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Characteristics of odors emitted from municipal wastewater treatment plant and methods for their identification and deodorization techniques

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a b s t r a c t

Odors emitted from municipal wastewater treatment plants belong to a group of pollutants, which is the main cause of people complaining about atmospheric air quality. The limitation of emissions of un-pleasant odors generated by wastewater treatment plants by using appropriate deodorization methods is omitted on numerous occasions. This can have a negative influence on public trust and the quality of atmospheric air. The article presents basic information on the characteristics of odors from wastewater treatment lines and wastewater processing and management lines in a model biological wastewater treatment plant conducting the biogas recovery process and also information is provided on deodor-ization methods, such as odor masking, biofiltration, thermal disposal and diffusion through activated sludge dedicated to neutralization of odors in biological treatment plants. The main focus is on the field olfactometry technique, which is one of the tools used in environmental protection. Its application fa-cilitates performance of tests concerning the assessment of olfactory properties of odorants in polluted air.

Keywords: Dynamic olfactometry, Odors, Odor nuisance Sewage, sludge analysis

Contents

1. Introduction

Municipal waste landfills, wastewater treatment plants and other plants where air pollution is generated used to be built on

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the outskirts of cities. At present, due to progressing urbanization, the distance between residential areas and such plants has decreased. Odors and other air pollutants are a growing problem, which is not only ecological one, but also a social one (Fang et al., 2012; Aatamila et al., 2011). The municipal wastewater treatment process, which allows reduction of odor emissions, is often omitted and the unpleasant smell of atmospheric air and the smell of treated water may have a negative impact on the community's life (Agus et al., 2012). Over the past decade, an increase in the number of residents' complaints on the occurrence of onerous odors in atmospheric air in areas adjacent to large industrial and municipal plants. As a result, the interest in the environmental impact of wastewater treatment plants has been growing and EU Member States are spending more and more money on limiting odor emissions and deodorization (Kim et al., 2014).

For technological reasons, wastewater treatment plants always occupy a large surface area, ranging from several to more than a dozen hectares and, as a result, are often considered responsible for odor emissions. On many occasions, large plants are regarded as responsible for emissions of unpleasant odors despite the fact that the largest quantities of odors are not emitted by the plants. Even the surface area occupied by small treatment plants with the throughput of up to 550 m^3 a day is relatively high; however, the range of odor impact does not usually exceed 200 m (Bruszkiewski and Skorupski, 1999). However, it is important to have on mind topographic and meteorological conditions. On the basis of analyzing the results of the research conducted so far, it can be concluded that concentrations of volatile organic compounds in the area of the treatment plant occur at relatively low levels as compared to the level of these pollutants in areas, where wastewater is discharged from sanitation tanks, composting plants or municipal landfills. Odors emitted from such installations stimulate human olfactory receptors, cause unpleasant olfactory sensations and can have a significant impact on the quality of the environment (Fang et al., 2012; Bruszkiewski and Skorupski, 1999).

The article specifies characteristic groups of odorants emitted into the air at individual stages of the wastewater treatment process and excess sludge management. The assessment of odor emissions was conducted for the model wastewater treatment plant where mechanical, biological and chemical wastewater treatment is assumed together with biogas recovery from excess sludge and burning of post-fermentation residues. In the article, air pollutant emissions are assessed from individual technological systems, which can be found at a wastewater treatment plant, and technological treatments are described, which can reduce odor emissions. Also, deodorization methods were also described, which can be used at wastewater treatment plants, and the field olfactometry technique, which is presented as a tool enabling specification of odor intensity, which, indirectly, makes it possible to control emissions of odorous substances. Its application allows verification of complaints from residents related to the impact of onerous odors occurring near municipal wastewater treatment plants. It can constitute a tool allowing the monitoring of the environment condition to maintain its appropriate quality.

2. Characteristics of odor emissions for municipal wastewater treatment plant areas

A wastewater treatment plant is a complex network of interconnected technological systems with different process conditions at every stage of the treatment. Wastewater, which reaches each treatment plant, may differ considerably in terms of their physical and chemical properties, which defines an appropriate technology. As a result, various groups of air pollutants can be generated at each stage wastewater treatment and sludge management. All kinds of processing media, runoff water and stormwater as well as precipitation reaching treatment plants, together with wastewater, may cause the formation of precursors of odoriferous compounds. Alcohols, volatile fatty acids, aldehydes and ketones are carbohydrate decomposition products. Ammonia is produced as a result of fat and protein distribution. Hydrogen sulfide is generated during anaerobic decomposition of sulfur-containing proteins. Decay processes of vegetables may cause emissions of carbon disulfide and mercaptans into the atmosphere. Decay processes of fish, veal, poultry waste and hot spices can contribute to emissions of ethylamine, trimethylamine and indoleamines (Fang et al., 2012). Wastewater can be a mixture of all of the aforementioned kinds of waste. A high contribution of industrial waste, e.g. from the oil industry, the tanning industry or the cosmetic industry and food waste may result in the presence of a broad range of odorants and precursors of their formation (El-Shafai et al., 2004; Annadurai et al., 2003). As a result, the identification and quantitative determination of chemical compounds, which cause unpleasant sensations, often prove to be very complex, especially if the composition of the odorous mixture is conditioned by the presence of various groups of odorous compounds (Hort et al., 2009; Agus et al., 2012). Table 1 presents basic information about the characteristics of selected odorous compounds emitted from municipal wastewater treatment plants.

It should be noticed that volatile compounds are not the only group of odorants and pollutants released into the air by municipal wastewater treatment plants. Hydrogen sulfide and ammonia belong to the group of three basic pollutants occurring in the air above the area, where wastewater treatment plants are located, which are released in the largest amounts (Agus et al., 2012). On the premises of wastewater treatment plants that occupy a small area, the concentrations of hydrogen sulfide and methane are usually below the limit of detectability of average measuring systems used for determining concentrations of these chemical compounds (16.7 $\mu g/m^3$ of air). Ammonia, on the other hand, usually occurs at higher concentrations (from 0.39 mg/m^3 to 0.56 mg/m^3), especially in the area of facilities used for mechanical and biological treatment of wastewater (Fang et al., 2012). The values of pollutant concentrations in the air in the areas surrounding small wastewater treatment plants do not constitute a hazard to the environment or human health and, therefore, their treatment is often regarded as economically unjustified (Bruszkiewski and Skorupski, 1999). The problem is more serious in areas with entities with a much larger and usable surface area, where hundreds of thousands cubic meters of wastewater are treated every day and thousands of cubic meters of primary and excess sludge are processed further.

Two basic process lines can be distinguished on the premises of municipal wastewater treatment plants with a large surface area:

- wastewater treatment line called the wastewater line,
- sludge processing and management line called

the sludge line.

Zones can be separated within each of them, in which a specific group of air pollutants is emitted. Depending on the wastewater treatment or processing technology use, other types of odoriferous compounds are emitted. The majority of odors emitted at a treatment plant, regardless of the emission zone, are generated during anaerobic processes. This emission is related to a low oxygen content in the treated wastewater, processed sludge and with the conditions, under which a technological process is conducted (aerobic or anaerobic) (Shao et al., 2014). Reduced sulfur compounds are mostly odors edited during processes of anaerobic treatment and during wastewater and sludge processing (Liu et al., 2012). The majority of odorants emitted as a result of solid

