# Tracking nonregulated micropollutants in sewage sludge: antimicrobials, OH-PAHs, and microplastics — environmental risks, fertilizer implications and energy considerations

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## Abstract

This study analysed the content of selected antimicrobials agents (AAs), microplastics (MP), hydroxyl derivatives of polycyclic aromatic hydrocarbons (OH-PAHs) in stabilized sewage sludge and fertilizers produced from them. Eighteen AAs were identified and quantified in both sewage sludge and fertilizer samples using the LC-MS/MS method. The highest concentrations, exceeding 3,000 μg kg$^{-1}$, were found for sulfasalazine, clindamycin, ketoconazole and its deacetylated form, azithromycin, and desmethylated azithromycin. While the fertilizer production process successfully reduced the number of AAs present, 20 compounds persisted, with five exceeding 1,000 μg kg$^{-1}$, posing potential environmental concerns. The FTIR method revealed an average MP content of 2,429 ± 758 fractions in stabilized sewage sludge. Both black and colored microplastic fragments were detected, with an average of 1,070 and 665 particles, respectively. These findings suggest that microplastic contamination remains an issue even after sewage sludge stabilization. GC-MS/MS analysis identified six OH-PAHs in sewage sludge and fertilizer samples. In stabilized sewage sludge, concentrations ranged from 53 µg kg$^{-1}$ (2-HydroxyFluorene) to 587 µg kg$^{-1}$ (1-HydroxyNaphthalene), while in fertilizers, values ranged from 4.7 µg kg$^{-1}$ (2-HydroxyNaphthalene) to 31 µg kg$^{-1}$ (1-HydroxyPyrene). The fertilizer production process effectively removed from 46% to 88% of OH-PAHs, with 3-OH-BaP levels falling below detection limits. Despite the effectiveness of the fertilizer production process in reducing several contaminants (e.g., sulfamethoxazole, metronidazole, trimethoprim, pyrazinamide, sulfadiazine, delamanid, and piperacillin), certain pollutants, including clindamycin and ketoconazole, persisted. Additionally, the economic analysis of the annual profitability of processing sewage sludge into a fertilizer product was performed. The estimated costs and profits were taken into account. This analysis indicates that the total annual income from the operation of the installation will amount to USD 233,300. However, further research is needed to fully investigate and develop this method in reference of Circular Economy management.

**Keywords:** Sewage sludge, micropollutants, GC-MS, LC-MS, antimicrobial agents, microplastics, OH-PAHs

## 1. Introduction

In recent years, there has been increasing interest in researching the presence of antibiotics, microplastics, polycyclic aromatic hydrocarbons, and other micropollutants in sewage sludge and their potential impact on the environment and emerging pollutants. Thus, they can escape into the adjacent environment, be retained on activated sludge particles, and accumulate in stabilized sewage sludge (Matesun et al. 2024). Sewage sludge (SS) is generated in wastewater treatment plants (WWTP) as a specific, nutrient-rich by-product from wastewater treatment processes and requires appropriate management. The increase in population and new regulations requiring secondary wastewater treatment (e.g., activated sludge) result in a significant increase in the amount of SS produced. Consequently, the costs associated with SS processing and management are also increasing. The costs associated with the treatment of SS and its subsequent management are estimated to represent 20-60% of the total expenditure related to the operation of a WWTP (Pyssa, 2019a). In EU countries, such as Poland, the management of SS has been significantly affected by the legal requirements. This resulted in a ban on the storage of SS (from 1 January 2016) and an annual increase in SS generation due to the expansion of sewage networks and sewage treatment plants. For these reasons, EU countries face significant economic, technical, and ecological problems. Often, the final stage of SS is mechanical dewatering and drying (Pyssa, 2019b). However, legal, aesthetic, and practical issues require that SS generated in sewage treatment plants is appropriately disposed of. Treated SS derived from small and medium sewage treatment plants can usually be used for agricultural purposes, while those from large sewage treatment plants may require additional pre-treatments because of too high concentrations of heavy metals (HMs) in the SS (Pyssa, 2019b).

Due to its fertilizer and humus-forming properties, municipal SS enriches the soil with valuable components (nitrogen, phosphorus, sulphur, or magnesium) and organic matter. However, factors limiting or even excluding their use in agriculture or for environmental purposes are often excessive HM concentrations, the presence of organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), adsorbable organically bound halogens (AOX) or pathogenic organisms and parasite eggs (Lamastra, Suciu, Trevisan, 2018). Considering the above, recent studies have been reviewed on pharmaceuticals and their derivatives and other micropollutants in SS (Bolesta et al., 2022).

Wastewater network can be used to utilized wastewater in WWTP with about 100% efficiency through extraction and fermentation in order to obtain the methane gas, while the sewage sludge can be transform into organic fertilizers and to purify water for agriculture (Nassar et al., 2024). Nevertheless, the conventional WWTPs are not adapted to degrade the emerging contaminants, including AAs, MPs and OH-PAHs. Therefore, from the ecological point of view, despite the significant benefits of using treated SS as fertilizers, their production involves the risk of spreading micropollutants along with the product, which might result in their transfer to the environment (Corradini et al., 2019; Verma et al., 2023). This emission can lead to contamination of soil, groundwater, and water systems, which, in turn, carries risks for human health.

One of the groups of substances that are present in wastewater is Antimicrobial Agents. These compounds can kill or inhibit the growth of microorganisms such as bacteria, viruses, fungi or parasites. The main categories of AAs include antibiotics, antivirals, antifungals, and antiparasitics. Among other pharmaceuticals most frequently found in the environment are nonsteroidal anti-inflammatory drugs, antibiotics, hypolipidemic drugs, hormonal agents, β-blockers, and psychotropic drugs (Nikolaou et al., 2007). The presence of AAs in SS is essential to the natural environment due to its strong negative impact on living organisms. Gene transfer, antibiotic resistance, changes in animal physiology, and damage to their organs are some of the recorded effects of the secondary transfer of biocides into the environment (Chen et al., 2016; Frková et al., 2020; Küster, Adler, 2014; Rodríguez-López et al., 2022; Murray et al., 2019; Yuan et al., 2022; Jauregi et al., 2021). Although a statistically significant decrease in the average consumption of AAs was observed in European countries in the 2012-2021 span, these compounds are still detected and determined, for example, in natural or drinking water. According to the European Antimicrobial Consumption Network (ESAC-Net), in 2012, the average total consumption of antibacterial drugs for internal use in countries in the EU/EEA

(EEA – European Economic Area) was 21.2 DDD (defined daily dose per 1,000 inhabitants per day), while in 2021 it was 16.4 DDD (Antimicrobial consumption in the EU/EEA, 2021). Unfortunately, in 2022, the average consumption of antimicrobial drugs increased again (19.4 DDD per 1,000 inhabitants per day) (Antimicrobial consumption in the EU/EEA, 2022). This signals that the level of drugs circulating in the environment should be monitored continuously. As a result of their hydrophobic properties, many antimicrobial drugs tend to adsorb onto solid particles rather than dissolve in the aqueous phase. Taking into account the presence of antibiotics in municipal wastewater and SS and their potential use in the form of fertilizers in agriculture, planned production of fertilizer should be preceded by tests of the potential substrate intended for processing into fertilizer in terms of the content of biocidal drugs (Głodniok et al., 2019).

Microplastics (MPs) are another alarming SS contaminant group. These polymer particles, which are less than five millimeters in size, have attracted considerable attention in recent years due to their ubiquity in the environment on a global scale (Sun et al., 2019). Polymers most commonly used, such as polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polyurethane (PU), polypropylene (PP), and polystyrene (PS), are significantly introduced into the environment as a result of the large global production and consumption of plastics materials (Andrady, 2011; Gigault et al., 2016). The phrase "*microplastics in fertilizers*" appears more than 2,700 times in the *ScienceDirect* database, with the most significant increase in scientific articles occurring in 2018/2019. These tiny particles enter wastewater from a variety of sources, including incorrect recycling and disposal of plastic waste and its decomposition (*secondary* MPs), microbeads in cosmetics and personal care products (PCPs) (*primary* MPs), and even synthetic fibers shed from clothes during laundering (Li et al., 2018; Dey et al., 2021; Sarma et al., 2022). Wastewater in wastewater treatment plants is not effectively filtered out of such small particles; therefore, MPs can be deposited in the SS. It has been proven that MPs can be vectors for toxic substances, such as HMs, pesticides, and other organic chemicals (Sarma et al., 2022; Worek et al., 2023; Ding et al., 2021; Vimalkumaret al., 2022). Moreover, alarming scientific studies indicate their presence in organic fertilizers derived from sewage sludge (SS) (Dey et al., 2021; Schell et al., 2022). Many studies have confirmed that the presence of MP particles has increased in soils after applying organic fertilizers compared to soils without fertilization (Diaz-Basantes, 2022). For example, Corradini et al. (2019) researched farmland where SS was used and found evidence of the gradual accumulation of MPs over time. The data revealed a high concentration of MPs in the soil (Corradini et al., 2019). Currently, there is a lack of standardized separation and identification methods for MPs. Therefore, many different approaches are tested. Digestion and density separation in saturated salt solution are most commonly used for extraction, while identification is carried out by microscopic and spectroscopic methods, including confocal and Raman techniques (Nguyen et al., 2022).

