Archives of Environmental Protection
Vol. 48 no. 3 pp. 3–20

PL ISSN 2083-4772
DOI 10.24425/aep.2022.142685

# Preliminary analysis of the state of municipal waste management technology in Poland along with the identification of waste treatment processes in terms of odor emissions

Marcin Pawnuk[1], Bartosz Szulczyński[2], Emilia den Boer[1], Izabela Sówka[1]*

[1]Department of Environment Protection Engineering, Faculty of Environmental Engineering,
Wroclaw University of Science and Technology, Poland
[2]Department of Process Engineering and Chemical Technology, Faculty of Chemistry,
Gdańsk University of Technology, Poland

*Corresponding author's e-mail: izabela.sowka@pwr.edu.pl

**Keywords:** municipal waste management in Poland, mixed waste, odors, volatile organic compounds, emission

**Abstract:** Waste management faces more and more serious challenges, especially given the growing amount of municipal waste generated in Poland and the resulting environmental impact. One of the significant environmental aspects of waste management is the emission of odorants and odors. Taking into account the odor problem, the majority of municipal waste generated is being collected as mixed waste (62% of municipal waste), which by weight contains approximately 32.7% of kitchen and garden waste. These organic fractions are mainly responsible for the emission of odor and odorants. Those substances can be emitted at every stage: from the waste collection at residential waste bins, through transport, waste storage, and transfer stations, up to various respective treatment facilities, i.e., mechanical-biological waste treatment plants, landfills, or waste incineration plants. The gathered data during the study showed that it is necessary to increase the share of different waste management methods, i.e., recycling, composting, or fermentation processes rather than landfilling to meet all necessary regulations and to fulfill provisions of the waste hierarchy. One of the actions indicated in the legal solutions is expansion, retrofitting, and construction of new sorting plants, anaerobic digestion plants, composting plants, and increase in thermal treatment capacity. Variety of different processes that could emit odors and a diversity of different odor-generating substances released from particular waste management steps should be taken into consideration when building new facilities which are suitable for waste treatment. The overall aim of the work was to characterize and summarize available knowledge about waste management system in Poland and to gather information about odor-generating substances emitted from different waste management steps and facilities, which could be a potential source of information for preparing legal solutions to reduce possible odor nuisance form broadly understood waste management.

## Introduction

According to the available literature and various studies, the issue of excessive odor emission linked to the processes of broadly understood waste management, concerns many societies and is directly related to the complaints of residents about the deteriorating air quality (Aatamila et al. 2010, Bruno et al. 2007, Liu et al. 2020, Palmiotto et al. 2014, Schlegemilch et al. 2005, Wu et al. 2020). The environmental impact of waste management facilities is significant. Their activity is related to the emission of various substances to water, soil and air (Giusti 2009). Apart from odors, other air pollutants, such as dust, bioaerosols, methane, carbon dioxide, carbon monoxide, nitrogen oxides, or volatile organic compounds in general may also be emitted to the atmosphere (Forastiere 211, Guisti 2009, Sonibare et al. 2019). When it comes to the emission of odors into the air, it is necessary to define them correctly. Odor is a term that describes a mixture of substances, the so-called odorants, which are defined by the Polish version of European Standard EN 13725:2003 (Polish Committee for Standardization 2007) as substances stimulating the human olfactory system so that the person feels the smell understood as an organoleptic feature perceived by the olfactory organ while smelling certain volatile substances. The exposure of humans to odors (including individual odorants) may cause odor nuisance and health problems in the event of prolonged exposure (Forastiere et al. 2011, Palmiotto et al. 2014, Wu et al. 2020, Zhang et al. 2013). These effects, however, are generally considered not very harmful and cause more nuisance than serious health effects (Bax et al. 2020, Palmiotto et al. 2014). Nevertheless, the potential odor nuisance from waste management facilities is a serious environmental problem. The existence of people and the fulfillment of their basic needs generates significant amount of waste at different stages of life and functioning of societies, especially in terms of municipal waste. Due to the diversity of societies, taking into account the global and local level, both the management of and control over the generated municipal waste at the level of individual countries, cities or specific areas is a difficult task. As indicated in the literature, waste management is an extremely topical problem, e.g., due to the growth trends in waste generation, which result directly from the rapid development of societies and inhabited areas (Alwaeli 2015, Bruno et al. 2007, Sonibare et al. 2019, Wiśniewska et al. 2019, Wu et al. 2020, Zhang et al. 2013). The growing amount of waste requires a number of measures to minimize the undesirable effects associated with its generation. At the European level, in 2008, *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste* was adopted summarizing and regulating the law related to waste management in the member states. In 2018, changes were introduced to the aforementioned *Directive* focusing the overall waste management towards circular economy. Main task of the *Directive* was to introduce measures to protect the environment and human health by preventing and reducing the negative effects associated with waste management, such as excessive emissions to the environment, as mentioned earlier (Giusti 2009). The aforementioned *Directive* introduces into the legislation the concept of waste hierarchy, which defines priority actions to be taken in order to prevent and manage waste. It defines five steps, where the most important and the most favorable is waste prevention, followed by preparation for reuse, recycling, other recovery methods, e.g., energy recovery and, finally, waste disposal as the least favored option.

Municipal waste management is a multi-stage process, in which almost every process may cause the emission of odors and odorants to the air. This stems from the fact that municipal waste generated by people contains organic waste (Alwaeli 2015, den Boer 2010, Burnley 2007, Chen 2018), which undergoes biological degradation, i.e., biodegradation, which is the main cause of the emission of odors and odorants to the air (Bruno et al. 2007, Sonibare et al. 2019, Wang et al. 2021). Biodegradation can occur both under aerobic (He et al. 2020) and anaerobic (Wiśniewska 2020a) conditions. The processes related to the management of municipal waste containing organic fractions, which can generate odors, include: waste collection at residential areas (Liu et al. 2020, Shi et al. 2020, Tan et al. 2017), transport (Tan et al. 2017, Xu et al. 2020), waste transfer stage at transfer stations (Chang et al. 2019, Zhao et al. 2015) and the activities related to waste management at mechanical-biological treatment (MBT) plants and biological waste treatment plants (Colón et al. 2017, Hou et al. 2013, Kulig and Szyłak-Szydłowski 2016, Sironi et al. 2006), including aerobic stabilization and anaerobic stabilization technology, in the case of mixed municipal waste treatment, as well as composting and anaerobic digestion, in the case of selectively collected bio-waste (Mustafa et al. 2017, Sánchez-Monedero et al. 2018, Sironi et al. 2007, Wiśniewska et al. 2020b, Wiśniewska et al. 2019, Zhang et al. 2013), thermal treatment of waste in waste incineration plants (Guo et al. 2017, Çetin Doğruparmak et al. 2018) or landfilling (Duan et al. 2021, Wang et al. 2021, Zhang et al. 2021). Figure 1 shows the waste management chain with the possible individual waste management steps. The processes shown in Figure 1 will be characterized in terms of odorants and odors emissions in the later part of the paper.

In order to characterize the aforementioned sources in terms of emissions of both odorants and odors, it is necessary to apply various analytical methods. The available literature includes a number of studies on these issues (Bax et al. 2020, Brattoli et al. 2011, Capelli et al. 2013a, Capelli et al. 2013b, Conti et al. 2020, Jońca et al. 2022, Maurer et al. 2018). Among the methods most often used for characterizing odorous emissions to air, we can distinguish the dynamic olfactometry method (in accordance with EN 13725: 2003), which allows to determine the concentration of odors in the air,

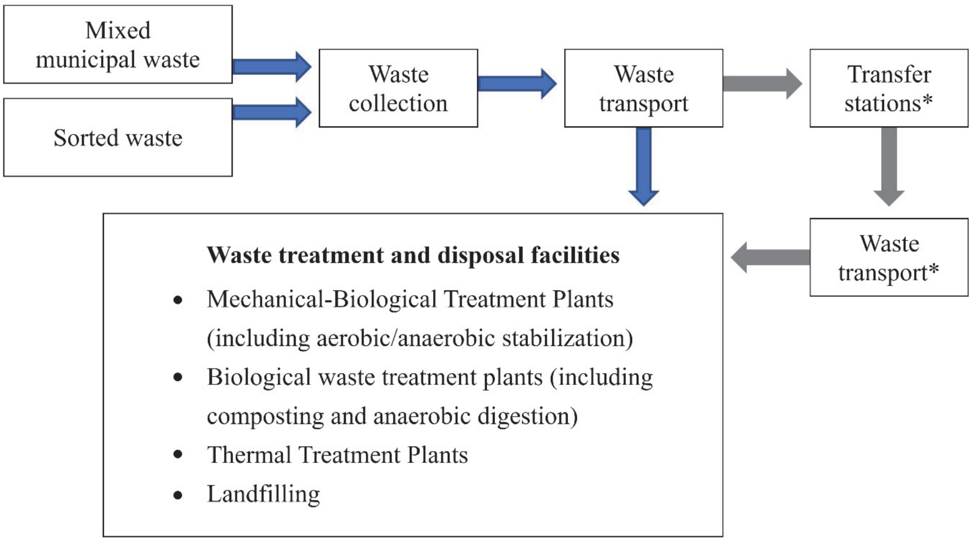

**Fig. 1.** The waste management chain that shows the possible individual waste management steps (* – optional, depends on the waste management system) (Di Foggia and Beccarello 2021, Iakovou et al. 2010)

and gas chromatography with a mass spectrometer (GC-MS), which allows for quantitative and qualitative determination of individual odorants. Tools applying a matrix of chemical sensors, the so-called electronic noses, are also often used (Jońca et al. 2022, Szulczyński et al. 2017). One of the important tools to determine the range of the odor impact of objects, and, consequently, the potential odor nuisance, are tools for simulating the dispersion of pollutants in the air (Capelli and Sironi 2018). Selecting an appropriate measurement method is crucial to determine the emissions of substances from municipal waste management facilities. Obtaining the information about the emissions of odorous substances is one of key tasks in preventing and controlling them. Other important aspects in odor management are legal regulations as well as activities and methods aimed at reducing odorous emissions from municipal waste management facilities. This issue, however, will not be discussed in this paper. The authors' considerations on this subject were already presented in another article (Pawnuk et al. 2020).

The purpose of this work is presented in Figure 2. The first part focuses on the characteristics of the state of waste management in Poland over the last few years. The investigation includes the analysis of the trends in generating municipal waste in the country, the analysis of the methods of waste management and waste disposal in accordance with applicable legal regulations. The characteristics of the state of waste management in Poland includes the most recent data available, which gives the reader the most up-to-date overview of waste management in the country. The second part characterizes waste management processes in terms of the emission of odors and odor-generating substances, indicating the dominant substances emitted during specific municipal waste treatment processes. The aim of the work is to summarize the available knowledge on the state of municipal waste management in Poland and to collect information on odor-generating substances and odors emitted from municipal waste management facilities in general to prepare a database of available information and to take into account the most significant processes and odors emitted in waste management in the planned activities aimed at preparing legal solutions to reduce possible odor nuisance form broadly understood waste management.

