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ECOLOGICAL AND ECONOMICAL BENEFITS FROM SEWAGE SLUDGE HYGIENISATION WITH THE USE OF LIME IN A MEDIUM-SIZE TREATMENT PLANT

Sewage sludge classified as hazardous waste requires searching for advanced and more effective methods of utilization. Waste produced in treatment plants, should be subject to proper reprocessing on the grounds of health, economic and legal reasons. In treatment plants, hygienisation with the use of lime (CaO) is commonly applied. The main advantage of the aforementioned method is the growth of pH value of sewage sludge and the reduction of pathogens. Apart from this, sewage sludge hygienisation with the application of lime is characterized by the high costs associated with the acquisition of lime. Assuming the price of highly reactive lime ranging from EUR 67-82 per one tone, additional cost of approximately EUR 8600 is generated for a medium treatment plants per year. Additionally, the liming of sewage sludge requires the modernization of treatment plants and the acquisition of new equipment. But due to the fertilizing properties of aforementioned waste, the agricultural utilisation of sewage sludge is the best method for small and medium treatment plants. The financial feasibility analysis showed that the whole undertaking will pay off within 7 years. This paper presents the cost-effective analysis of sewage sludge hygienisation in medium municipal treatment plant. In this article, the main mechanism of process and the influence of liming on sewage sludge characteristics are also showed.

Keywords: sewage sludge, liming, sewage sludge hygienisation, sewage sludge management, cost analysis

INTRODUCTION

Sewage sludge has been defined as mineral and organic compound derived from treated wastewater. With the increasing number of new residents attached to the sewerage system and the tightening requirements concerning the wastewater quality all over the world, the production of aforementioned waste reached an alarming level [1]. Due to the specific chemical and physical properties of sewage

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sludge, its treatment and utilization is a significant problem for wastewater treatment plants. In line with the restriction placed on landfill waste with a calorific value above 6 MJ/kg introduced on 1 January 2016, the most economically and environmentally-friendly method of sewage sludge utilization is its agricultural use [2]. The possibility of agricultural sewage sludge application is associated with the high content of nutrients and organic matter [3]. Additionally, the positive impact of sewage sludge on the plants growth was confirmed by different authors. Gondek and Filipek-Mazur [4] proved that sewage sludge has affected the increase of calcium in plants. From the economical point of view, the use of sewage sludge in agricultural practices or for reclamation is characterized by the lowest costs of approximately EUR 100 for 1 Mg sludge. In contrast, combustion and co-combustion of sewage sludge are more expensive, even fourfold (Table 1) [5, 6].

Table 1. Predicted costs of sewage sludge management using different methods

Ways of sewage sludge utilisation	**Average disposal costs for 1 Mg sewage sludge EUR**
Agricultural use	100
Composting	150
Combustion	350
Co-combustion	430

Agricultural and natural ways of utilization of sludge management are legally permitted if they do not exceed permissible concentrations of heavy metals and biogenic compounds, as stated in Regulation on Urban Sewage Sludge of 15 February 2015 [7].The agricultural value of municipal sewage sludge also depends on the content of pathogen microorganisms. Pathogens entering the soil could lead to both surface and ground water contamination [1]. Before the application of sewage sludge in agriculture, detailed research is required in order to not exceed the content of heavy metals and microorganism.

The reduction of pathogens might be reached with the use of hygienisation process. Yu et al. [8] divided hygienisation methods into two categories: Class A and Class B. In Class B, the amount of microorganism is reduced to below 2 million colony forming units (CFU) per gram of total solids dry weight. By contrast, Class A could lead to the microorganism reduction at less than 1000 most probable numbers (MPN) per gram of total solids dry weight. Podedworna and Umiejewska [9] also classified the hygienisation process as: thermal, chemical, biological and radiation disinfection (Fig. 1).

In Poland, sewage sludge hygienisation with the use of lime is commonly applied for disinfection purposes. The addition of lime into aforementioned waste results in the increase of pH value and the significant reduction of pathogens [10]. Additionally, the mixture of sewage sludge and lime might be used as a natural and valuable fertilizer improving the plant growth. Detailed information concerning the hygienisation with the use of lime is included in further section of the article.

