicate that the measured odor concentration is in fact greater than 78 ou/m^3, because once this value is reached, the volatile organic compounds concentrations continues to increase. This may indicate the need of use a different D/T dial with Nasal Ranger olfactometer that would allow for higher range of measured odor concentrations.

23/11/2022
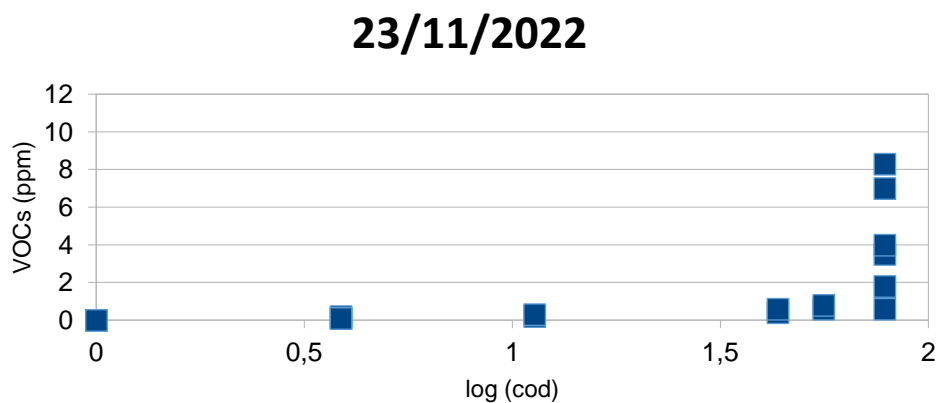
Figure 58. Logarithm of odor concentration plotted against volatile organic compounds concentration in a given measuring day at Facility #2.

Figures 59 and 60 shows the distribution of odor concentration and volatile organic compounds concentration at the premises of Facility #3. As stated in the Methodology chapter (*Chapter 6.2*) Facility #3 is different than the Facility #1 and #2. It has no landfill, no anaerobic phase of waste treatment, sorting is not that sophisticated, and overall technological regime represents lower quality. By analyzing the odor distribution at both measuring days it can be observed that in almost whole facility, independent of the measuring points location, the highest range of odor concentration can be found (43.49 ou/m^3 – 78.49 ou/m^3). Those points over, among others, different mixed waste storage places, RDF storage, biological part of the Facility, or points located inside the waste reception/storage hall and waste sorting hall. The lowest concentrations can be found around leachate tanks and selective collected waste storage area. Volatile organic compounds concentration is in the compliance with the odor distribution. This is especially observed during measurements carried out in 24/10/2022. Figure 61 shows the plotted logarithm of odor concentration against volatile organic compounds concentrations. It

shows that in most case odor concentration for that given day was at the level of 78.49 ou/m^3 and volatile organic compounds concentration was at the level of 1.26 ppm or above. This is in compliance with the results obtained in previous cases. It indicates that measured odor concentrations can be much higher than measured with used field olfactometer, therefore the higher dilution range is needed. Some of the points in the case of 02/11/2022 does not correlate in the same way. It can be observed that in some cases the odor concentration reaches 78.49 ou/m^3 and the concentration of volatile organic compounds is less than 1.26, but the overall pattern is kept, which is confirmed in the 61.
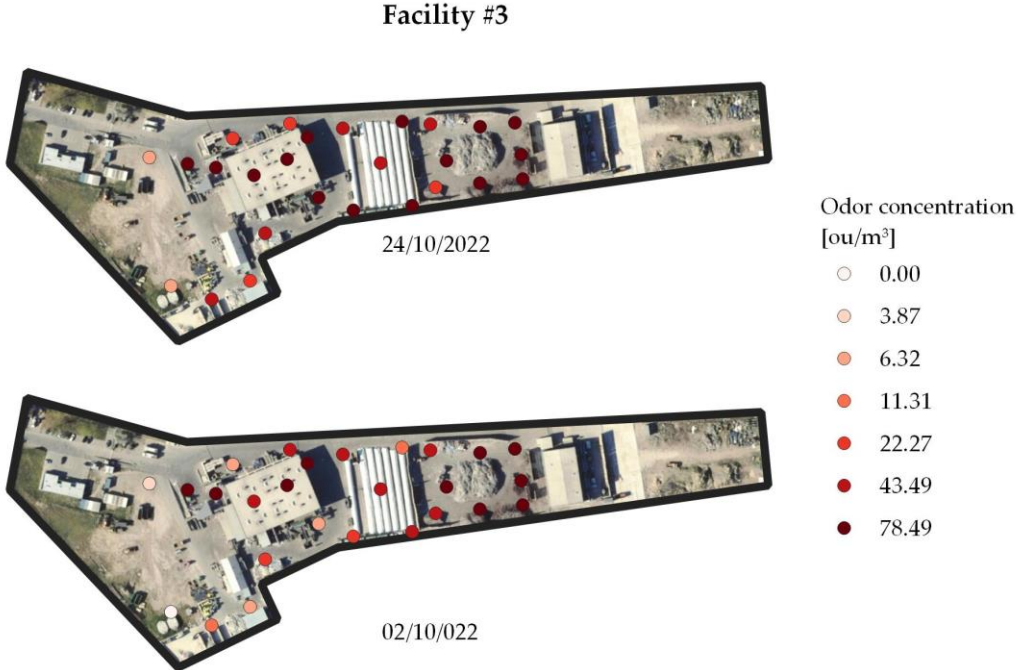
Figure 59. Odor concentration distribution at Facility #3 during measurements for realization of Strategy No. IV.