Polycyclic aromatic hydrocarbons (PAHs) are one of the largest groups of compounds described as micropollutants. This group contains over 10,000 substances (Wirnkor et al., 2019). PAHs are generally persistent semivolatile organic pollutants formed due to incomplete combustion process of organic material (Celma et al., 2023). In terms of structure, these compounds consist of 2 or more aromatic rings, ensuring hydrophobic and lipophilic character (Celma et al., 2023; Maciejczyk et al., 2023). There are two groups of polycyclic aromatic hydrocarbons: high molecular weight (HMW) and low molecular weight (LMW) (Wang et al., 2022). The first group of compounds tends to settle on particles in the air, and the second group remains in the environment in gaseous form (Lag et al., 2020). PAHs may enter the environment naturally (for example, forest fires) or anthropogenically, for instance, in industry, transport, and households, due to incomplete combustion of organic materials (Maciejczyk et al., 2023). PAHs are ubiquitously present near factories using fossil fuels, such as fuel refineries, gasworks, and factories producing and using coal tar and coke, or near roads with heavy traffic. These compounds can also be found in water bodies: rivers, lakes, or even drinking water, although, due to their high hydrophobicity, their concentration in water samples is significantly lower than in sediments and soils (Celma et al., 2023). PAHs and their derivatives can enter the environment through different pathways, depending on the method of removal of the SS. Their concentration in the SS depends on the differences in geography and the nature of the processes that occur in the wastewater treatment plants. Furthermore, organic pollutants, such as PAHs, can stay in the soil for months and years due to their sorption to the soil's mineral, organic, and amorphous phases and slow biodegradation (Mohammed et al., 2021). PAHs are particularly dangerous because of their negative impact on organisms. It has been confirmed that they can be mutagenic (Umbuzeiro et al., 2008), toxic (Bandowe et al., 2019), and carcinogenic (Patel et al., 2020). The European Union and the US Environmental Protection Agency (US EPA) classified PAHs as priority pollutants (Chen et al., 2019). PAHs are metabolized in organisms, thus transforming themselves, among others, into hydroxy derivatives of PAHs (OH-PAHs), which are biomarkers of human exposure to PAHs. These derivatives are then excreted into the urine and end up in sewage treatment plants (Yang et al., 2021; Pojana, Marcomini, 2007). Other studies have shown that air pollution can be a source of OH-PAHs in wastewater, which subsequently accumulate in sediments. Research suggests a strong correlation between the seasonal variability of OH-PAH concentrations in wastewater in Kraków and air quality, with higher levels of these metabolites observed during winter, coinciding with increased air pollution (Styszko et al., 2025a). Concentrations of hydroxyl derivatives of aromatic hydrocarbon may be even higher in the runoff than in the inflow to sewage treatment plants due to the formation of these derivatives (Pojana, Marcomini, 2007).

While considering the formation of fertilizers from SS, the economical aspect should also be taken into account. Difficulty in estimating the cost of preparing sewage sludge installation for producing of fertilizers should be based on the economic conditions, as well as local economic situation and applicable law.

At the same time, an equally important consideration is the energy potential of sewage sludge, which, if effectively utilized, can contribute to both economic feasibility and environmental sustainability. Although wastewater treatment plants play a crucial role in environmental protection, their operation is highly energy-intensive. However, they also hold untapped energy potential that can be recovered through renewable sources (Biedrzycka, 2016). In particular, it is possible to use both the hydropower potential (related to the height of the wastewater gradient) and the biomass potential (resulting from the organic matter content of the sludge) (Awad et al., 2023). Wastewater treatment plants that are located in high places can provide opportunities for generating sustainable energy, by installing hydroturbines at inlet and exit pipes of wastewater treatment plants, as well as exploiting the sludge resulting from the treatment process as a source for generating biogas, which can be used to generate electric power (Miskeen et al. 2023). In the context of the circular economy and low-emission energy policy, renewable energy sources derived from local resources play a key role, especially in the water and wastewater management sector (Biedrzycka, 2016). Environmental assessments suggest that the implementation of this hybrid system could lead to a substantial reduction in $CO_2$ emissions from the power generation sector (Nassar et al., 2023). According to the circular economy concept, converting sewage sludge into biogas represents an example of energy recovery from waste, contributing to a reduced reliance on conventional energy sources and lowering greenhouse gas emissions (Nassar et al., 2024). Therefore, the analysis of sewage sludge is not limited solely to assessing the presence of contaminants such as antibiotics, OHPAHs, or microplastics but also includes evaluating its potential as a renewable energy source (Miskeen et al., 2023).

This paper concern both the ecological and economical, as well as energical aspects. This study investigated the presence and concentration of common, selected AAs, OH-PAHs, and MP particles in stabilized SS and fertilizers produced from it. Additionally, we aim to investigate how the processing and preparation of fertilizers from stabilized sewage sludge affects the reduction of pollutants in these sludges. The concentrations of the compounds from the first two groups were determined by the QuEChERS-LC/GC-MS/MS method. Confocal-Raman microscopy and Fourier transform infrared spectroscopy (FT-IR) assessed the quality and quantity of separated MPs.

## 2. Methods

### 2.1 Reagents and chemicals

The representative compounds were:

**- AAs:** Pyrazinamide (PZA), Isoniazid (INH), Metronidazole (MTZ), Nalidixic acid (NAL), Emtricitabine (FTC), Sulfapyridine (SPY), Sulfadiazine (SDZ), Sulfamethoxazole (SMX), Trimethoprim (TMP), Linezolid (LZD), Penicillin V (PenV), Ofloxacin/Levofloxacin (OFX), Sulfasalazine (SLZ), Delamanid (DMD), Clindamycin (CLI) Erythromycin (ERY), Clarithromycin (CLR), Azithromycin (AZM), N-Desmethyl azithromycin (dmAZM) Isonicotinic acid (INa), 5-hydroxypyrazinoic acid (hPZA), S, S-ANP (2-amine-1-(4-nitrophenyl)-1,3-propanediol (S, S-ANP), N-Desmethyl erythromycin (dmERY), N-desmethyl clarithromycin (dmCLR), Ketoconazole (KTC), Deacetyl-ketoconazole (daKTC) Piperacillin (PIP) were purchased from Sigma-Aldrich and LGC Standards.

**- OH-PAHs:** 1-naphthol (1-OH-NAP), 2-naphthol (2-OH-NAP), 2-fluorenol (2-OH-FLU), 9-phenanthrol (9-OH-PHEN), 1-pyrenol (1-OH-PYR), 3-benzo(a)pyrenol (3-OH-BaP). Analytical and stable isotope standards (>98%) were also purchased from Sigma-Aldrich and LGC Standards.

Methanol and water were HPLC-grade and purchased from Sigma-Aldrich. Formic acid (>95% purity) was purchased from Sigma-Aldrich.

Stock standard solutions of all tested AAs and OH-PAHs analytes were prepared by dissolving in methanol and stored at -20°C in a freezer.

Supel™ QuE Citrate Extraction Tubes and Supel™ QuE PSA Tubes for extraction and purification, and N-tert-butyldimethylsilyl-N-methyltrifluoroacetamide (MTBSTFA) used as a derivatizing agent were purchased from Sigma Aldrich.

For MPs analysis, standard 30% hydrogen peroxide ($H_2O_2$) solution and zinc chloride ($ZnCl_2$) solutions were purchased from Sigma-Aldrich.

### 2.2 Sampling

Stabilized sewage sludge samples were collected from a wastewater treatment plant in Kraków-Płaszów (Plaszow WWTP). The plant is the city's largest and the third largest in the country and handles more than 70% of the wastewater from the city centre from more than 680,000 inhabitants. Plaszow WWTP has an average capacity of 165,000 $m^3$ per day. Stabilised SS samples were collected in October 2021 and July 2022, transferred to the laboratory, and stored in the freezer until lyophilization and analysis. The characteristics of stabilized sewage sludge are presented in Table S1 in the supplementary material.

### 2.3 Processing sludge into fertilizer

The fertilizer was prepared according to Polish patent Pat.233754 dated October 7, 2019 (Głodniok et al., 2019). From each batch of SS samples taken, which was dehydrated in screw centrifuges after the methane fermentation process, 4 kg of stabilized SS was sent for processing into a full-value fertilizer product. The additives of this product also included dolomite flour, which absorbs moisture, alkalizes the soil, and enriches the product with Ca and Mg; hydrated lime to complete hygiene; and cellulose fibre, giving the granules physical durability. The percentages of individual ingredients were as follows: (i) sewage sludge – 74%, (ii) dolomite flour – 20%, (iii) hydrated lime – 5%, and (iv) microcellulose – 1%. All components are incorporated into a dynamic counter-rotating mixer and then into a disk granulator, forming and solidifying the particles. Fertilizer samples were dried for about three weeks at about 25°C before analysis.

## 2.4 Samples preparation for chromatographic analysis

Collected SS and obtained fertilizer samples were lyophilized (-50°C, at least 72h, vacuum atmosphere), crushed in a mortar, and sieved with a 40 μm sieve. From that step, all sample types were then stored at -20°C and underwent further separate studies.