## Analysis of the state of waste management in Poland

### *Waste generated in Poland over the last years*

According to the data provided by Statistics Poland (Statistic Poland LDB 2021), in 2020 a total of approximately 122,600 Gg of waste was generated in Poland. This amount concerns both the generated industrial and municipal waste, of which industrial waste accounted for approx. 89.3% of the total generated waste (109,500 Gg), while municipal waste accounted for 10.7% of the total (approx. 13,100 Gg). The amount of industrial waste in the years 2000–2020 ranged from approx. 110,000 to approx. 130,000 Gg of waste per year. The variability of the amount of generated municipal waste, which is the main subject of this study, is shown in Figure 3 (Statistic Poland LDB 2021). The presented data on municipal waste in Figure 3 cover the years 2010–2020. In 2010, the annual amount of municipal waste generated amounted to 10,040.11 Gg. In 2011–2013, the amount of generated waste decreased. Compared to 2010, the decrease was approx. 2.1% in 2011, 4.6% in 2012, and 5.6% in 2013. Since 2014 there has been a visible increase in the amount of municipal waste generated. Compared to 2010, the amount of municipal waste

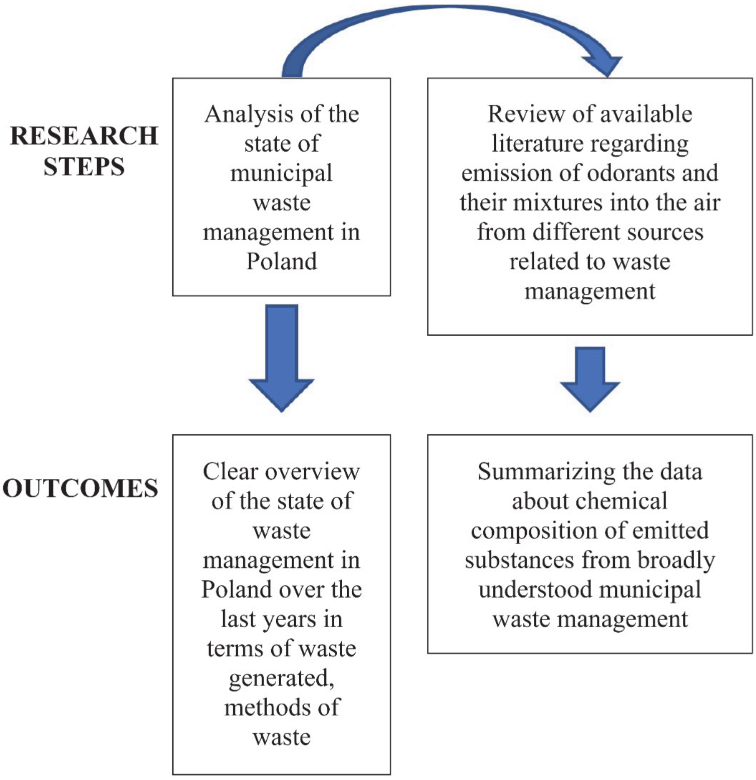

**Fig. 2.** Flow chart of research steps and outcomes of the study

generated increased by 2.9% in 2014 , 8.2% in 2015, 16.1% in 2016, 19.2% in 2017, 24.4% in 2018 and 27.0% in 2019. In 2020, it increased by 30.6% compared to 2010, and amounted to 13,116.90 Gg. It should be noted that the presented quantitative data concern both waste generated in households and waste generated from other sources, in which – according to the definition of municipal waste applied in Polish legislation and resulting directly from the *Directive* – the composition of generated waste is similar to that of municipal waste (the Act of 14 December 2012 on waste). The analyzed data show a clear upward trend in the amount of municipal waste generated over the last few years.

Figure 4 shows the mass of collected municipal waste over the years 2010–2019, according to voivodships (Statistic Poland LDB 2021). The data show that the general trend in the amount of waste generated in individual voivodships is consistent with the trend presented in Figure 3, i.e., in 2011–2013, the amount of waste generated either decreased or remained at a constant level, with a slight variation. In the case of 2014–2019, as in the case of the entire country, the amount of generated waste increased compared to 2010. Figure 5 shows the location of individual voivodship areas referred to in the text.

The data presented in Figure 4 clearly indicate the 4 main voivodships responsible for the highest amount of generated waste. These are, in turn, mazowieckie voivodship, śląskie voivodship, wielkopolskie voivodship and dolnośląskie voivodship. The amount of municipal waste generated in 2020 is, in turn, 1,879.21 Gg for mazowieckie voivodship, 1,780.47 Gg for śląskie voivodship, 1,254.68 Gg for wielkopolskie voivodship and 1,159.91 for dolnośląskie voivodship. In comparison with 2010, the amount of municipal waste generated in 2020 increased by 19.60% for mazowieckie voivodship, 29.00% for śląskie voivodship, 37.11% for wielkopolskie voivodship and 16.64% for dolnośląskie voivodship. Those top scores in generated waste may be influenced, among others, by population size or the lifestyle of the residents of a given voivodship. Mazowieckie, śląskie and wielkopolskie are the most populous voivodships in Poland, and dolnośląskie is the 4th most populous voivodship in the country. Voivodships where the least amount of waste is

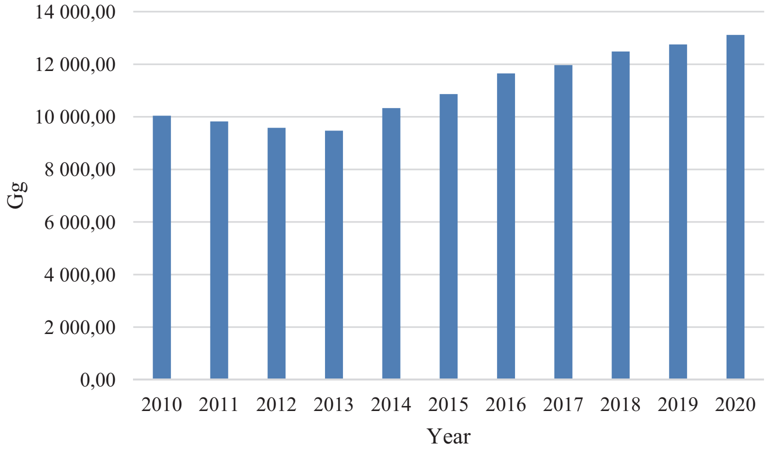

**Fig. 3.** Mass of municipal waste collected in Poland over the years 2010–2019 (Statistic Poland LDB 2021)

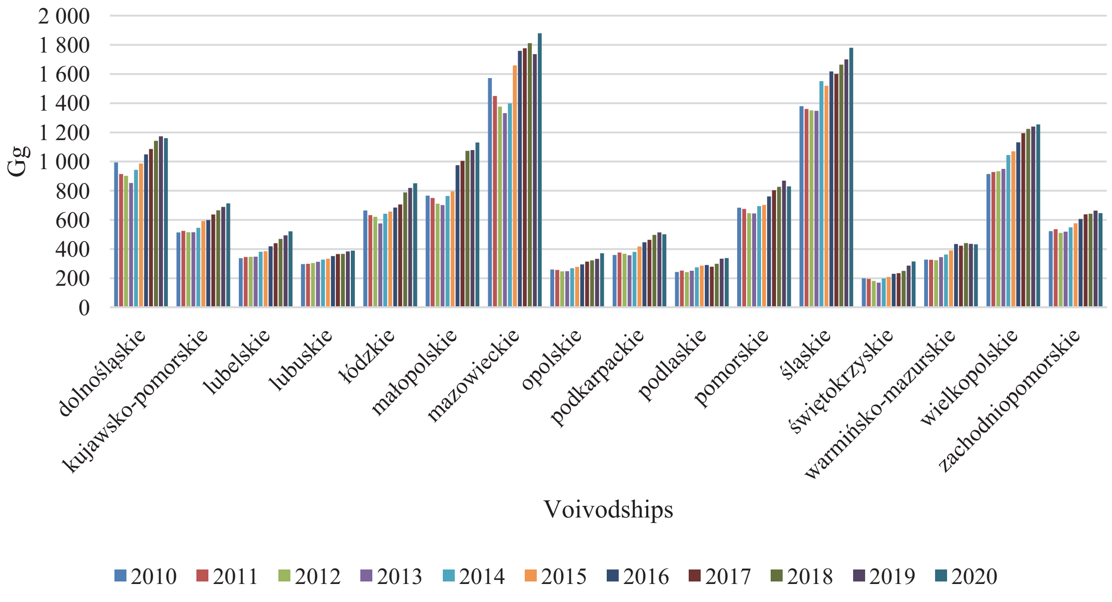

**Fig. 4.** Mass of municipal waste collected in Poland, according to voivodships, over the years 2010–2020 (Statistic Poland LDB 2021).

generated include, among others, świętokrzyskie (315.00 Gg), podlaskie (338.87 Gg) opolskie (371.64 Gg), and lubuskie (389.75 Gg). These are the least populous voivodships in Poland.

According to the data of Statistics Poland (Statistic Poland LDB 2021), the average amount of municipal waste generated in 2020 per capita in Poland amounts to 342 kg. In 2019 it was 332 kg, while the average in the European Union is 502 kg (Eurostat 2021). This placed Poland as the second country with the lowest amount of generated waste per capita in Europe in 2019. In Poland (2020) (Figure 6), the voivodship with the highest amount of waste generated per capita is dolnośląskie – 400 kg. The study of Statistics Central on the state of the environment indicates that western region, that is: dolnośląskie (400 kg), śląskie (395 kg) and lubuskie (386 kg) voivodships generate the largest amount of waste per capita. This is related to the highest shares of population living in cities and towns (especially śląskie 76,6% and dolnośląskie – 68,4%) and higher GDP per capita in western Poland as well as different pattern of consumption, i.e., the western way of life. Significantly less waste is generated per capita in the eastern regions of Poland, namely in podkarpackie (236 kg), lubelskie (248 kg), świętokrzyskie (256 kg) and podlaskie (288 kg) voivodships.

### *Waste composition in Poland*

Last official data on the waste composition in Poland which were published in the National Waste Management Plan 2022 (NWMP 2022) (M.P. 2016 poz. 784 – http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WMP20160000784) stem from analyses performed in 2008–2010. Since than a few seasonal

**Fig. 5.** Location of individual voivodship areas against the background of Polish borders

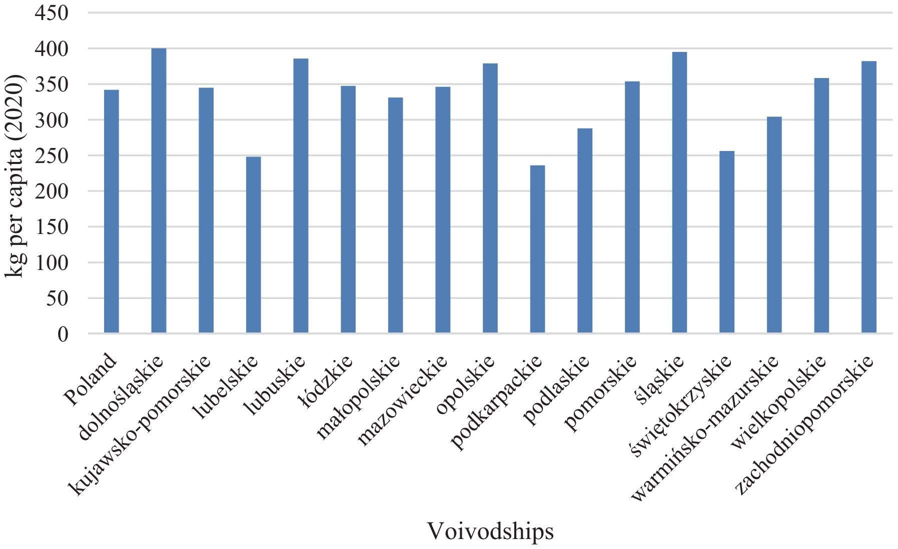

**Fig. 6.** The amount of generated waste (kg) per capita in 2020, according to voivodships in Poland (Statistic Poland LDB 2021)

studies have been performed related to the morphology of municipal waste, including separately collected and mixed waste streams, which became a basis for the estimation of municipal waste composition in (Jędrczak et al. 2020, Jędrczak et al. 2021). These data have been aggregated and presented against the 2008–2010 data, used for NWMP 2022 in Figure 7.

From Figure 7, it can be seen that the composition of municipal waste has shifted from higher kitchen waste content towards higher shares of recyclables, such as plastics, paper & cardboard and textiles. Significant reduction of kitchen waste share, from 32.2% to 21.4% may be related to change in lifestyles from traditional cooking to convenience foods. Surprisingly, there was an increase of fines content, which are often attributed to the individual heating systems based on solid fuels and the resulting ashes.

Majority of municipal waste is still collected in the mixed waste stream. In 2020, 8,142 Gg (62% of municipal waste) was collected as mixed waste. Analyses of the composition of mixed municipal waste have been used as a basis of various investment projects and published within the tendering procedures (den Boer et al. 2018, Butrymowicz 2018, Tyrała 2019, Zielnica and Cudakiewicz 2016).

The average composition of mixed municipal waste, based on the aforementioned recent studies is presented in figure 8. The major fraction is kitchen and garden waste, constituting 32.7% of the total mass. This is the fraction responsible for odor problems at various stages of waste collection, transport and its processing. Other biodegradable constituents include paper & cardboard (10.7%) and partly fines (10.1%).