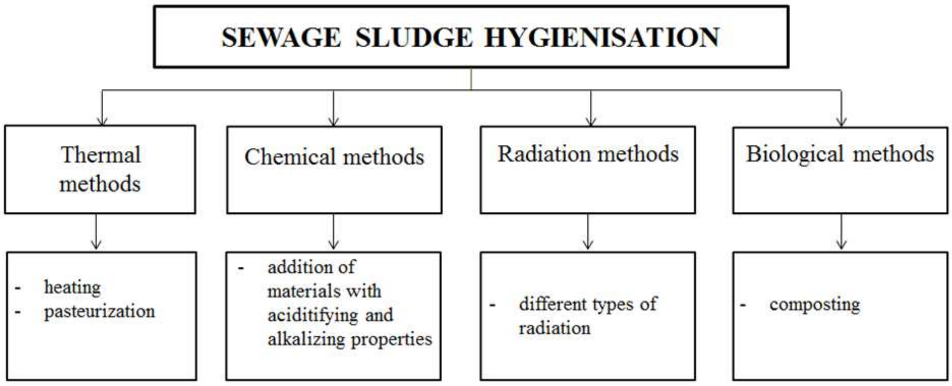

Fig. 1. Sewage sludge hygienisation methods

In Poland, there is a paucity of information on sewage sludge hygienization costs. Thus, this article presents the cost-effectiveness analysis of sewage sludge liming in a medium treatment plant. This paper also shows the impact of lime on sewage sludge properties and presents the main advantages associated with the application of aforementioned method in waste management.

1. THE MECHANISM OF SEWAGE SLUDGE HIGIENIZATION WITH THE USE OF LIME

Liming is commonly used as a conventional sewage sludge hygienisation method. According to different authors, the addition of lime into sludge contributes to the sludge stabilization and disinfection [7, 11]. The results of aforementioned processes are the immobilization of heavy metals and the change of structure of sewage sludge [7].

The main mechanism of sewage sludge hygienisation with the use of lime is based on the exothermic hydration reaction of calcium oxide, by the following equation (1) [11]:

$$CaO + H_2O \rightarrow Ca(OH)_2 + 1160\ kJ/kg\ CaO \quad (1)$$

For sewage sludge, the aforementioned reaction might be written as follows (2) [10]:

$$CaO + H_2O \rightarrow Ca(OH)_2 + 1160\,kJ/kg\,CaO + \text{stabilized sewage sludge} \quad (2)$$

As a result of the aforementioned reaction, hydroxyl ions are formed. It is estimated that 1 kg of CaO delivers 0,607 kg of OH^- ions. This phenomena results in the increase of alkalinity and the pH value of sewage sludge. Additionally, hydroxyl ions are highly toxic for pathogens and cause the change in ionization of microorganisms cells [11]. As a consequence, the activity of many enzymes could disappear. The results obtained by different authors [10, 12] confirmed that the high pH of sewage sludge is a major factor which influences the disappearance of compounds of proteins, especially in anion and carboxyl groups. For this reason, the growth of pH is a main destructive factor for pathogens in hygieniesation process. The research proved that most of bacteria and viruses contained in sewage sludge are inactivated in the pH above 9 [11]. In addition, ammoniac emitted during the hygienisation process, penetrates through cell membranes and intensifies the reduction of pathogens.

The literature review confirms that 1 kg of CaO absorbs approximately 0.32 kg of water and calcium hydroxide is formed [7, 11]. In line with the mass conservation law, the reaction might be written as follows (3) [10]:

$$1\,\mathrm{kg\,CaO} + 0.324\ \mathrm{kg\ H_2O} \rightarrow 1.324\ \mathrm{kg\ Ca(OH)_2} + 1160\ \mathrm{kJ/kg\,CaO} \qquad (3)$$

Depending on the amount of emitted warmth, about 0.5 kg of water is evaporated. As a result, sewage sludge is dried and the growth of sludge dry mass is observed [11].

Secondly, hydrated lime contained in sewage sludge reacts with carbon dioxide from the atmosphere and carbonate calcium is created, by the following equation (4) [7, 11]:

$$\mathrm{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O + 1678\,kJ/kg\,CaO} \qquad (4)$$

In line the mass conservation law, this reaction might be written as follows (5) [10]:

$$\mathrm{1{,}324kgCa(OH)_2 + 0{,}776kgCO_2 \rightarrow 1{,}776kgCaCO_3 + 0{,}324kgH_2O +}$$

$$\mathrm{+1678\,kJ/kg\,CaO} \qquad (5)$$

The aforementioned reaction contributes to further sewage sludge stabilization and the improvement of shear strength. During this stage of the process, such obtained energy is used to heating and drying of sludge [7, 10, 11].