## 2.5. Analysis of AAs and OH-PAHs

The selected compounds from AAs and OH-PAHs groups were extracted using the QuEChERS method. The final extract was subjected to LC-MS/MS and GC-MS/MS chromatographic analysis, as these methods are widely used to determine these compounds in environmental samples (Holton, Kasprzyk-Hordern, 2021; Styszko et al., 2021). To allow the GC-MS/MS analysis, samples were subjected to the chemical derivatization process to increase volatility by N-tert-butylodimelosililo-n-metamytrifluorocetamide (MTBSTFA). The chromatographic and mass spectrometric characterization of target compounds: RT (retention time), labelled internal standards, precursor and product mass fragments, product – main product ions (quantifier), recovery %, method detection limits, method quantitation limits for analysis of AAs are presented in Table S2 in the supplementary material.

Method validation parameters for AAs and OH-PAHs in samples of stabilized sewage sludge and fertilizers are presented in Tables S3 – S5 in the supplementary material.

## 2.6. Analysis of MPs

Samples of similar weight were flooded with 200 ml of 15% $H_2O_2$ per 10 g of sludge. The samples were then mixed on a shaker at a speed of 140 rpm and left for sedimentation (Worek, Styszko, 2025). The process was carried out several times. The top layer was decanted, washed with deionized water, and dried at ambient temperature. The MPs contained in the matrix residues were then separated in density using a saturated $ZnCl_2$ solution. Separation was performed several times to increase the recovery of MPs. Separated fragments were dried at room temperature and collected for further imaging. The morphology of the samples was examined using the Fourier transform infrared (FTIR) Spotlight 400 microscope and a confocal Raman microscope. Images were made with a WiTec Alpha 300 R microscope under a 10× air lens (Zeiss EC EpiplanNeofluar Dic 10/0.25) objective coupled with a 532 nm excitation laser, the UHRS 300 spectrometer (600 gratings/mm) with highly efficient thermoelectrically cooled CCD camera. A series of photographs of the samples were taken. The PerkinElmer Frontier Attenuated Total Reflectance Fourier Transform Infrared (ATR FTIR) spectrometer was applied. FTIR spectra were measured in the wavenumber range of 530-4000 $cm^{-1}$, averaging 64 scans per spectrum at room temperature (Worek et al., 2024).

## 2.7. Environmental impact as risk quotients values (RQ)

The ecological risk assessment as the RQ (risk quotients) in fertilizers were calculated for AAs and OH-PAHs. RQ values can be divided into 5 groups (Zhou et al., 2019):

- $RQ \geq 1$ – high environmental risk,
- $1 > RQ \geq 0.1$ – moderate risk,
- $0.1 > RQ \geq 0.01$ – endurable risk,
- $0.01 > RQ \geq 0$ – negligible risk,
- $RQ = 0$ -no risk – safe.

The RQ values were expressed as the ratio of the predicted environmental concentration (PEC) and the predicted no-effect concentration (PNEC) (Martín et al., 2012, Nikinmaa M., 2014). The PNEC values were provided by NORMAN Ecotoxicology Database and AMR Industry Alliance. The PEC values were calculated as follows (Martín et al., 2012):

$$PEC_{soil} = \frac{C_{sludge} \times APPL_{sludge}}{DEPTH_{soil} \times RHO_{soil}} \quad (1)$$

where $C_{sludge}$ means the concentration of tested compound in fertilizer in µg/kg, $APPL_{sludge}$ is the dry sludge application rate (equals 0.5 kg/m$^2$ year for agricultrure soils), $DEPTH_{soil}$ means the mixing depth of soil (equals 0.2 m for agriculture soils), and $RHO_{soil}$ is the bulk density of wet soil (equals 1700 kg/m$^3$ for agriculture soils).

## 2.8. Profitability for producing fertilizers from sewage sludge

There are known methods for calculating the price of fertilizers (Eteriki et al., 2023; Abdunnabi et al., 2023). However, in this work, calculations were made, estimating the costs incurred during the production of fertilizers in installations for obtaining fertilizers from sewage sludge and the profits obtained from its use. For this purpose, the prices of: electricity (Pająk, 2024), water (Waliduda, 2024), dolomite flour (Kłudka, 2025), lime (Kłudka, 2025), microcellulose (Vitaia, 2025), packaging (Kopciał, 2025), renovation and maintenance (Kwaśniewski, Bernaciak, 2015), depreciation (Łuczak, 2021), employee wages (Sedlak, Sedlak, 2025), insurance as an environmental policy (Wedziuk, 2022), property tax (Huczko, 2025) and other costs were estimated. The prices of profits from the sale of fertilizer (Daleszyński, 2018) and profits from reducing the costs of sewage sludge disposal (Biedrzycka, 2020) were also estimated.

## 2.9. Energy potential of sewage sludge

This subsection analyses the potential for energy recovery using the example of the Płaszów wastewater treatment plant in Kraków. On the basis of the available data, the potential power that can be obtained through the use of wastewater gradient energy (Hydropower Energy Potential) was calculated, and the energy value of sludge was estimated in terms of its use as a source of biogas (Biomass Energy Potential) (Awad et al., 2023). These analyses highlight the potential of wastewater treatment plants to operate not only as disposal sites but also as energy self-sufficient facilities.

In order to calculate the Hydropower Energy Potential [kW] of the inlet and outlet wastewater to the treatment plant, the following formula was used (Awad et al., 2023):

$$E_H = \left[\rho g Q \left(H - h_f\right)\right]_{inlet} + \left[\rho g Q \left(H - h_f\right)\right]_{outlet} \tag{2}$$

Where:

$\eta_t$ – the turbine’s hydraulic efficiency [%],

$\rho$ – the density of water [kg/m$^3$],

$g$ – the Earth’s gravitational acceleration [9,81m/s$^2$],

$Q$ – the volumetric flow rate of water [m$^3$/s],

$H$ – the hight from which the water drops [m]

$h_f$ – the pressure loss due to friction in the drainage pipe [m]

In the case of the Płaszów wastewater treatment plant, only the energy potential from the output (discharge of treated wastewater) is considered.

The Biomass Energy Potential ($E_B$, [kW]) in the sludge was calculated by the following formula (Awad et al., 2023):

$$E_B = W_{SW}\, SRG_{SW}\, H_{BG}\, \eta_{ele} \tag{3}$$

Where:

$W_{SW}$ – the average amount of treated wastewater [m$^3$/hr]

$G_{SW}$ – the rate of biogas production from sludge [243 $m^3$/ton]

SR – the amount of sludge in wastewater [1,3 kg/$m^3$]

$H_{BG}$ – calorific value of biogass [5,56 kHw/$m^3$]

$\eta_{ele}$ - – the electricity generation system's efficiency

The total energy recovered from the hydropower and biomass potential $E_t$ [kW] was calculated as follows (Awad et al., 2023):

$$E_t = E_H + E_B \tag{4}$$

## 2.10. Assumptions, limitations and uncertainties

According to research conducted so far, sample preparation for analysis is often the most error-prone step in environmental sampling, which increases the uncertainty of results. (Namieśnik, Górecki, 2000). In the case of environmental samples, a significant element influencing the accuracy of the analysis is the matrix effect. In this article, this effect was reduced by preparing the samples for analysis of the presence of antimicrobial compounds and hydroxyl derivatives of PAHs using the QuEChERS method. Errors may also be related to the selected analysis methods. In the case of LC-MS/MS and GC-MS/MS methods, the preparation of an appropriate method allows for the correct separation and effective ionization of the analytes. In the LC-MS/MS method, the separation is based on a properly selected gradient of the mobile phases, while in the case of the GC-MS/MS method, the temperature program determines the separation of the analytes (Patel, 2011; Frydel et al., 2025). A properly selected method of microplastic separation significantly affects the accuracy of the analysis. In the case of density separation, a significant parameter influencing its efficiency is a properly selected factor causing the separation of microplastics, which allows for the separation of both low-density and high-density microplastics. In this article, a $ZnCl_2$ solution was used, which allows for the separation of microplastics of different densities while maintaining a low purchase cost (Yang et al., 2021). Another factor influencing errors during the analysis is the estimated construction of an installation producing energy from a sewage treatment plant and the cost of producing fertilizers from sludge. In this case, the efficiency of energy production is influenced by the type of sewage treatment plant with its parameters, material costs and the local economic situation, which affects water prices, land purchase or inflation, as well as energy data including consumption and the local energy situation. Unfortunately, the economic and energy situation at the location of the sewage treatment plant is a factor that scientists conducting the research have no influence on (Nassar et al., 2022).

## 3. Results

### 3.1 AAs

In sewage sludge stabilized with methane fermentation, 27 biocidal drugs and derivatives were detected. Three compounds—SMX, MTZ, and TMP—were below the detection limit. The concentration of 18 compounds ranged from 5 to 1000 μg kg$^{-1}$ (Figure 1), with OFX reaching 879 μg kg$^{-1}$. Higher concentrations (>3000 μg kg$^{-1}$) were recorded for SLZ, CLI, KTC, their deacetylated forms, AZM, and dmAZM (Figure 2).