### Management of municipal waste

In order to be able to effectively direct the waste stream to recycling, composting or fermentation processes, it is necessary to conduct selective collection of municipal waste. According to the data of Statistics Poland (Statistic Poland

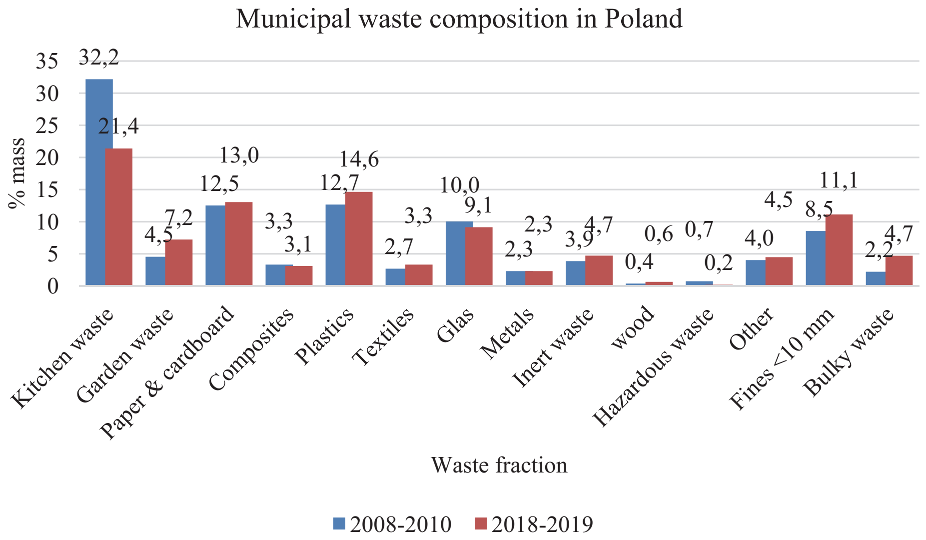

**Fig. 7.** Composition of municipal waste generated in Poland (Jędrczak et al. 2020, Jędrczak et al. 2021)

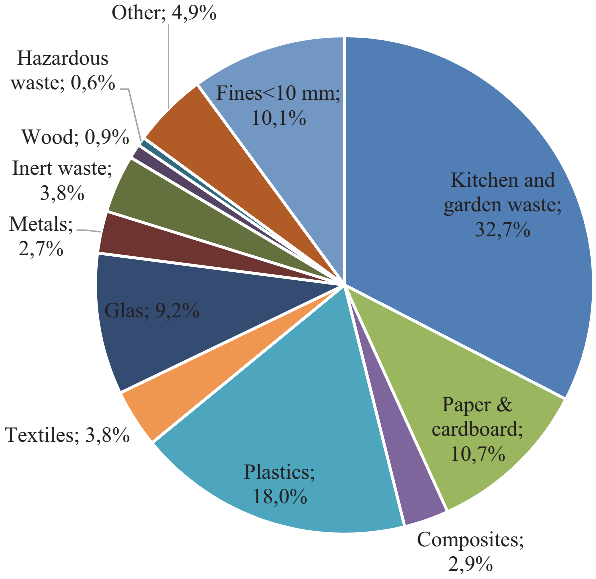

**Fig. 8.** Composition of mixed municipal waste, based on (den Boer et al. 2018, Butrymowicz 2018, Tyrała 2019, Zielnica and Cudakiewicz 2016)

LDB 2021), municipal waste collected selectively in Poland amounted to 4,974.56 Gg, which corresponds to 37.92% of total municipal waste generated. Mixed municipal waste was 8,142.33 Gg, which is 62.08% of the total. As indicated by the study of Statistics Poland (Statistic Poland 2020), the structure of waste collected selectively has changed significantly over the years. According to the study from 2005, the selectively collected fractions included paper and cardboard, which accounted for 32.4% of all separately collected waste in 2005, 33.60% was glass, 14.0% – plastics, 2.40% – metals, 11.60% – bulky waste, and other fractions – 6.0%. Over the years, the structure of municipal waste collected selectively has changed significantly. The report from 2010 shows an additional fraction – biodegradable waste, which in 2010 accounted for 21.1% of the total. The structure of separately collected municipal waste for 2019 is as follows: paper and cardboard – 8.80%, glass – 14.50%, plastics –10.00%, metals – 0.40%, biodegradable – 30.10% and other waste – 20.8% of all waste separately collected in Poland.

Figure 9 shows the shares of municipal waste undergoing different treatment options in the period 2004–2020, based on statistical data for Poland (Statistic Poland 2004–2021), except for recycling where data are available from 2013 only. It can be seen that major developments in waste treatment progressed since 2013, which was related with a significant reform of the municipal waste management, resulting in responsibility for waste management implementation being shifted from waste management companies and imposed on municipalities on July the 1st 2013. Since 2012 the recycling targets for paper, glass, metal and plastics were formally implemented by Polish 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*)), which triggered increase of material recycling. This coincided with the development of energy recovery of high caloric waste fractions, referred to as RDF (refuse derived fuel), mainly by its co-incineration in the cement industry. All these developments resulted in a significant reduction of waste landfilling from 9,194 Gg in 2004 to 5,218 Gg in 2020. On the other hand, it can be clearly seen that the trend was reversed in 2017, with an increase of waste being landfilled in the period 2017–2019 and only slight reduction in 2020.

Table 1 summarizes the quantitative data provided by Statistics Poland on the management of the generated municipal waste in 2017–2020 (Statistic Poland LDB 2021). Five main municipal waste streams were distinguished based on their management methods, which result directly from the waste hierarchy mentioned in the introduction to this paper, laid down by the *European Directive* and implemented into Polish legislation in *the Act of 14 December 2012 on waste (Journal of Laws of 2020, item 797)*. These are the mass of municipal waste for recycling, the mass of municipal waste for the composting or fermentation process, the mass of municipal waste for thermal processing with energy recovery, the mass of municipal waste intended for thermal transformation without energy recovery, and the mass of municipal waste intended for storage. The mass of municipal waste sent for recycling in 2020 amounted to 3,498.63 Gg and accounted for 26.67% of the total municipal waste generated and it increased compared to previous years. The stream of collected municipal waste processed via composting or fermentation processes in 2020 amounted to 1,577.93 Gg and accounted for 12.03% of the total municipal waste generated. The data show an upward trend in the amount of waste processed via composting or fermentation compared to 2017. The municipal waste stream sent incinerated with energy recovery in 2020 amounted to 2,656.21 Gg and constituted 20.25% of the total. The waste stream incinerated without energy recovery was only 166.40 Gg in 2020, which accounted for 1.30% of the total. Starting from 2017 a downward trend can be observed. The last of the streams, i.e., the mass of municipal waste landfilled amounted to 5,217.72 Gg in 2020, which constituted 39.78% of the total. In this case, there is an upward trend in both 2018 and 2019 compared to 2017 and a decrease compared to 2019. To sum up, for recovery processes, i.e., recycling, composting or fermentation processes, and thermal conversion with energy recovery, a total of 7,732.78 Gg was sent in 2020, which is 58.95% of total waste generated, while 5,384.12 Gg – 41.05% of the total generated waste – was sent for disposal processes. In the case of waste disposal, i.e.,

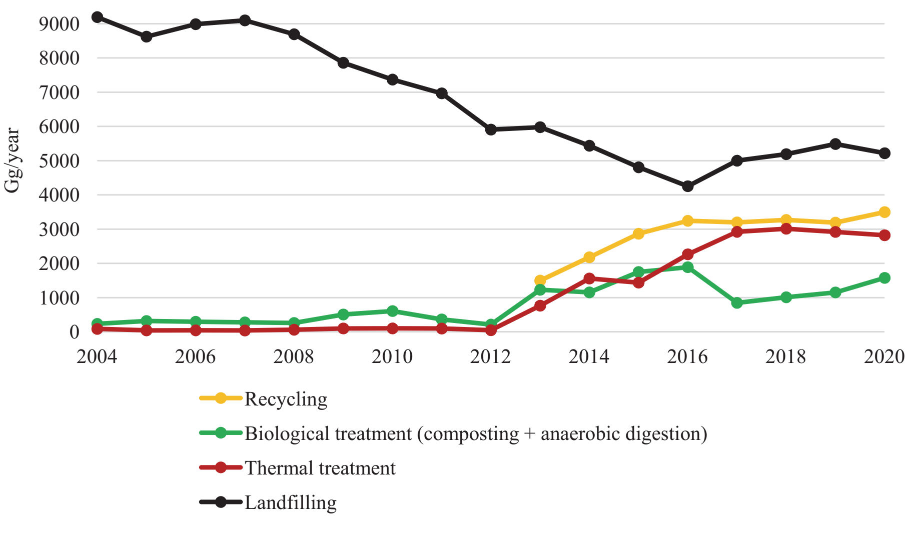

**Fig. 9.** Municipal waste treatment, based on the Statistical Office data (Statistic Poland 2004–2021)

**Table 1.** Management of collected municipal waste in 2017–2019 (Statistic Poland LDB 2021)

| 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 | 2017 | 2018 | 2019 | 2020 | 2017 | 2018 | 2019 | 2020 | 2017 | 2018 | 2019 | 2020 | 2017 | 2018 | 2019 | 2020 |
| | Gg | | | | | | | | | | | | | | | | | | | |
| Poland | 3,198.68 | 3,269.05 | 3,192.05 | 3,498.63 | 847.96 | 1,012.02 | 1,153.18 | 1,577.93 | 2,724.24 | 2,822.05 | 2,741.81 | 2,656.21 | 198.15 | 191.20 | 178.55 | 166.40 | 4,999.69 | 5,191.10 | 5,487.18 | 5,217.72 |
| dolnośląskie | 361.94 | 390.84 | 367.09 | 395.41 | 70.88 | 74.24 | 89.19 | 122.26 | 104.19 | 100.53 | 91.93 | 102.96 | 10.91 | 9.69 | 11.04 | 0.01 | 538.32 | 566.77 | 613.75 | 539.28 |
| kujawsko-pomorskie | 143.66 | 166.58 | 141.57 | 158.92 | 66.31 | 72.43 | 77.84 | 102.29 | 152.24 | 130.00 | 146.88 | 216.46 | 9.56 | 0.26 | 0.21 | 0.25 | 265.81 | 296.52 | 322.86 | 235.63 |
| lubelskie | 79.47 | 95.91 | 112.80 | 135.52 | 27.95 | 37.15 | 48.72 | 65.99 | 121.89 | 131.79 | 127.18 | 139.67 | 4.99 | 0.00 | 0.00 | 0.02 | 205.64 | 205.34 | 205.67 | 180.65 |
| lubuskie | 78.22 | 71.69 | 72.79 | 99.25 | 29.29 | 31.37 | 36.72 | 41.51 | 46.03 | 51.85 | 77.55 | 59.50 | 24.50 | 17.30 | 20.35 | 21.15 | 188.21 | 194.39 | 177.09 | 168.33 |
| łódzkie | 203.04 | 185.17 | 133.92 | 222.15 | 58.12 | 82.39 | 113.79 | 116.83 | 55.97 | 59.81 | 61.24 | 62.52 | 0.01 | 0.14 | 0.00 | 0.01 | 388.76 | 460.99 | 510.04 | 449.14 |
| małopolskie | 254.11 | 256.84 | 238.94 | 312.55 | 75.74 | 94.02 | 113.18 | 133.78 | 401.31 | 345.66 | 288.90 | 270.60 | 66.60 | 58.78 | 68.67 | 82.12 | 206.78 | 318.13 | 369.10 | 331.27 |
| mazowieckie | 411.24 | 380.55 | 438.59 | 527.11 | 100.71 | 111.02 | 90.20 | 212.42 | 530.34 | 579.87 | 417.32 | 355.22 | 49.20 | 53.26 | 37.53 | 20.07 | 685.47 | 687.13 | 752.53 | 764.39 |
| opolskie | 82.08 | 79.28 | 94.36 | 72.19 | 28.00 | 31.73 | 35.03 | 47.63 | 63.45 | 62.61 | 46.83 | 60.38 | 0.00 | 0.00 | 0.00 | 0.01 | 140.39 | 149.00 | 157.11 | 191.44 |
| podkarpackie | 90.09 | 89.32 | 95.48 | 115.41 | 16.42 | 18.41 | 22.87 | 31.27 | 158.40 | 157.13 | 137.70 | 123.57 | 14.30 | 13.65 | 12.58 | 12.83 | 184.35 | 219.02 | 245.72 | 218.59 |
| podlaskie | 55.05 | 65.88 | 74.87 | 94.67 | 15.63 | 21.07 | 25.13 | 40.40 | 99.08 | 121.86 | 129.47 | 108.53 | 0.00 | 0.00 | 0.02 | 0.00 | 108.91 | 90.14 | 104.56 | 95.27 |
| pomorskie | 163.78 | 159.61 | 172.35 | 191.31 | 86.61 | 90.89 | 102.69 | 137.98 | 243.17 | 153.57 | 166.79 | 145.48 | 2.99 | 6.98 | 9.54 | 11.60 | 307.09 | 415.61 | 417.52 | 343.67 |
| śląskie | 682.05 | 697.66 | 659.50 | 538.98 | 108.62 | 170.12 | 183.62 | 229.08 | 97.71 | 128.21 | 155.12 | 187.56 | 14.44 | 31.01 | 17.92 | 2.32 | 697.90 | 637.07 | 684.78 | 822.52 |
| świętokrzyskie | 57.62 | 64.23 | 70.44 | 68.58 | 8.36 | 6.79 | 11.20 | 15.83 | 24.11 | 23.06 | 17.92 | 17.95 | 0.03 | 0.02 | 0.57 | 15.47 | 144.32 | 155.98 | 186.32 | 197.17 |
| warmińsko-mazurskie | 82.31 | 83.78 | 87.39 | 131.55 | 18.41 | 23.56 | 24.30 | 36.96 | 127.00 | 108.83 | 115.97 | 88.23 | 0.53 | 0.01 | 0.00 | 0.40 | 195.47 | 225.21 | 208.18 | 175.15 |
| wielkopolskie | 265.07 | 310.07 | 259.21 | 287.12 | 97.04 | 103.32 | 123.52 | 172.58 | 380.91 | 427.44 | 473.97 | 489.14 | 0.09 | 0.10 | 0.12 | 0.14 | 451.03 | 382.79 | 383.53 | 305.71 |
| zachodnio-pomorskie | 188.97 | 171.63 | 172.74 | 147.92 | 39.89 | 43.51 | 55.20 | 71.13 | 118.45 | 239.83 | 287.05 | 228.43 | 0.00 | 0.00 | 0.01 | 0.00 | 291.22 | 187.01 | 148.43 | 199.49 |