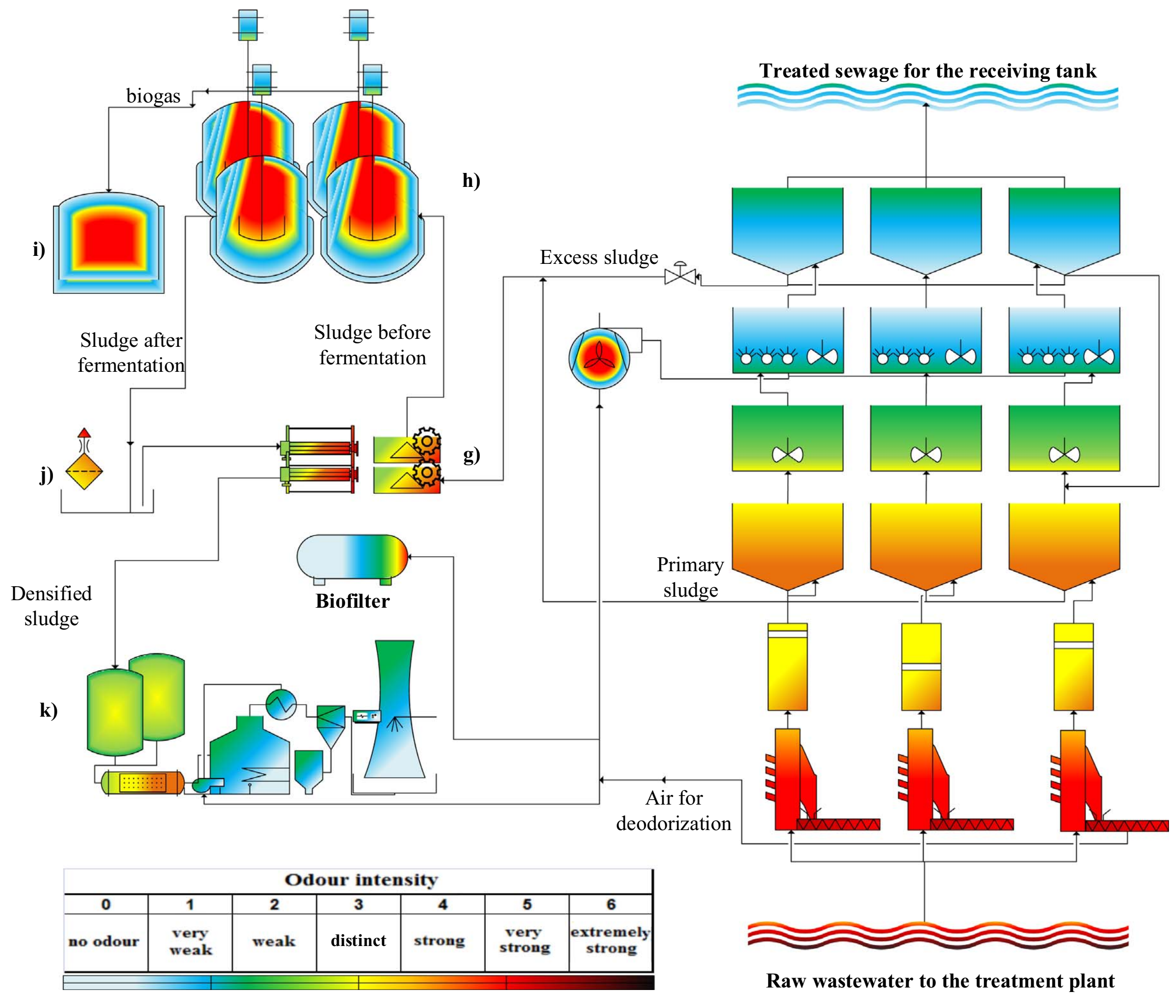


Fig. 1. A diagram of process installations in the model wastewater treatment plant and characteristics of odor emissions at every municipal wastewater treatment stage; a) grills, b) sludge separator, c) initial settling tanks, d) anaerobic biological reactors, e) aerated biological reactors, f) secondary settling tanks, g) sludge densification and dehydration station, h) closed fermentation chambers, i) biogas tank, j) sludge degasification station, k) thermal sludge and screenings processing station (Doshi et al., 2005) (EN 13725, 2003).

biowaste processing and which are processed on the sludge line to form organic sulfur compounds, such as diethyl sulfides, dimethyl sulfides and methanethiol (Agus et al., 2012). In the case of treated wastewater, which contains methyl mercaptan, or dimethyl sulphoxide, which belongs to the group of onerous odorants, larger amounts of volatile sulfur compounds and hydrogen sulfide are emitted (Kim et al., 2014; Krach et al., 2008). These compounds are emitted during the process of biological treatment of wastewater mostly by means of decomposition of organic substances contained in wastewater. As an example *E. coli* bacteria can contribute to emissions of mentioned odorants and of many other odorants belonging to the group of volatile aromatic compounds (Chen et al., 2011; Lebrero et al., 2011).

Particles of all odorants listed above can spread over very large distances. The stream of contaminants is then diluted, thanks to which odorants may occur at a level of concentrations below their olfactory detectability thresholds. However, this does not solve the problem of air pollution as these compounds still may pose a threat to human health and to the environment. The modified version of the AERMOD model can be used to evaluate process of air pollutants dispersion. The results show that the probability of detection of H_2S exceed 50% at 400 m distance from the main emission sources, especially during the summer. Hydrogen sulfide is one of the main chemical compounds that cause odor nuisance (Latos et al., 2011).

Masking odors with deodorizing substances, despite of an increase in the public satisfaction level, does not solve the problem of environmental pollution, either. A more ecological approach is limitation of emissions, adsorption of emitted air pollutants or their transformation into non-odorous derivatives, compounds which are safe for the environment and human health (Zhang et al., 2013). For this purpose, it is possible to undertake attempts involving the reduction of bioavailability of promoters of bacterial production of individual odorants by bonding them, e.g. with metals contained in various additives which may improve wastewater treatment processes or sludge management. In some cases, it is necessary to use biological gas treatment methods, namely biofiltration or diffusion by activated sludge. The application of methods mentioned above may result in increased efficiency of the entire process and reduction of running costs (Lebrero et al., 2011; Agus et al., 2012). The efficiency of the gas treatment process and reduction of a given group of air pollutants is conditioned by the selection of an appropriate biological gas treatment method. For this reason, to design an appropriate system of biofilters and/or biological deposits, it is important to determine and characterize emitted air pollutants, the type of which depends on the functioning of the wastewater treatment plant or a technological line within a given entity. Thermal neutralization is an alternative to biological treatment method. This method is used, in particular, for treatment plants conducting thermal processing of sludge and

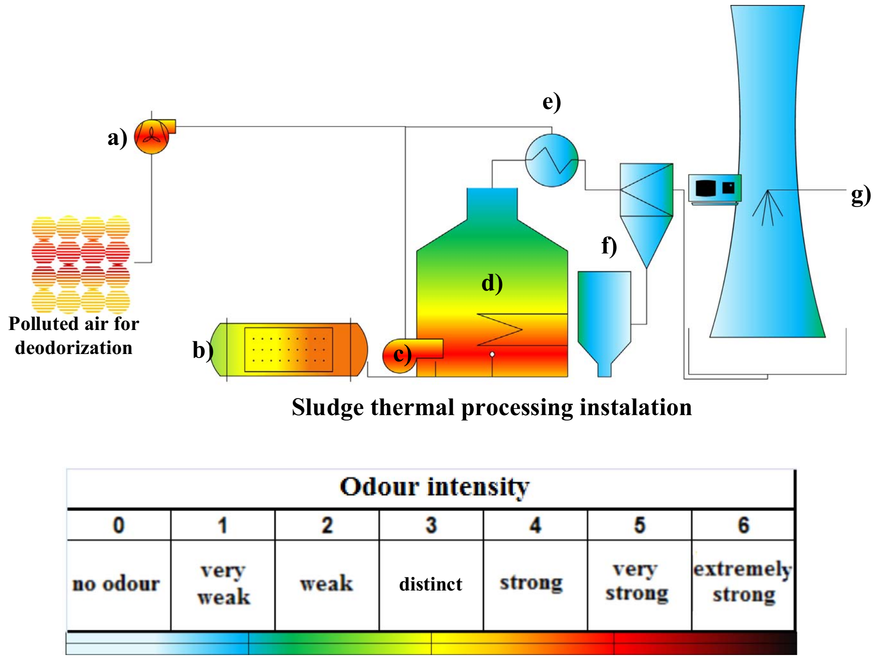


Fig. 2. Diagram of thermal neutralization of odors in installations for thermal processing of sludge and screenings; a) a pump bringing the air for deodorization to the exchanger or blower b) a sludge drying system, c) a blower providing oxygen to the furnace, d) a furnace, e) a heat recovery system, f) a dedusting system, g) exhaust (Zhang et al., 2013; Lotito and Lotito, 2014; Cieślik et al., 2015) (EN 13725, 2003).

screenings. Each of processes of treatment of gases emitted from individual technological wastewater treatment facilities should, however, be designed separately, taking into account the wastewater treatment technology and characteristics of emitted odors (Hort et al., 2009). Individual facilities and process line in the model wastewater treatment plant, together with estimated odor emissions within a given installation, are presented in Fig. 1.

3. Municipal wastewater treatment line

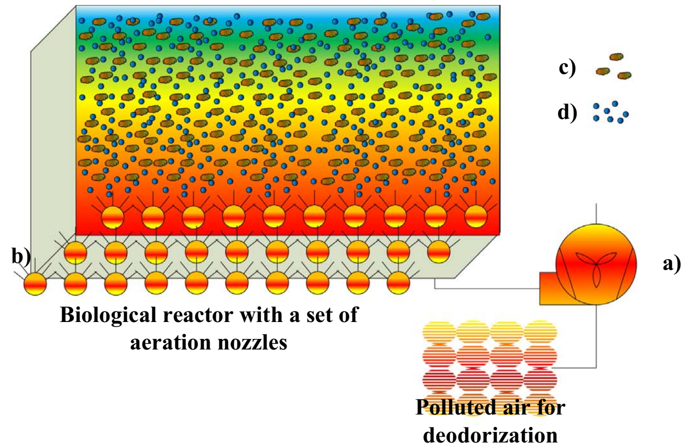
The municipal wastewater treatment line in the model waste treatment plant consists of two basic units:

- mechanical treatment,
- biological treatment.