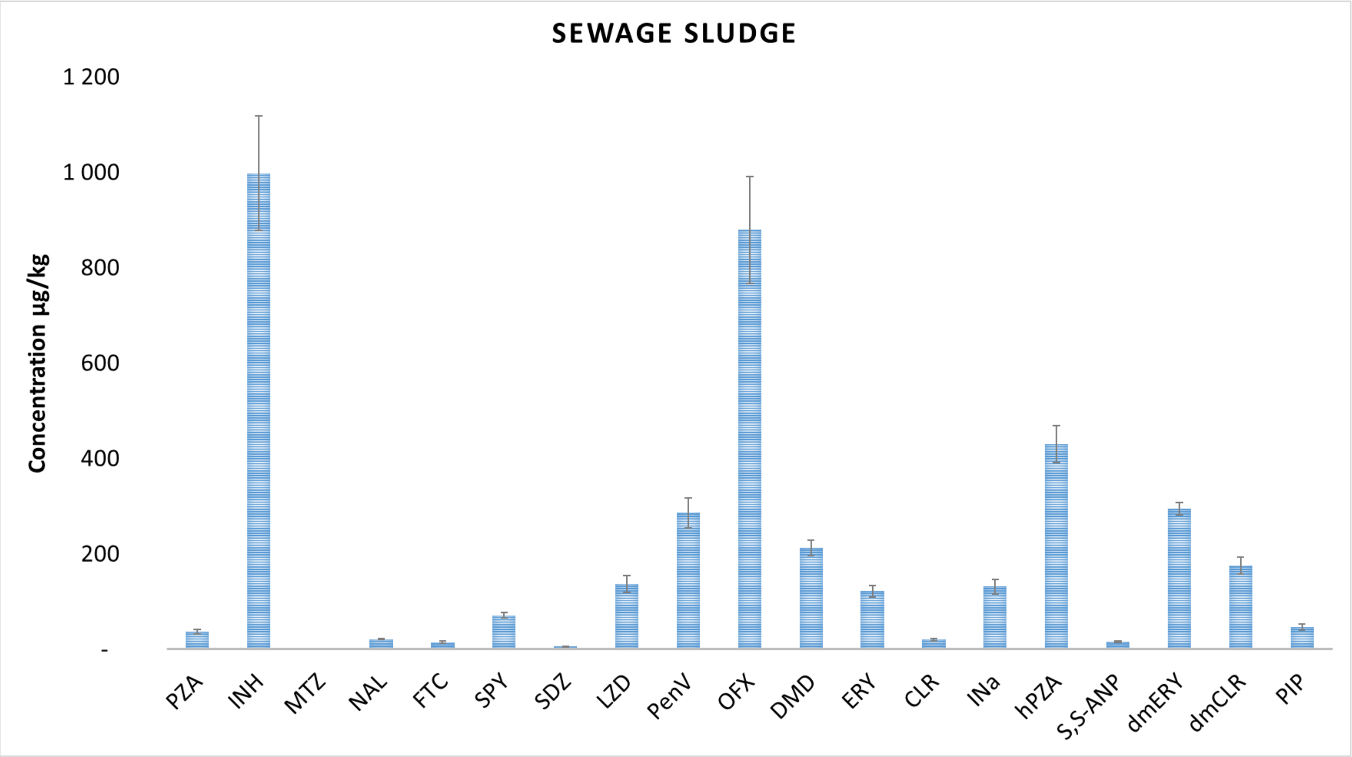

Figure 1. Average concentrations of antimicrobial agents in the stabilized sewage sludge (µg kg$^{-1}$). Standard deviations indicate variation between sampling days.

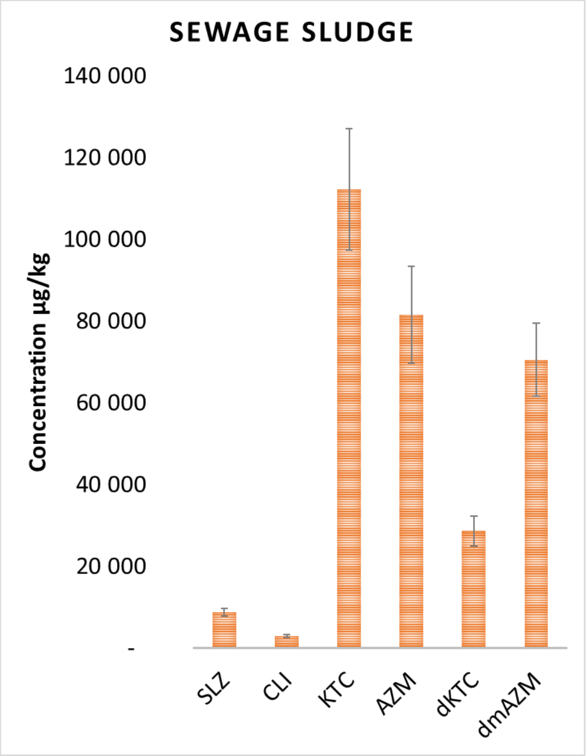

Figure 2. Average concentrations of antimicrobial agents in the stabilized sewage sludge with concentration above 3000 (µg kg$^{-1}$). Standard deviations indicate variation between sampling days.

In fertilizers, 27 biocidal drugs were detected, with 7 compounds—sulfamethoxazole, metronidazole, trimethoprim, pyrazinamide, sulfadiazine, delamanid, and piperacillin—below the detection limit. The concentration of 15 compounds ranged from 4 to 830 µg kg$^{-1}$ (Figure 3), while other compounds exceeded 1000 µg kg$^{-1}$ (Figure 4).

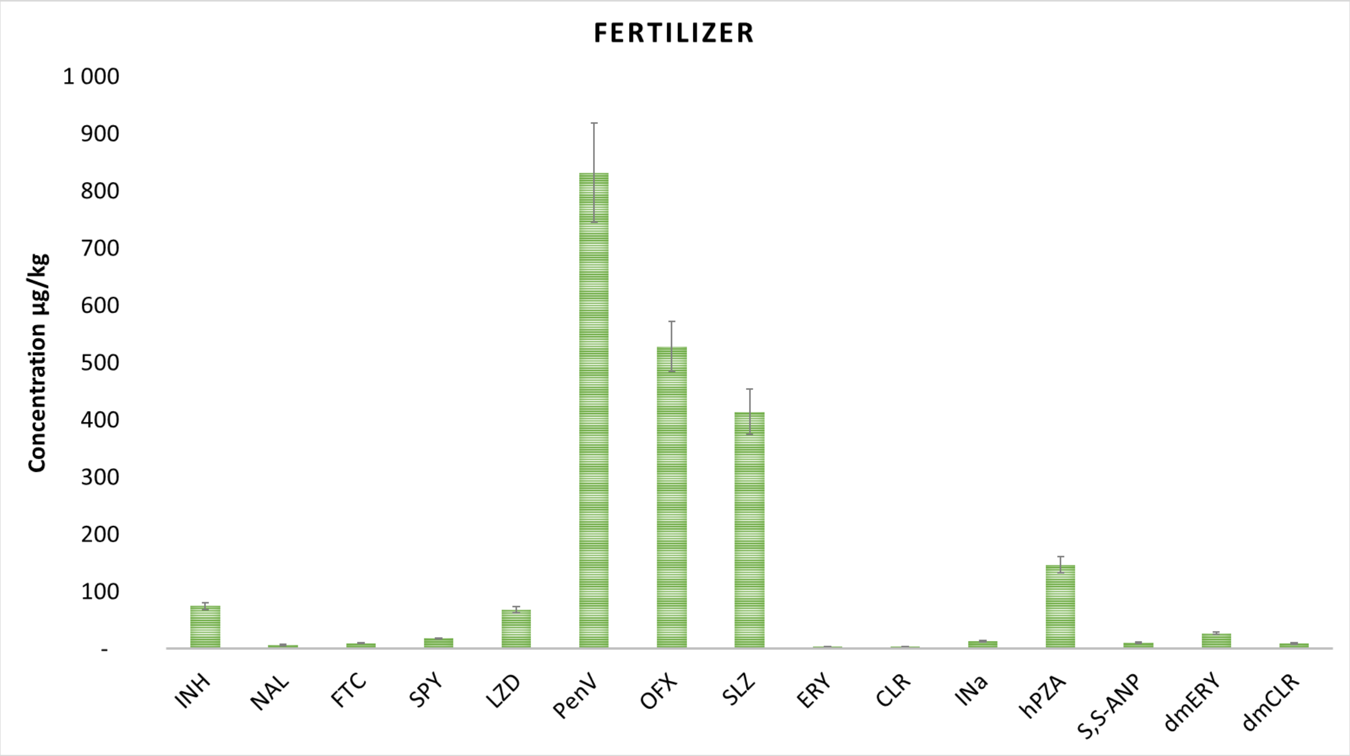

Figure 3. Average concentrations of antimicrobial agents in the fertilizers (µg kg$^{-1}$). Standard deviations indicate variation between sampling days.

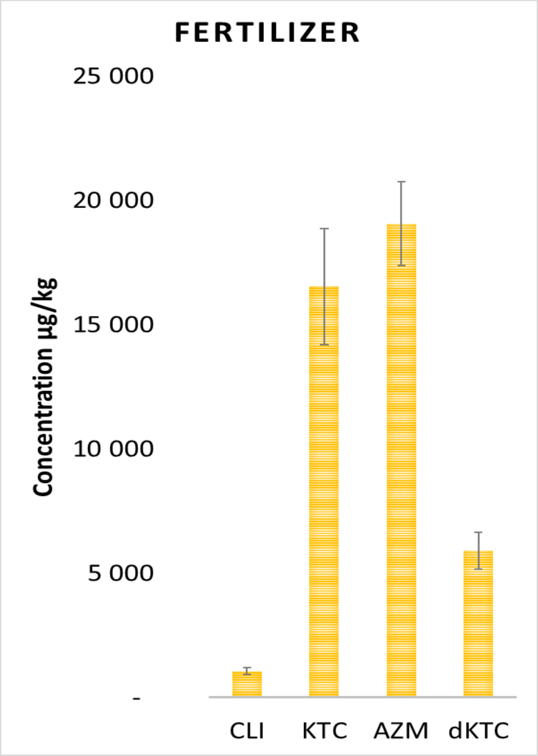

Figure 4. Average concentrations of antimicrobial agents in the fertilizer with a concentration above 1000 µg kg$^{-1}$. Standard deviations indicate variation between sampling days.