incineration without energy recovery and landfilling, an upward trend can be observed over the years 2017–2019 and a decrease in year 2020 compared to previous years. Comparison of the analyzed data with the waste hierarchy shows a negative trend in waste management in Poland, especially given the amount of waste that is managed in the least favorable ways, i.e., disposal and landfilling. Regarding the analyzes of individual voivodships, the general trend is similar to the data presented in Figure 4. The mass stream of waste intended for recycling in 2020 prevails in śląskie, mazowieckie, dolnośląskie and wielkopolskie voivodships, while the voivodships with the lowest amount of waste sent for recycling are świętokrzyskie, lubuskie, podlaskie and opolskie. The stream of waste sent for composting or fermentation in 2020 was the highest in śląskie, mazowieckie, wielkopolskie and pomorskie voivodships, and the lowest in świętokrzyskie, podkarpackie, warmińsko-mazurskie and podlaskie voivodships. The dominant mass of waste sent for thermal treatment with energy recovery (2020) is noted in wielkopolskie, mazowieckie, małopolskie and zachodniopomorskie voivodships, which hold waste incineration plants. Considering the waste stream for landfilling (2019), śląskie, mazowieckie, dolnośląskie and łódzkie voivodships are in the lead, while the least waste was landfilled in podlaskie, lubuskie, warmińsko-mazurskie, and lubelskie voivodships.

### *Available infrastructure for waste management*

An important aspect of municipal waste management is appropriate and specialized infrastructure for the effective management of the generated waste such as composting plants, biogas plants, waste incineration plants, waste landfills and mechanical-biological waste treatment plants (MBT plants). In Poland all municipal waste must be pretreated before final disposal. The mixed municipal waste is pretreated either in mechanical-biological treatment plants or in waste incinerators. According to the data published by Marshal Offices, there are currently 174 MBT plants with a permit to treat mixed municipal waste and 8 incinerators accepting either mixed municipal waste or sorting residues (Figure 10) (den Boer et al. 2021). 8 MBT plants use anaerobic digestion process as one stage of biological treatment (Wiśniewska et al. 2019). According to the data of Statistics Poland (Statistic Poland LDB 2021), in 2020 there were 271 active municipal landfills in Poland (Figure 10). Based on the data of Marshal Offices (Jędrczak et al. 2020) only 163 of them have a status of municipal landfills, which means that they can accept pretreated municipal waste or sorting residues. In 2010–2020, a clear trend towards reducing active landfills can be observed. In 2010, according to the data from Statistics Poland (Statistic Poland LDB 2021), there were 633 municipal waste landfills, and 362 have been closed since then. Despite this cutback, landfilling is still one of the most common municipal waste management processes. The separately collected biowaste is treated in 220 installations, of which 144 are located together with MBP plants (Jędrczak et al. 2020). Only one anaerobic digestion plant for separately collected biowaste is operated and two more are under construction.

All the above-mentioned issues are very important as the upward trends in the amount of municipal waste generated on a local and global scale, require intensification of the management processes of municipal waste generated in societies. These processes may affect the emission of odor-generating substances to the air and the periodic deterioration of air quality in the vicinity of waste management facilities, which carry out processes that cause the emission of various odorous substances. Therefore, the following chapter presents the characteristics of the emitted odor-generating substances from selected processes and waste management facilities.

## Emission of odors and odorants from municipal waste management facilities and processes

Municipal waste management facilities are a source of odors and odorants emissions into the air. Due to the aforementioned multi-stage processes and the fact that individual technological processes of waste treatment consist of many different unit operations, the emission of individual odorants and their mixtures in the form of odors may take place at various stages of waste management. Therefore, a review of the literature on odorant and odor emissions into the air is presented below, taking into account individual stages of general municipal waste management.

### *Waste collection and transport*

One of the first stages of municipal waste management is waste collection at the place of its production, e.g., in waste containers in residential areas, as well as waste collection and transport processes (Cheng et al. 2020, Liu et al. 2020, Shi et al. 2020, Tan et al. 2017, Xu et al. 2020). The emission of odor-generating substances in these processes is mainly related to the initial process of decomposition of the organic substance contained in municipal waste (Cheng et al. 2020, Liu et al. 2020, Tan et al. 2017, Xu et al. 2020). In the case of waste collection and transportation, the process is influenced, among others, by ambient temperature, waste composition and waste storage time in containers (Tan et al. 2017), which may vary depending on the method and areas of waste collection (Liu et al. 2020). There are several references on the testing of the emissions of odor-generating substances in the initial stages of waste management, i.e., collection and transport of waste. Liu et al. 2020 in their research simulated the process of initial decomposition of organic matter contained in municipal waste for samples with different content of the readily biodegradable fraction of municipal waste, which contained, respectively, 15%, 45% and 60% of this fraction. During the research, a total of 43 different volatile organic compounds were identified, divided into 5 groups: sulfur compounds, aromatics, halogenated compounds, hydrocarbons and oxygenated compounds. In the case of samples containing 45% and 65% of the organic fraction, oxygenated compounds had the highest emission, with ethanol as the dominant substance. The mean concentration of ethanol from the samples taken during the tests was 17.23 ppm. The odor concentration was also determined with the dimensionless Co unit. Methyl sulfide, ethanol, dimethyl disulfide and ethyl acetate were indicated as the main odorants. For waste containing 60% of readily biodegradable organic matter, the highest Co was determined for methyl sulfide and it was 162.72, followed by ethanol (66.19), ethyl acetate (9.19), and dimethyl disulfide (6.41). For 45% organic matter, the dominant substance in terms of Co was ethanol (56.95), followed by methyl sulfide (18.00), ethyl acetate (1.05), and dimethyl disulfide in 5th place with a Co value of 0.92. In the case of 15% composition, dimethyl disulfide (56.03) came first, followed by methyl sulfide (3.15), and ethanol was on the 6th place (0.33). The results of the research indicate that the main factor responsible for the emission of volatile organic compounds (VOCs) was the percentage of readily biodegradable waste, the higher the value, the higher the VOC emission. The average VOC emission for 60% composition was 50.72 ppm, while for 45% it was 37.66 ppm. In one of the summarizing conclusions the authors indicate that

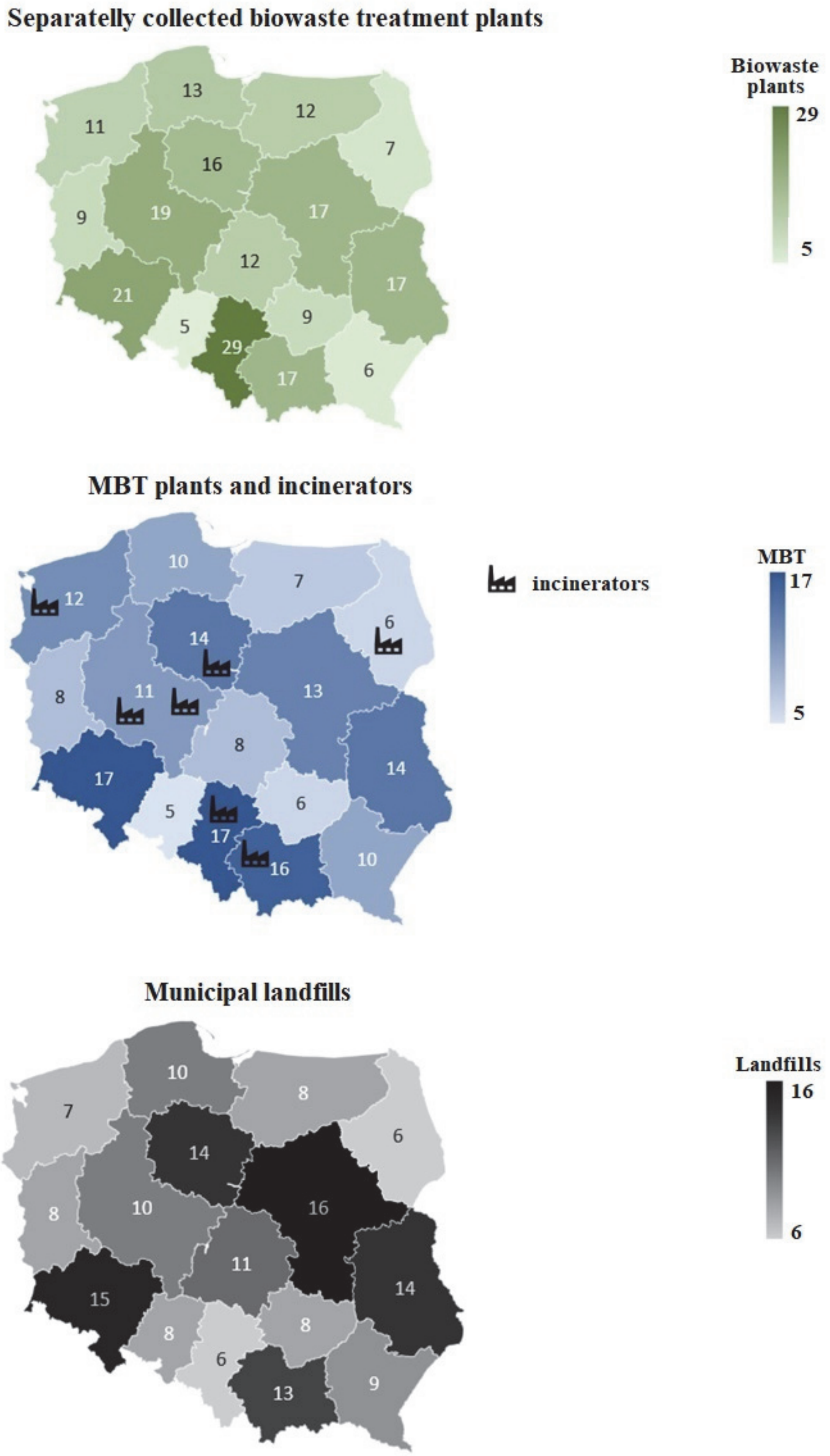

**Fig. 10.** The number of the major municipal waste treatment installations within the borders of individual voivodeships, based on data of Marshal Offices, based on (Jędrczak et al. 2020)