Each unit consists of smaller components, in which unit processes take place, which are aimed at cleaning wastewater from various fractions and types of impurities. This variety results in emissions of other groups of pollutants into air, including odors. The wastewater treatment technology used may limit the application of certain methods of emission reduction or gas treatment. It should be taken into consideration that the application of physical methods of odor emissions usually does not solve the problem completely (Zhang et al., 2013). As a result, a justified approach in this matter is the application of biological methods, which allow for neutralization of emitted odors and prevent the introduction of an additional stream of pollutants characterized by an unpleasant odorous sensation into the air (Lebrero et al., 2011).

3.1. *Mechanical waste treatment*

The mechanical treatment unit is situated before the biological treatment unit mostly for technological reasons. Solid waste contained in the wastewater and fine mineral fractions, such as sand, should be retained on sieves, grills and in sand separators so as to prevent damage to treatment plant fittings at further sections of the process line. Grills, separators and other devices for removing waste carried by wastewater are thus the first stage of wastewater treatment. In some cases such pretreatment operations as fat removal may cause particularly strong odor emission. It is especially observed when wastewater arrives at the plant under pressure. Wastewater, which reaches these facility, usually contains large amounts of odorants and malodorous compound precursors, such as alcohols, aldehydes, ketones, organic waste, sulfur compounds (mercaptanothiols, sulfides, ethanethiol, dimethyl sulfide), preliminary ammonification which takes place already in the sewage system (mostly ammonia) and many other potentially harmful pollutants emitted into the air (Kim et al., 2014; Scaglia et al., 2011). Solid fractions removed from wastewater also contribute to emissions of a broad range of odorous compounds. Sand removed from sand separators usually contains approx. 5% of the organic fraction including polycyclic aromatic hydrocarbons and polychlorinated biphenyls. At this stage of the process, it is not possible to stop emissions of the aforementioned pollutants. As a result, it is necessary to use appropriate deodorization methods, e.g. thermal disposal, biofilters, chemical scrubbers, and diffusion of contaminated air through active sludge. To be able to conduct the air purification process properly, objects, such as grills or sand separators, should be placed in closed buildings or placed under polyethylene covers, which make it possible to collect and further neutralize odors (Zhang et al., 2013). Solid waste should be managed appropriately to avoid emissions of pollutants into the air, soil or water. They can be stabilized using various additives or incinerated. Incineration can take place at the waste treatment plant or at another facility adapted to incinerating such waste. Directing air contaminated with odors to treatment systems can often be a problem. Capture systems for closed screw conveyors, which are used to transport solid waste removed from wastewater and which are used to direct the air to biofilters, can often become blocked. In such situations, it is necessary to design belt conveyors in a way ensuring that the conveyor space is not filled fully and screenings and sand do not block the capture systems. Designing an efficient pumping system, which collects air from closed objects, in which mechanical treatment processes occur as described above.



Odour intensity						
0	1	2	3	4	5	6
no odour	very weak	weak	dictinct	strong	very strong	extremely strong

Fig. 3. Diagram of the process of odors purification using diffusion of polluted air through activated sludge in aerated biological reactors; a) pump supplying the air to aeration nozzles, b) system of aeration nozzles placed at the bottom of the biological reactor, c) activated sludge flock, d) purified air bubbles (Pathak et al., 2009) (EN 13725, 2003).

Initial settling tanks are usually placed behind grills and sand separators. Their tasks involves removing fractions floating on the surface of the wastewater stream (scum) and organic fractions, which settle easily. Due to the use of physical sedimentation processes and floatation in initial settling tanks, this installation is a part of the mechanical treatment block. Sedimenting organic sludge is moved to collection funnels and, together with the collected scum, it is transported to the waste processing and management line. From wastewater, which contains solid fractions, groups of odors are emitted with similar properties as in the case of wastewater deprived of solid fractions. At this stage of wastewater treatment, no processes of mechanical separation of solid fractions are conducted, which results in reduced odor emissions. As a result, unpleasant odorous compounds occur at lower concentrations. On the surface of the scum, on the other hand, which mostly contains of fats, increased quantities of volatile fatty acids are emitted (Kim et al., 2014).

3.2. *Biological wastewater treatment*

After removing solid fractions, wastewater reaches biological reactors, which are often called activated sludge chambers. Activated sludge, which is circulating in reactors, is a live suspension of microorganisms, mostly bacteria and protozoa. In the presence of microorganisms, numerous metabolic processes occur through oxygenation or reduction of organic compounds contained in the wastewater to organic or inorganic derivatives of these compounds. These processes are conducted under variable anaerobic and aerobic conditions, which results in reduced nutrients levels in the wastewater by integrating phosphorus compounds in the sludge structure. Due to very high biological variation of the activated sludge, various metabolic transformations occurring in the sludge can result in the formation of highly varied secondary mixtures of contaminants, which can be released from the wastewater in the form of polluted air (Hort et al., 2009). Naturally occurring fecal bacteria, such as the previously mentioned example *E. coli* bacteria can cause emissions of odors of the group of organosulfur compounds. Moreover, their development may also cause an increase in pathogenic bacteria, such as *Salmonella* and other types of bacteria causing higher odor emissions (e.g. secreting methionine-metabolizing enzymes, to malodorous methylthiol). Nevertheless one should remember, bacteria mentioned are only an example while thousands of bacteria species in activated sludge are capable of producing volatile odoriferous compounds (Chen et al., 2011).

Together with an increase in the feces content in the treated municipal wastewater, hydrogen sulfide emissions grow. The stream of wastewater, which reaches the treatment plant from small rural agglomerations, may contain up to 40% of fecal contaminants. Apart from the onerous odor, released hydrogen sulfide may cause corrosion of fittings in the entire treatment plant area (Bruszkiewski and Skorupski, 1999). Other groups of bacteria present in wastewater, such as *Pseudomonas* sp., are characterized by the reducing ability of odorant typical of treatment plants, such as ammonia or hydrogen sulfide. Keeping bacterial strains, which are able to neutralize certain groups of odoriferous compounds, makes it necessary to keep appropriate conditions in the activated sludge chambers to keep the desired population. Controlling and maintaining appropriate process conditions, such as pH, temperature and the degree of aeration, which promote both wastewater treatment and deodorization may prove to be costly, but it is often a very effective alternative, which makes it possible to solve the odor emission problem (Zhang et al., 2013). However biological phosphorus and nitrogen removal efficiency have to be maintained. According to results of research pertaining to the specification of relationships between hydrogen sulfide emissions from activated sludge chambers to the numerical values of the COD and BOD parameters, it can be concluded that wastewater aeration does not contribute to increased hydrogen sulfide emissions. At the same time, a high ammonia content in the wastewater is related to a higher degree of oxidation of volatile sulfur compounds by bacteria, and, in the same way, by lower emissions of odors derived from sulfur. In addition, the increase in the pH of the wastewater may result in hydrogen sulfide transformation to the HS^- anion form, which also reduces emissions of this odorant (Hort et al., 2009). Ammonia concentrations in the air stays at a high level in this situation. There is still not enough data concerning direct relationships between the degree of the odor

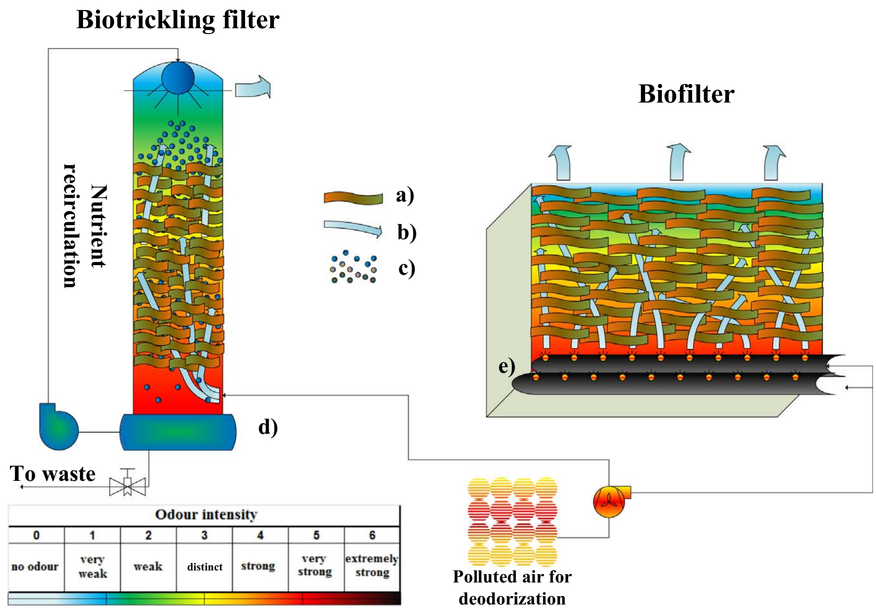


Fig. 4. Diagram of the process of odors purification using biofilters and biotrickling filter deodorization systems: a) organic or synthetic bed, b) treated air flow, c) nutrient droplets, d) nutrient solution tank, e) perforated pipes (Pathak et al., 2009; Chen et al., 2016; Talaiekhozani et al., 2016; Fulazzaky et al., 2016; Tsang et al., 2015a, 2015b; Wu et al., 2016) (EN 13725, 2003).

nuisance with concentrations of individual odorants and multi-ingredient odor mixtures. For this reason, it cannot be unambiguously concluded that adding ammonia to the biological treatment process is justified (Fang et al., 2012; Liu et al., 2014).

