ENVIRONMENTAL IMPACT ASSESSMENT OF PLASMA TECHNOLOGY APPLICATION TO ODOUR REDUCTION IN SEWAGE SLUDGE TREATMENT

Technical Report v.01

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INTRODUCTION

Wastewater treatment plants facing the problems on climate change and human health impact issue while utilize sewage sludge. Volatile organic as well as inorganic compounds released during the wastewater and its sludge treatment shall be reduced by application of modern and energy saving odour reduction methods. One of the sustainable ways to solve unpleasant odour discharging is the employment of the non-thermal plasma technique [1]. Efficiency of non-thermal plasma reactor designed to reduce the emission of volatile chemicals released during the sludge treatment' research has been carried out as part of the implementation of the STEP (Sludge Technological Ecological Progress - increasing the quality and reuse of sewage sludge) project funded by EU Interreg-V-A South Baltic Programme 2014-2020. During the project, the project lead partner - West Pomeranian University of Technology in Szczecin designed the non – thermal plasma method. One of the aims of the STEP project was to analyse and apply effective method for sludge utilization, taking into account the assessment of the environmental impact of the designed technology.

While treating the odorous gases emitted during the sewage sludge preparation for composting process the first testing of the designed non-thermal plasma equipment was completed. The unpleased odour emissions are observable during the different stages of the sewage treatment: during the mechanical wastewater treatment, where significant amount of the sediments (sludge) separated from the sewage flow; during the dewatering of the excess sludge; as well thermal sludge drying processes with or without biogas production. The developed method of the non-thermal plasma gas treatment can be used for any wastewater treatment plants and represent the reliable solution for an unpleased odour reduction or elimination all over, where organic matters are degrading.

The wastewater sludge treatment as well post-treatment (i.e. sludge composting) has a footprint in the environment, especially in terms of odorous gases. The odorous gas treatment using the aforementioned developed non-thermal plasma technology reduces the emissions effectively up to 81% of some gases if the technology not combined with other gas treatment technologies [2]. The availability of the non-thermal plasma technology experimental data allows assessing the environmental impact of application of technology and evaluate the environmental footprint of planned installations. In this research, the Life Cycle Impact

Assessment (LCIA) was completed collating the data of the environmental impact of the odorous gases released to the atmosphere during the wastewater sludge composting process without gas non-thermal plasma treatment and applying the gas non-thermal plasma treatment.

SHORT DESCRIPTION OF SEWAGE SLUDGE TREATMENT PROCESS

The unwanted odour removing technologies are desirable at wastewater sludge treatment's facilities especially those located in the vicinities of the cities and living communities. The scope of this research is to emphasize the abilities of the application of sludge odour removal state of the art technologies at the Klaipeda city wastewater treatment plant (WWTP).

The overall technological process of the wastewater sludge treatment at the Klaipeda wastewater treatment plant is set in the following way [3]. The primary sludge retained in the primary sedimentation tanks periodically discharged to gravity thickeners, and the already thickened sludge pumped to a sludge-mixing reservoir. Part of the activated sludge removed as an excess sludge during the biological treatment. The thickened excess sludge then mixed with the primary sludge and the sludge and grease from other facilities in the same sludge-mixing reservoir pumped to the sludge digesters. The sludge digested in a mesophilic mode, within temperature of 35 – 37 °C in two digesters. Organic matter is decomposed under anaerobic conditions, where methane bacteria decomposing organic compounds into ammonia, carbon dioxide and methane gas. Such methane digestion makes it possible to obtain rotted, black, less odour sludge. The temperature required for the mesophilic sludge digestion process in the digestion tanks is obtained by heating the sludge. The sludge formed during wastewater treatment digested in two digesters, then dewatered by centrifuges and dried in sludge dryer. The biogas produced during digestion, which contains about 60 – 65% methane used for energy production in a central heat and power plant. The energy of gas-powered engines converted into electrical and thermal energy. Electricity is used for own WWTP needs. 91.5% of electricity has been generating in the WWTP, which is the amount of electricity required for the entire wastewater treatment and sludge treatment process in the plant. The generated thermal energy of the engines used as a heat source for digesters and biogas treatment. The heat generated from the generators used to dry the sludge; an additional 600 kW generator using natural gas installed. The decomposed sludge is further dried (using dry – type flocculants) in centrifuges (with about 75% of moisture) and transported to sludge dryer. The low temperature (inside the dryer is 85 °C) belt sludge dryer, which consists of two belts, transports the dried sludge through the drying zones. Water evaporated from the dried sludge by circulating heated air in the drying zone. The exhaust air formed during drying is cleaned in a scrubber, bio-filter and released into the environment (The exhaust air treatment scheme is presented in the Annex II). The dried sludge, which retains no more than 10 % of moisture further crushed and enters dried sludge storage (150 m^3) where it is stored until it is unloaded. The dried sludge is loaded into containers and handed over for the post-treatment.