Facility #3
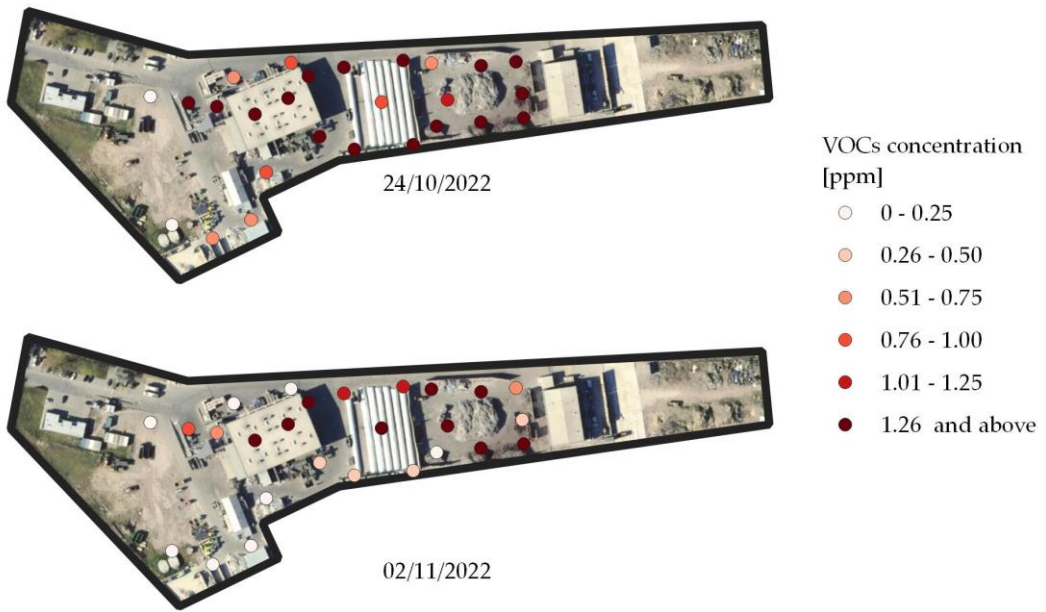
Figure 60. Volatile organic compounds concentration distribution at Facility #3 during measurements for realization of Strategy No. IV.

24/11/2022
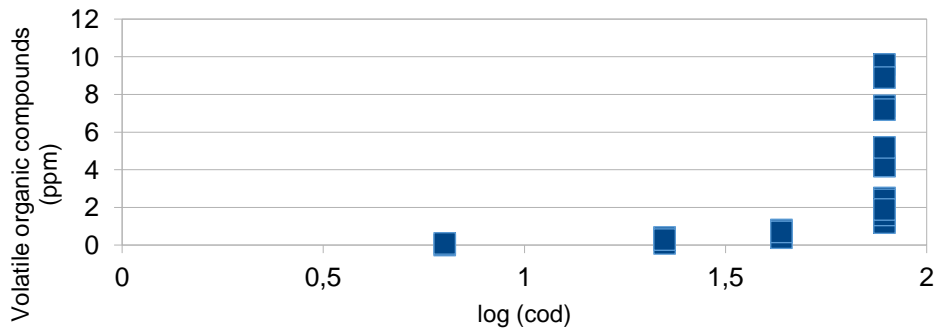
02/11/2022

Figure 61. Logarithm of odor concentration plotted against volatile organic compounds concentration in a given measuring days at Facility #1.

In order to assess the degree of correlation between measured odor concentrations and volatile organic compounds concentrations a Spearman r_s coefficient was calculated. The results are provided in Table 15.

Table 15. Values of r_s for the relationship between odor concentration and volatile organic compounds concentration.

	Facility #1		Facility #2	Facility #3	
	13.11.2022	17.02.2023	23.11.2022	24.11.2022	02/11/022
Spearman coefficient r_s	0.70	0.65	0.97	0.89	0.74

The results provided in Table 15 confirms the results described above. i.e. the highest correlation between odor concentration and volatile organic compounds can be found in Facility #2 during 23.11.2022, and at Facility #3 during measurements in 24.11.2022. However, the rest of the measuring period are also characterized by relatively high levels of correlation.

7.4.2 Discussion

As in the case of the previously analyzed correlations between odor concentrations and odor intensity, there are only a few literature studies dealing with this subject, especially when regarding waste management facilities. Example can be found in [30,34,59,76,125]. The authors of [59] carried out a series of measurements at 6 different mechanical-biological waste treatment plant, which were characterized by a similar technology as the analyzed Facilities #1 and #2. At those 6 facilities at 7 different odor sources including waste reception, mechanical treatment, preparation area for waste fermentation, aerobic stabilization area, biofilter and digestate dewatering area authors of [59] measured the concentration of volatile organic compounds at the level of 0-10 ppm. They also used a photoionization detector for this purpose. They found that in the most of the cases the volatile organic compounds concentrations increased together with odor concentration. However, this pattern is not always present. Similar pattern can be found in [76]. In both cases a high levels of volatile organic compounds concentrations can be found inside mechanical treatment/waste storing phase. In [30] authors were able to measure the volatile organic compound concentration at the level of 25 ppm at the measuring point located around waste prepared for the fermentation process. In [34] authors found much higher values of volatile organic compounds in analyzed mechanical-biological waste treatment plants. It was in the range of 0 up to 50 ppm. The highest concentration were at the point located at aerobic stabilization area where digestate is processed. During their research authors [34] calculated odor activity value [13,39] for volatile organic compounds based on toluene. The results shows a high degree of correlation between calculated odor activity values and measured odor concentrations in relation to the waste treatment stage when these values were measured. However, analyzing the results obtained by the authors [34], it can be concluded that results of odor activity values vary significantly form the measured concentrations as high differences in odor activity value and measured odor concentrations are present. The measurement was made in relation to the sum of volatile organic compounds. The air mixture could contain many different substances. Calculations of odor activity values were related to toluene, which was selected on the basis of literature reports. This may have resulted in the omission of the true influence of the analyzed mixture on the perception of odors. The authors of the aforementioned studies did not find a similar pattern to presented in this study, i.e. they did not report that concentration of volatile organic compounds keep increasing when odor concentration reached a certain level.