Various chemical compounds are added to activated sludge chambers to keep appropriate conditions and parameters of the treatment process. However, this can lead to odor emissions. Compounds supporting the wastewater treatment process include:

- flocculants,
- compounds used to phosphorus precipitation ($AlCl_3$, $FeCl_3$, CaO, polyacrylamides, ashes, etc.).

Adding such compounds usually results in increased pH of treated wastewater, which results in increased ammonia emissions. This change may, however, cause a reduction in hydrogen sulfide emissions. Some of the additives listed may lead to hydrogen sulfide neutralization by oxidation of S^{2-} ions during the reduction of Fe^{3+} or precipitation of sulfur together with phosphates by means of metals (also copper and zinc, apart from those listed above), which are added to the process (Liu et al., 2012).

If the degree of aeration of the treated wastewater is not sufficient, SO_4^{2-} ions contained in the wastewater can be used as electron acceptor. The process of sulfate-to-sulfide reduction can also lead to increased hydrogen sulfide emissions. With oxygen deficiency, apart from emissions of volatile sulfur compounds, organic odorants can be formed, such as alcohols, aldehydes, ketones and organic acids (Lebrero et al., 2013).

Under process conditions, especially at large treatment plants, where the wastewater flows through a single reactor, can reach up to several thousand square meters an hour, all contaminants contained in the wastewater will never be oxidized. Organic sulfur compounds which remain in the solution, such as dimethyl sulfide or diethyl sulfide, are released into the air during the aeration stage. An exception is the alternate oxidation process or discontinuation of oxygen supply immediately after the completion of the denitrification process. For municipal wastewater treatment plants which are characterized by large volumes of wastewater flow, the biological treatment process is usually conducted in the flow mode, which means that the time of keeping wastewater in biological reactors is calculated on the basis of the volumetric flow intensity and the wastewater itself is not kept in reactors. In this situation, it is important that the volumetric flow intensity should be controlled so as to ensure that wastewater reaches the secondary settling tanks immediately after the completion of the denitrification process, which allows maximum limitation of volatile sulfur emissions into the air (Kim et al., 2014).

After the completion of the biological treatment process, the treated wastewater, together with biological sludge, is transferred to secondary settling tanks, where the activated sludge is separated from the liquid phase. The majority of the activated sludge goes to the beginning of the biological treatment line in the form of recirculate and its excess is transported to the waste processing and management line. Treated wastewater after passing through activated sludge chambers, in which all organic contaminations were oxidized, usually do not contain malodorous compounds any more (Zhang et al., 2013). If large numbers of filamentous bacteria are present in the sludge, their suspension is carried to the surface of secondary settling tanks, collected in the form of scum and further processed on the sludge line. In secondary settling tanks, as opposed to initial settling tanks, emissions of organic odors are much lower, mostly due to the high degree of sludge oxygenation (Lebrero et al., 2013). In the treated wastewater, which leaves the treatment plant usually to natural receiving bodies and compounds, such as 2,4,6-trichloroanisole, geosmin, 2-methylisoborneol. The aforementioned chemical compounds may be a source of earthy or musty odor of water, which can sometimes be reminiscent of kerosene. The odor of kerosene generated near bodies of water, from which water intended for drinking is collected and processed, is usually socially acceptable (Agus et al., 2012).

4. Sludge processing and management lines

A sludge processing and management line can be a very complicated technological system, the task of which involves preparation of initial sludge, excess sludge and scum from settling tanks, which are appropriate for further management. This waste

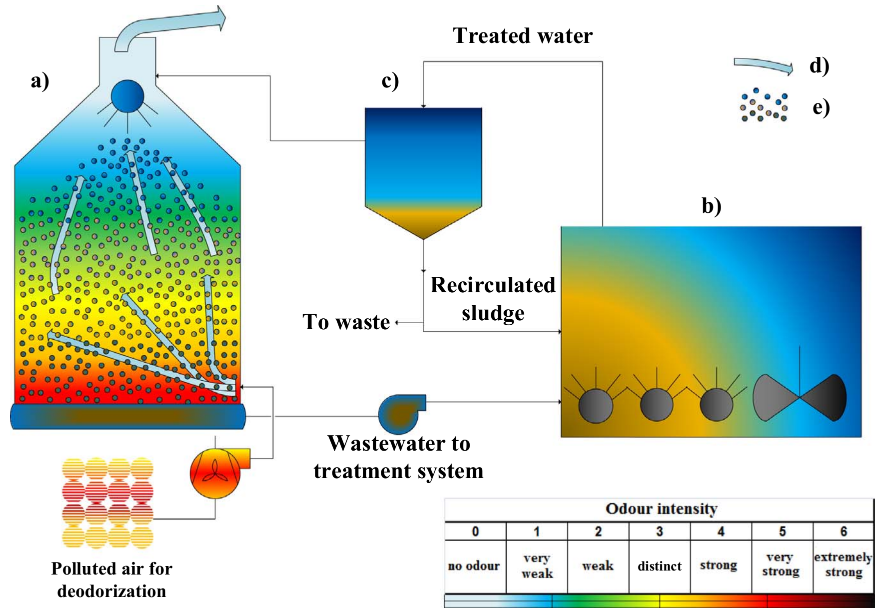


Fig. 5. Diagram of the process of odors purification using bioscrubbers: a) bioscrubber column, b) aeration tank with activated sludge for wastewater treatment, c) settling tank d) treated airflow, e) droplets absorbing contaminants (Potivichayanon et al., 2006; Talaiekhozani et al., 2016).

is generated during the wastewater treatment process, regardless of the size of the treatment plant. At small treatment plants, the construction of complicated sludge processing systems is usually economically unjustified; therefore, sludge from small agglomerations is usually used as fertilizers used for soil reclamation or stored at landfills for non-hazardous waste. At high-throughput treatment plants, due to considerable amounts of recovered waste, methane fermentation with biogas recovery turns out to be ecologically and economically advantageous. Unfortunately, anaerobic processes usually caused increased emissions of odors connected with the production of volatile organic compounds generated by microorganisms and sulfur compounds, the presence of which can be observed in sludge. Other types of sludge can be thermally processed, which may result in neutralization of all emitted odors (under appropriate process conditions) (Cieślik et al., 2015).

4.1. Biogas recovery

Biogas production at wastewater treatment plants involves an anaerobic fermentation process, during which initial and excess sludge recovered during wastewater treatment processes, constitutes the source of carbon for methane bacteria. Biogas is usually burnt with recovery to generate heat or electric power. These utilities are used at the wastewater treatment plant for local amenities and process purposes (Cieślik et al., 2015).

All anaerobic processes leading to a reduction in organic compounds contained in wastewater lead to the formation of many types of odorants, such as hydrogen sulfides, volatile organic sulfur compounds, aldehydes, ketones, alcohols and other organic odorants, the emissions of which lead to the generation of a decaying and rancid odor (Liu et al., 2012). Precursors of nitrogen odorous compounds are compounds, such as urea, proteins and amino acids. Their decomposition leads to the formation of ammonia emitted from fermented sewage sludge in an amount ranging from 18 g to 150 g per one ton of sludge (Hort et al., 2009). The most onerous odors smelling of feces may be a source of mercaptans and sulfides emissions which are mostly generated by anaerobic or facultatively anaerobic hydrolyzing bacteria (Lebrero et al., 2013).