Comparing the pharmaceutical concentrations in the sewage sludge and fertilizer, a reduction in the drug content of pyrazinamide, sulfadiazine, delamanid and piperacillin to a level below the limit of quantification was observed (Figure 5).

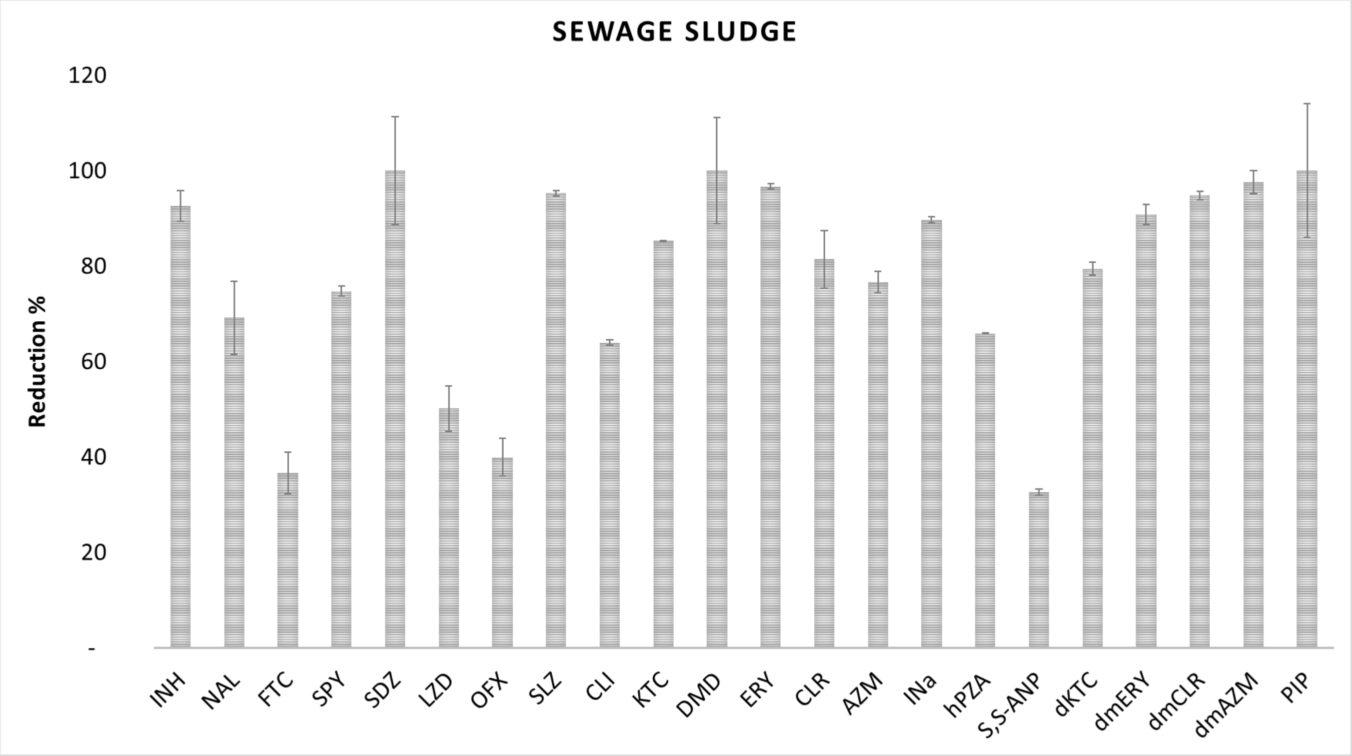

Figure 5. Average percentage of antimicrobial agents reduction in the process of production of fertilizer. Standard deviations indicate variation between sampling days.

## 3.2 MPs

Samples of stabilized sewage sludge (SS) and fertilizer were tested for microplastics (MPs) (Figure 6). The average MP content in SS was 2429 ± 758 particles per 100 g of dry SS. The volatility was 31%, with the majority of MPs being fragments (1734 per 100 g). Fibers accounted for 694 per 100 g of dry SS, with black fractions comprising 1343 and colored fractions 1086 (Figure 7). Fertilizer samples were also analysed (Figure 8). Fertilizer samples contained an average of 720 ± 119 MPs per 100 g, with a volatility of 17% (Figure 9). The fragment content was 463 per 100 g, and fiber content was 257 per 100 g. Black fractions dominated (477 per 100 g), followed by transparent (143) and colored (100).

Figure 6. Examples of separated fragments of MPs from samples of stabilized sewage sludge

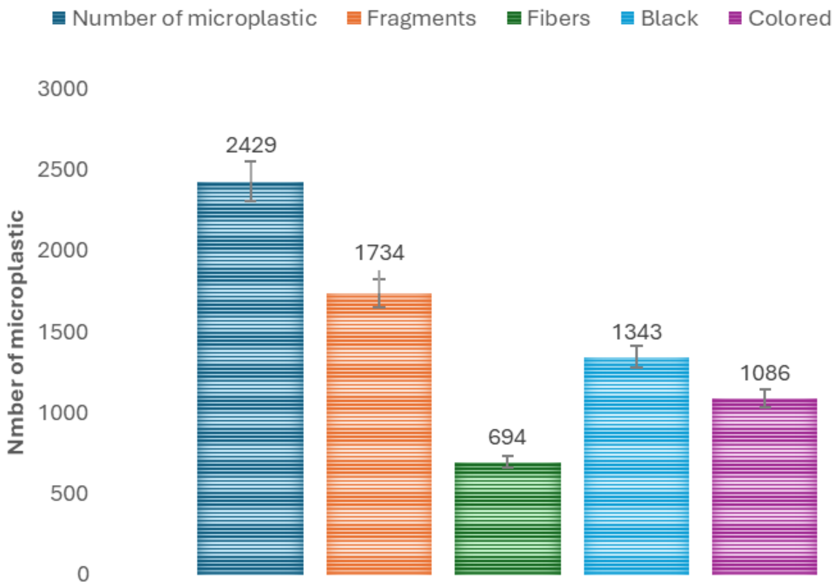

Figure 7. Number of microplastics in samples of stabilized sewage sludge taking their shape and colour into account. Standard deviations indicate variation between sampling days.

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Figure 8. Examples of separated fragments of microplastics from samples of fertilizer

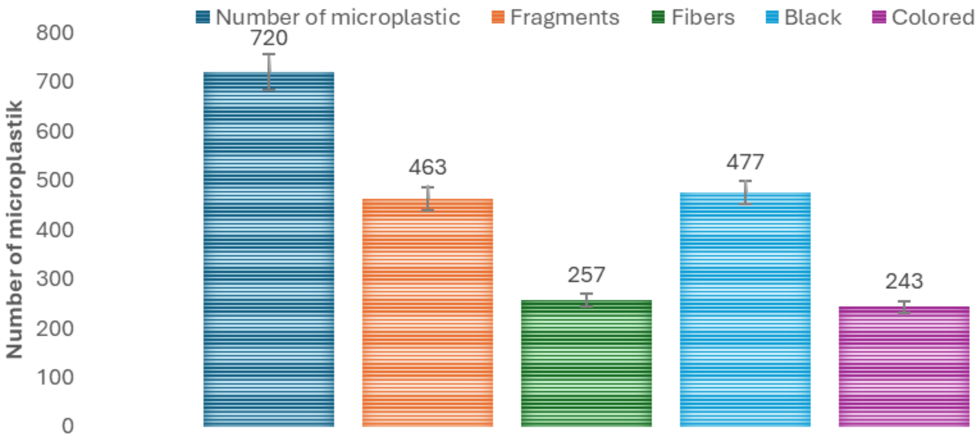

Figure 9. Number of MPs in fertilizers considering shape and colour. Standard deviations indicate variation between sampling days.

Spectral analysis confirmed the presence of LD-PE as the dominant MP type (Figure 10). C-H stretching vibrations were observed around 2920 cm$^{-1}$, with additional peaks at 1457 cm$^{-1}$ and 1397–1377 cm$^{-1}$, characteristic of LD-PE.