The effectiveness of sewage sludge hygienisation with the use of lime is determined by physical, chemical and microbiological properties of waste. The essential factor influencing the process effectiveness is also the contact time between sludge and lime. According to Malej [13], almost 100% reduction of pathogens might be achieved after one hour contact time. Marcinkowski [10] also proved that *Salmonella* bacteria had died off after one hour contact time with the pH value at least 11.6. That is the reason why the application of lime in sewage sludge treatment is justified.

2. METHODS

On the basis of investment and operation costs, financial feasibility analysis was calculated. The analysis included the calculation of the following elements: payback period (PP), net present value (NPV), profitability index (PI), internal rate of return (IRR), cash inflow (CIF), cash outflow (COF) and cash flow (CF).

Payback period (PP) was calculated as shown by the following equation:

$$PP = \frac{W}{Z}$$

where: *PP* – payback period, year; *X* – capital spending, EUR; *Y* – average annual investment income, EUR.

Net present value (NPV) was estimated by the following equation:

$$\mathrm{NPV} = \sum_{t=1}^{i} \frac{C_t}{(1+r)^t} - C_o$$

where: NPV – net present value, -; C_t – net cash inflow during the period *t*, EUR; C_o – total initial investment costs, EUR; *r* – discount rate, %; *t* – number of period times, -.

Profitability index (PI) was solved by the equation below:

$$\mathrm{PI} = \frac{\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t}}{I}$$

where: PI – profitability index, -; C_o – net after-tax cash flow in year *t*, EUR; *r* – cost of capital, EUR; *t* – capital investment project's cash outlay assumed to occur in the current year, *n* – number of year, -.

Internal rate of return (IRR) was calculated by the following below:

$$\mathrm{IRR} = r_a + \frac{\mathrm{NPV}_a \cdot (r_b - r_a)}{(\mathrm{NPV}_a - \mathrm{NPV}_b)}$$

where: IRR – internal rate of return, -; r_a – lower discount rate chosen, %; r_b – higher discount rate chosen, %; NPV_a – NPV at rate *a*, -; NPV_b – NPV at rate *b*, -.

The influence of lime on the properties of sewage sludge was evaluated on the basis of pH value and the sewage sludge dry mass. pH of sewage sludge after hygienisation was analyzed with pH-meter HACH HQ40d according to PN-EN 15933:2013-02. In order to asses a dry mass, sewage sludge was dried at 105^{o}C. The aforementioned parameter was calculated as shown by the following equation:

$$d.m. = \frac{m_s}{m_u} \cdot 100\%,$$

where: *d.m.* – sewage sludge dry mass, %; m_s – mass of sludge after drying, g; m_u – mass of hydrated sludge, g.

3. THE COST ANALYSIS OF SEWAGE SLUDGE HYGIENISATION BY MEANS OF LIME

The layout of devices for sewage sludge hygienisation is shown in Fig. 2. The complete technology of sewage sludge hygienisation consists of: the lime container, the lime feeder, the lime dispenser, the screw feeder of lime, the mixer of sludge and lime, the screw feeder of sludge and the screw feeder of obtained product. As wastewater treatment and previous stages of sludge treatment are not considered in the cost analysis, they are eliminated from this scheme.

Design criteria regarding the sewage sludge hygienisation in a medium treatment plant are shown in Table 2. This data and information were selected from manufacturer's index cards. Based on the calculation, the number of equipment was selected in order to fit proper conditions and requirements.

The cost analysis of sludge hygienisation was calculated and presented in Table 3. The value of equipment was obtained from EKO-MONTAŻ company. The presented analysis includes only the costs of necessary equipment and lime. The detailed cost analysis also requires determining the energy costs associated with the installation working.