Odorant particles are formed during anaerobic processes which confirms the fact that the formation of onerous odors is related to a low oxygen content in processed waste. The addition of oxidizing compounds or preparations such as Odoreze™ may deactivate enzymes responsible for the formation of malodorous compounds (e.g. ammonia and hydrogen sulfide), elimination of anaerobic bacteria and development of aerobic bacteria. The addition of such substances during the fermentation process would limit odor emissions and lead to destabilization of the fermentation process (Zhang et al., 2013). Fermentation processes with biogas recovery are conducted in airtight, closed fermentation chambers, which considerably facilitates the solution of problems related to odor neutralization. In the case of uncontrolled emissions of odor from the methane fermentation process, it is possible to use commercially available deodorizing agents such as Phytoncide, Munizyme, NaOCl and many others. The use of such chemical agents is not recommended as the main method of odor neutralization and it does not solve the air pollution problem, but only masks onerous odors. These preparations, however, can be successfully used in emergency situations, e.g. if the integrity of the biogas recovery installation is lost (Shao et al., 2014).

4.2. Stored sludge and sludge introduced into soil

The simplest methods of sewage sludge management are methods assuming the introduction of sludge into soil, which mostly include:

- storage,
- using sludge in agriculture for soil and land reclamation.

Before introducing sludge into the natural environment, they are to be subjected to a range of various technological treatments, e.g. sludge dehydration and drying, biological stabilization or disinfection. The adjustment of parameters, such as pH or emissions of odors, to a legally or socially acceptable level is equally important. While performing the aforementioned technological operations from sewage sludge, there can be emitted various air pollutants and namely also chemical compounds, such as:

- hydrogen sulfide, methanothiol, dimethyltrisulphide and other organic sulfur compounds as well as aldehydes, ketones and various organic acids or ammonia, which are products of

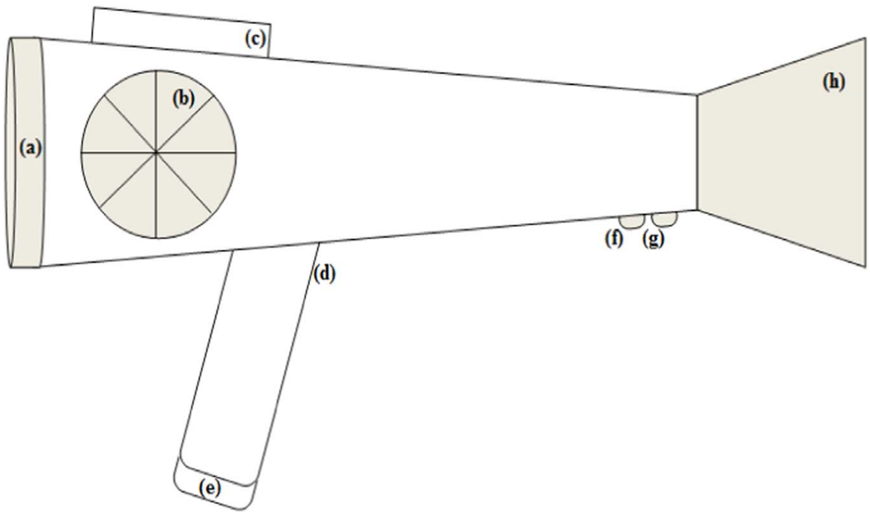


Fig. 6. Diagram of the filed olfactometer design Nasal Ranger; a) storage tank with a solution, b) carbon filter, c) electronic display of the measurement result, d) battery chamber, e) battery compartment in the handle, f) place for strap attachment, g) switch, h) replaceable nose and mouth mask.

anaerobic nutrition of bacterial products of the processed sludge;

- benzene, toluene and benzaldehyde present in the sludge in large amounts, especially if large amounts of industrial wastewater are present
- limonene and its derivatives brought with wastewater with a content of terpene-based cleaning agents (Lebrero et al., 2013)

Emissions of volatile sulfur compounds from sewage sludge grows with a decrease in its oxygenation. Anaerobic conditions and an increase in the temperature promote the generation of such air pollutants, which are usually emitted as a result of composting of sewage sludge at an amount of 9.2 g of volatile organic sulfur compounds per ton of fresh compost. Anaerobic processes of decomposition of organic matter contained in the processed sewage sludge may also generate ammonia. In this case, emissions of such a mixture of odorants may generate high-intensity odors and exacerbate the air quality (Lebrero et al., 2013; Hort et al., 2009).

There are many methods for limiting emissions of odors from composted sludge. One of them involves adding organic additives to sludge, e.g. rice straw, which results in decreasing odorous sulfur compounds. This does not have a significant influence on emissions of other odorants, such as volatile fatty acids, alcohols, aldehydes, ketones, aromatic compounds or ammonia (Shao et al., 2014). On many occasions, better results can be obtained by changing composting conditions, e.g. by changing the pH. The addition of NaOH or $Mg(OH)_2$ may result in a significant reduction in hydrogen sulfide emissions by transforming it to the ionized form. The addition of sodium hydroxide, due to the better solubility of this substance in water as compared to the solubility of magnesium hydroxide, results in a faster change of the pH. The addition of magnesium hydroxide, on the other hand, improves the value of composted sludge as the fertilizer (Krach et al., 2008). Another method of odor emissions assuming a change in the pH is the lime treatment of processed sludge. This method significantly reduces the emissions of hydrogen sulfide and organic sulfur compounds, but its application, due to higher pH levels of the sludge, may result in higher ammonia emissions. A very effective method of limiting ammonia emissions is ensuring aerobic conditions in the processed sludge. This process results in limiting the production of this pollution by anaerobic bacteria present in the compost (Krach et al., 2008; Liu et al., 2012, 2014).

Increasing the oxygen content in the managed waste leads to significant inhibition of odor emissions from sewage waste introduced into the soil. Keeping an appropriate level of aeration of composted sludge is not always a technologically simple operation. It is often necessary to use strong oxidizing agents, e.g. hydrogen peroxide (35% and 50% solution) or chloride dioxide (0,3% solution), which, when introduced, reduce or even fully eliminate sulfide, phenol and mercaptans emissions (Zhang et al., 2013). Other oxidizing agents include: ozone, perhydrole (50% and 27%), potassium permanganate (it works already after a few minutes at concentrations of 10 mg/l. Most used as 6% solution), iron compounds (VI) and oxidizing chloride compounds, e.g. chloride dioxide. The introduction of chloride compounds for sludge intended for the use in agriculture or reclamation of soil is not recommended as chloride may react with organic compounds contained in the sludge, which form compounds potentially harmful for the environment (Zhang et al., 2013). One of the methods of neutralizing odors involves conducting the sludge oxidation process, together with the neutralization of odors with the application of Fenton reactions. While conducting this reaction, sulfur compounds are transformed into a very stable form of sulfates, sulfones or sulfone acids (Liu et al., 2016). As a result, emissions of sulfur compounds from processed sludge in the form of onerous odors are reduced. Oxidation with the use of perhydrole can be enhanced by gamma radiation emitted, for example by the cobalt isotope ^{60}Co. However, the addition of sodium or calcium nitrate usually results in a greater reduction in the emissions of sulfur and nitrogen compounds than sludge oxidation using perhydrole. It should be remembered, however, that the addition of mineral reagents to the processed sludge may result in a higher ash volume after sludge incineration. Moreover such methods cannot be used as wastewater treatment step, while such approach will lead to total destabilization of treatment or management process (Liu et al., 2014; Yulin et al., 2010).

To support the sludge oxidation process, appropriate mixing of the sludge must be ensured. Regular mixing of the sludge limits the development of anaerobic fermentation bacteria, which leads to a reduction in emissions of sulfur and nitrogen compounds. Moreover, mechanical drying causes significantly lower odor emissions, as compared to thermal drying. Biodrying, prisms and other high-temperature technologies, which are usually applied at temperatures of approx. 200 °C (not higher than 400 °C), contribute to an increase in the intensity of odor emissions mostly due to the acceleration of vaporization. The group of odors emitted during these processes mostly includes oxidized sulfur compounds (Krach et al., 2008; Liu et al., 2014·, 2012).

Table 1
Characteristics of selected odors emitted from municipal wastewater treatment plants.

Odorous compound	Average concentration [μg/m³][a,b]	Odor threshold [μg/m³][b]	Type of odor[a,c,d]
Acetone	1853	34,700	Sweet, solvent
Propanol	1263	6010	Alcohol
Butanol	285	1510	Banana-like, harsh, alcoholic
2-butanol	740	5250	Sweet, reminiscent of acetone
Ethanol	3106	55,000	Chemical odor
Pentanal	209	25.1	Pungent
Methacrolein	14,315	389	Unpleasant
Hexanal	259	57.7	Grass
Methanol	256	186	Chemical odor
Hydrogen sulfide	17,400	25.7	Rotten eggs
Dimethyl disulfide	280	47.9	Rotten cabbage
Ethanal	10,228	342	Ethereal
Dimethyl sulfide	320	5.89	Cabbage, sulfurous
Acetic acid	3118	363	Vinegar
Propanoic acid	1372	110	Unpleasant, intense
Isobutyric acid	931	72.4	Rancid butter
Butyric acid	1923	14.5	Unpleasant and obnoxious
Hexanoic acid	510	60.3	Goat-like

[a] Lehtinen and Veijanen, 2011.
[b] Anet et al., 2013.
[c] Rosenfeld and Suffet, 2004.
[d] Suffet et al., 2004.