The main unwanted odour problems in the wastewater treatment plant under consideration occur in the different wastewater treatment stages:

- The primary mechanical wastewater treatment, where comes all different fractions in inflow chamber, screening facility;
- Biological wastewater treatment – gravity thickeners;
- During wastewater sludge processing as sludge dewatering, drying, composting or storage.

OVERVIEW OF THE PLASMA APPLICABILITY IN WWTP ODOURS REMOVAL

Many methods of exhaust air treatment exist including filtration, scrubbing, absorption, catalytic treatment, thermal oxidation and bio filtration. Recent years have shown a rapid development of heterogeneous processes combining different technologies, including the non– thermal plasma processing [1]. Non-thermal plasma can be generated in the main exhaust gas flow or in a bypass by means of a gas discharge, e.g., corona or barrier discharge. The plasma generates active molecules, like radicals and ions as well, as ozone that oxidize odorous substances. Every industrial exhaust gas configuration can be complex and specific, where the efficiency and ability of plasma assisted treatment methods depends on many conditions, i.e., type and concentration of pollutants, temperature and humidity of the gas [4].

One of the examples is the hybrid, plasma – supported removal of VOC’s as formaldehyde, ammonia and methanol from exhaust gas mixtures. Both direct and indirect methods given as examples here. The two different configurations of the exhaust treatment systems presented in Figure 1.

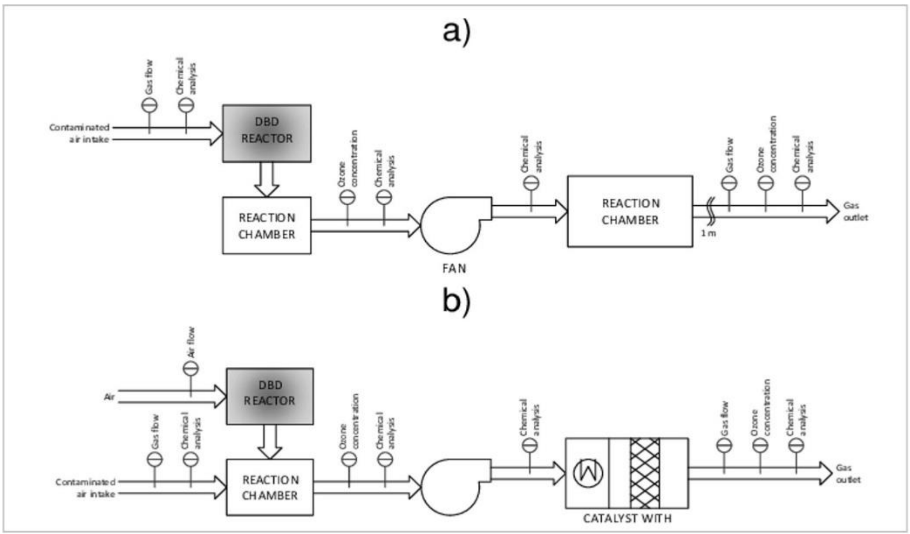

Fig. 1. Exemplary configurations of the test stand: a) direct plasma treatment; b) indirect, plasma – supported catalysis [1].

A large – scale, plasma – assisted exhaust treatment facility was investigated by researchers in Poland, as suitable for formaldehyde, methanol and ammonia removal operation. Plasma proven effective but only for limited input concentrations, where no significant differences between indirect and direct methods noticed. Over 90% of removal efficiency proven for plasma – assisted catalytic treatment for a very broad range of input concentrations of all pollutants [1].

The plasma treatment combined with a catalytic (copper-manganese) unit, a scrubbing unit, or a bio-filter in order to demonstrate the abilities for waste air deodorization. The study focussed on the emission at the thermal sludge dryer as the most odorous site in the proposed wastewater treatment facility “Aquanet” at Poznan (schematics of test facility in the Figure 2). The waste air after the thermal sludge dryer station treated by a bio-filter that showed partly not satisfying results in the past. The main problem was that the bio filter could be hardly controlled by operation parameters that would be beneficial in a real situation with fluctuating odour emissions [4].