This particular pattern seems to be interesting especially from the perspective of odor monitoring strategies. By coupling field olfactometric measurements with sensor measurements of, for example, volatile organic compounds concentrations, it is possible to obtain precise information about odor sources. Determining the correlation between these parameters allows to draw conclusions about the variability of odors and odorants, and to indicate, based on the odorant concentrations, places or sources where odor concentrations may be higher than indicated by the range of the device used.

7.5 STRATEGY NO. 5 – ODOR DISPERSION MODELLING – CALMET/CALPUFF SYSTEM

7.5.1 Calculations scheme

In order to obtain distributions of odor concentrations in the analyzed area with the use of CALMET/CALPUFF system, grids with land cover and terrain elevations were prepared in the first step. Subsequently, data from a global meteorological model for the analyzed area were acquired. Data from grids with a resolution of 500 meters (land cover and elevations) were combined with data from the WRF meteorological model and input into the CALMET meteorological preprocessor. The preprocessor allowed for obtaining a series of hourly meteorological data for each grid cell with a resolution of 500 m. The year 2022 was adopted as the base year for meteorological calculations. The next step was focused on determining the odor emission factors, therefore sampling campaign was carried out at the premises of Facility #1. On the basis of obtained odor concentrations and odor emission factors were established. Two modelling scenarios were assumed. The first one was assuming the constant emission from odor emitting sources. The emission did not vary over time. In the second scenario, the variable emission of odors was considered. In the second scenario, the variable emission of odors was considered. The emission of odors was made dependent on the operating time of individual emitters and on the variability of the odor emission factors for selected emitters, taking seasonality into account. Additionally, a simple diffusion equation was included, assuming the presence of hydrogen sulfide and ammonia in the mixture of odors emitted from the sources. Meteorological, topographical, and emission data were processed by the main CALPUFF dispersion model to obtain results of spatial distributions.

7.5.2 Dynamic olfactometric measurements

The results of dynamic olfactometric measurements at selected area odor sources at Facility #1 are provided in Table 16. Analyzing the results of olfactometric measurements, it

can be clearly stated that the samples taken from the green waste storage area were characterized by the highest odor concentration, i.e. 5743 ou_E/m^3 on average. The second highest odor concentration was determined in samples taken from biological leachate tank (average of 1911 ou_E/m^3). Two landfill leachate tanks were characterized by average odor concentration equals to 492 and 501 ou_E/m^3, respectively. Average odor concentration determined with the use of dynamic olfactometry method in the samples taken from the active landfill area and aerobic stabilization area were 148 ou_E/m^3 and 138 ou_E/m^3, respectively. Those results were obtained during summer 2022. In addition to that, measurements carried out at biofilters were measured during 3 winter/cold months and during 3 summer/warm months. A clear seasonality can be observed, i.e. the average odor concentration for biofilter for aerobic processes measured with the use of dynamic olfactometry method was at the level of 165 ou_E/m^3 for cold months (average based on all 3 measuring months and on all individual measurements) and 285 ou_E/m^3 during warm months. An increase of almost 73% in an average measured odor concentrations can be observed. Similar pattern is present in the case of second biofilter. During cold months, the average odor concentration was at the level of 19 ou_E/m^3, while in warm months it was 49 ou_E/m^3 (258% increase). By looking at the results obtained for both biofilters, an interesting observation can be drawn. The biofilter of aerobic processes is characterized by much higher odor concentration that biofilter for anaerobic processes. It is a well-known fact that the fermentation process is much more odor-generating process, which was also assumed in the initial phase of research. The expected result was that odor concentrations in samples taken from the surface of the anaerobic processes biofilter would be much higher. The results show otherwise. It is the samples from the biofilter of the aerobic treatment of waste that are characterized by a much higher concentration of odors. By comparing cold months, the odor concentration is almost 869% in samples taken from biofilter for aerobic processes. By comparing warm months, the difference is almost 620%. This may be explained by a greater load of pollutants per biofilter surface unit, or by inappropriate working conditions of the biofilter for aerobic waste treatment. However, more sophisticated research should be provided in that matter.

Table 16. Measured odor concentration during the whole measuring campaign.

Sampling date	Date of odor concentration measurements	Odor source	Odor concentration per sample (ou_E/m^3)	Average odor concentration by individual sampling day (ou_E/m^3)	Average odor concentration by source (ou_E/m^3)
18.11.2021	19.11.2021	Biofilter for aerobic processes	155	128	165
			90		
			149		
			169		
			79		
09.12.2021	10.12.2021		50	49	
			42		
			62		
			49		
			44		
20.01.2022	21.01.2022		318	316	
			396		
			305		
			292		
			270		
27.06.2022	28/06/02022		306	154	285
			200		
			52		
			69		
			143		
26.07.2022	27.07.2022		514	561	
			515		
			318		
			792		
			668		
29.08.2022	30.08.2022		281	138	
			131		
			87		
			94		
			98		