A well-designed lagoon, where the excess sludge composting process is conducted, should not allow odor emissions. If the problem of uncontrolled emissions of unpleasant odors occurs, it is only possible to use commercially available agents, which deactivate enzymes responsible for the formation of malodorous compounds, such as ammonia or hydrogen sulfide. Some of these preparations, e.g. Odoreze™, may cause limitation in the development of microorganisms, the presence of which contributes to the formation of all kinds of odorants. As mentioned above, such preparations may not be used during the methane fermentation process. A musty or earthy smell of sludge of low intensity introduced into the environment is socially acceptable (Krach, et al., 2008).

4.3. Thermally processed sludge

High-temperature methods of high-temperature sludge processing are becoming more and more popular due to the possibility of total mineralization of thermally processed media. During the thermal stabilization process, organic pollutants are transformed into stable forms, which are not toxic to the environment (Cieślik et al., 2015). The thermal stabilization process of the sludge according to the regulations included in Directive 2000/76/EC should be conducted at a temperature below 850 °C or over 1100 °C if the sludge contains more than 1% of chloroorganic substances. The application of high-temperature processing already at 650–750 °C leads to complete mineralization, thus neutralizing the majority of organic odorous compounds. As a result, the thermal stabilization process is a solution to a problem pertaining to emissions of onerous odors of processed sludge (Zhang et al., 2013). Diagram of thermal neutralization of odors is presented in Fig. 2.

The process of thermal stabilization of sewage sludge at large treatment plants is usually held at fluidized-bed furnaces located at the treatment plant. If small amounts are involved, the investment related to the construction of a thermal wastewater processing installation is usually economically unjustified; therefore, sludge can be transported and disposed at a treatment plant with a large usable area. The location of such an installation at a municipal wastewater treatment plant has certain benefits regarding odor emissions. Initial and excess sludge, scum, screenings and other process residues can be neutralized at the wastewater treatment plant without causing increased emissions of odors related to the transport of sludge to storage yards or to other installations dealing with disposal of such waste. Moreover, due to a high demand for oxygen during the burning process, it is possible to design a system collecting odor-polluted air from the other technological systems situated at the wastewater treatment plant. Owing to the designed system, it is possible to obtain mineralization and neutralize sludge and neutralization of odors emitted into the atmosphere at other stages of the wastewater treatment process (Lotito and Lotito, 2014). The problem of reducing odor emissions from sewage sludge applies only to sulfur and nitrogen oxides, which are not always neutralized during high-temperature processes and which can generated during the thermal stabilization of sludge. According to the currently established legal standards contained in Directive of the European Parliament and the Council No. 2000/76/EC, these compounds must be removed from the exhaust gas stream. For this purpose, an addition to reactors of sodium bicarbonate or activated carbon, liming filters, scrubbers, biological filters or a deposit with activated carbon. The application of active carbon leads to a reduction of emissions of sulfur compounds; however, it turns out to be ineffective for nitrogen compounds. Therefore, it will find application mostly for exhaust gas treatment from installations of thermal sludge processing, which, due to a high content of ammonia in incinerated sludge, are characterized by low NO_x emissions (Rajbansi et al., 2014).

Pyrolytic transformation of sewage sludge is an alternative for conventional incineration processes with bio-oil recovery. This process is conducted under oxygen deficiency conditions at temperatures between 400–600 °C and, as a result, it is not as effective in terms of odor neutralization as other conventional processes. Bio-oil, which is a product recovered during the sludge pyrolysis process, may contain numerous odorants, such as: short-chain fatty acids (formic acid, acetic acid, propionic acid, butyric acid) can be a source of an unpleasant odor of feces; palmitic, myristic, oleic and stearic acids, which can be the source of a rancid odor; cresol can be the source of a tar odor and dimethyl sulfides contribute to the generation of a rotten cabbage odor. The most effective method of deodorization of short-chain fatty acids, which at the same time considerably reduce the energy value of bio-oils, is the one that involves the esterification process. Water is a side product of esterification, the presence of which exacerbates the bio-oil quality. This process occurs spontaneously and it is commonly called bio-oil ageing. It is possible to improve the esterification process by adding short-chain alcohols to the process (from methyl to butyl alcohol). Optimal esterification conditions are obtained by adding ethanol at 20% v/v. Esters formed in this way a source of non-onerous pleasant odors. At the same time, a layer of water is separated from the solution, which contains approx. 5% of ethanol, which can be easily separated from bio-oil. Approx. 40% of the ethanol content does not undergo esterification; it can, however, cause an increase in the calorific value of bio-oil stabilized in this way by 8.8%. The addition of 200% v/v of ethanol may result in the formation of the so-called fruity smells. However, due to a large amount of the reagent used, this process is not justified economically, just like adding esters, which mask onerous odors as it causes solidification of the end product obtained (Doshi et al., 2005; Cieślik et al., 2015).

Table 2
Use of the field olfactometry technique for the assessment of the odor nuisance of the municipal wastewater treatment plant.

Application	Device	Team of panelists	Location	References
Monitoring of concentrations of odors emitted by a municipal wastewater treatment plant	Nasal Ranger (St. Croix Sensory, Inc.)	nd	Bellevue, WA, USA	(Witherspoon and Barnes, 2004)
Monitoring of the odor nuisance of facilities at the process line at a municipal wastewater treatment plant	Field Olfactometer (St. Croix Sensory, Inc.)	2 panelists	Warsaw, Poland	(Barczak, et al., 2012)
Monitoring of the olfactory detectability threshold for an odor over the area of a municipal wastewater treatment plant	Odor Pen Kit (St. Croix Sensory, Inc.)	2 teams of persons: 39 experts, 39 trained panelists	Lake Elmo, MN, USA	(Lay and McGinley, 2004)
Verification of complaints of people concerning emissions of onerous odors into the environment near a municipal wastewater treatment plant	Nasal Ranger (St. Croix Sensory, Inc.)	no data available	Duluth, MN, USA	(Hamel, et al., 2004)
Monitoring of the intensity of the air odor over the area of a municipal wastewater treatment plant	Nasal Ranger (St. Croix Sensory, Inc.)	Municipal wastewater treatment plant personnel	Melbourne, Australia	(Cesca, et al., 2007)

nd - no data available.

5. Biological methods of odor removal

There are other methods of deodorization than mentioned thermals and biological processes (eg. activated carbon, chemical oxidation etc.) but these are not the subject of presented study and would not be described here. The basic advantage of biological deodorization methods over high-temperature methods is the fact that they are much less labor-consuming. The conditions for high-temperature pollutant neutralization processes must be closely controlled. The quantity of pollutants contained in the exhaust must be monitored in a continuous manner and the quality of exhaust emitted to the atmosphere must meet the guidelines contained in previously mentioned directive no. 2000/76/WE. At the same time, investment costs of implementing biological methods of odor purification are usually much lower as compared with the costs of high-temperature deodorization methods (Zhang et al., 2013).

Two types of biological methods of odor removal, namely:

- the biofiltration method,
- the method of diffusing odor-polluted air through a biological deposit, e.g. activated sludge used in biological reactors at wastewater treatment plants.

The biological efficiency of odor removal systems is usually determined by their biological diversity. The development of biological deposits is related to an increase in the bacterial flora which, during the nutrition stage, reduces the number of emitted air pollutants (Hort et al., 2009).

5.1. *Diffusion through activated sludge*

As mentioned before, diffusion through the activated sludge is the method for biological neutralization of odors, which involves the odor-polluted air being passed through activated sludge. The activated sludge flora by conducting the metabolic processes decomposes the pollutants as a result of oxidation of chemical compounds. Process parameters are the pH, the oxygen content and the quantity and condition of the activated sludge. Activated sludge may adapt to the conditions in activated sludge chambers, which change together with the inflow of pollutants, both those arriving with raw wastewater and those introduced together with deodorized air. The principle of odor removal from the air in biological reactors is presented in Fig. 3. If strains of sulfur- and iron-oxidizing bacteria develop in the activated sludge, the bacteria it contains acquire the ability to reduce odor emissions, which are responsible for the rotten smell (Pathak et al., 2009).