the content of organic matter is an important factor influencing the emission of odor pollutants (Liu et al. 2020). Cheng et al. 2020 in their research analyzed samples taken from, among others, waste bins located in residential areas. The authors carried out analyzes aimed at identifying individual odorants and the odor concentration (dimensionless). The identified substances were divided into the following groups: $NH_3$, sulfide compounds, aromatics compounds, oxygenated compounds, halogenated compounds, alkanes, among them the main identified compounds emitted from containers include: methyl mercaptan, $NH_3$, dimethyl disulfide, acrolein, dimethyl sulfide, methacrolein, benzene, toluene, ethylbenzene, and m, p-xylene. The concentration of $NH_3$ ranged from 912.3 ± 106.8 $\mu g/m^3$, the concentration of sulfide compounds was 15.6 ± 9.2 $\mu g/m^3$, the concentration of halogenated compounds was 220.2±192.1 $\mu g/m^3$, the concentration of alkanes was 5.9±1.7 $\mu g/m^3$. The dimensionless odor concentration (in line with Chinese emission standards) was below 20. Additionally, an analysis of the environmental impact of odors emitted in the vicinity of residential areas in comparison to transshipment stations and a landfill was conducted. Odors around waste containers had the lowest environmental impact. Tan et al. 2017 simulated early decomposition of organic matter in a prepared sample of waste containing readily biodegradable, biodegradable and non-biodegradable fractions. During the research, 52 odor-generating substances were identified and divided into 7 main groups: saturated hydrocarbons, unsaturated hydrocarbons, aromatics, halogenated compounds, oxygenated compounds, sulfur compounds and terpenes. The results obtained by the authors indicate that in most cases the highest concentration of emitted substances was obtained for ethanol (the average percentage is approx. 80%, 379.85 ± 409.57 ppm), similarly to Liu et al. 2020. The second substance was propylene (the average percentage is approx. 13%, 67.18 ± 79.86 ppm), which belonged to the group of unsaturated hydrocarbons. The data (Tan et al. 2017) also show the variability of the emitted substances over time and at different temperatures. The emission of odor-generating substances was definitely lower at 5°C than in the case of the emission tested at 30°C. For example, the share of ethanol in the total identified odorous substances increased from approx. 22.30% to 70.01% with the temperature increase from 5°C to 30°C, while in the period from 6 h to 24 h, the percentage of ethanol increased from 40.1% to 82.9%. In their research on the simulation of odor pollution during transport, Xu. et al. 2020 used substances such as ethanol, dimethyl disulphide and methylene chloride. Shi et al. 2020 observed a total of 40 volatile organic compounds emitted from waste containers divided into 5 groups: terpenes, alkanes, sulfur compounds, aromatic compounds and hydrocarbons, for various types of collection in containers (mixed waste containers, kitchen waste and other waste containers). Research carried out on an annual scale for 4 seasons shows that it is mainly mixed waste containers that have the highest VOC emissions, and that the season in which the most VOCs are emitted from mixed waste containers is summer.

### Waste transfer stations

Another important issue from the perspective of the emission of odorants and their mixtures in the form of odors are transfer stations (Chang et al. 2019, Cheng et al. 2020, Curren et al. 2016, Zhao et al. 2015), serving as temporary storage places for waste in cases where the destination of waste management, e.g., a landfill or a mechanical-biological waste treatment plant (MBT) is too far from the waste collection point, which would make the costs of transport without reloading too high (Mozambe et al. 2021, Zemanek et al. 2011). It should be mentioned that transfer stations are an optional element of waste management systems. While analyzing the emission of odors from transfer station, Cheng et al. 2020 identified $NH_3$, acrolein, methyl mercaptan, methacrolein, dimethyl disulfide, benzene, toluene, dimethyl sulfide, m, p-xylene and propanal as the main odorous substances among the sulfide compounds, aromatics compounds, oxygenated compounds, halogenated compounds and alkanes groups. Analyzing the four selected sources at the transfer station in terms of odor concentration (dimensionless, according to Chinese emission standards), i.e., the plant boundary (below 20), the waste discharge area (approx. 442), the waste compaction area (approx. 300) and the leachate tank (approx. 120), he indicated the area of waste discharge as one with the highest odor concentration (approx. 442, dimensionless). The environmental impact analysis showed that reloading stations were ranked between the odors emitted from residential containers and landfills, but the impact was much smaller than in the case of landfills. In their research on odor emissions from the transfer station, Chang et al. 2019 identified a total of 76 odorous compounds divided into 6 groups: saturated hydrocarbons, unsaturated hydrocarbons, aromatic hydrocarbons, sulfur compounds, oxygenated compounds and halogenated hydrocarbons. The authors indicated that the dominant substances were ethanol with an average concentration of 7.14 $mg/m^3$ (belonging to the group of oxygenated compounds), dimethyl disulfide ($4.63 \times 10^{-2}$ $mg/m^3$) and methyl mercaptan ($3.45 \times 10^{-4}$ $mg/m^3$) (sulfur compounds). Zhao et al. 2015 identified 76 odor--generating compounds divided into 7 groups: sulfur compounds, oxygenated compounds, aromatics, terpenes, halogenated compounds, saturated hydrocarbons and unsaturated hydrocarbons, emitted from a transfer station. The results obtained by the authors indicated methane thiol, hydrogen sulphide, ethanol, dimethyl disulphide, dimethyl sulphide as the most odor-generating substances. Ethanol was characterized by the highest concentration –15.6 ± 9.2 $\mu g/m^3$, while methane thiol was the dominant substance due to the low odor detection threshold of 0.00007 ppm. Curren et al. 2016 identified, *inter alia*: methyl mercaptan, hydrogen sulfide, acetaldehyde, acetic acid, butyric acid and terpenes as the main odor-generating substances in their research at the transfer station.

### Mechanical-biological waste treatment plants

One of the largest sources of odor emissions into the air are mechanical-biological waste treatment plants (MBT). As indicated in the available literature, the activity of MBT plants is associated with the emission of odors and odorants into the atmospheric air (Almarcha et al. 2012, Colón et al. 2017, Fei et al. 2018, Hou et al. 2013, Kulig and Szyłak-Szydłowski 2016, Mustafa et al. 2017, Ragazzi et al. 2013, Scagila et al. 2011, Schiavon et al. 2017, Wiśniewska 2020a, Wiśniewska 2020b, Wiśniewska and Szyłak-Szydłowski 2021, Wiśniewska et al. 2020a, Wiśniewska et al. 2020b, Wiśniewska et al. 2019, Wiśniewska et al. 2021). The activities of MBT plants mainly include processes related to the management of mixed municipal waste and are indicated as one of the key elements of waste management (Ragazzi et al. 2013). Mixed municipal waste is treated in MBT plants in two stages. The first stage is mechanical preparation of waste for biological processes, and the second stage is biological decomposition of waste (Colón et al. 2017, Wiśniewska and Szyłak-Szydłowski 2021, Wiśniewska et al. 2020a). The biological process can be carried out in an aerobic manner (in the form of composting) or using anaerobic conditions (fermentation) and then subjecting the fermentation residues to aerobic stabilization (Fei et al. 2018, Wiśniewska and Szyłak-Szydłowski 2021, Wiśniewska et al. 2020b). The combination of mechanical and biological processes minimizes the amount of landfilled waste and recovers useful fractions from the waste stream that can be reused, e.g., ferrous and non-ferrous metals. MBT processes can generate products such as RDF fuel or biogas, which can be used for energy purposes of a given plant (Fei et al. 2018, Wiśniewska et al. 2019).

Fang et al. (2013) conducted research on the emission of odorous substances at the MBT plant, where the technological process consisted of pre-mechanical treatment, pre-biotreatment, post-mechanical treatment and post--biotreatment. He identified 75 gaseous substances emitted during these processes, divided into 9 groups: nitrogen compounds, sulfur compounds, carbonyls, alcohols, aromatics, alkanes, alkenes, terpenes, and volatile fatty acids. The authors indicated acetic acid, butyric acid, valeric acid, isovaleric acid, and dimethyl sulfide as the most odor-generating substances. In the case of pre-mechanical treatment, the concentrations of gaseous substances ranged from 64 to 175 ppm depending on the collection point, in the pre-biotreatment the concentrations ranged from 132 to 317 ppm (the highest concentration of 317 ppm was obtained on the 7th day during the aerobic process). Post-mechanical treatment was characterized by concentrations ranging from 91 to 119 ppm, depending on the place of collection, in the case of post-biotreatment the concentrations ranged from 128 to 185 ppm. The authors indicated acetic acid, butyric acid, valeric acid, isovaleric acid, and dimethyl sulfide as the most odor-generating substances.

Wiśniewska et al. (2019, 2020) researched the emission of odorants and odors from 6 MBT plants in Poland, which had the installation for anaerobic decomposition (fermentation) of the organic matter contained in mixed municipal waste (Wiśniewska 2020a, Wiśniewska 2020b, Wiśniewska and Szyłak-Szydłowski 2021, Wiśniewska et al. 2020a, Wiśniewska et al. 2020b, Wiśniewska et al. 2019, Wiśniewska et al. 2021). The conducted research concerned mainly the analyzes of substances such as VOC (measured values of a dozen or so ppm on average), ammonia (a dozen or so ppm on average), hydrogen sulfide (not more than a few ppm), dimethyl sulfide, methyl mercaptan (usually below one ppm) and analyzed the concentration of odors using field olfactometry. Among the sources that were taken into account at the MBT plants studied, authors distinguished, inter alia, waste storage areas, part of the mechanical waste treatment process, a place for preparation of the load for fermentation, a place for digestate dewatering, aerobic stabilization stage and biofilter surfaces.

### ***Landfilling***

As indicated in the second section of this paper, landfilling in Poland is the most frequently applied municipal waste management process. In 2020, 39.78% of all municipal waste generated was landfilled. Such an amount of landfill waste requires the maintenance of an appropriate number of landfills. In Poland, despite the continuous drop in the number of landfills (see Section 2 for details), in 2020 there were 271 active municipal landfills. The operation of municipal waste landfills has negative impact on the environment through, among others, the emission of pollutants into the air. The available literature includes a number of studies on these issues (Capelli and Sironi 2018, Cheng et al. 2020, Cheng et al. 2019, Duan et al. 2021, Fang et al. 2012, Forastiere et al. 2011, Giusti 2009, Heyer et al. 2013, Jiang et al. 2021, Ko et al. 2015, Le Bihan et al. 2020, Liu et al. 2019, Long et al. 2017, Lou et al. 2015, Lucernoni et al. 2016, Meišutovič-Akhtarieva and Marčiulaitienė 2017, Naddeo et al. 2018, Sonibare et al. 2019, Tagliaferri et al. 2020, Wang et al. 2021, Yao et al. 2019, Zhang et al. 2021). The main cause of the emission of odor-generating substances from landfills is municipal waste deposited in a landfill, which undergoes three main processes: biodegradation of the organic substance contained in the deposited waste (biogenics), direct volatilization of compounds (xenobiotics), and biological or chemical reactions between waste contained in the deposit and reaction products (Duan et al. 2021). The biological decomposition of waste in the deposit begins under aerobic conditions and, after the consumption of oxygen by microorganisms, it turns to anaerobic conditions. During various types of reactions, landfill gas (LFG) is emitted, consisting mainly of methane, carbon dioxide and trace substances, which are mainly responsible for the emission of odors to the air (Duan et al. 2021). As indicated in the literature (Fang et al. 2012) a waste deposit in a landfill is not the only source of odor emissions, other sources include landfill leachate tanks or wells which degas a landfill deposit and collect landfill gas from it.

Cheng et al. 2019 identified 6 main groups of substances in the study of odorant emissions from a waste landfill and composting plant: alkanes, oxygenated compounds, sulfide compounds, aromatics, halogenated compounds, and $NH_3$. Among them, the main substances identified in the landfill responsible for odor contamination were $H_2S$ (up to 129 ppb on average), benzene (up to 291 ppb on average), $NH_3$ (up to 1132 ppb on average), ethyl acetate (up to 1292 ppb on average), ethyl benzene (up to 143 ppb on average), ethyl disulfide (up to 216 ppb on average), p-ethyl toluene (up to 18 ppb on average), n-hexane (up to 54 ppb on average), 1,2-dichlorobenzene (up to 22 ppb on average), trichloroethylene (up to 0.4 ppb on average). The odor nuisance of the tested landfill, compared to the waste composting plant, was indicated to be much lower. Yao et al. 2019 identified 63 substances emitted from the waste treatment plant, which used 3 main technologies: fermentation, eco-biological-mechanical treatment and waste disposal. The substances were divided into 6 groups: halogenated compounds, sulfuric compounds, alkanes, alkenes, aromatic compounds, and oxygenated compounds. The main odor-generating substances in the tested object were methanethiol (15136–29087 $\mu g/m^3$), dimethyl sulfide (36847–43307 $\mu g/m^3$), dimethyl disulfide (2945–4561 $\mu g/m^3$), carbon disulfide (2385–4928 μg/m$^3$), styrene (μg/m$^3$), m-xylene, 4-ethyltoluene, ethylbenzene, 2-hexyl ketone and n-hexane. Fang et al. 2012 identified a total of 35 odor-generating substances in 6 compound groups: aromatic compounds, sulfur compounds, oxygenated compounds, amines, atty acids and $NH_3$. The highest concentrations among the identified substances in the tested landfill were observed 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 2250 ppb), dimethyl sulfide (up to up to 78 ppb), dimethyl disulfide (up to 121 ppb) and ammonia (up to 70 000 ppb). Concentrations varied depending on the sampling site.