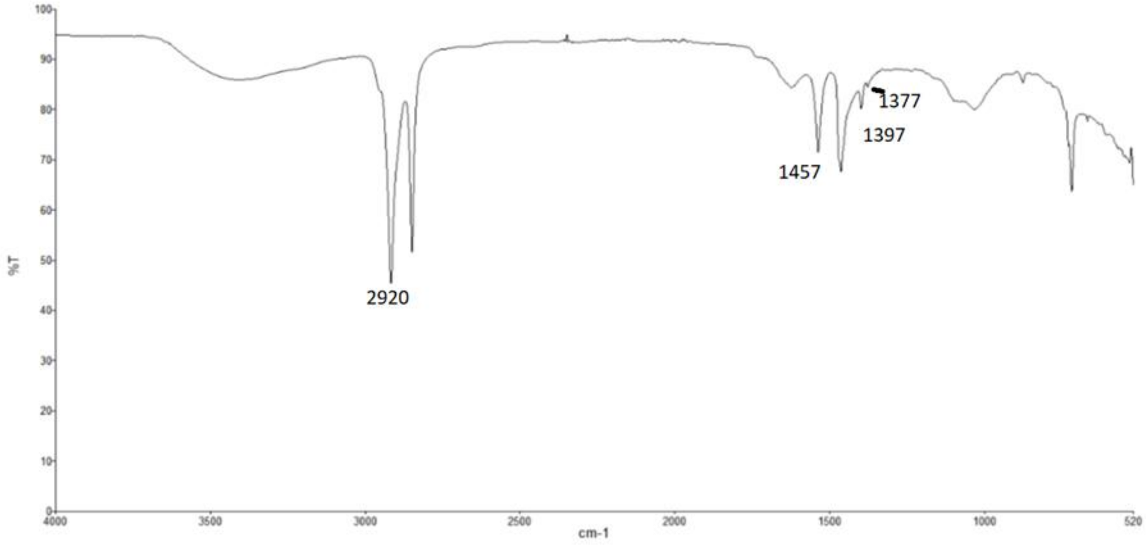

Figure 10. ATR-FTIR Spectrum of LD-PE microplastic

### 3.3. OH-PAHs

OH-PAHs were analyzed in stabilized sewage sludge (SS) and fertilizer with grain sizes <40 µm. Six compounds were detected: 1-OH-NAP, 2-OH-NAP, 2-OH-FLU, 9-OH-PHEN, 1-OH-PYR, and 3-OH-BaP. Except for 3-OH-BaP, all were present in every sample, while 3-OH-BaP appeared in only one SS sample.

The highest concentration in SS was 1-OH-NAP (744 µg $kg^{-1}$), while the lowest was 2-OH-FLU (89 µg $kg^{-1}$). In fertilizer, 1-OH-PYR had the highest concentration (159 µg $kg^{-1}$), and 3-OH-BaP was below the limit of detection (LOD) (Figure 11). The percentage reduction of OH-PAHs during sludge processing is shown in Figure 12.

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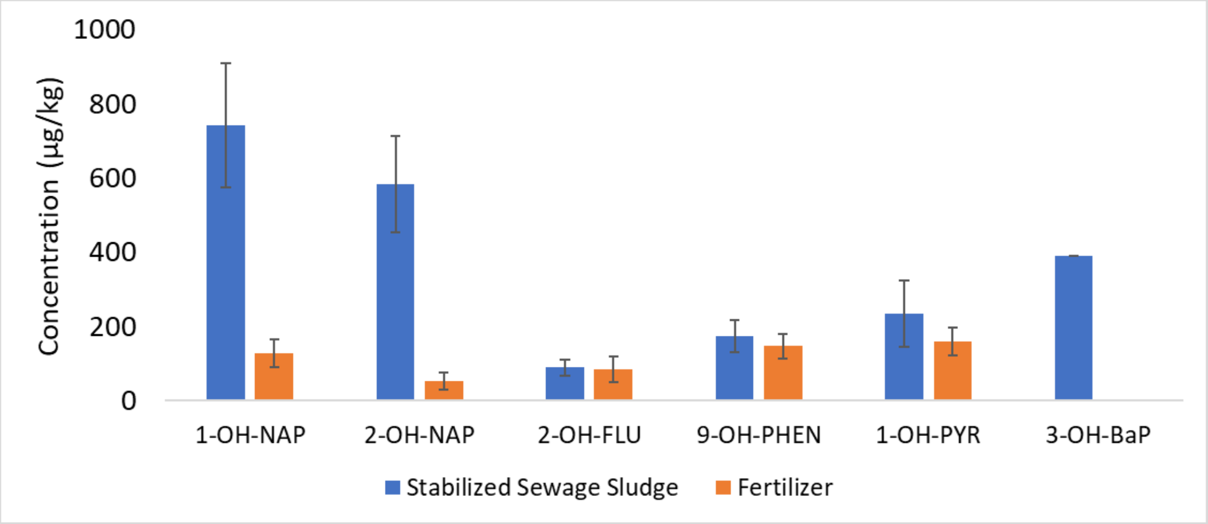

Figure 11. The average concentrations of OH-PAHs in the stabilized sewage sludge and fertilizers (µg/kg). Standard deviations indicate variation between 8 samples from four sampling days.

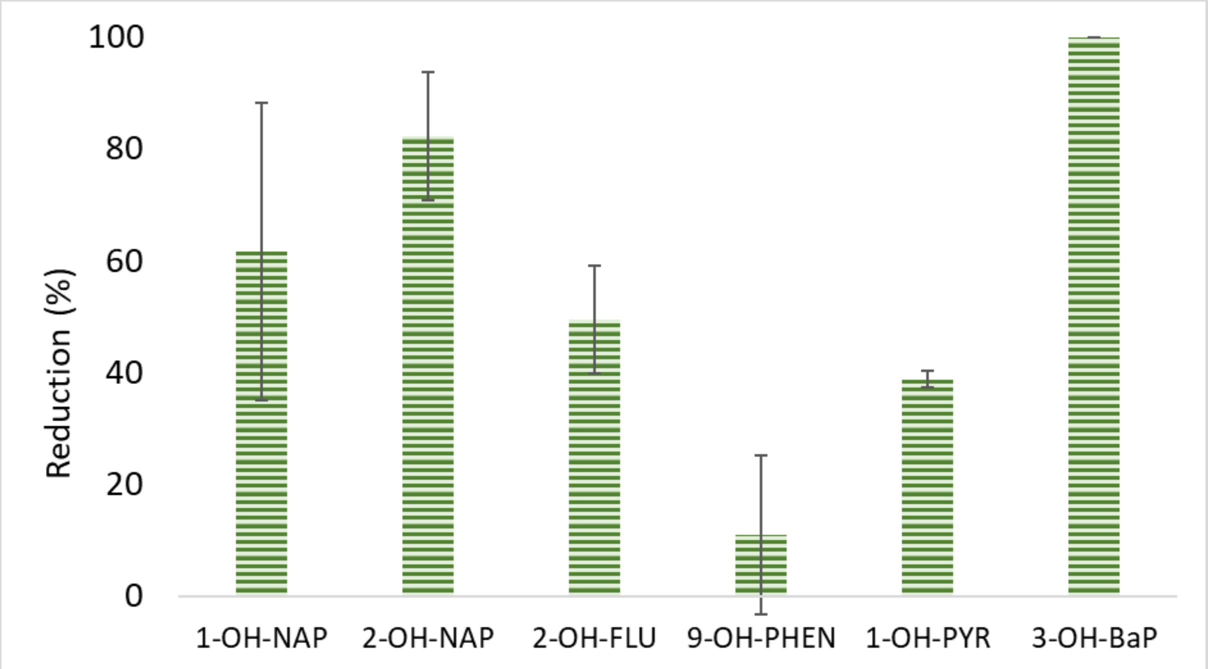

Figure 12. The average percentage of OH-PAHs' reduction in the process of fertilizer production. Standard deviations indicate variation between 8 samples from four sampling days

## 3.4 Environmental application

The values of PNEC, $PEC_{soil}$ and RQ are collected in Table 1.

Table 1. Ecotoxicological data for tested compounds.

| **Compound** | **$PNEC_{sediment}$ (µg/kg)** | **PEC (µg/kg)** | **RQ** |
|---|---|---|---|
| PZA | 166 | 0 | 0 |
| INH | 0.35 | 0.14 | 0.39 |
| MTZ | 0.58 | 0 | 0 |
| NAL | 190 | 0.01 | $5.13 \bullet 10^{-5}$ |
| FTC | 102 | 0.01 | $1.39 \bullet 10^{-4}$ |
| SPY | 4.13 | 0.03 | $6.47 \bullet 10^{-3}$ |
| SDZ | 7.28 | 0 | 0 |
| SMX | 3.67 | 0 | 0 |
| TMP | 3.64 | 0 | 0 |
| LZD | 146 | 0.11 | $7.57 \bullet 10^{-4}$ |
| PenV | 1.41 | 1.23 | 0.87 |
| OFX | 12.7/6.35 | 0.81 | 0.06/0.13 |
| SLZ | 0 | 0.69 | 0 |
| DMD | 130 | 0 | 0 |
| CLI | 0.43 | 1.50 | 3.49 |
| ERY | 657 | 0.01 | $1.04 \bullet 10^{-5}$ |
| CLR | 269 | 0.01 | $2.25 \bullet 10^{-5}$ |
| AZM | 40.8 | 31.88 | 0.78 |
| dmAZM | n.a. | 2.48 | - |
| INa | 335 | 0.02 | $6.10 \bullet 10^{-5}$ |
| hPZA | n.a. | 0.23 | - |
| S,S-ANP | 0 | 0.02 | 0 |
| dmERY | n.a. | 0.05 | - |
| dmCLR | 3481 | 0.02 | $5.24 \bullet 10^{-6}$ |
| KTC | 19.4 | 25.90 | 1.34 |
| daKTC | 0 | 8.29 | 0 |
| PIP | 0 | 0 | 0 |
| 1-OH-NAP | 3.11 | 0.19 | 0.06 |
| 2-OH-NAP | 143 | 0.08 | $5.49 \bullet 10^{-4}$ |
| 2-OH-FLU | 410 | 0.12 | $3.02 \bullet 10^{-4}$ |
| 9-OH-PHEN | 211 | 0.22 | $1.02 \bullet 10^{-3}$ |
| 1-OH-PYR | 151 | 0.23 | $1.55 \bullet 10^{-3}$ |
| 3-OH-BaP | n.a. | - | - |

### 3.5 Economical analysis

To conduct the economic analysis, it was assumed that 4,500 Mg of stabilized sewage sludge would be processed into a fertilizer product created in the amount of 4,880 Mg. Table 2 provides detailed data accepted for the analysis for one year of operation of the installation. It should be clearly emphasized that they are highly individual for the local economic situation and may vary depending on the availability of raw materials, materials, water prices, electricity, other raw materials, employee maintenance or demand for fertilizers.