The results of the research conducted can be the basis for concluding that in the case of air purification from substances, such as limonene, acetone, butanone and benzene, the efficiency of odorants, which undergo oxidation as a result of diffusion by the activated sludge, is even 99%. The purification efficiency is much lower in the case of purification of chemical compounds, such as toluene and dimethyl trisulphide, and it amounts to approx. 80%. The level of concentrations of some odorants, such as α-pinene, can be reduced at the beginning to a very small degree ($7.3 \pm 1.9\%$), as the activated sludge must be adapted by the formation of appropriate organisms to reduce the level of specific pollutants. The degree of pollutant purification may increase even up to 65%. If appropriate strains of bacteria are introduced to the sludge, which have the ability to metabolize a specific pollution, the degree of concentration reductions can be much bigger (89% of α-pinene reduction if appropriate strains of fungi are introduced into the sludge). It should be remembered that not all organisms show the ability to keep its population in the active sediment, especially if they are characterized by sensitivity to pollutants brought in the wastewater. In such situations, it may be necessary to periodically inoculate appropriate bacterial cultures in biological reactors to keep the degree of reduction of all pollutants at a stable level (Lebrero et al., 2013).

The use of diffusion of polluted air through activated sludge is a particularly profitable alternative in wastewater treatment plants, where the process of biological treatment of wastewater. Entities conducting such a process has necessary fittings, which considerably reduce investment costs. Operation costs are usually related to the costs of the treatment process and, thus, the cost of the odor treatment process may be regarded as relatively low. Despite the fact that the degree of reduction of the hydrogen sulfide concentration is very high 96–100%), the use of diffusion of polluted air through the activated sludge is still not characterized by such efficiency of reduction in the odorant concentration level as in the case of the use of biofilters (Lebrero et al., 2013).

5.2. *Biofiltration*

Biofiltration is one of the best-researched methods of air purification. Biofilters have already been used since the early 1950s, mostly due to low costs, both investment costs related to the construction of the installation and maintenance costs. This method is characterized by a much higher efficiency of removing volatile organic compounds from the air as compared to other methods, which do not use a biological deposit, such as filters or scrubbers (Hort et al., 2009; Lebrero et al., 2013). However, some authors say that despite the fact the biological treatment methods are ecologically and environmentally friendly, they are considered as insufficient compared with chemical methods. In some cases even 99% removal efficiency could be unsatisfactory. As an example if hydrogen sulfide, which occurs in treated gas at level of 10 mg/L, would be reduced to 0,1 mg/L, the H2S concentration is still twenty times above usual threshold (around 0,05 mg/L) (Chen, et al., 2016). The principle of biofilter operation is simple. Polluted air is introduced into the biological deposit, which is placed in an open chest filled with pine bark, sawdust, compost, inorganic materials or a mixture of these products and directed to the chamber so that the biological deposit is reached by as much air as possible. In case of biotrickling filters several layers of packing, may be filled with variety of organic and inorganic materials such as activated sludge, compost, bark, coconut fiber, activated carbon, polyurethane foam, ceramic rings and many others (Chen et al., 2016). Bacteria in the form of biofilm formed on the surface of the deposit absorb and biodegrade pollutants contained in the air (Otten et al., 2004). The filling of a biological filter should have parameters, which ensure a high permeability of gases and liquids, should be characterized by a good buffering ability and the biofilm formed on its surface should be as biologically diverse as possible, which makes it possible to retain and biodegrade a broad range of pollutants. The filling of the deposit should comprise of high-quality materials; otherwise, the purification efficiency will be low. It is possible to prepare a biological deposit using sewage sludge or even shipyard waste (Tsang et al., 2015b; Talaiekhozani et al., 2016). However, this requires appropriate preparation and preconditioning of the materials used. Regardless of the material used as the biofilter filling, each biological treatment system requires appropriate preconditioning under conditions identical with those, under which the air purification process will be conducted. Such an operation usually lasts from 6 to 7 days. During this time, the biofilm flora is adapted to the neutralization of specific kinds of waste, which are present in the air which reaches the deposit (Lebrero et al., 2013; Hort et al., 2009). Some biofilter systems require more time to adapt, but their application usually allows the achievement of higher efficiency of purified air or a broader range of degraded chemical units. The use of biofiltration using *Psedomonas* sp. bacteria makes it possible to achieve high efficiency of air treatment as regards pollutants, such as hydrogen sulfide and ammonia. Therefore, the biofiltration method can be used in the case of purification of gases from various installations present at a wastewater treatment plant. Such systems are often used for cleaning the air in closed rooms. In municipal wastewater treatment plants, they can be used mostly at grill halls, densification buildings and sludge-drying buildings (Bruszkiewski and Skorupski, 1999). The efficiency of removing organic pollutants, such as toluene or butanone, can range from 82% to 99.9% and from 98.9% to 99.5%, respectively. Ammonia, on the other hand, is removed in amounts ranging from 94% to 99%. (Zhang et al., 2013; Lebrero et al., 2013; Hort et al., 2009). As aforementioned biofilters are often used for hydrogen sulfide and ammonia deodorization but there is lack of literature describing their efficiency of simultaneous removal of mentioned odorants. However, biotrickling filers can successfully be used for simultaneous H_2S and NH_3 removal. In these case the efficiency of deodorization process can reach up to 98,5% in relation to H_2S and 99,9% in relation to NH_3 in laboratory scale (Tsang et al., 2015a, 2015b). The functioning principal and main differences between biofilters and biotrickling filters systems are shown in the Fig. 4.

Alternatively bioscrubbers may be used as air treatment in wastewater treatment plants. However such installation are mainly used for treatment of water soluble contaminants. Nevertheless in these case activated sludge is also used as biological treatment medium. Describing the detail about biological treatment process is not the aim of presented study. More comprehensive information are given by (Talaiekhozani et al., 2016; Tsang et al., 2015a, 2015b; Alfonsin et al., 2015). The main principal of air treatment using bioscrubbers is shown in the Fig. 5.

There is a change in the value of parameters, such as pH, the water content and accumulation of waste products of biofilter fauna and flora metabolism, in particular, inhibitors of biodegradation processes. To achieve possibly the highest efficiency of air pollutants using biofiltration systems, chemical analysis turns out to be an effective tool in many cases, as it makes it possible to identify and determine possibly the largest number of air pollutants emitted from the areas of a given installation. The use of chemical analysis makes it possible to select an appropriate system of biofilters. There is still not enough information on odor formation and efficiency of biofiltration systems used in various branches of industry. In a vast majority of research projects aimed at assessing air quality, the research is conducted using odorous substances produced by means of chemical synthesis, in which concentration levels do not change in time as it takes place in the case of odorous substances produced under process conditions. For this reason, the efficiency and capacity of various biofiltration systems used on a technical scale cannot always be predicted as regards odor removal from the air. It should be remembered that the composition of the odorous mixture does not only depend on the type of the installation, from which odors are emitted, but also on the functioning of a given wastewater treatment plant. Biofiltration systems should be designed individually for each wastewater treatment plant and installation (Lebrero et al., 2013; Hort et al., 2009).

6. Assessment of odor nuisance of the air

Over the past few decades, the interest in the impact of municipal wastewater treatment plants on the population living in adjacent areas and the impact on the surrounding environment increases. One of the reasons for complaints on the part of persons exposed to the wastewater treatment plant involves emissions of chemical compounds, which are a sensory nuisance (odors) (McGinley and McGinley, 2002). Chromatographic techniques are analytical techniques recommended for the determination of such chemical compounds. Conducting research with the use of these techniques allows the determination of a broad range of chemical compounds, such as volatile organic sulfur compounds, amines, esters and mercaptans, which belong to the most onerous odors. Also, the techniques listed below are often used for the determination of odors emitted at wastewater treatment plants: SPME GC-MS, GC-FID, GC-PFPD, GC-O, and IC (Kim et al., 2014; Rajbansi et al., 2014; Krach et al., 2008; Fang et al., 2012; Doshi et al., 2005; Tsang et al., 2015a, 2015b).

Tests of chemical substances, which are characterized with an unpleasant odor and which are present in the air, can be also performed using olfactometric techniques. The olfactometric technique, which is most often used for the assessment of the odor nuisance of the air, is field olfactometry. Dilution methods are used to describe the properties of odorants present in the air. The use of these methods allows for defining the degree, to which the tested sample must be diluted using air, which is considered to be odor-free, so that its smell is no longer detectable. The diluted air sample is presented to a team of trained panelists. Members of the team assess the sensory characteristics of the analyzed air sample. The olfactory sensitivity of each panelist must be defined using a reference substance: *n*-butanol. The result of the measurement is the concentration of odorants expressed in odor units in accordance with guidelines contained in standard EN 13725:2003.