Table 13. continued

Sampling date	Date of odor concentration measurements	Odor source	Odor concentration per sample (ou_E/m^3)	Average odor concentration by individual sampling day (ou_E/m^3)	Average odor concentration by source (ou_E/m^3)
18/18/2021	19.11.2021	Biofilter for anaerobic processes	16	20	19
			21		
			17		
			27		
			21		
09.12.2021	10.12.2021		42	23	
			19		
			20		
			18		
			15		
20.01.2022	21.01.2022		15	15	
			15		
			14		
			15		
			14		
27.06.2022	28/06/02022		42	43	46
			52		
			40		
			40		
			42		
26.07.2022	27.07.2022		21	21	
			23		
			23		
			12		
			24		
29.08.2022	30.08.2022		64	74	
			76		
			73		
			54		
			102		

Table 13. continued

Sampling date	Date of odor concentration measurements	Odor source	Odor concentration per sample (ou_E/m^3)	Average odor concentration by individual sampling day (ou_E/m^3)	Average odor concentration by source (ou_E/m^3)
12.07.2022	13.07.2022	Green waste storage area	4235	5743	5743
			4673		
			8320		
12.07.2022	13.07.2022	Aerobic stabilization area	111	138	138
			189		
			149		
			102		
12.07.2022	13.07.2022	Active landfill	227	148	148
			137		
			80		
14/07/2022	15/07/2022	Biological leachate tank	1947	1911	1911
			2213		
			1572		
14/07/202	15/07/2022	Landfill leachate tank 1	378	492	492
			562		
			537		
14/07/2022	15/07/2022	Landfill leachate tank 1	451	501	501
			347		
			704		

7.5.3 Determination of odor emission factors from selected sources of odors

Based on odor concentration measurements at selected sources, odor emission factors were established. CALMET/CALPUFF system as an input emission data requires, in the case of area sources, surface-based emission factors, necessary calculations were made to establish emission factors. A simple equation was used for this purpose (eq. 17), which is usually used for the purposes of determining the emission from the whole surface of area sources when using ventilated sampling hoods for sample collection [119].

$$Odor\ Emission\ Factor \tag{17}$$

$$= \frac{odor\ cocentration\ x\ Q_{air}}{A_{base}}$$

where:

$odor\ concentration$ – is the odor concentration measured with the use of dynamic olfactometry (ou$_E$/m^3),

Q_{air} – air flow inside sampling hood – 0.075 m^3/s,

A_{abase} – area of the sampling hood – 0,5 m^2,

$Odor\ Emission\ Factor$ – is the calculated odor emission factor expressed in ou$_E$/m^2/s.

The results of calculation of emission factors are provided in Table 17.

Table 17. Calculated emission factors for selected area sources.

Odor source	Odor emission factor (ou$_E$/m^2/s)
Biofilter (aerobic processes)	24.7 (cold months) 43.7 (warm months)
Biofilter (anaerobic processes)	2.9 (cold months) 6.9 (warm months)
Green waste storage area	861.4
Aerobic stabilization area	20.7
Active landfill	22.2
Landfill leachate tank 1	73.9
Landfill leachate tank 2	75.1
Biological leachate tank	286.6

The values of the specified factors directly reflect the values of the measured concentrations. Therefore, the highest indicator was determined for the green waste storage

area, while to lowest were calculated for biofilter of anaerobic processes. Obtained values of odor emission factors were used in odor dispersion modelling.

In addition to area sources, two point sources were included in odor dispersion modeling. These were fans located at the roof of the waste sorting hall and at the roof of waste reception hall. On the roof of the waste reception hall, there were 4 point emitters in the form of roofed fans. In case of the waste sorting hall, there were 5 point emitter in the form of roofed fans. Average emission rate in each fan located at the roof of waste reception hall was at the level of 56.8 ou_E/s, while in fans at the roof of waste sorting hall, the emission rate was at the level of 12.8 ou_E/s on average in each fan. these data were not collected during the current measurement campaign due to the impossibility of entering the roof for safety reasons. The source of this data is the old measurement database. Despite the lack of current results, it was decided to include these sources in the modelling. This allowed for a greater diversity of emissions.

7.5.4 Determination of odor emission variability

In the odor dispersion modelling, two scenarios were adopted based on different degrees of complexity of the variability of odor emissions from the sources under study. The first scenario assumes a constant emission from each analyzed source. Since the CALPUFF/CALMET system operates with a one-hour resolution, it was assumed that the operating mode of each emitter was equal to 8760 hours without any variations in the emission during this time. The emission was constant and the odor emission factors for each source is as presented in Table 14, however, in the case of biofilter an average values of odor emission factors were taken into account. Same situation was for the point sources, i.e., operating time of each emitter was equal to 8760 h. The second scenario assumed variable emission for each analyzed sources. During this scenario a different operating modes were assumed, and are characterized below:

- biofilter for aerobic processes:
  - operating time during cold months (February – April and November – December) – 4344 hours with odor emission factor at the level of 24.7 ou_E/m^2/s;
  - operating time during warm months (May – October) – 4040 hours with odor emission factor at the level of 43.7 ou_E/m^2/s;