### *Thermal treatment of municipal waste*

Waste incineration plants are another group of facilities that may potentially emit odor-generating substances. Waste incineration plants allow for the effective reduction of waste mass as a result of thermal treatment of waste. Due to their mode of operation, the primary sources of emissions of odorants and their mixtures to the air may potentially be vehicles delivering waste to the plant and the site of waste storage (usually in the form of a storage bunker) (Guo et al. 2017, Oleniacz 2014). In the case of waste incineration plants, the main emission sources under consideration are emissions from the stack after the waste incineration process. These emissions include, among others, dust, SOx, HCl, NOx, Dioxins, Furans, $NH_3$, CO, VOC, and heavy metals (Cd, Hg, Pb) (Beylot et al. 2018, Ciangialosi et al. 2008, Damgaard et al. 2010, Oleniacz 2014). The waste delivered to the incineration plant is mainly waste in an early stage of biodegradation, so the main emissions of odor-producing substances may be similar to emissions from collection, transport and transfer stations.

Guo et al. 2017 identified in their research a total of 75 volatile compounds emitted from waste incineration plants with an average concentration of 33,129.25 μg/m$^3$. The authors measured sources such as a storage bunker (70 compounds, 53 305.83 μg/m$^3$), waste unloading site (72 compounds, 72 053.89 μg/m$^3$), and also measured the background value in the incinerator (48 compounds, 1607.19 μg/m$^3$). The waste unloading site was characterized by the highest concentration of substances. In the study, the authors compared the concentrations from the waste incineration plant with those from the transfer station and the landfill. The waste incineration plant was characterized by the highest values. Hydrocarbons and oxygenated compounds had the largest share in the identified VOCs. The identified substances were divided into: halogenated compounds, terpenes, hydrocarbons, oxygenated compounds, aromatics, and sulfur compounds.

## Main Findings and Conclusions

The analysis of the state of waste management in Poland indicated that over two last decades much progress has been achieved in implementing waste treatment and recovery operations which allowed to reduce the share of municipal waste being landfilled from 96.6% in 2004 up to 39.8% of all municipal waste in 2020. On the other hand, the landfilling of waste remains one of the most common methods of waste management, which, in combination with the content of the *Directive* implemented into the Polish law in the *Act of Waste*, does not meet the provisions of the waste hierarchy. The waste hierarchy indicates that the disposal of waste through landfilling is the least desirable way of managing the generated municipal waste. Comparing the available data on the state of waste management in Poland with the data at the European level (Statistic Poland LDB 2021, Eurostat 2021) Poland is one of the countries with the highest percentage of waste designated for landfilling. Taking into account the current growth of municipal waste quantities in Poland and the recent increase of waste landfilling in the period 2017–2019, some difficulties may be anticipated in meeting the goal set for the Member States of the European Union in the *Directive on the landfilling of waste*, which is to reduce the amount of municipal waste landfilled to a maximum of 10% of generated waste in 2035. It is necessary for Poland to increase the share of separate collection, enabling higher material recycling and, especially, organic recycling of biowaste with the use of fermentation and composting processes. Other waste management methods, such as the treatment of mixed municipal waste at MBT plants and incinerators and other thermal treatment plants, can effectively reduce the amount of waste sent for landfilling. Recent growth of municipal waste quantities and of the landfilling does not necessarily mean that Poland will not be able to achieve its goal. In many EU countries, such as Lithuania, Estonia, Finland and Slovenia, the amount of waste sent to landfills has been significantly reduced over the last 10 years (Eurostat 2021). Many of the European countries have achieved the goal so far, such as Germany, Sweden, Belgium, Denmark, the Netherlands, Austria, Luxembourg and Slovenia. The data analyzed in Section 2 of this study indicate that it is necessary to undertake a number of actions in Poland in order to improve the condition of municipal waste management and to increase more friendly and desirable methods of waste management. This was addressed by the adopted in May 2021 amendment to National Waste Management Plan 2022 encompassing the evaluation of investment needs in waste management in Poland in connection with the new EU financial perspective 2021–2027 (Resolution No. 57 of the Council of Ministers of 6 May 2021 amending the resolution on the National Waste Management Plan 2022 (M.P.2021.509). The abovementioned investments plan foresees a need for expanding and retrofitting the existing plants and the construction of new ones, including 200 new sorting plants for separately collected recyclables and major developments of the biowaste treatment capacity. For biowaste, it has been estimated that in the short term (by 2028), the construction of installations with a capacity of at least 1,700,000 Mg/year, including 34–50 anaerobic digestion plants with a capacity of 20,000–30,000 Mg/year and 47–70 composting plants with a capacity of 15,000–10,000 Mg/year will be needed. Moreover, an increase of thermal treatment capacity by 2.5 mln. Mg/year is needed.

Municipal waste management is a multi-stage and complex process characterized by a negative impact on the environment through excessive emissions to water, soil, and air. In the case of emissions to the air, one of the particular threats posed by waste management processes is the emission of odorants and their mixtures, which are mainly products of the aerobic or anaerobic decomposition of biodegradable waste. Literature review showed the presence of available literature in terms of odor-generating substances from different waste management processes. Table 4 summarizes the identified groups of substances for the 5 main sources of odor emissions to air, i.e., for the initial decomposition of organic matter associated with collection, transport and transfer stations, for mechanical and biological waste treatment processes, for landfilling and thermal waste treatment processes. All groups are dominated by chemical compounds related to self-running microbiological processes. As a result of anaerobic processes, mainly sulfur and nitrogen compounds are emitted: hydrogen sulfide, sulfides, ammonia and amines (Di et al. 2013). In the case of oxygen processes, oxygenated compounds (alcohols, esters and carboxylic acids) (Defoer et al. 2002) have a significant share among the emitted gases. In all groups there are also aromatic compounds (toluene, styrene, xylenes), the presence of which is associated with the processes of decomposition of petroleum materials (especially polymers). These compounds, along with PAH, are also produced in the case of thermal waste treatment processes.

As shown during the literature review, odorants and odors are formed at the initial stages, such as collection and transport, and at their final processing sites, for example, MBT plants. Odor-generating substances could be divided into several groups: sulfur compounds, nitrogen compounds, aromatics, halogenated compounds, hydrocarbons, oxygenated compounds, alkanes, and terpenes. Odorants are emitted in low concentrations (usually up to a dozen or so ppm). However, due to the relatively low thresholds of odor perception, these low concentrations may cause a negative impact on the environment and cause complaints from the residents. Therefore, taking into account the growing trends in the mass of generated municipal waste, there is a necessity in a reduction in the amount of waste directed to the least desirable management methods with highest environmental impact, i.e., disposal through, *inter alia*, landfilling. One of the measures to reduce the mass of waste sent to landfills is to use mechanical-biological waste treatment, with the use of aerobic stabilization or anaerobic stabilization for mixed municipal waste treatment. As stated above, there is a significant need in Polish waste management system to increase the capacity for recycling, composting and fermentation processes, and thermal

**Table 2.** Odorants groups and dominant odorants identified in various waste management processes

| Process/Source of odor emissions to air | Identified groups of substances | Dominant substances | Literature source |
|---|---|---|---|
| Collection, transport | sulfur compounds, sulfide compounds, aromatics, halogenated compounds, hydrocarbons (unsaturated and saturated), oxygenated compounds, alkanes, terpenes | ammonia, ethanol, propylene, methyl sulfide, dimethyl disulfide, methylene chloride, methyl mercaptan, acrolein, methacrolein, benzene, toluene, ethylbenzene, m,p-xylene, ethyl acetate, hydrogen sulfide | (Cheng et al. 2020, Liu et al. 2020, Shi et al. 2020, Tan et al. 2017, Xu et al. 2020) |
| Transfer stations | sulfur compounds, aromatics compounds, oxygendated compounds, halogenated compounds, (saturated and unsaturated), alkanes, terpenes | Ammonia, ethanol, acrolein, methyl mercaptan, methacrolein, dimethyl disulfide, dimethyl sulphide, hydrogen sulphide, methane thiol, benzene, toluene, m,p-xylene, propanal, acetaldehyde, acetic acid, butyric acid | (Chang et al. 2019, Cheng et al. 2020, Curren et al. 2016, Zhao et al. 2015) |
| Mechanical biological treatment of waste (including composting and fermentation) | nitrogen compounds, sulfur compounds, carbonyls, alcohols, aromatics, alkanes, alkenes, terpenes, and volatile fatty acids | ammonia, hydrogen sulfide, dimethyl sulfide, methyl mercaptan, acetic acid, butyric acid, valeric acid, isovaleric acid, dimethyl sulfide, ethyl acetate, benzene, ethyl benzene, n-hexane, dimethyl disulfide, hexachlorobutadiene, naphtalene, o-xylene, benzyl chloride | (Wiśniewska 2019b, Wiśniewska and Szyłak-Szydłowski 2021, Wiśniewska et al. 2021, Wiśnieska et al. 2020a, Wiśniewska et al. 2020b, Wiśniewska et al. 2019, Fang et al. 2013, Cheng et al. 2019) |
| Landfilling | alkanes, oxygenated compounds, sulfide compounds, aromatic compounds, halogenated compounds, alkenes, amines, fatty acids | $H_2S$, benzene, $NH_3$, ethyl acetate, ehyl benzene, ethyl disulfide, p-ethyl toluene, n-hexane, 1,2-dichlorobenzene, trichloroethylene, methanethiol, dimethyl sulfide, dimethyl disulfid, carbon disulfide, styrene, m-xylene, 4-ethyltoluene, ethylbenzene, 2-hexyl ketone, n-hexane, toluene, xylene, acetone, methanol, n-butanone, n-butaaldehyde, acetic acid, ammoniathyl disulfide | (Fang et al. 2012, Cheng et al. 2019, Yao et al. 2019) |
| Thermal waste treatment | halogenated compounds, terpenes, hydrocarbons, oxygenated compounds, aromatics, sulfur compounds (also could be simillar as for collection, transport and transfer stations) | Ethyl acetate, 2-butanone, iso-butane, hydrogen sulfide, dimethyl disulfide, methyl mercaptan (also could be simillar as for collection, transport and transfer stations), dust, SOx, HCl, NOx, dioxins, furans, $NH_3$, CO, VOC, heavy metals | (Beylot et al. 2018, Cangialosi et al. 2008, Damgaard et al. 2010, Guo et al. 2017, Oleniacz 2014) |

treatment of waste. Despite the fact that reducing the amount of waste being landfilled with increase of share of waste being processed with more environmental friendly methods, odor could be still potentially emitted from waste management due to the presence of organic fractions. In accordance with the waste hierarchy introduced in the *European Union Waste Directive*, preventing excessive waste generation should be considered the main and the most important activity in terms of odor emission. Reducing the organic fraction in municipal waste, especially in mixed municipal waste, can significantly reduce odor emissions in waste management. Therefore, decreasing waste generation should become a priority action in the EU countries, including Poland.