Field olfactometers are tools used for diluting the stream of the tested air. *Nasal Ranger* or *Scentometer* field olfactometers can be used for research in the area of olfactometry. The Nasal Ranger field olfactometer is a tool equipped with two replaceable filters with activated carbon and a regulation valve, which makes it possible to choose one of six proportions between the volume of odor-free air and the volume of air with odors. The accuracy and repeatability of results obtained using a field olfactometer amount to ± 10% and ± 5%, respectively (Kośmider and Krajewska, 2007; Hamel et al., 2004). One of the elements of the olfactometer is a sensor, which allows the measurement of the flow rate of gas leaving the device (Bokowa, 2012). The volumetric flow intensity should be independent of the dilution level of the sample and not less than 20 dm^3/min (EN 13725, 2003). After approx. one minute after the commencement of the test, the assessing team gradually increases the volumetric flow of the air bypassing the filters until the odor is detectable. The diagram of the field olfactometer design is presented in Fig. 6.

The use of field olfactometers makes it possible to conduct research on defining the concentration of odorous substances and odor emissions in-situ at the municipal wastewater treatment plant (Barczak et al., 2012; Witherspoon and Barnes, 2004). The use of field olfactometers is possible to estimate the olfactory threshold of odor detectability at a given measurement point (Lay and McGinley, 2004). Olfactometers can be used as measuring devices for scientific research and for research, the results of which provide information that allows for verifying residents' complaints on odor nuisance (Hamel et al., 2004). Field olfactometers are also used to estimate the intensity of the odor in the atmospheric air near municipal wastewater treatment plant (McGinley and McGinley, 2002). The use of field olfactometers allows identification of odor sources and estimation of the hedonic quality of the odor (Brandt et al., 2009). It involves observation of the size of sensory differences between tested samples and ranking them according to the odor sensation scale. In Table 2, literature information is summarized on the possibilities of using the field olfactometry technique in air quality research at the municipal wastewater treatment plant.

Olfactometry is one of the best techniques used to determine the odor nuisance air. However, the results of olfactometric measurements often be correlated with results of measurements obtained by means of other tools, such as portable H_2S analyzers or portable SO_2 analyzer (Bufaroosha et al., 2013; Alnaqbi et al., 2016; Marzouk and Al-Marzouqi, 2012). It should be remembered, that the sense of smell in humans can receive and register the sensory impression when the odor olfactory threshold is not exceeded by any of the chemical compounds which are part of the odor mixture. Similarly, the odor of a chemical compound can not be detected by the human nose despite the fact that the olfactory detection threshold has been exceeded (Kośmider et al., 2012). Consequently, it is necessary to use devices capable of determining the concentration levels of each gas in-situ (Marzouk et al., 2010). Application of field olfactometers and portable gas analyzers at the same time allows to correlate the odor concentration values estimated on the basis of data obtained from the olfactometric analysis with the values of the concentrations obtained using portable gas analyzers.

Determination of the odor intensity of the test sample using the sensory technique which is olfactometry and identification of odor compounds using the chromatographic method is time consuming and labor intensive. In order to connect the resolution power of capillary gas chromatography (GC) with a selectivity and sensitivity of the human nose there was developed an analytical method used to identify the key odor compounds present in the environment (Plutowska & Wardencki, 2012). This analytical method is gas chromatography coupled to olfactometry. Separation of the components of the analyzed mixture takes place in a chromatography column. Subsequently, the flow of the test sample flowing out of the column is split into two streams. The first stream is directed to the detector forming part of the GC system (eg. MS) and the second stream is directed to the olfactometric detector (sniffing port). The olfactometric detector is the human nose, as in the case of olfactometric technique (Giungato et al., 2016). A main requirements of this method is to maintain a small and constant time delay between the GC signals and the odor event at the sniffing port. It is also important that the flow paths are characterized by low absorption, especially in the case of a stream directed to the sniffing port (Boeker et al., 2013). Comparison of the results obtained simultaneously with the chromatographic analysis and olfactometric analysis allows the identification of compounds that cause the unpleasant olfactory sensation in the sample. Application of GC-O is an attempt to solve the odor complexity issue of test sample (Brattoli et al., 2011).

7. Conclusion

Odor emissions from municipal wastewater treatment plants is the cause of complaints on the deteriorating living conditions and health of the local community. Appropriate deodorization systems are not use at the municipal wastewater treatment plant mainly for economic reasons. Fortunately, sometimes these are not needed due to the air dispersion phenomena and favorable topographic or meteorological conditions. In the majority of cases, odorant concentrations, both organic and inorganic, are not an environmental hazard. As a result, removal of odors from gases is regarded as economically unjustified; however, it should often be implemented for environmental or social reasons. The presence of some organic odorant in the air, such as phenol or benzene, may already constitute a threat to the environment at concentrations below the olfactory detectability threshold by people, as a result of which the problem may be unnoticed or ignored. As a result, it is necessary to determine all odorous compounds included in the odorous mixture in polluted air, which comes from technological installations and systems, which can be found at wastewater treatment plants. Analytical techniques, which can find applications, including amongst other things: for the determination of selected odorous substances during the estimation of the efficiency of odor removal systems, include the following: GC-MS, GC-FID, GC-PFPD, and GC-O-MS. Field olfactometry, on the other hand, can be used to define odor nuisance for odors emitted by technological installations and systems at a municipal wastewater treatment plant. The use of this technique makes it possible to perform in-situ tests in real time, thanks to which it is possible to identify sources of odor emissions and to define the intensity and the range of the impact of the unpleasant odor as well as to design and implement an effective method, which limits emissions of malodorous substances. There is the definition of the problem of the odorant content in the air at the wastewater treatment plant and the control of their emissions. Appropriate aeration of treated wastewater usually solves the problem of emissions of the majority of odors, where it is not possible to perform such an operation (e.g. during fermentation or other anaerobic reactions), it is necessary to use such deodorization systems.

The most commonly used group of deodorization methods are biological methods, among which biofiltration is one of the best known ones. However, despite considerable experience in biofiltration, thanks to long-term use of such systems; however, there are still no literature data concerning differences in the odor nuisance of single odorants and the odor nuisance of a mixture of many various odorants and also on efficiency, which characterizes the biological treatment systems on a technical scale. A more rarely used biological deodorization method is diffusion through activated sludge. Its low applicability is related to the fact that this method is dedicated only to a wastewater treatment plant, where aeration of biological reactors occurs. The implementation of systems operating on the basis of the diffusion of air polluted by activated sludge in newly built wastewater treatment plants could bring a lot of benefits, including gaining valuable information on removing odors from the air and improving the process of implementing such systems in already existing units. Another group of deodorization methods are thermal methods. Such methods are much better known and they are often used to neutralize all kinds of odorant limitations and other organic air pollutants. Their implementation is, however, much more expensive as compared to the use of biological waste treatment methods. The use of thermal deodorization methods at wastewater treatment plants, where no thermal sludge and screenings stabilization is used, may prove to be unjustified for economic and ecological reasons. However, they are an excellent alternative to biological methods if thermal installations for sludge and screenings processing exist or are to be built on the premises of a wastewater treatment plant. It is then possible to completely neutralize all air pollutants, which occur at the wastewater treatment plants without the necessity of implementing additional biological deodorization systems. A third method of odor reduction involves introduction of various additives into processed wastewater plants (the most frequently oxidizing chloride compounds, e.g. chloride dioxide and other oxidizing compounds, such as potassium permanganate and iron compounds (VI)). In this case, it is necessary to prevent the release of precipitated salts of metals into the environment and the formation of secondary pollutions and namely organic chloride compounds. Such additives may not be used in many cases to reduce odor emissions form wastewater treatment installations as it could result in interferences in the technological process or its total destabilization. The aim of using some additives involves masking odorant emissions and their application often does not cause the formation of secondary pollutants. In this case, they will be used in wastewater line installations. On the other hand, the use of the odor masking method does not solve the problem of pollutant emissions into the air. The use of this odor masking method is recommended only in emergency situations, which can take place at the treatment plant (leaks, loss of integrity, maintenance downtime). Characteristics of emitted odors can be different for each treatment plant even despite using the same technological systems. The chemical characteristics of wastewater reaching the treatment plant and process conditions have a significant influence on this fact. The control of odor emissions should take place at the moment of implementing economically justified emissions of odors and deodorization of air polluted with malodorous substances. However, it should be remembered that the economically promoted approach to stop emissions together with neutralization of the appearing air pollution.

The article was an attempt at a critical summary of knowledge on odor emissions from various technological systems of wastewater treatment lines and sewage sludge processing and management lines at wastewater treatment plants. Methods of thermal and biological odor removal and it was specified in what cases the use of a given method is justified from the economic and ecological point of view. The field olfactometry technique was also presented by means of which it is possible to assess the odor nuisance of the air near each technological system situated at the wastewater treatment plant. The analysis of research conducted using the field olfactometry will make it possible to identify the main sources of onerous emissions and to implement the solutions, which are the best to solve the problem of onerous odors. Taking into account literature reports, it should be assumed that an increase in the use of this technique for the assessment of the air quality will occur in the nearest future and the sources of odors, which are the cause of onerous odors at the municipal wastewater treatment plant, will be identified.

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