Table 2. Economic analysis of the annual profitability of processing sewage sludge into a fertilizer product.

| **No** | | **worth [$]** |
|---|---|---|
| 1 | electricity | 390 000 |
| 2 | water | 300 |
| 3 | dolomite flour | 135 000 |
| 4 | lime | 51 500 |
| 5 | microcellulose | 57 500 |
| 6 | packaging | 28 500 |
| 7 | renovations and maintenance | 13 000 |
| 8 | depreciation | 182 000 |
| 9 | wages | 52 000 |
| 10 | insurance | 15 500 |
| 11 | property tax | 20 000 |
| 12 | other costs | 26 000 |
| | | **- 971 300** |
| 13 | Profit from product sales* | **+ 854 000** |
| 14 | Sewage sludge disposal costs | **+ 350 600** |
| | **Annual profit (after taking into account incurred costs, generated revenues and savings** | **233 300** |

* - price of 1 Mg of fertilizer = 175 $

The analysis also took into account savings resulting from the lack of expenses related to the current need for paid collection and disposal of sludge, which brings real profits for the company. Assuming that the annual cost of processing 4,500 Mg of sewage sludge will amount to USD 971,300, and the effect will be the production of fertilizer, from the sale of which the company will earn a profit of USD 854,000, while at the same time saving the amount of USD 350,600 related to the lack of the need for paid sludge disposal, the total annual income from the operation of the installation will amount to USD 233,300.

### 3.6 Energy recover potential

In this study, the energy recovery potential from wastewater treatment processes at the Płaszów plant was evaluated by calculating three key parameters: hydropower energy potential ($E_H$) biomass energy potential ($E_B$), and total energy potential ($E_T$). The calculations were based on available data on wastewater flow, sludge composition, and system efficiency.

The obtained values are as follows:

$E_H$ = 44.1 kW (energy from treated wastewater discharge)

$E_B$= 1224.8 kW (energy potential from sewage sludge)

$E_T$ = 1268.8 kW (total energy recovery potential)

The results of the analysis show that the Płaszów wastewater treatment plant has significant energy potential to support the development of renewable energy sources. The total energy recovered is 1268.8 kW, demonstrating that this type of plant can make a real contribution to sustainable energy production. 1224.8 kW can be recovered from sludge biomass and 44.1 kW from hydropotential energy.

## 4 Discussion

4.1 AAsIn eight SS tests stabilized with methane fermentation, 27 different biocidal drugs, and their derivatives were detected. The concentration of 3 of them were below the detection limit of the method, i.e., SMX, MTZ, and TMP. SMX is an antibiotic, and its content has also been analysed in other studies, but its low concentration also did not allow the detection or determination of this compound in secondary SS samples (Ajibola, Zwiener, 2022) limed, digested, dried, liquid, and composted samples (Peysson, Vulliet, 2013) or in thickened sediment samples (Martín et al., 2012; Petrie et al., 2016). TMP was detected in secondary sludge at a level of 3.5 ng/g (Ajibola, Zwiener, 2022) and in thickened sludge - 21.5 ng/g (Petrie et al., 2016). The content of 18 compounds oscillated between 5 and 1000 µg kg-1. The content of biocidal drugs in the sludge up to 1000 µg kg-1 is shown in Figure 1. Values in this range were obtained in other studies for erythromycin - 36 µg kg-1 (Clarke, Smith, 2011) and 19.8 ng g-1 (Ajibola, Zwiener, 2022) in sewage sludge. Higher concentrations of OFX were found at 879 µg kg-1. Meanwhile, in secondary sewage sludge, the concentration of this antibiotic was 168.3 and 276.9 µg kg-1 (Ajibola, Zwiener, 2022), and in activated sludge samples, the content of OFX was 730 µg kg-1 (Clarke, Smith, 2011). In other studies, OFX was determined at much higher levels of 4673 µg kg-1 and 4126 µg kg-1 in the winter and summer seasons (Riva et al., 2021). On the other hand, an average concentration of OFX of only 27.4 µg kg-1 was found in sewage sludge samples in 2015 (Gago-Ferrero et al., 2015). The CLR content was recorded in a similar order of magnitude and was 6.6 and 5.4 ng g-1 (Ajibola, Zwiener, 2022) in secondary SS, and in other studies, the mean of the analysed samples was 18 ng g-1 (Gago-Ferrero et al., 2015). Much higher concentrations for SLZ, CLI, KTC, and theirs deacetylated form were recorded, as well as AZM and dmAZM. Meanwhile, for AZM in other studies, much lower results were obtained, i.e., 220.3 and 255.2 ng g-1 (Ajibola, Zwiener, 2022), average results of 156 ng g-1 (Gago-Ferrero et al., 2015), and 666 and 200 ng g-1 (Peysson, Vulliet, 2013). The level of these substances was higher than 3000 µg kg-1.

In the fertilizers, 27 different biocidal drugs were detected, but the concentration of as many as 7 of them was below the detection limit of the method, namely: sulfamethoxazole, metronidazole, trimethoprim, as well as pyrazinamide, sulfadiazine, delamanid, and piperacillin. The content of 15 compounds oscillated between 4 and 830 µg kg$^{-1}$ (Figure 3). The levels of the other compounds were generally greater than 1000 μg $kg^{-1}$. Therefore, these substances were included in Figure 4. The specificity of the patented technology to process sewage sludge into a fertilizer product does not allow for a meaningful comparative analysis of the results obtained. The addition of specific raw materials, their proportions in relation to the processed sludge, and the method of fertilizer preparation are individual parameters determined for a given sludge that can affect the content of AAs. The technology use in this study is different from other SS processing technologies, therefore, it is difficult to make direct comparisons.

According to Figure 5 detailed data on the average results, along with the percentage of reduction in the content of pharmaceuticals in the sludge after processing it into fertilizer, are presented in Table S5. Attention should be paid to the special case of penicillin V, whose content was concentrated. The process of converting SS into a fertilizer product promoted the decomposition of AAs and led to further research on this method of sludge management. Other research has shown that a similar phenomenon was observed for ofloxacin and levofloxacin, where the drying process led to an increase in their concentrations. In the context of sewage sludge processing, which may involve energy-intensive steps (e.g., drying in fertilizer production), the concentration of certain AAs can change during these processes (Styszko, et.al., 2025b).

### 4.2 MPs

Samples of stabilized SS and fertilizer were tested for the presence of microplastics (Figure 6). The average MP content in SS samples was 2429 +/- 758 fractions per 100 g of dry SS. On the basis of the mean, the standard deviation and relative standard deviation for the coefficient of variation samples were estimated. An average volatility of 31% is visible. (Figure 7). The samples were dominated by fragments, an average of 1734 fractions per 100 g of dry SS. In the case of fibres, the average content was 694 fibres per 100 grams of dry sewage sludge. Black fractions accounted for 1343 and coloured fractions for 1086 (Figure 7). Fertilizer samples were also analysed (Figure 8). The microplastic content in the fertilizer samples averaged 720 particles +/- 119 per 100 g of fertilizer. The average content of fragments is 463, and the average fibre content is 257 per 100 grams of dry matter of the fertilizer. Based on the arithmetic mean, standard deviation and relative standard deviation were estimated for the coefficient of variation samples. An average volatility of 17% is visible (Figure 9). Black fractions accounted for 477 particles per 100 grams of dry fertilizer. The average amount of transparent particles is 143 per 100 grams of dry fertilizer, and the average value of coloured particles is 100 (Figure 9). In both sewage sludge and fertilizer samples, LD-PE is the vast majority. The spectral analysis identified several characteristic functional groups (Figure 10). Bands around 2920 $cm^{-1}$ are associated with C-H stretching vibrations, typical of pure polyethylene, while peaks in the 2840–2950 $cm^{-1}$ range indicate symmetric and asymmetric C-H stretching vibrations (Tsai et al., 2004). Vibrations at 1457 $cm^{-1}$ are linked to C-H deformation, reflecting the crystallinity of polyethylene. In contrast, high-density polyethylene (HDPE) would exhibit a more complex pattern of peaks. Peaks at 1397 and 1377 $cm^{-1}$ indicate polymer branching, characteristic of LDPE (Kamble et al., 2022). Scientific articles report that in samples of mixed sludge, 183 ± 84 particles/g were detected (Edo et al., 2020). This represents a higher quantity of microplastics compared to the samples analyzed in this study. On the other hand, analyses conducted by other scientists showed smaller amounts of microplastics. Research has shown 353.30 ± 97.00 particles per 1 kg of sewage sludge (Jiang et al., 2020) and 51.20 ×103 particles per 1 kg of SS (Gies et al., 2018). The difference may result from various reasons, such as season, greater/lesser consumption of products containing MPs, different separation methods, or the method of identification (Worek et al., 2025). Hatinoglu et al. found that most of the MPs in the sludge are white (80%), clear and black (70%), and red and blue (40%) fragments

(Hatinoğlu, Sanin, 2021). Similar results are obtained by Franco et al. (2023) due to the same reasons as their amount. Additionally, stronger methods of digestion of samples cause their colour to fade. When using 30% hydrogen peroxide, most microplastics lose their shape and colour (Franco et al., 2023). In other research, the main sources of MPs in sewage sludge were identified as commonly used daily products such as plastic bags, bottles, nets, and drinking straws (Worek, et al., 2025). Increased consumption of disposable utensils and packaging during certain months leads to higher levels of MPs in sewage systems (Worek, et al., 2025). Additionally, higher temperatures promote plastic fragmentation and may lead to increased use of disposable plastic products, further contributing to MPs contamination in wastewater (Worek, et al., 2025).