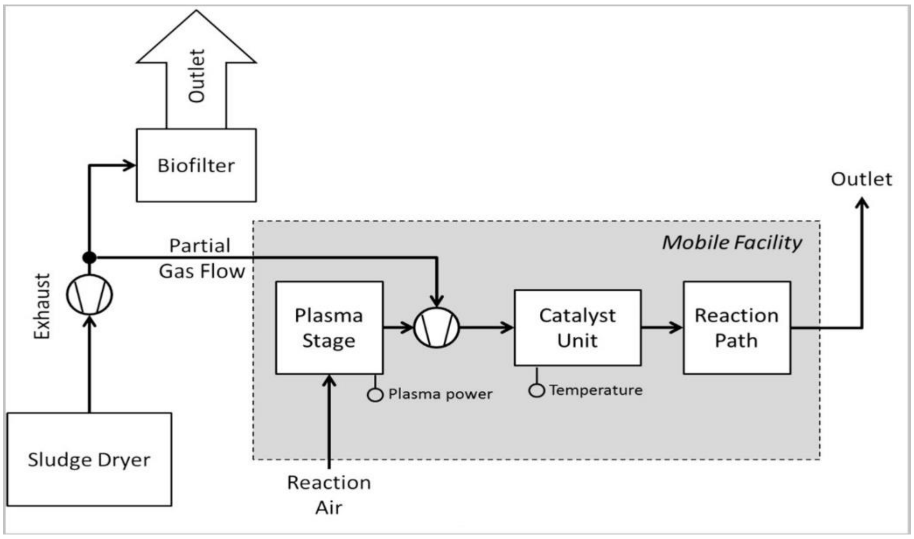

Fig. 2. Non-thermal plasma application in the sludge dryer at Poznan [5].

Effects of a plasma-catalytic treatment of waste air from a wastewater treatment facility (thermal sludge dryer emissions) have been studied in the field tests in order to demonstrate its feasibility for deodorization. The plasma catalytic treatment was combined with scrubbing or existing bio filters. The waste gas treatment of a given wastewater treatment plant should be a combination of at least two techniques. Due to the high content of H_2S a scrubber unit (NaOH with H_2O_2 admixture) used for the reduction of H_2S emissions with reliable operation cost. The scrubber plasma-catalytic stage downstream can be utilized for removal of remaining sulphides and hydrocarbons. In the given installation at Poznan it was recommended to remain with the existing bio-filter but with a scrubber and a plasma-catalyst unit upstream. The bio filter may provide a long retention time for the reaction with plasma generated species (e.g., O_3 as an oxidizing agent) while the plasma treatment leads to the enlargement of bio-filter lifetime and activity due to prior reduction of hydrocarbons [5].

Here, outlined the main conclusions: plasma is effective in reduction of singular (or dominant) odorants but in case of industry applications (complex gas composition); usually the plasma technology enhanced by catalysis, scrubbing or bio-filtration and shows better results. Plasma deodorization can be cost effective and does not require a lot of space or volume. Power electronic supplies increase the efficiency and controllability of the system [6].

DATA ACQUISITION DURING THE TESTS OF THE NON-THERMAL PLASMA APPLICATION METHODS IN SEWAGE SLUDGE COMPOSTING PROCESS

The data analysis in this research was completed using the available data obtained at the field research of optimal sludge utilization process that was carried out as part of the implementation of the STEP project by the company "Wodociągi i Kanalizacja Sp.z.o.o. z Goleniowa", at Goleniow in Poland and the efficiency of non-thermal plasma reactor designed to reduce the emission of volatile chemicals released from wastewater sludge treatment at Goleniow pilot plant. Sludge composting process at pilot plant carried out in two independent stages during field research. Four series were planned during the field research. Both series lasted about 5 months and consisted of monitoring of the composting process carried out in windrows of approx. 50 m^3 each. In both series, a different proportion between components was used. The basic components were a mechanically dewatered sewage sludge; barley straw; wood chips and mature compost (inoculum). The two series were done in the first stage. In the series, No 1 the mass ratio between components forming the compost mixture was respectively 4:1:(0.5+0.5), as described later in the report as the ratio 4:1:1. In the series No 2, the mass ratio between the components was respectively 8:1:(1+1), as described later in the report as 8:1:2. Each series repeated in the stage No II [7].

The data regarding the odorous gases collected during the evaluation of the efficiency of the plasma reactor used to remove VOC's from gas streams released from sludge composting maturation phase carried out in the sewage treatment plant in Goleniów, Poland. The research fulfilled by West Pomeranian University of Technology in Szczecin. The direct treatment method was used with a prototype of a single, corona discharge tube (Figure 3).

Fig. 3. Prototype of a single-tube corona discharge unit during STEP project [6].

The odorous gases sampled for testing in a municipal wastewater treatment plant located in Goleniów (West Pomeranian Voivodeship), Poland. In order to carry out the planned tests, two compost heaps from the plant were prepared, differing in the ratio of sewage sludge to the added straw. Both piles were located on the indoor compost ripening area. During the gas sampling stage, the given pile was covered in order to limit the exchange of gas stream released from the heap with atmospheric air [6].

Gas samples were taken both before the gas entered the plasma equipment and after leaving it (schematics in the Figure 4). In total, the 10 gas samples were taken in “Tedlar” bags and 10 air samples using solid sorbent packed tubes [7].