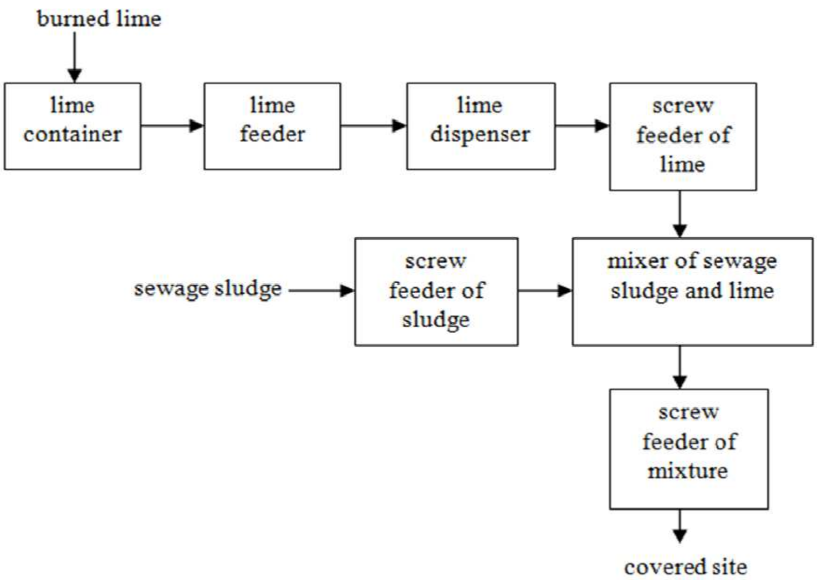

Fig. 2. Layout of devices for sewage sludge hygienisation in considered treatment plant

Table 2. Design parameters of equipment for sewage sludge hygienisation

Device	Design parameter	Number of devices
Lime container	volume: 20-30 m^3	1
Lime feeder	capacity: 1.5-2 m^3/h	1
Lime dispenser	capacity: 1.5-2 m^3/h	1
Screw feeder of lime	capacity: 1.5-2 m^3/h	1
Screw feeder of sewage sludge	capacity: 1.5-2 m^3/h	1
Mixer of lime and sewage sludge	capacity: 2 m^3/h	1
Screw feeder of obtained product	capacity: 1.5-2 m^3/h	1

The installation for lime dosing consists of the container with a volume in the range of 20-30 m^3 , the lime feeder, the dispenser and the screw feeder which is responsible for the transport of lime. Additionally, the lime container is equipped with scrubbers. In order to avoid the lime agglomeration, special electrovibrators are located in the side wall of the container. In the bottom part of the device, there is a knife gate and the lime feeder. When the knife gate is opened, lime is given to the feeder containing the knife deflector. The rotation of the knife detector results in the transport of lime into the dispenser. The amount of lime is precisely controlled by the regulation of routes of screw feeder. The investment costs associated with the acquisition of aforementioned devices is approximately EUR 21 400. However, it will be also necessary to include additional costs associated with the energy consumption by the aforementioned devices (0.5-4.5 kWh) and workers training.

Table 3. Average costs of equipment and reagent
for sewage sludge hygienisation

Device	**Cost EUR**
Lime container	16 000
Lime dispenser	2 500
Screw feeder of lime	2 900
Screw feeder of sewage sludge	4 400
Mixer of lime and sewage sludge	10 000
Screw feeder of obtained product	4 400
Automatic regulation	3 200
Transport of devices	14 000
Lime	8 600
COST	66 000

The transport of dewatered sewage sludge into the mixer is ensured by the screw feeder of sludge. For a medium treatment plant, the capacity of aforementioned device should be in the range of 1.5-2.0 m^3/h. The screw feeder consists of: the trough with chute, the charging hopper, the so-called screw and the power unit. The part of aforementioned elements is made from sheet steel. In the bottom part of a trough, there are special holes enabling the water evaporation. The transported material is given to the dispenser by means of a hole in a lid. The main advantage of screw feeders is the possibility to integrate with other devices, for example: filter press for sewage sludge dewatering. The costs associated with the acquisition of a screw feeder is approximately EUR 4 400. The operation costs are mainly associated with the energy consumption of about 4.5 kWh. During the exploitation of a screw feeder, it is necessary to avoid the full inflation of feeder in order to prevent friction between a trough and sewage sludge. The experimental tests proved that the full inflation of aforementioned device could contribute to the blockage of rotation of a screw.