- biofilter for anaerobic processes:
  - operating time during cold months (February – April and November – December) – 4260 hours with odor emission factor at the level of 2.9 $ou_E/m^2/s$;
  - operating time during warm months (May – October) – 4416 hours with odor emission factor at the level of 6.9 $ou_E/m^2/s$;
- green waste storage area:
  - operating time during cold months (February – April and November – December) – 4344 hours with odor emission factor at the level of 258.42 $ou_E/m^2/s$ (determined value x 0.3)
  - operating time during warm months (May – October) – 4332 hours with odor emission factor at the level of 861.4 $ou_E/m^2/s$;
- aerobic stabilization area:
  - operating time – 8760 hours with emission factor at the level of 20.7 $ou_E/m^2/s$;
- active landfill:
  - operating time – 8760 hours with emission factor at the level of 22.2 $ou_E/m^2/s$;
- landfill leachate tank 1:
  - operating time – 8760 hours with emission factor at the level of 73.9 $ou_E/m^2/s$;
- landfill leachate tank 2:
  - operating time – 8760 hours with emission factor at the level of 75.1 $ou_E/m^2/s$;
- biological leachate tank:
  - operating time – 8760 hours with emission factor at the level of 286.6 $ou_E/m^2/s$;
- 4x fans at the roof of waste reception hall:
  - operating time for each fan – 6072 hours with emission factor at level of 56.9 ou_E/s
- 5x fans at the roof of waste sorting hall:
  - operating time for each fan – 6072 hours with emission factor at level of 12.8 ou_E/s.

The operational times of biofilters were diversified due to the obtained values of odor emission factors. 8760 hours were divided into warm and cold months, and an appropriate emission factor was adopted for a given period. Additionally, days/hours during which the air circulation in the biofilter was turned off for technological reasons (data obtained from the facility workers) were taken into account, and it was assumed that the emission was equal to 0.0 ou_E during this time. In the case of green waste storage during cold months, the emission factor was established at the 30% of its initial value due to the change in the amount of waste stored in that time (data obtained from the facility workers). Due to the lack of information and measurements on other area sources of odor emission, the operating time of those sources as established as 8760 hours. In the case of point sources, their operational time was set to 6072 hours in accordance with data provided by facility workers. It is necessary to indicate that the applied CALMET/CALPUFF system operated with an hourly resolution, therefore, an appropriate odor emission factor was assigned for each hour of the year. In the case of hours when a given source did not work (biofilters or waste sorting/reception hall), the emission factor took the value equal to 0 in a given hour.

Additionally, an attempt was made to relate the variability of odor emissions to the diffusion coefficient. This was based on the assumption that hydrogen sulfide and ammonia are emitted from the sources analyzed. Since the data obtained from the meteorological preprocessor (temperature) also had a resolution of one hour, the odor emissions from each of the aforementioned sources were multiplied by the obtained diffusion coefficient for each hour.

7.5.5 Emitter parameters

Table 18 and Table 19 shows the basic parameters of odor sources included in modeling. Each source where the odor concentration was measured and thus the odor emission factor was determined was treated as a separate source. The data shown in the tables below have been included in the modeling algorithm. In the case of fans at the roof of waste reception hall and waste sorting hall, the fans were roofed type, thus no additional data was needed (only heights of each fan was used).

Table 18. Parameters of area sources.

Emitter name	Type of the emitter	Area (m^2)	Emitter height (m)	Odor emission factor (ou$_E$/m^2/s)
Biofilter (aerobic process)	area	139	3.20	34.2 (average)
Biofilter (anaerobic process)	area	160	3.20	4.90 (average)
Green waste storage area	area	640	3.00	861.4
Aerobic stabilization area	area	3473	3.00	20.7
Active landfill	area	12265	11.00	22.20
Landfill leachate tank 1	area	622	0.00	73.9
Landfill Leachate tank 2	area	629	0.00	75.1
Biological leachate tank	area	311	1.00	286.6

Table 19. Parameters of point sources.

Emitter name	Type of the emitter	Emitter height (m)	Odor emission factor (ou$_E$/s)
Waste sorting hall fan 1	point (roofed)	13.00	12.8
Waste sorting hall fan 2	point (roofed)	12.50	12.8
Waste sorting hall fan 3	point (roofed)	12.50	12.8
Waste sorting hall fan 4	point (roofed)	11.00	12.8
Waste sorting hall fan 5	point (roofed)	11.00	12.8
Waste reception hall fan 1	point (roofed)	13.00	56.8
Waste reception hall fan 2	point (roofed)	13.00	56.8
Waste reception hall fan 3	point (roofed)	13.00	56.8
Waste reception hall fan 4	point (roofed)	13.00	56.8

7.5.6 Computational grids

In order to perform the modeling. Three different computation grids were prepared. The first two grids (Figure 62) were created for the purposes of meteorological preprocessing data obtained from WRF model by CALMET preprocessor. The land cover grid and terrain grid have dimensions of 13,500 m by 13,500 m with the grid step set to 500 m. In n the case of land cover, the terrain around the object under analysis is characterized by low variability, with agricultural fields dominating and a small amount of areas categorized as medium green areas (land cover classification according to the methodology contained in the instruction manual for the CALMET meteorological preprocessor [164]). In the case of heights grid, it can be observed that the area located north of the studied Facility #1 is located lower than the Facility, while the area to the south is located higher. The height difference in the analyzed area is approx. 37