During the gas emissions’ measurements of approximately 1000 different chemical compounds were formed, from which 126 compounds were identified with over 80% detection probability. 12 VOC’s were identified quantitatively and measured consecutively [7].

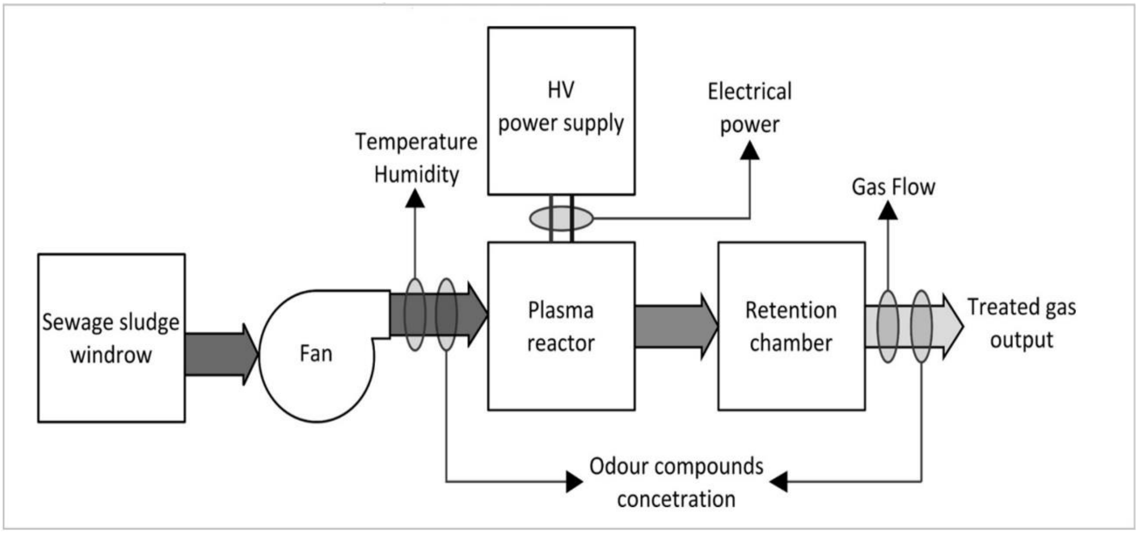

Fig. 4. Schematics of the plasma odour control system at pilot plant in Goleniów [6].

These measured 12 different the most important toxic or carcinogen pollutants listed as: Ammonia, Hydrogen Sulfide, Hexane, Dimethyl disulfide, 1-Methoxy-2-propanol, Toulene, Pentatane, Methanethiol, 2-methylbutanal, Benzaldehyde, Benzene, Dichloromethane.

LIFE CYCLE IMPACT ASSESSMENT (LCIA) METHOD

The Life Cycle Impact assessment of the emissions of the gases that are released form sludge dryer (Figure 2) applying the non-thermal plasma equipment was completed. The LCIA indices for the odorous gases flows modelled and compared while extracted before and after non-thermal plasma treatment using the Gabi® software [8]. The flow parameters were used for modelling, using ±5% parameter of the statistical standard deviation. The flow inputs for analysis were used 12 different the most important toxic or carcinogen gases (see previous section), that are listed in the Gabi® software's odour inventory [9]. The evaluation of impact to environmental of obtained gas flows modelled using the TRACI 2.1 model assessing the following impacts: *Global warming potential*, *Acidification potential*, *Air Eco toxicity*, *Human health criteria Air*, *Human toxicity*, *Smog in Air*. The schematics of the plasma technology in process along with modelling chart presented in the Figure 5.