The mixing of sewage sludge with lime is ensured by the application of a mixer. Depending on the kind and the moisture content of sludge, a twin-screw or paddle mixer is applied. The whole process is controlled by means of control cabinet. The mixer of sludge and lime is made from sheet steel and consists of two steel containers. One of them is filled with lime and the other is filled with dewatered sewage sludge. The sewage sludge hygienisation with the use of lime results in the increasing of temperature and the pH value which could contribute to the reduction of pathogens in waste. Such obtained mixture has a consistent structure and might be transported by means of the screw feeder to a covered site. The average cost of a mixer is approximately EUR 10 000. The price of a screw feeder is about EUR 4 400. However, it might be also necessary to include additional costs associated with the energy consumption.

In sewage sludge hygienisation, burned lime CaO is applied. The dosage of aforementioned reagent depends on the sewage sludge moisture content, the concentration of chemical compounds and the microbiological characteristics of waste. The literature review showed that the dosage of lime in sewage sludge liming is in the range of 0.15-0.25 kg CaO/kg d.m. In practice, the amount of applied burned lime is in the range of 22-23% of sewage sludge dry mass. In order to obtain the high effectiveness of sludge hygienisation, lime with a high level reactive is typically used. It is recommended to apply burned lime with a value of TS_{60} parameter below 1 minute. Depending on the distance of transport, the cost of 1 Mg of burned lime is in the range of EUR 67-82.

The above-mentioned cost analysis showed that the total costs of installation for sewage sludge hygienisation with the use of lime is approximately EUR 66,000. But the presented cost analysis includes only the price of devices and the applied reagent. One should also take into consideration additional costs associated with the workers training and the assembly of aforementioned devices.

Table 4. Financial feasibility analysis of sewage sludge hygienisation

Parameter	**Unit**	**Value**	**Profitability of investment**
PP (Payback period)	year	7	-
NPV (Net present value)	-	2241.61	>0
PI (Profitability index)	-	1.034	>1
IRR (Internal rate of return)	%	0.00	-
CIF (Cash inflow)	EUR	200 000	-
COF (Cash outflow)	EUR	186 000	-
CF (Cash flow)	EUR	14 000	-

The financial feasibility analysis was presented in Table 4 and in Fig. 3. The profit of treatment plant was calculated by the comparison of sewage sludge hygienisation and agricultural utilization with the landfilling and combustion of waste. The operation costs included the price of lime and other media required in the aforementioned process. By taking the annual profit from the sewage sludge hygienisation in a treatment plant of approximately EUR 10 000 and the annual operating cost of about EUR 20 000, the investment will pay off within 7 years. Additionally, other financial parameters confirm the profitability of sludge hygienisation. It is worth highlighting that the product of sewage sludge hygienisation might be further managed as a fertilizer in agricultural practices. By means of that, it is possible to eliminate the storage of sewage sludge gradually.

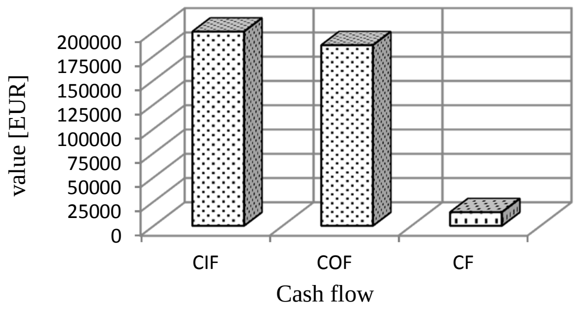

Fig. 3. Chart of cash flow

4. THE INFLUENCE OF LIME ON SEWAGE SLUDGE CHARACTERISTICS

Apart from the high temperature, the main factor that affects the reduction of microorganisms is the high pH value of sewage sludge after hygienisation. It is commonly known that the high concentration of hydroxyl ions resulted in the change of protein's ionization. As a consequence, the activity of many pathogens has decreased [11].

The influence of lime on pH of sewage sludge after hygienisation was presented in Fig. 4. After the application of burned lime in the amount of 10% of sewage sludge dry mass, the pH value increased by 106%. The aforementioned results were consistent with findings made by Marcinkowski [14] and Bazeli [12]. However, the pH value of sewage sludge was decreasing all the time. After 24 hours contact time of sewage sludge and lime, the pH decreased by approximately 5% to the value of 12.85 (Fig. 5). Consequently, the long-time storage of sewage sludge after hygienisation results in the decrease of pH and could contribute to the secondary growth of pathogens [15].