meters. The Figure 63 shows a computational grid of receptor points, where odor concentrations were modeled. The receptor grid is smaller and its dimensions are 5600 m x 5100 m with the grid step set to 100 m. In each grid cell a receptor was placed. In addition, receptor grid contains information of terrain heights, land cover was not needed.
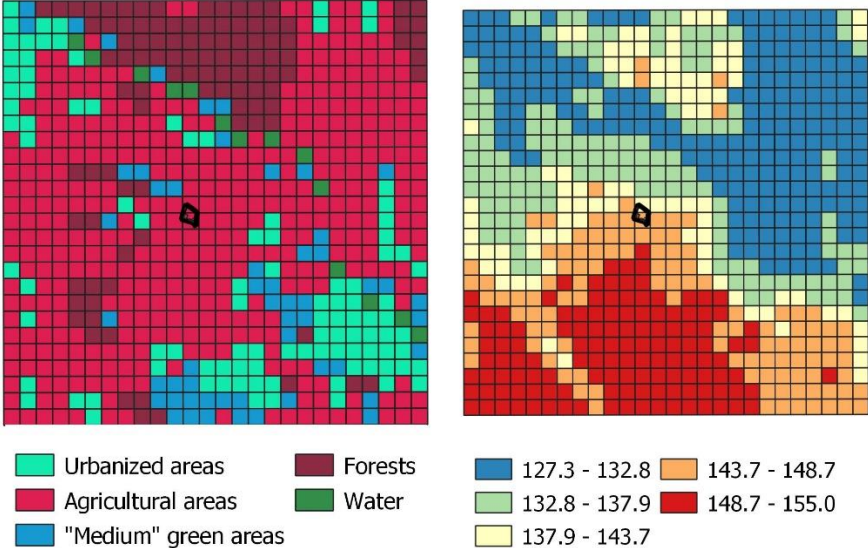
Figure 62. Computational grids determined for the purposes of CALMET calculations, land cover on the left, on the right.

Figure 63. Grid of receptor points.

7.5.7 Results of odor dispersion modelling

The results of dispersion modeling with the use of CALMET/CALPUFF system for both scenarios are shown in Figures 64 to 65. Figure 64 shows the maximum values of 1 hour concentrations in the considered computational grid (5500 m X axis and 5000 m Y axis) with receptors spaced every 100 m. When analyzing the obtained spatial distributions of odor concentrations for both scenario a clear difference is observed. When considering the potential impact on residential development, in the case of a scenario with constant emissions, it can be observed that in some residential areas the concentration of odors for the given emission conditions ranges from 83 ou_E/m^3 to 163 ou_E/m^3. This is particularly noticeable in the case of residential areas located approximately 1000 meters west of the Facility #1 boundaries. The development located to the east and southeast of the facility's boundaries is also, to a small extent, exposed to such concentrations of odors. In the case of the remaining residential areas - the maximum one-hour concentrations range from 24 ou_E/m^3 to 83 ou_E/m^3. The situation changes significantly in the case of the second scenario, where the impact of variable emissions on the range of the facility's impact was examined. The maximum one-hour concentrations, in the case of the second scenario, are significantly lower at the residential areas than in the previous case. The range of odor concentrations varies between 0.3 and 3.17 ou_E/m^3. The development located to the west of the facility is exposed to the widest range of concentrations. For example, the development located to the north of the facility is exposed to concentrations in the range of 0.3 to 1.09 ou_E/m^3. Taking into account the recognition of the value of 1 ou_E/m^3 as the detection threshold, these concentrations may not be perceptible. Taking into account the value of the odor detection threshold equal to 1 ou_E/m^3, a better indicator for assessing the potential odor impact of the facility on the residential areas is the use of the number of hours in a year during which the concentration value at a given point in the computational grid is above the odor detection threshold.

ou_E/m³   83 - 163   561 - 1173   ou_E/m³   1.09 - 1.96   5.05 - 8.55
   24 - 83   163 - 290   1173 - 2270   0.371 - 1.09   1.96 - 3.17   8.55 - 14.8
   290 - 561   3.17 - 5.05
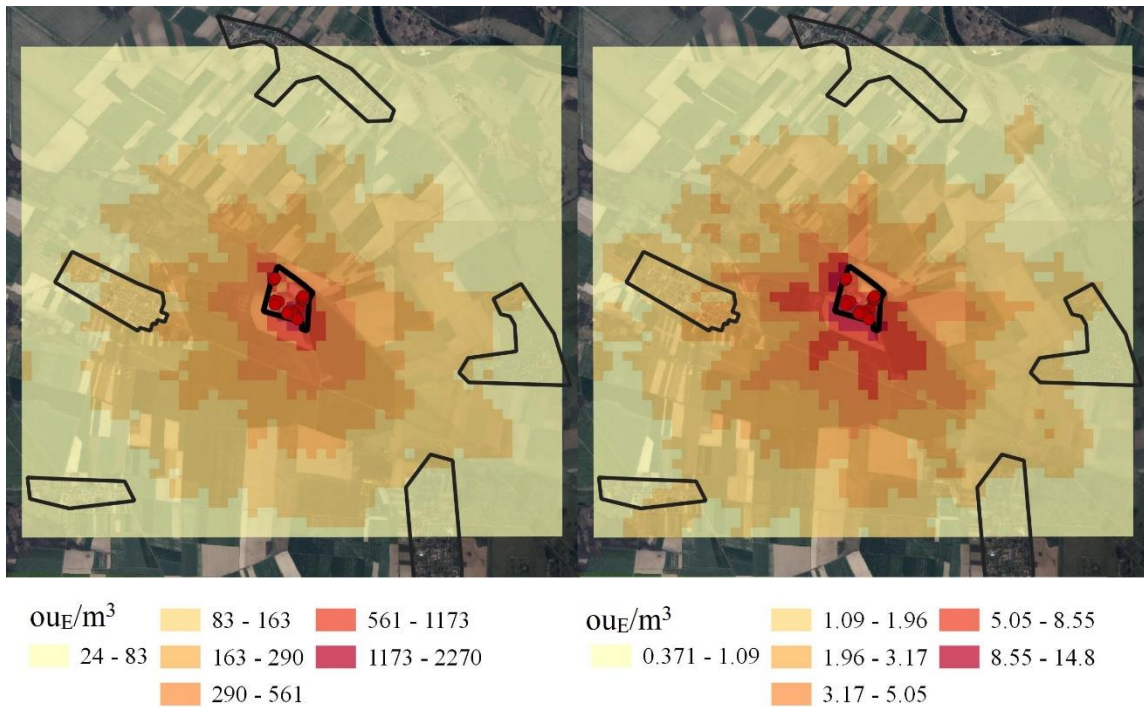
Figure 64. Maximum values of 1 hour concentrations in the computation grid for both scenarios: constant emission on the left, variable emission on the right.