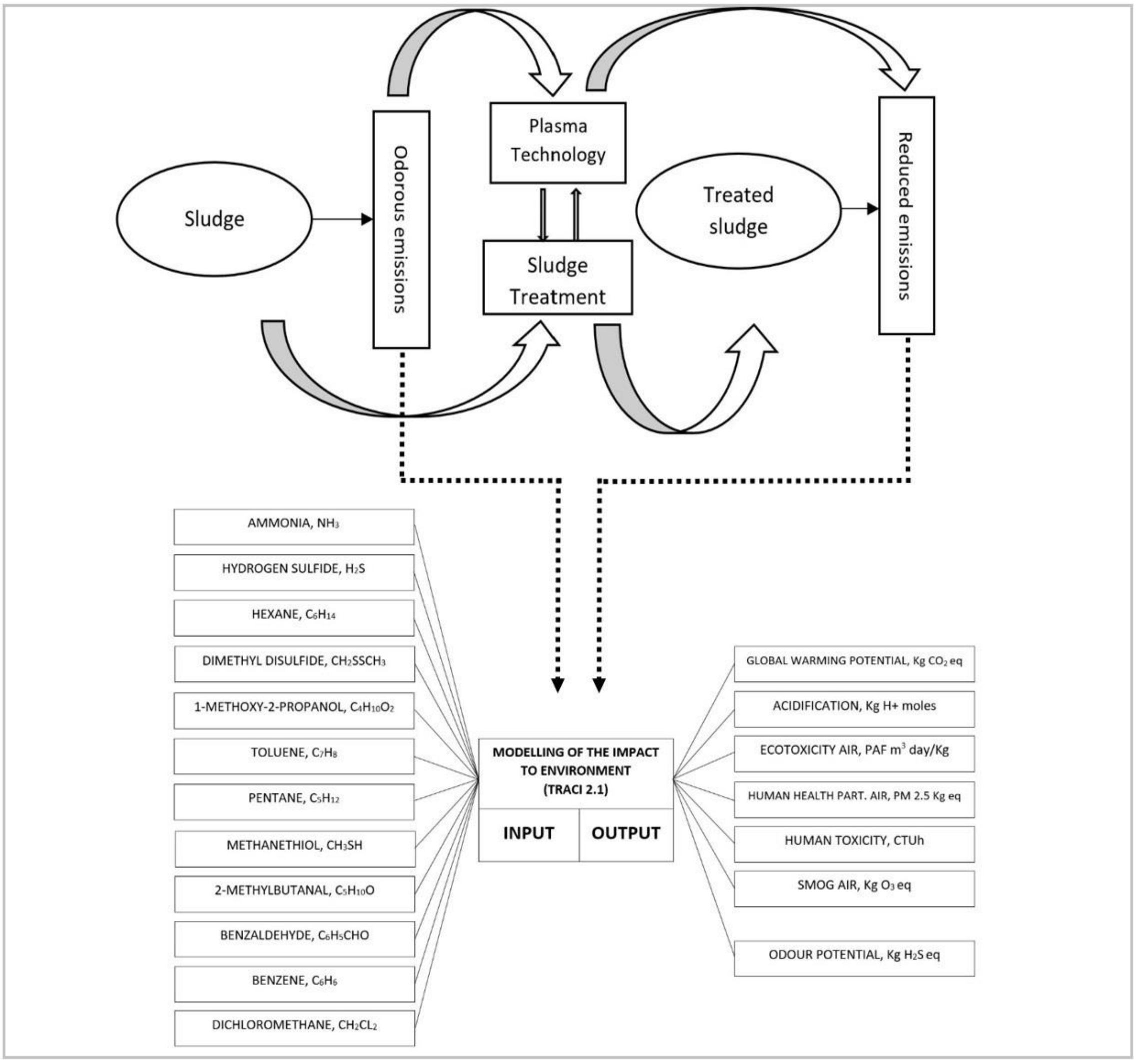

Fig. 5. LCIA model applied to assess the impact of odorous gases before and after non-thermal plasma treatment.

TRACI 2.1 model uses the *Global warming potential* (GWPs) evaluation for the calculation of the potency of greenhouse gases relative to CO_2. *Acidification* assessed using the model that incorporates the increasing hydrogen ion potential within the environment without incorporation of site-specific characteristics such as the ability environments to provide buffering capability. The *Human toxicity* and *Eco toxicity for urban air* (emissions to air) are modelled using the "USEtox" model that cover toxicity potentials for over 3000 substances including organic and inorganic compounds. The method for calculation of *Human health impact (particulate)* includes the modelling of the fate and exposure of intake fractions (i.e., that portion of the emitted substance, which expected to be inhaled by a human being). These intake fractions calculated as a function of the amount of substance emitted into the environment, the resulting increase in air concentrations, and the breathing rate of the exposed population. Concentrations of emitted particles in the air are the function dependent on location, on release of substances and meteorology. Substances characterized using PM2.5 (“fine particles” which are smaller than or equal to 2.5 micrometres in diameter, and are often the products of combustion as the reference substance). The *Smog air potential* (photochemical smog formation) modelled within TRACI 2.1 using the „Maximum Incremental Reactivity (MIR)“ that covers human and environmental effects. The MIR model covers nearly 1200 substances, where Ground level ozone created by various chemical reactions with the energy of the sunlight and forms smog (PM - particulate matters) in the air [10]. The most common chemical PM components include sulphates, nitrates, ammonia, other inorganic ions such as sodium, potassium, calcium, magnesium and chloride ions, organic and elemental carbon, crustal minerals, water bound by particles, metals (including vanadium, cadmium, copper, nickel and zinc) and volatile organic compounds (VOC). The composition of PM also contains biological components, such as allergens and microorganisms [12]. The *Odour potential* modelled considering the odour detection threshold, the diffusion rate and the kinetics of degradation of odorants. The impact assessment currently contains 33 characterization factors for the units of hydrogen sulphide equivalents [9, 11].