The influence of lime on sewage sludge dry mass was shown in Fig. 6. The obtained results confirmed the positive impact of aforementioned reagent on the decreasing moisture content. After the application of burned lime in the amount of 10% of sewage sludge dry mass, the pH value increased by approximately 16%. Similar results were achieved by other authors [12, 14]. This phenomena is caused by the heat emission, which results in the evaporation of water from sewage sludge. The influence of lime on the sewage sludge moisture content reduction contributes to the decreasing transport costs to places where sewage sludge will be utilized.

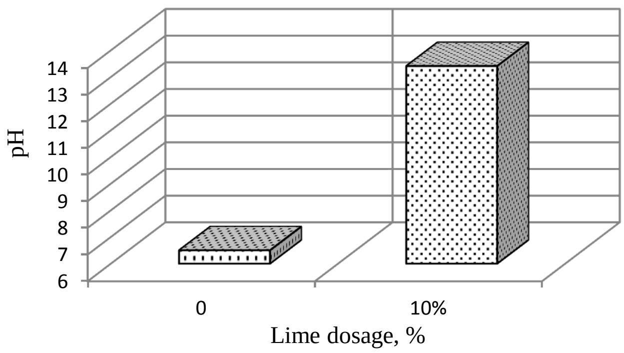

Fig. 4. The influence of lime on the pH value of sewage sludge

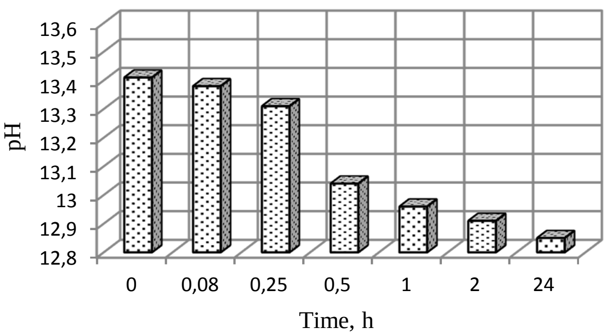

Fig. 5. The changes of pH value over time

Another advantage of hygienisation is the fact that obtained product might be successfully used in the cultivation of energy plants plantations. The aforementioned method allows retaining the turnover of nutrients, which closes the circuit elements in the local ecosystem [16, 17]. Moreover, chemical compounds contained in sewage sludge are excluded from the human food chain. Particular features of the energy plants construction help to take nutrients contained in sewage sludge without environmental contamination. For this reason, sewage sludge after hygienisation might be treated as an alternative for traditional mineral fertilizers, which in turn might successfully provide valuable nutrients for plants and could substitute popular fertilizers [6]. Additionally, energy plants have a high demand for nutrients and are characterized by a large absorbent surface [18]. The application of sewage sludge in energy plants plantations could help to achieve 20% share of renewable energy in final energy production in compliance with the requirements of the EU climate and energy package (3 x 20%).

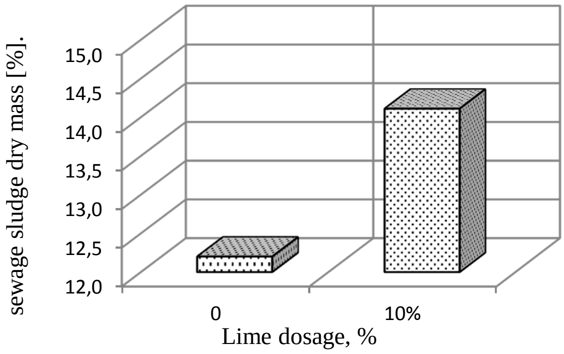

Fig. 6. The influence of lime on sewage sludge dry mass

5. CONCLUSIONS

The technology of sewage sludge hygienisation demonstrated the increase of pH and sewage sludge dry mass. However, the aforementioned process demands the acquisition of new devices for mixing and dosing of products, which increases the investment costs in treatment plant. The financial feasibility analysis showed that the whole undertaking will pay off within 7 years. Additionally, the mixture of sewage sludge and lime might be applied in agricultural practices, for example: in energy plants plantations. This investment could contribute to the elimination of sewage sludge storage in treatment plants.