### 4.3. OH-PAHs

The results show concentrations of OH-PAHs in SS and fertilizers with grain sizes of < 40 μm. Six OH-PAHs were determined in samples: 1-napthol (1-OH-NAP), 2-napthol (2-OH-NAP), 2-fluorenol (2-OH-FLU), 9-phenanthrol (9-OH-PHEN), 1-hydroxypyrene (1-OH-PYR) and 3-hydroxybenzo(a)pyrene (3-OH-BaP). These compounds are biomarkers of one of the most commonly detected PAHs. These compounds, except 3-hydroxybenzo(a)pyrene, were detected in all samples. 3-OH-BaP was detected in only one sample in stabilized sewage sludge. The comparison of OH-PAHs concentration determined in stabilized sewage sludge and fertilizer is presented in Figure 11, and the percentage of OH-PAHs' reduction in the process of processing sludge into fertilizer (%) is presented in Figure 12. The highest concentration was determined for 1-naphthol (744 μg kg-1) and the lowest for 2-fluorenol (89 μg kg-1) in stabilized sewage sludge. In fertilizer samples, the highest concentration was obtained for 1-hydroxypyrene (159 μg kg-1) and the lowest for 3-hydroxybenzo(a)pyrene (below the value of LOD), although the determination of this compound in sewage and sewage sludge is extremely difficult. 3-hydroxybenzo(a)pyrene is a metabolite of benzo(a)pyrene, which can enter the environment through sewage and sewage sludge with urine. However, the study has shown that almost 100% of 3-hydroxybenzo(a)pyrene in human urine was excreted as sulfate or glucuronide. It is worth noting that based on previous studies, 3-OH-BaP, detected in urine, required sensitivity in the pg L-1-range (Hu et al., 2016, Rögner et al., 2021). However, its presence in the sample of sewage sludge may also be related to the precipitation that occurred during sampling and air contamination of 3-OH-BaP (Frydel et al., 2025. Taking into account this information, the concentration of 3-OH-BaP in stabilized sewage sludge is probably lower than the value of the limit of detection for this compound, which equals 28.62 ng ml-1 (Table S4). Nevertheless, the concentration of OH-PAHs is much higher in sewage sludge samples than in fertilizer samples. The reduction of OH-PAHs concentration in sludge during the fertilizer preparation process, despite 3-OH-BaP, is the highest for 2-naphthol and 1-naphthol (82 and 62%, respectively). The lowest difference in concentration of OH-PAHs in sludge and fertilizers is obtained for 9-OH-PHEN (11%). These results give valuable information concerning the formation of fertilizer from sludge and the usage of this fertilizer in agriculture. Removal of contaminants from sludge in the process of formation of fertilizer from this sludge is the first step meeting the goals of the Circular Economy.

### 4.4 Environmental application

The application of stabilised sewage sludge or fertilizers based on it as an amendment to land could account for the greater part of the nitrogen and phosphorus requirements for many crops. While their use to bring nutrients and organic matter could be beneficial for the soil, it also represents a risk due to the content of contaminants such as heavy metals, organic compounds, and pathogens. As the results show, with respect to the presence of AAs, OH-PAHs and microplastics have decreased predominantly in fertilizers. However, increasing trends in the use of these materials in agriculture present a potential risk because of the higher transfer of nonregulated micropollutants into the soils. According to the European Commission in the Technical Guidance Document on Risk Assessment EUR 20,418 EN/2 (EC-TGD 2003), the dry sludge application rate is 0.5 kg/m$^2$ per year for agricultural soils (Technical Guidance Document on Risk Assessment, 2003; Hernando et al., 2006). This means that the average cumulative mass of OH-PAHs transferred into the soils is 739 mg and 58 mg, respectively, with stabilized sewage sludge and fertilizers. The submission of AAs with stabilized sewage sludge is 154 mg and 23 mg with fertilizer. The emission of microplastics with stabilized sewage sludge can result from the dispersion of more than 12100 pieces into the soil and 3600 pieces with fertilizer.

According to Table 1, based on 5 groups defined based on RQ values, we can assign the tested compounds and the environmental risk posed by the content of these compounds in the tested fertilizers. Compounds such as: PZA, MTZ, SDZ, SMX, TMP, SLZ, DMD, dmAZM, hPZA, S,S-ANP, dmERY, daKTC, PIP and 3-OH-BaP do not pose any environmental risk. NAL, FTC, SPY, LZD, ERY, CLR, INa, dmCLR, 2-OH-NAP, 2-OH-FLU, 9-OH-PHEN and 1-OH-PYR show negligible risk. 1-OH-NAP may have endurable risk. INH, PenV and AZM may indicate moderate risk, and clindamycin and ketoconazole show high environmental risk. Most compounds are below the level indicating environmental risk, but it is worth noting the high level of environmental risk posed by CLI and KTC.

### 4.5 Economical analysis

There are known studies on calculating the cost of producing fertilizers and the profit obtained from their production, taking into account environmental losses caused by excessive release of carbon dioxide into the atmosphere. Strategies regarding energy security and the impact of various industrial sectors, energy consumption in residential buildings, or installations for the production of fertilizers from sewage sludge are a crucial aspect concerning the broadly understood energy consumption (Eteriki et al., 2023, Abdunnabi et al., 2023).

In this paper, in the economic context, undertaking an investment in the form of a sewage sludge processing installation should be based on economic conditions, applicable law and local economic situation. Economic issues are considered through mathematical estimation and financial capabilities of a given organization. In turn, the legal aspect is indisputable and depends on the legal regulations in force in a given country regarding the method of handling waste such as sewage sludge. Before making a decision to build an installation for the production of fertilizer from sewage sludge, local conditions should be considered, such as: demand for such products or interest of potential recipients. However, these issues are difficult to estimate and highly specific to the location of a given treatment plant.

Nevertheless, the economic profitability of implementing a fertilizer product from sewage sludge can be easily assessed based on several estimated data, where such data as: the cost of creating the installation, the costs of purchasing other necessary raw materials and materials, the costs of operating and maintaining the installation or the profit from selling the fertilizer product are taken into account.

### 4.6 Energy recover potential

Realizing this potential has many benefits. Firstly, it reduces the operating costs of the wastewater treatment plant by reducing the need to purchase electricity. Secondly, it increases its self-sufficiency and independence from external energy suppliers. In addition, the production of biogas from sewage sludge reduces the amount of waste requiring landfilling and reduces associated emissions.

Energy recovery from hydropotential and biogas fits in with the objectives of a closed-loop economy and a low-carbon policy. This makes it possible to reduce greenhouse gas emissions such as $CO_2$, which supports climate protection and sustainability measures.

## Conclusions

This paper provides insights into the presence and fate of various pollutant groups (antimicrobial agents, microplastics, and hydroxyderivatives of polycyclic aromatic hydrocarbons) during the fertilizer production process and if SS-derived fertilizers might cause negative impacts on the soul environment discussed. Eighteen compounds with antimicrobial properties were detected and quantified in…sewage sludge and …in the fertilizer using the LC-MS/MS method. The highest concentrations (above 3000 ug kg$^{-1}$) of sulfasalazine, clindamycin, ketoconazole and its deacetylated form, azithromycin, and desmethylated azithromycin were recorded in stabilized sewage sludge. The fertilizer production process successfully reduced the number of AAs, with 27 and 20 persisting, where 5 AAs with concentrations greater than 1000 above ug kg$^{-1}$, which is a concern.

The average MP content in the samples of stabilized sewage sludge measured with the FTIR method was 2 429 fractions +/- 758. Black and coloured microplastic fragments were detected. The black fragments represented an average of 1070 particles, while the coloured fragments represented an average of 665 fragments.

The presence of 6 tested OH-PAHs was determined in sewage sludge and fertilizer samples using the GC-MS/MS method. Concentrations of OH-PAHs in the stabilized sewage sludge varied from 53 for 2-OH-FLU to 587 μg kg$^{-1}$ for 1-OH-NAP, and in fertilizers, this value varied from 4.7 μg kg$^{-1}$ for 2-OH-NAP to 31 μg kg$^{-1}$ for 1-OH-PYR. Results for 3-OH-BaP were below the limit of detection. This is due to the effective removal of OH-PAHs ( 46 to 88%) during the fertiliser production process.

This paper has shown that sludge derived fertilizer production, although effective in the removal of some contaminants (sulfamethoxazole, metronidazole, trimethoprim, as well as pyrazinamide, sulfadiazine, delamanid, and piperacillin) might still trigger adverse environmental effects due to persistence of some pollutants (clindamycin, ketoconazole).

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