*This paper was co-financed within the "Excellent Science" program of the Polish Ministry of Science and Higher Education.*

Ministry of Science
and Higher Education
Republic of Poland

## References

Aatamila, M., Verkasalo, P.K., Korhonen, M.J., Viluksela, M.K., Pasanen, K., Tiittanen, P. & Nevalainen, A. (2010). Odor annoyance near waste treatment centers: A population-based study in Finland. *J. Air Waste Manag. Assoc.*, 60, pp. 412–418, DOI: 10.3155/1047-3289.60.4.412

Almarcha, D., Almarcha, M., Nadal, S. & Caixach, J. (2012). Comparison of the depuration efficiency for voc and other odoriferous compounds in conventional and advanced biofilters in the abatement of odour emissions from municipal waste treatment plants. *Chem. Eng. Trans.*, 30, pp. 259–264, DOI: 10.3303/CET1230044

Alwaeli, M. (2015). An overview of municipal solid waste management in Poland. The current situation, problems and challenges. *Environ. Prot. Eng.*, 41, pp. 181–193, DOI: 10.5277/epel50414

Bax, C., Sironi, S. & Capelli, L. (2020). How can odors be measured? An overview of methods and their applications. *Atmosphere (Basel).*, 11, DOI: 10.3390/atmos11010092

Beylot, A., Hochar, A., Michel, P., Descat, M., Ménard, Y. & Villeneuve, J. (2018). Municipal Solid Waste Incineration in France: An Overview of Air Pollution Control Techniques, Emissions, and Energy Efficiency. *J. Ind. Ecol.*, 22, pp. 1016–1026, DOI: 10.1111/jiec.12701

den Boer, E. Banaszkiewicz, K. & Sebastian M. (2018). Badania ilości i składu odpadów komunalnych w cyklu rocznym pochodzących z terenu gminy Wrocław. Raporty Wydziału Inżynierii Środowiska Politechniki Wrocławskiej. Ser. SPR nr 30, 226. (in Polish)

den Boer, E., Jedrczak, A., Kowalski, Z., Kulczycka, J. & Szpadt, R. (2010). A review of municipal solid waste composition and quantities in Poland. *Waste Manag.*, 30, pp. 369–377, DOI: 10.1016/j.wasman.2009.09.018

Brattoli, M., de Gennaro, G., de Pinto, V., Loiotile, A.D., Lovascio, S. & Penza, M. (2011). Odour detection methods: Olfactometry and chemical sensors. *Sensors*, 11, pp. 5290–5322, DOI: 10.3390/s110505290

Bruno, P., Caselli, M., de Gennaro, G., Solito, M. & Tutino, M. (2007). Monitoring of odor compounds produced by solid waste treatment plants with diffusive samplers. *Waste Manag.*, 27, pp. 539–544, DOI: 10.1016/j.wasman.2006.03.006

Burnley, S.J. (2007). A review of municipal solid waste composition in the United Kingdom. *Waste Manag.*, 27, pp. 1274–1285, DOI: 10.1016/j.wasman.2006.06.018

Butrymowicz T. (2018). Badania odpadów w Jarocinie. Centralne Laboratorium Instytutu Inżynierii Środowiska, Uniwersytet Zielonogórski., unpublished. (in Polish)

Cangialosi, F., Intini, G., Liberti, L., Notarnicola, M. & Stellacci, P. (2008). Health risk assessment of air emissions from a municipal solid waste incineration plant – A case study. *Waste Manag.*, 28, pp. 885–895, DOI: 10.1016/j.wasman.2007.05.006

Capelli, L. & Sironi, S. (2018). Combination of field inspection and dispersion modelling to estimate odour emissions from an Italian landfill. *Atmos. Environ.*, 191, pp. 273–290, DOI: 10.1016/j.atmosenv.2018.08.007

Capelli, L., Sironi, S. & del Rosso, R. (2013a). Odor sampling: Techniques and strategies for the estimation of odor emission rates from different source types. *Sensors*, 13, pp. 938–955, DOI: 10.3390/s130100938

Capelli, L., Sironi, S., Del Rosso, R. & Guillot, J.M. (2013b). Measuring odours in the environment vs. dispersion modelling: A review. *Atmos. Environ.*, 79, pp. 731–743, DOI: 10.1016/j.atmosenv.2013.07.029

Chang, H., Tan, H., Zhao, Y., Wang, Y., Wang, X., Li, Y., Lu, W. & Wang, H. (2019). Statistical correlations on the emissions of volatile odorous compounds from the transfer stage of municipal solid waste. *Waste Manag.*, 87, pp. 701–708, DOI: 10.1016/j.wasman.2019.03.014

Chen, Y.C. (2018). Effects of urbanization on municipal solid waste composition. *Waste Manag.*, 79, pp. 828–836, DOI: 10.1016/j.wasman.2018.04.017

Cheng, Z., Zhu, S., Chen, X., Wang, L., Lou, Z. & Feng, L. (2020). Variations and environmental impacts of odor emissions along the waste stream. *J. Hazard. Mater.*, 384, 120912, DOI: 10.1016/j.jhazmat.2019.120912

Cheng, Z., Sun, Z., Zhu, S., Lou, Z., Zhu, N. & Feng, L. (2019). The identification and health risk assessment of odor emissions from waste landfilling and composting. *Sci. Total Environ.*, 649, pp. 1038–1044, DOI: 10.1016/j.scitotenv.2018.08.230

Colón, J., Alvarez, C., Vinot, M., Lafuente, F.J., Ponsá, S., Sánchez, A. & Gabriel, D. (2017). Characterization of odorous compounds and odor load in indoor air of modern complex MBT facilities. *Chem. Eng. J.*, 313, pp. 1311–1319, DOI: 10.1016/j.cej.2016.11.026

Conti, C., Guarino, M. & Bacenetti, J. (2020). Measurements techniques and models to assess odor annoyance: A review. *Environ. Int.*, 134, 105261, DOI: 10.1016/j.envint.2019.105261

Curren, J., Hallis, S.A., Snyder, C. (Cher) L. & Suffet, I. (Mel) H. (2016). Identification and quantification of nuisance odors at a trash transfer station. *Waste Manag.*, 58, pp. 52–61, DOI: 10.1016/j.wasman.2016.09.021

Çetin Doğruparmak, Ş., Pekey, H. & Arslanbaş, D. (2018). Odor dispersion modeling with CALPUFF: Case study of a waste and residue treatment incineration and utilization plant in Kocaeli, Turkey. *Environ. Forensics*, 19, pp. 79–86, DOI: 10.1080/15275922.2017.1408160

Damgaard, A., Riber, C., Fruergaard, T., Hulgaard, T. & Christensen, T.H. (2010) Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. *Waste Manag.*, 30, pp. 1244–1250, DOI: 10.1016/j.wasman.2010.03.025

Defoer, N., De Bo, I., Van Langenhove, H., Dewulf, J. & Van Elst, T. (2002) Gas chromatography-mass spectrometry as a tool for estimating odour concentrations of biofilter effluents at aerobic composting and rendering plants. *J. Chromatogr. A*, 970, pp. 259–273, DOI: 10.1016/S0021-9673(02)00654-4

Di Foggia, G., Beccarello, M. (2021) Market structure of urban waste treatment and disposal: Empirical evidence from the italian industry. *Sustain.*, 13, DOI: 10.3390/su13137412

Di, Y., Liu, J., Liu, J., Liu, S. & Yan, L. (2013). Characteristic analysis for odor gas emitted from food waste anaerobic fermentation in the pretreatment workshop. *J. Air Waste Manag. Assoc.*, 63, pp. 1173–1181, DOI: 10.1080/10962247.2013.807318

Directive 2008/98/EC of The European Parliment and of The Council of 19 November 2008 on waste and repealing certain Directives.

Duan, Z., Scheutz, C. & Kjeldsen, P. (2021). Trace gas emissions from municipal solid waste landfills: A review. *Waste Manag.*, 119, pp. 39–62, DOI: 10.1016/j.wasman.2020.09.015

European Comission Eurostat Available online: https://ec.europa.eu/eurostat/web/main/data/database.

European Union Council Directive 1999/31/EC on the landfill, 1999.

European Union Directive 2018/851 amending Directive 2008/98/EC on waste.

Fang, J.J., Yang, N., Cen, D.Y., Shao, L.M. & He, P.J. (2012). Odor compounds from different sources of landfill: Characterization and source identification. *Waste Manag.*, 32, pp. 1401–1410, DOI: 10.1016/j.wasman.2012.02.013

Fang, J., Zhang, H., Yang, N., Shao, L. & He, P. (2013). Gaseous pollutants emitted from a mechanical biological treatment plant for municipal solid waste: Odor assessment and photochemical reactivity. *J. Air Waste Manag. Assoc.*, 63, pp. 1287–1297, DOI: 10.1080/10962247.2013.822439

Fei, F., Wen, Z., Huang, S. & De Clercq, D. (2018). Mechanical biological treatment of municipal solid waste: Energy efficiency, environmental impact and economic feasibility analysis. *J. Clean. Prod.*, 178, pp. 731–739, DOI: 10.1016/j.jclepro.2018.01.060

Forastiere, F., Badaloni, C., De Hoogh, K., Von Kraus, M.K., Martuzzi, M., Mitis, F., Palkovicova, L., Porta, D., Preiss, P. & Ranzi, A. (2011). Health impact assessment of waste management facilities in three European countries. *Environ. Heal. A Glob. Access Sci. Source*, 10, pp. 1–13, DOI: 10.1186/1476-069X-10-53

Giusti, L. (2009). A review of waste management practices and their impact on human health. *Waste Manag.*, 29, pp. 2227–2239, DOI: 10.1016/j.wasman.2009.03.028

Guo, H., Duan, Z., Zhao, Y., Liu, Y., Mustafa, M.F., Lu, W. & Wang, H. (2017). Characteristics of volatile compound emission and odor pollution from municipal solid waste treating/disposal facilities of a city in Eastern China. *Environ. Sci. Pollut. Res*., 24, pp. 18383–18391, DOI: 10.1007/s11356-017-9376-8

He, P., Du, W., Xu, X., Zhang, H., Shao, L. & Lü, F. (2020). Effect of biochemical composition on odor emission potential of biowaste during aerobic biodegradation. *Sci. Total Environ.*, 727, 138285, DOI: 10.1016/j.scitotenv.2020.138285

Heyer, K.U., Hupe, K. & Stegmann, R. (2013). Methane emissions from MBT landfills. *Waste Manag*., 33, pp. 1853–1860, DOI: 10.1016/j.wasman.2013.05.012

Hou, J.Q., Li, M.X., Wei, Z.M., Xi, B.D., Jia, X., Zhu, C.W. & Liu, D.M. (2013). Critical components of odors and VOCs in mechanical biological treatment process of MSW. *Adv. Mater. Res.*, 647, pp. 438–449, DOI: 10.4028/www.scientific.net/AMR.647.438

Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A. & Malamakis, A. (2010). Waste biomass-to-energy supply chain management: A critical synthesis. *Waste Manag.*, 30, pp. 1860–1870, DOI: 10.1016/j.wasman.2010.02.030

Internet source, website accessed on 15.07.2021, available online https://www.portalsamorzadowy.pl/gospodarka-komunalna/spalarnie-w-polsce-gdzie-dzialaja-kto-buduje-a-kto-ma-je-w-planie,253488.html.

Jędrczak, A., den Boer, E., Kamińska-Boerak, J., Kozłowska B., Szpadt, R., Mierzwiński A., Krzyśków, A. & Kundegórski, M. (2020). Analysis of waste management costs – assessment of investment needs in the country in the field of waste prevention and waste management in connection with the new EU financial perspective 2021–2027, IOŚ-PIB, NFOŚiGW, Warszawa (in Polish) (unpublished report). Available online: https://odpady.net.pl/wp-content/uploads/2021

Jędrczak, A., den Boer, E., Kamińska-Borak, J., Szpadt, R., Krzyśków, A. & Wielgosiński, G. (2021). Analysis of the possibilities and barriers to the management of plastic waste from separate collection of municipal waste, and the issues of circular economy, IOŚ-PIB, NFOŚiGW, Warszawa (in Polish) (unpublished report). Available online: https://ios.edu.pl/aktualnosci/analiza-mozliwosci-i-barier-zagospodarowania-odpadow-z-tworzyw-sztucznych-a-goz/

Jiang, J., Wang, F., Wang, J. & Li, J. (2021). Ammonia and hydrogen sulphide odour emissions from different areas of a landfill in Hangzhou, China. *Waste Manag. Res.*, 39, pp. 360–367, DOI: 10.1177/0734242X20960225

Jońca, J., Pawnuk, M., Arsen, A. & Sówka, I. (2022) Electronic Noses and Their Applications for Sensory and Analytical Measurements in the Waste Management Plants – A Review. Sensors, 22, 1510. https://DOI:10.3390/s22041510

Ko, J.H., Xu, Q. & Jang, Y.C. (2015). Emissions and Control of Hydrogen Sulfide at Landfills: A Review. *Crit. Rev. Environ. Sci. Technol.*, 45, pp. 2043–2083, DOI: 10.1080/10643389.2015.1010427

Kulig, A. & Szylak-Szydlowski, M. (2016). Assessment of range of olfactory impact of plant to mechanical-biological treatment of municipal waste. *Chem. Eng. Trans.*, 54, pp. 247–252, DOI: 10.3303/CET1654042

Le Bihan, Y., Loranger-King, D., Turgeon, N., Pouliot, N., Moreau, N., Deschênes, D. & Rivard, G. (2020). Use of alternative cover materials to control surface emissions (H2s and vocs) at an engineered landfill. *Detritus*, 10, pp. 118–126, DOI: 10.31025/2611-4135/2020.13909

Liu, Y., Lu, W., Wang, H., Gao, X. & Huang, Q. (2019). Improved impact assessment of odorous compounds from landfills using Monte Carlo simulation. *Sci. Total Environ.*, 648, pp. 805–810, DOI: 10.1016/j.scitotenv.2018.08.213