THE DATA OF ODOURANTS OBTAINED DURING THE TESTS OF THE NON-THERMAL PLASMA TECHNOLOGY APPLICATION

The average reduction of 25 % was reached (of all compounds) in the first phase of plasma application and 40 % (of all reductive compounds) in the second phase [6, 7]. The obtained data of reductions of odorous gases summarized in the Figure 6.

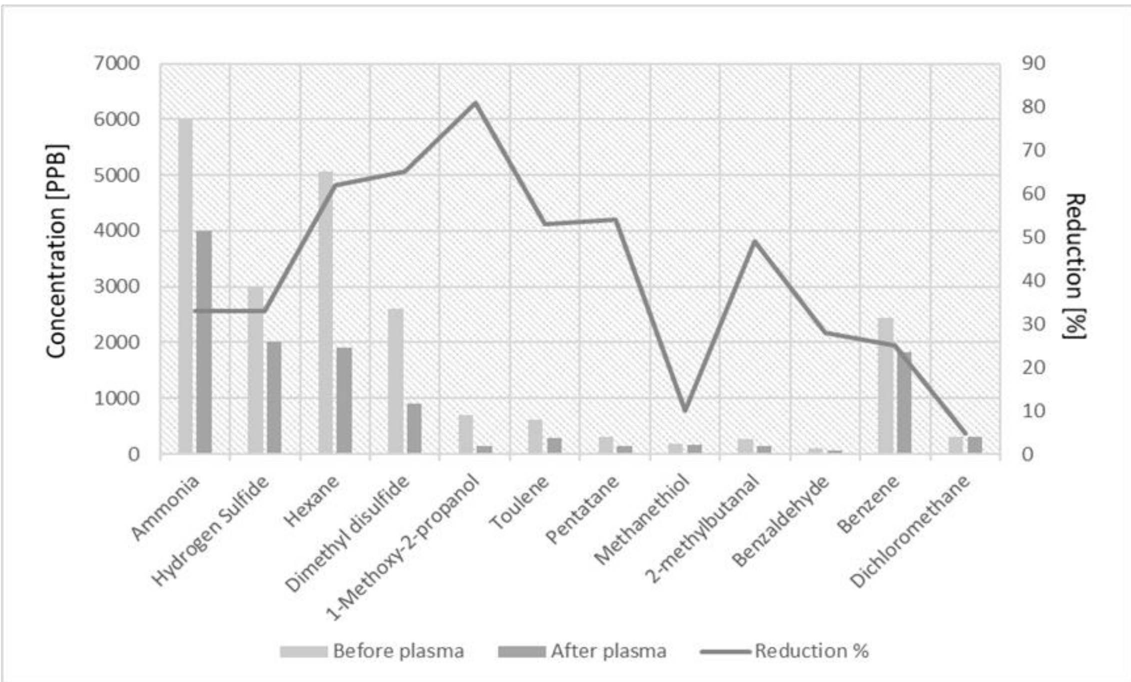

Fig. 6. Reduction efficiency of chemical gas compounds using the non-thermal plasma technology.

Plasma treatment can be cost effective treatment solutions for low concentration of exhaust pollutants and for deodorization. In case of sludge treatment, the satisfactory results obtained during experiments in Poland, still as speculated by designers of the technology the plasma device should be extended with another technology to remove a wider variety of compounds. Main advantages of this technology are listed as : low operating and investment costs; waste – free processing; relatively small size of necessary equipment; low pressure drop in case of CD and UV units; additional disinfection of treated gases; reasonable efficiency. Main disadvantages of the developed technology are listed as: risk of corrosion of installation parts; presence of strongly oxidizing agents; possible ozone presence after treatment; efficient only for compounds which are susceptible to oxidation; possible synthesis of undesired by-products. These advantages and disadvantages inevitably had the influence on the data obtained during the experiments [7].

LIFE CYCLE IMPACT ASSESSMENT OF THE ODOURS RESULTING FROM NON-THERMAL PLASMA TREATMENT APPLICATION

To assess the gas flows formed at the sludge treatment plants, the two different scenarios were simulated: the untreated gas flows forming the odours and plasma treated gas flows forming the odours. To simulate these gas flows the input model parameters were used (Marcin Hołub, 2021 on personal communication):

Table 1. Input data for LCIA assessment: emissions of the sewage sludge treatment gases before and after odour plasma treatment (per m^3 of gas).

Gas	Parts per billion [PPB]	
	Before treatment	**After treatment**
Ammonia	6000	4000
Hydrogen Sulfide	3000	2000
Hexane	5056	1902
Dimethyl disulfide	2601	910.8
1-Methoxy-2-propanol	701.3	133.6
Toulene	610.5	284.4
Pentane	306.9	140
Methanethiol	192	172
2-methylbutanal	269	137
Benzaldehyde	97	70
Benzene	2432	1824
Dichloromethane	317	302

The LCIA modelling results (the inventory of the modelling outputs are given in the Annex I) revealed the reduction of all modelled environmental impact indices. The highest reduction, while applying the non-thermal plasma treatment of odorous gases is reached of Air Smog formation potential (photochemical smog formation); Human toxicity potential and Air ecotoxicity potential (Figure 7).