Figure 65 shows the number of hours in a year during which the odor detection threshold of 1 ou_E/m^3 is exceeded. As in the previous case, depending on the emission variability scenario applied, the results differ significantly from each other. In the case of the scenario based on constant emissions, the highest number of hours exceeding 1 ou_E/m^3 was recorded for the development located east of the facility's boundaries. This development encompasses as many as 3 classes, the class from 841 ou_E/m^3 to 1404 ou_E/m^3 (the buildings located closest to the residential areas boundary), the class 478 ou/m^3 to 841 ou/m^3 (almost the entire development is located in this class) and to a small extent the class 184-478 ou_E/m^3. The development located to the west also features a significant number of hours where exceedances of 1 ou_E/m^3 occur. As indicated in the literature section, in Poland in 2009, there was a proposal for a law on preventing odor nuisance. The draft law included, among others, guidelines regarding comparative values of odor threshold and frequency of exceedances, which could be the basis for assessing odor impact through modeling. According to the draft, the odor detection threshold value was set at 1 ou_E/m^3 and the permissible level of frequency exceedance of was set 1 ou_E/m^3 at 3% of hours on an annual scale (about 262 hours). According to this draft, practically throughout the entire area analyzed, there are exceedances of the 3% value on an annual scale. In the case of the second scenario, the situation changes significantly. Taking into

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account the given modeling conditions, throughout the entire development area, there are no exceedances of the permissible value of exceedance frequency.
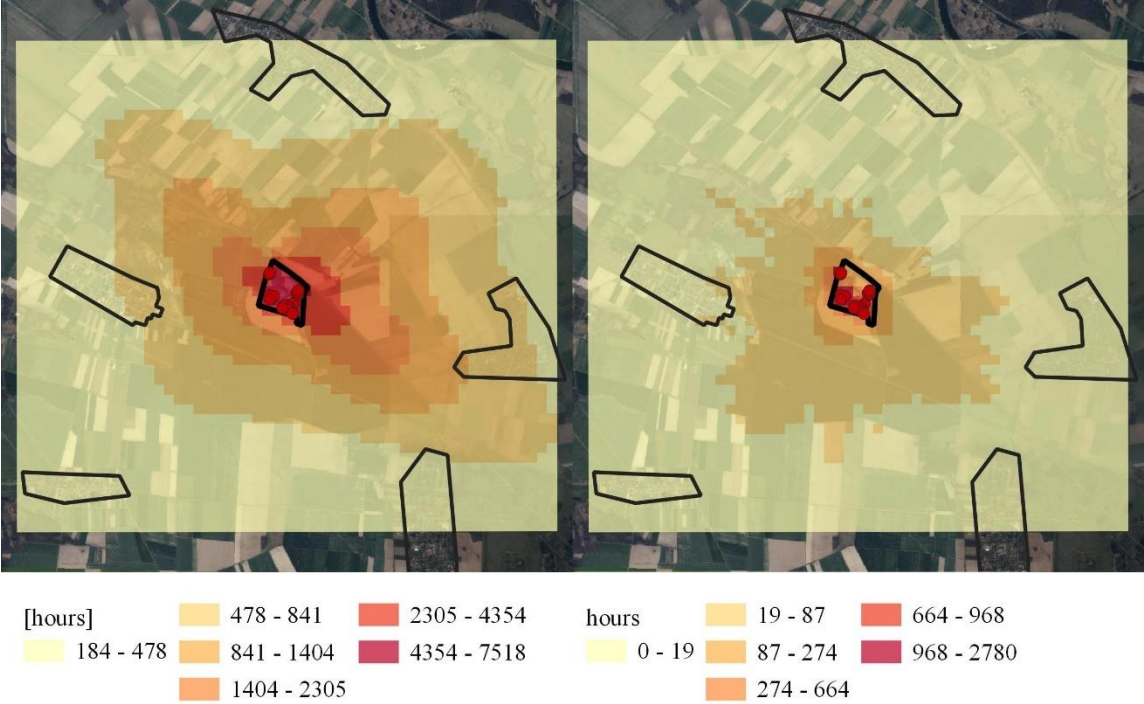
Figure 65. Numbers of hours of exceeding 1 ou$_E$/m^3 for both scenarios: constant emission on the left, variable emission on the right.

7.5.8 Discussion

Only a few available studies indicate the necessity of proper parameterization of odor emissions from the sources under investigation in order to obtain high-quality results of odor dispersion modeling. The fundamental element is the determination of odor emission factors. Examples of considerations on determining odor emission indices for wide range of waste management facilities can be found in [27,174–176]. Available studies indicate various approaches to determining emission factors from the odor sources. They can be determined based on odor concentrations, taking into account various factors such as landfill gas flow through the landfill deposit, type of waste, or calculations of odor activity value parameters. Despite the various approaches, the authors of the available literature studies agree that the determined odor emission factors should be treated as specific to the given facility under investigation [27,176]. Some of the available studies attempt to describe emission variability using emission factors [27]. The authors of [177,178] concluded that employing an approach in dispersion modeling that assumes a constant emission of odors from the modeled sources can

lead to obtaining imprecise results burdened with significant error. Taking the above into account, it can be stated that the obtained results of own research for the scenario with a constant odor emission do not reflect real conditions. Proper parameterization of variability is a key task in order to obtain qualitatively correct modeling results.