Liu, Y., Yang, H. & Lu, W. (2020). VOCs released from municipal solid waste at the initial decomposition stage: Emission characteristics and an odor impact assessment. *J. Environ. Sci. (China)*, 98, pp. 143–150, DOI: 10.1016/j.jes.2020.05.009

Long, Y., Zhang, S., Fang, Y., Du, Y., Liu, W., Fang, C. & Shen, D. (2017). Dimethyl sulfide emission behavior from landfill site with air and water control. *Biodegradation*, 28, pp. 327–335, DOI: 10.1007/s10532-017-9799-4

Lou, Z., Wang, M., Zhao, Y. & Huang, R. (2015). The contribution of biowaste disposal to odor emission from landfills. *J. Air Waste Manag. Assoc*., 65, pp. 479–484, DOI: 10.1080/10962247.2014.1002870

Lucernoni, F., Tapparo, F., Capelli, L. & Sironi, S. (2016). Evaluation of an Odour Emission Factor (OEF) to estimate odour emissions from landfill surfaces. *Atmos. Environ.*, 144, pp. 87–99, DOI: 10.1016/j.atmosenv.2016.08.064

Maurer, D.L., Bragdon, A.M., Short, B.C., Ahn, H. & Koziel, J.A. (2018). Improving environmental odor measurements: Comparison of lab-based standard method and portable odor measurement technology. *Arch. Environ. Prot.*, 44, pp. 100–107, DOI: 10.24425/119699

Meišutovič-Akhtarieva, M. & Marčiulaitienė, E. (2017). Research on odours emitted from non-hazardous waste landfill using dynamic olfactometry. *10th Int. Conf. Environ. Eng. ICEE 2017*, pp. 27–28, DOI: 10.3846/enviro.2017.034

Monzambe, G.M., Mpofu, K. & Daniyan, I.A. (2021). Optimal location of landfills and transfer stations for municipal solid waste in developing countries using non-linear programming. *Sustain. Futur.*, 3, 100046, DOI: 10.1016/j.sftr.2021.100046

Mustafa, M.F., Liu, Y., Duan, Z., Guo, H., Xu, S., Wang, H. & Lu, W. (2017). Volatile compounds emission and health risk assessment during composting of organic fraction of municipal solid waste. *J. Hazard. Mater.*, 327, pp. 35–43, DOI: 10.1016/j.jhazmat.2016.11.046

Naddeo, V., Zarra, T., Oliva, G., Chiavola, A., Vivarelli, A. & Cardona, G. (2018). Odour impact assessment of a large municipal solid waste landfill under different working phases. *Glob. Nest J.*, 20, pp. 654–658, DOI: 10.30955/gnj.002770

Oleniacz, R. (2014). Impact of the municipal solid waste incineration plant in Warsaw on air quality. *Geomatics Environ. Eng.*, 8, 25, DOI: 10.7494/geom.2014.8.4.25

Palmiotto, M., Fattore, E., Paiano, V., Celeste, G., Colombo, A. & Davoli, E. (2014). Influence of a municipal solid waste landfill in the surrounding environment: Toxicological risk and odor nuisance effects. *Environ. Int.*, 68, pp. 16–24, DOI: 10.1016/j.envint.2014.03.004

Pawnuk, M., Grzelka, A., Miller, U. & Sówka, I. (2020). Prevention and reduction of odour nuisance in waste management in the context of the current legal and technological solutions. *J. Ecol. Eng.*, 21, pp. 34–41, DOI: 10.12911/22998993/125455

Polish Committee for Standardization. Polish Standard PN-EN 13725:2007: Air Quality – Determination of Odour Concentration by Dynamic Olfactometry, Polish Committee for Standardization: Warsaw, Poland, 2007.

Ragazzi, M., Tosi, P., Rada, E.C., Torretta, V. & Schiavon, M. (2014). Effluents from MBT plants: Plasma techniques for the treatment of VOCs. *Waste Manag.*, 34, pp. 2400–2406, DOI: 10.1016/j.wasman.2014.07.026

Sánchez-Monedero, M.A., Fernández-Hernández, A., Higashikawa, F.S. & Cayuela, M.L. (2018). Relationships between emitted volatile organic compounds and their concentration in the pile during municipal solid waste composting. *Waste Manag.*, 79, pp. 179–187, DOI: 10.1016/j.wasman.2018.07.041

Scaglia, B., Orzi, V., Artola, A., Font, X., Davoli, E., Sanchez, A. & Adani, F. (2011). Odours and volatile organic compounds emitted from municipal solid waste at different stage of decomposition and relationship with biological stability. *Bioresour. Technol.*, 102, pp. 4638–4645, DOI: 10.1016/j.biortech.2011.01.016

Schiavon, M., Martini, L.M., Corrà, C., Scapinello, M., Coller, G., Tosi, P. & Ragazzi, M. (2017). Characterisation of volatile organic compounds (VOCs) released by the composting of different waste matrices. *Environ. Pollut.*, 231, pp. 845–853, DOI: 10.1016/j.envpol.2017.08.096

Schlegelmilch, M., Streese, J. & Stegmann, R. (2005). Odour management and treatment technologies: An overview. *Waste Manag.*, 25, pp. 928–939, DOI: 10.1016/j.wasman.2005.07.006

Shi, X., Zheng, G., Shao, Z. & Gao, D. (2020). Effect of source--classified and mixed collection from residential household waste bins on the emission characteristics of volatile organic compounds. *Sci. Total Environ.*, 707, 135478, DOI: 10.1016/j.scitotenv.2019.135478

Sironi, S., Capelli, L., Céntola, P. & Del Rosso, R. (2007). Odour emissions from MSW composting process steps. *Int. J. Environ. Technol. Manag.*, 7, pp. 304–316, DOI: 10.1504/IJETM.2007.015148

Sironi, S., Capelli, L., Céntola, P., Del Rosso, R. & Il Grande, M. (2006). Odour emission factors for the prediction of odour emissions from plants for the mechanical and biological treatment of MSW. *Atmos. Environ.*, 40, pp. 7632–7643, DOI: 10.1016/j.atmosenv.2006.06.052

Sonibare, O.O., Adeniran, J.A. & Bello, I.S. (2019). Landfill air and odour emissions from an integrated waste management facility. *J. Environ. Heal. Sci. Eng.*, 17, pp. 13–28, DOI: 10.1007/s40201-018-00322-1

Statistic Poland Environment 2020. Stat. Anal. 2020, pp. 154–161.

Statistic Poland Local Data Bank (2021) Available online: https://bdl.stat.gov.pl/BDL/dane/podgrup/temat.

Szulczyński, B., Wasilewski, T., Wojnowski, W., Majchrzak, T., Dymerski, T., Namieśnik, J. & Gębicki, J. (2017). Different ways to apply a measurement instrument of E-nose type to evaluate ambient air quality with respect to odour nuisance in a vicinity of municipal processing plants. *Sensors (Switzerland)*, 17, DOI: 10.3390/s17112671

Tan, H., Zhao, Y., Ling, Y., Wang, Y. & Wang, X. (2017). Emission characteristics and variation of volatile odorous compounds in the initial decomposition stage of municipal solid waste. *Waste Manag.*, 68, pp. 677–687, DOI: 10.1016/j.wasman.2017.07.015

Tagliaferri, F., Invernizzi, M., Sironi, S. & Capelli, L. (2020). Influence of modelling choices on the results of landfill odour dispersion. *Detritus*, 12, pp. 92–99, DOI: 10.31025/2611-4135/2020.13998

The Act of 14 December 2012 on waste (Journal of Laws of 2020, item 797). (in Polish)

Tyrała K. (2019. Conducting research on the quantity and morphological composition of municipal waste in Bydgoszcz. Final report. Collective analysis of the entire study, R.O.T. RECYCLING ODPADY TECHNOLOGIE S.C. K, Gliwice. (in Polish)

VDI 3882 PART 1 Olfactometry, determination of odour intensity, Verein Deutscher Ingenieure, Germany, 1992.

VDI 3880: Olfactometry. Static Sampling, Verein Deutscher Ingenieure, Germany, 2011.

Wang, Y., Li, L., Qiu, Z., Yang, K., Han, Y., Chai, F., Li, P. & Wang, Y. (2021). Trace volatile compounds in the air of domestic waste landfill site: Identification, olfactory effect and cancer risk. *Chemosphere*, 272, 129582, DOI: 10.1016/j.chemosphere.2021.129582

Wiśniewska, M. (2020a). Analysis of Potential Exposure to Components of Municipal Solid Waste in a Mechanical Biological Treatment. *Proceedings*, 51, 10, DOI: 10.3390/proceedings2020051010

Wiśniewska, M. (2020b) Methods of assessing odour emissions from biogas plants processing municipal waste. *J. Ecol. Eng.*, 21, pp. 140–147, DOI: 10.12911/22998993/113039

Wiśniewska, M., Kulig, A. & Lelicińska-Serafin, K. (2021). The use of chemical sensors to monitor odour emissions at municipal waste biogas plants. *Appl. Sci.*, 11, DOI: 10.3390/app11093916

Wiśniewska, M., Kulig, A. & Lelicińska-Serafin, K. (2020a). Odour emissions of municipal waste biogas plants-impact of technological factors, air temperature and humidity. *Appl. Sci.*, 10, DOI: 10.3390/app10031093

Wiśniewska, M., Kulig, A. & Lelicińska-Serafin, K. (2020b). Olfactometric testing as a method for assessing odour nuisance of biogas plants processing municipal waste. *Arch. Environ. Prot.*, 46, pp. 60–68, DOI: 10.24425/aep.2020.134536

Wiśniewska, M., Kulig, A. & Lelicińska-Serafin, K. (2019). Comparative analysis of preliminary identification and characteristic of odour sources in biogas plants processing municipal waste in Poland. *SN Appl. Sci.*, 1, pp. 1–10, DOI: 10.1007/s42452-019-0534-0

Wiśniewska, M. & Szyłak-Szydłowski, M. (2021). The air and sewage pollutants from biological waste treatment. *Processes*, 9, pp. 1–13, DOI: 10.3390/pr9020250

Wu, C., Shu, M., Liu, X., Sang, Y., Cai, H., Qu, C. & Liu, J. (2020). Characterization of the volatile compounds emitted from municipal solid waste and identification of the key volatile pollutants. *Waste Manag.*, 103, pp. 314–322, DOI: 10.1016/j.wasman.2019.12.043

Xu, A., Chang, H., Zhao, Y., Tan, H., Wang, Y., Zhang, Y., Lu, W. & Wang, H. (2020). Dispersion simulation of odorous compounds from waste collection vehicles: Mobile point source simulation with ModOdor. *Sci. Total Environ.*, 711, 135109, DOI: 10.1016/j.scitotenv.2019.135109

Yao, X.Z., Ma, R.C., Li, H.J., Wang, C., Zhang, C., Yin, S.S., Wu, D., He, X.Y., Wang, J. & Zhan, L.T. (2019). Assessment of the major odor contributors and health risks of volatile compounds in three disposal technologies for municipal solid waste. *Waste Manag.*, 91, pp. 128–138, DOI: 10.1016/j.wasman.2019.05.009

Zemanek, J., Wozniak, A. & Malinowski, M. (2011). The role and place of solid waste transfer station in the waste management system. *Polish Acad. Sci. Cracow Branch 2011*, 11, pp. 5–13.

Zhang, Y., Ning, X., Li, Y., Wang, J., Cui, H., Meng, J., Teng, C., Wang, G. & Shang, X. (2021). Impact assessment of odor nuisance, health risk and variation originating from the landfill surface. *Waste Manag.*, 126, pp. 771–780, DOI: 10.1016/j.wasman.2021.03.055

Zhang, H., Schuchardt, F., Li, G., Yang, J. & Yang, Q. (2013). Emission of volatile sulfur compounds during composting of municipal solid waste (MSW). *Waste Manag.*, 33, pp. 957–963, DOI: 10.1016/j.wasman.2012.11.008

Zhao, Y., Lu, W. & Wang, H. (2015). Volatile trace compounds released from municipal solid waste at the transfer stage: Evaluation of environmental impacts and odour pollution. *J. Hazard. Mater.*, 300, pp. 695–701, DOI: 10.1016/j.jhazmat.2015.07.081

Zielnica J. & Cudakiewicz P. (2016). Morphological studies of municipal waste generated in the Szczecin City Commune 2015–2016, SWECO. (in Polish)