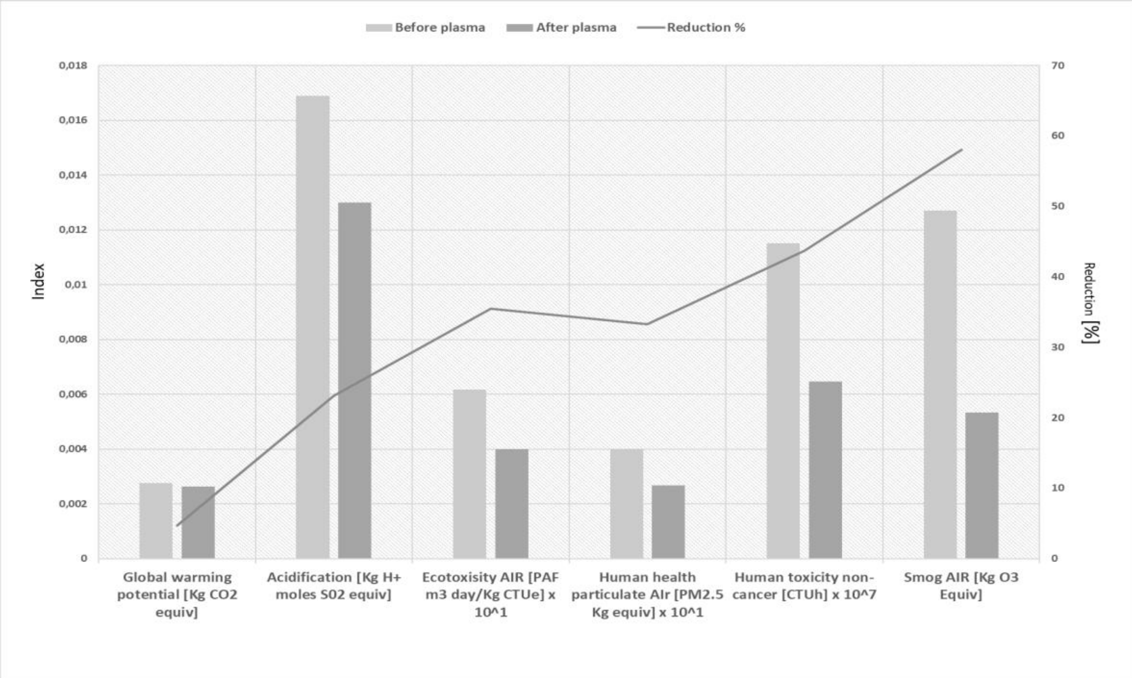

Fig. 7. LCIA modelling results of the odorous gases before and after plasma treatment (indices provided per m^3 of the gas flow).

Despite the highly reduced LCIA indices (58% Smog formation potential index reduction is reached) with an application of the non-thermal plasma treatment, the total Odour potential is assessed as can be reduced up to 33% (Index is reduced from 0.0672 to 0.0448 per cubic meter of gas). The comparison of modelled Odour potential indices provided in the Figure 8.