8   CONCLUSIONS

As part of the completed research work, a series of studies related to the use of 5 different odor monitoring strategies were presented. The main objectives of the work were:

- assessment of the suitability of selected odor monitoring strategies for short and long-term purposes;
- determining the variability of odor emissions from selected processes or installations located on the premises of a selected waste management facilities;
- conducting an analysis of the temporal and spatial variability of odor concentrations, odor intensity, and volatile organic compounds in the area of selected waste management facilities alongside with an assessment of their correlation;
- and evaluation of the influence of the variability of odor emissions from selected processes in the seasonal cycle on the range of odor impact of selected waste management plant.

In reference to the theses presented in the study, and based on the obtained own research results, the following conclusions can be drawn:

1) The field olfactometry method can be successfully used as an integral part of odor management plans. Waste management facilities considered in this work have been successfully characterized using the aforementioned method, which allowed for the determination of variability in odor concentrations, classification of odor sources in terms of measured concentrations, and identification of the most problematic areas at the premises of the facilities under study. Analyzing the results obtained, field olfactometry can be used as a tool for long-term odor monitoring as well as instantaneous monitoring. In both cases, it was possible to successfully differentiate the studied odor sources.

2) The conducted research concerning the correlation between the measured odor concentration using the field olfactometry method and meteorological

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parameters (temperature and relative humidity) indicates the existence of weak or moderately strong dependencies between these parameters. Available literature data does not directly confirm or contradict the obtained correlation results. This is due to the approach to determining these correlations. In the own research, the measurements of the mentioned parameters were instantaneous, which could affect the results of the correlation studies.

3) The use of the inverse distance weighted interpolation method indicates the potential application of this method for the identification of problematic areas in terms of odor emissions. The obtained results indicate the presence of statistically significant cross-validation errors, which leads to an overestimation of variability of concentrations of odors in the obtained spatial distributions. Despite this fact, the spatial distributions successfully, to a certain level, retain information about the spatial variability of odors. This method can potentially find application as a tool supporting decision-making and can be included in odor management plans.

4) The analysis of the correlation between the odor concentration obtained using the field olfactometry method and the odor intensity indicates the existence of a high degree of correlation between these parameters. They can be used interchangeably as tools for determining the variability of odor emissions and identifying problematic areas. This approach potentially allows for reduction in the complexity of measurements, as parametric measurements using odor intensity do not require knowledge of handling additional measuring equipment, which means that intensity assessments could be successfully conducted by the waste management facility employees after proper training.

5) The correlation between intensity and odor concentration was also confirmed by applying the Weber-Fechner law, with a high linear agreement between the measured parameters being found. Despite this fact, attempting to determine odor concentration based on odor intensity through the implementation of the Weber-Fechner law yields very imprecise values, i.e., the odor concentrations determined using this approach differ from the values measured using field olfactometry. The values from 0.00 ou/m^3 to 6.32 ou/m^3, and the values at the other end of the range, i.e., 78.49 ou/m^3, differ significantly when calculated using the Weber-Fechner law. This approach is only valid for values in the

middle of the range. Further research should be undertaken to find a more precise approach.

6) Measurements of volatile organic compounds have shown the existence of significant correlations between them and odor concentrations. Odorant concentrations based on volatile organic compounds allow for determining the variability of odorous substances at the premises of studied facilities. From the perspective of the measurements conducted, an interesting trend was found. In cases where the odor concentration reaches a maximum value of 78.49 ou/m^3 (the highest possible value of used olfactometer), the concentration of volatile organic compounds reaches values of 1.26 ppm and higher. The existence of this trend suggests that the odor concentration may be higher than measured, and therefore, in such a situation, it is recommended to use an olfactometer with a higher range of detectable concentrations. i.e., different D/T dials should be used in the case of Nasal Ranger olfactometer. Incorporating simultaneous measurements of volatile organic compounds and odor concentrations into odor management plans can provide the highest quality information on the distribution of concentrations and their variability. In the case of using a non-wide-range field olfactometer, the measurement of volatile organic compounds may suggest locations with potentially higher than measured odor concentrations.

7) The employed CALMET/CALPUFF system allowed for effectively obtaining spatial distributions for the given meteorological conditions and specified conditions of emission variability. The developed emission variability model for two cases with different degrees of its parameterization, indicated significant differences between the obtained results. Proper parameterization of the variability of odor emissions from their sources significantly affects the potential range of odor impact. Based on this, it can be concluded that it is crucial to collect a broad database concerning emissions from the studied sources, including measurements in different seasonal cycles, measurements in different operational modes of the sources, and containing information on the technological characteristics of these sources. To accomplish the last step, active participation of the authorities of the odor emitting facilities is necessary.

8) Proper, highly standardized parameterization of the variability of odor emissions is a key aspect that affects the quality of the results obtained from modeling. This applies not only to the CALMET/CALPUFF system used but also to any other model.

9) Taking into account the quality of the results obtained during the implementation of the 5 adopted odor monitoring strategies, it can be stated that each of the above strategies can be used as tools incorporated into odor management plans in accordance with the Best Available Techniques Conclusions for waste treatment. Most of the applied techniques allows for determining the variability of odor emissions and can be used in both short and long-term monitoring. Due to the necessity of collecting an accurate database concerning emissions, the modeling of the dispersion of odorous pollutants should be used exclusively in long-term monitoring.

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