Based on the results of cost-effectiveness analysis of investment, the following findings and conclusions could be made:

- the investment costs associated with the acquisition of equipment for sewage sludge hygienisation in a medium treatment plant is approximately EUR 66 000;
- prior to the implementation of aforementioned technology in treatment plants, it is necessary to choose the efficiency of the device. The proper selection of devices ensures the optimization of working conditions in a treatment plant;
- the annual costs of lime necessary in sewage sludge hygienisation is approximately EUR 8 600. In order to obtain the best process effectiveness, a high level reactive burned lime with a value of TS_{60} parameter below 1 minute is recommended;
- the financial feasibility analysis of the whole investment has shown that the technology of sewage sludge hygienisation is profitable and beneficial from the economical, environmental, legal and social point of view. It is estimated that the aforementioned investment will pay off within 7 years;
- the addition of lime to sewage sludge influences the growth of pH of sewage sludge. The addition of 10% of lime to sewage sludge results in

the increase of pH of approximately 106% to the value of 13.41. The high pH value of sewage sludge after hygienisation could contribute to the reduction of pathogens in a significant way. As the decline of pH is possible in time, the control of sanitary and microbiological characteristics of sewage sludge is necessary;

- additionally, the application of burned lime to sewage sludge results in the increase of dry mass. The sewage sludge moisture reduction could decrease the cost of transport to the places of its utilization;
- what is more, the mixture of lime and sewage sludge might be successfully used in the cultivation of energy plants plantations. The aforementioned method allows retaining the turnover of nutrients, which closes the circuit elements in the local ecosystem. The aforementioned application of sewage sludge after hygienisation could help to achieve 20% share of renewable energy in final energy production in compliance with the requirements of the EU climate and energy package (3 x 20%).

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EKONOMICZNO-EKOLOGICZNE ASPETY TECHNOLOGII WAPNOWANIA OSADÓW ŚCIEKOWYCH NA PRZYKŁADZIE ŚREDNIEJ OCZYSZCZALNI ŚCIEKÓW

Wzrost świadomości społecznej dotyczącej zagrożenia spowodowanego niewłaściwie prowadzoną gospodarką odpadami skutkuje rozwojem nowych metod ich utylizacji, zgodnie z wymogami prawnymi ekologicznymi i społecznymi. Celem implementowania nowych zasad gospodarki odpadami wprowadzane są nowe lub zaostrzane dotychczas obowiązujące akty prawne, mające kształtować prawidłowe strategie postępowania z odpadami. Intensyfikacja zabudowy i przyłączanie do systemu zbiorowego odprowadzania ścieków nowych odbiorców skutkuje produkcją ogromnych ilości osadów ściekowych. Specyficzne właściwości ubocznych produktów oczyszczania ścieków wymagają poszukiwania nowych metod ich przeróbki i unieszkodliwiania zgodnie z zasadami ochrony środowiska, z jednoczesnym uwzględnieniem aspektów ekonomicznych. Ze względu na obecność mikroorganizmów patogennych w osadach ściekowych, proces higienizacji osadów ściekowych jest jednym z najważniejszych etapów ich przeróbki. Studium literatury potwierdza, że powszechnie w oczyszczalniach ścieków stosuje się proces wapnowania z użyciem CaO. Niewątpliwą zaletą wspomnianego procesu jest możliwość redukcji patogenów do bezpiecznego poziomu, umożliwiającego dalsze zagospodarowanie osadów ściekowych w zabiegach przyrodniczych. Aplikacja wapna palonego w procesie higienizacji osadów ściekowych generuje jednak wysokie koszty eksploatacyjne oczyszczalni ścieków, związane z zakupem wspomnianego reagenta. Przy średniej cenie wysokoreaktywnego wapna na poziomie 67-82 euro za tonę, roczne koszty zakupu reagenta niezbędnego do procesu higienizacji wynoszą około 8 600 euro w przypadku średniej oczyszczalni ścieków. Dodatkowo, wdrożenie technologii wapnowania osadów ściekowych wiąże się z koniecznością modernizacji istniejącego ciągu technologicznego części osadowej i zakupem nowych urządzeń. Analiza opłacalności inwestycji wykazała jednak, że wprowadzenie procesu higienizacji w średniej oczyszczalni ścieków może się zwrócić po około 7 latach. Prezentowany artykuł przedstawia analizę ekonomiczną wdrożenia procesu wapnowania osadów ściekowych na przykładzie średniej oczyszczalni ścieków, z jednoczesnym wskazaniem korzyści ekologicznych.

Słowa kluczowe: osady ściekowe, wapnowanie, higienizacja, gospodarka osadami ściekowymi, analiza ekonomiczna

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