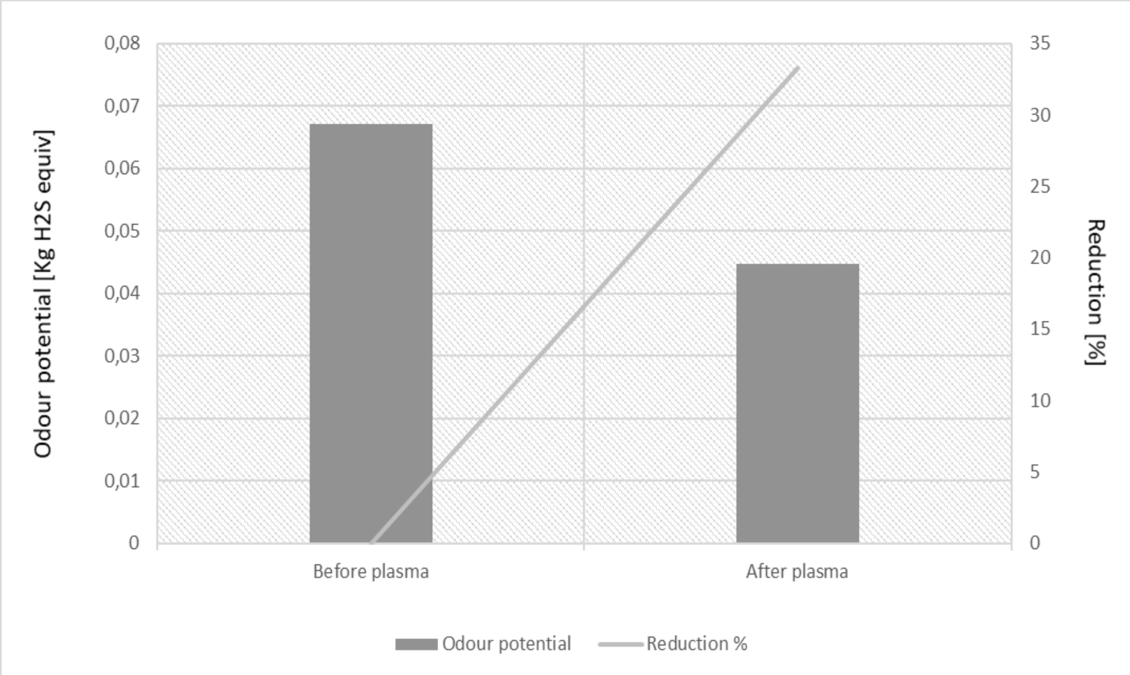

Fig. 8. Modelled odour potential index for two trial cases: gas treated with plasma and untreated with plasma.

The obtained Odour potential's indices suggest that the non-thermal plasma odorous gas treatment has a potential to reduce the odours although even higher effectiveness reachable using non-thermal plasma in combination of other gas treatment options [1].

CONCSLUSIONS

- The gas emissions of wastewater sludge treatment's process (for instance, composting) can be reduced effectively using the non-thermal plasma treatment. The life cycle impact - Global warming potential (CO_2 equiv, kg) can be reduced up to 4.7%; Acidification (H+ moles S02 equiv, kg) by up to 23%; Ecotoxisity in air (PAF m^3 day/kg CTUe) by up to 35.4%; Human health particulate in air (PM2.5 equiv, kg) by up to 33.25%; Human toxicity non-cancer (CTUh) by 43.7% . Smog formation in air (O_3 equiv, kg) by 58%.
- The LCIA odour potential (H_2S equiv, kg) using the non-thermal plasma odorous gas treatment system can be reduced up to 33% at sludge drying and storage facilities, where even higher reduction can be achieved using the hybrid systems (for instance, scrubbers) incorporating the non-thermal plasma odorous gas treatment techniques;

- The odorous gas emissions of sludge treatment process can be effectively reduced by using the non-thermal plasma treatment in combination with other technologies or separately where this technology can be applied to treat the odorous gases forming during the different stages of sludge treatment, such as mechanical separation, drying or composting.

ACKNOWLEDGEMENTS

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ANNEX I

ODOUR TREATMENT LCIA MODELLING OUTPUTS

Index	With plasma treatment <u-so>	Outputs
TRACI	TRACI 2.1, Acidification [kg SO2 eq.]	0.0113
	TRACI 2.1, Ecotoxicity (recommended) [CTUe]	0.000399
	TRACI 2.1, Eutrophication [kg N eq.]	0.000476
	TRACI 2.1, Global Warming Air, excl. biogenic carbon [kg CO2 eq.]	0.00263
	TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2 eq.]	0.00263
	TRACI 2.1, Human Health Particulate Air [kg PM2.5 eq.]	0.000267
	TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	5.65E-10
	TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	6.47E-10
	TRACI 2.1, Smog Air [kg O3 eq.]	0.00533
USEtox	USEtox, Human toxicity, cancer (recommended) [CTUh]	5.65E-10
Odour	Odour potential [kg H2S eq.]	0.0448
Technical quantities	Mass [kg]	0.0119
	Standard volume [Nm3]	1

Index	Without plasma treatment <u-so>	Outputs
TRACI	TRACI 2.1, Acidification [kg SO2 eq.]	0.0169
	TRACI 2.1, Ecotoxicity (recommended) [CTUe]	0.000618
	TRACI 2.1, Eutrophication [kg N eq.]	0.000714
	TRACI 2.1, Global Warming Air, excl. biogenic carbon [kg CO2 eq.]	0.00276
	TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2 eq.]	0.00276
	TRACI 2.1, Human Health Particulate Air [kg PM2.5 eq.]	0.0004
	TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	7.50E-10
	TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	1.15E-09
	TRACI 2.1, Smog Air [kg O3 eq.]	0.0127
USEtox	USEtox, Human toxicity, cancer (recommended) [CTUh]	7.50E-10
Odour	Odour potential [kg H2S eq.]	0.0672
Technical quantities	Mass [kg]	0.0216
	Standard volume [Nm3]	1

ANNEX II

WWTP EXHAUST AIR TREATMENT SCHEME [2]