Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2021.27199

227 (2021) 16–25
July

Evaluation of the possibility of utilization of sewage sludge from a wastewater treatment plant – case study

Anatoly Hurynovich[a,b], Marian Kwietniewski[c], Valentin Romanovski[d,e,*]

[a]*Belarusian National Technical University, Faculty of Civil Engineering, Nezavisimosty ave., 65, 220013 Minsk, Belarus, Tel. +375295696874; email: a.gurinowicz@pb.edu.pl*
[b]*Bialystok University of Technology, 45E Wiejska Str., 15-351 Białystok, Poland*
[c]*Warsaw University of Technology, Faculty of Building Services, Hydro and Environmental Engineering, 20 Nowowiejska Str. 00-653 Warsaw, Poland, email: marian.kwietniewski@gmail.com*
[d]*Institute of General and Inorganic Chemistry, National Academy of Sciences of Belarus, 220072 Minsk, Belarus, email: vramano@kth.se*
[e]*Center of Functional Nano-Ceramics, National University of Science and Technology "MISIS", 119049, Moscow, Russia*

Received 6 February 2021; Accepted 25 February 2021

ABSTRACT

The starting point for the research discussed in this study was the assumption that sewage sludge generated by wastewater treatment plants (WWTP) should be treated as a valuable raw material in the Circular Economy. Hence, the results of the research are part of the search for the best technological solutions aimed at achieving the maximum possible efficiency of sludge management in WWTP. The research was carried out on the example of a sewage treatment plant in Minsk (the capital of Belarus), where the dominant technology is still the storage of sewage sludge, and annually more than 5 million tons of sludge accumulates, which represents a significant hazard to the environment. The research takes into account the real economic, environmental, economic and social conditions in this country. As an alternative to the current technology, which is no longer recommended in EU countries, the effectiveness of three technological solutions was analyzed: (1) thermophilic digestion option with the production of biogas and subsequent combustion of the fermented sludge in the territory of treatment facilities, (2) high-temperature drying followed by the use of sludge in cement production and (3) production of fertilizers (soil-improving additives). A comparative analysis of these technologies was performed by the ranking method using weighting indicators (significance factors). The methodology takes into account technical, economic, environmental and social criteria. As a result of the evaluation, it was found that the most effective technology for the management of sewage sludge of the WWTP in Minsk is the technology of drying and then using the sludge as an alternative fuel in cement production. This technology provides, among others waste-free utilization of the entire volume of sewage sludge generated in Minsk, and also gives opportunities to create new jobs in the area of production of alternative fuel from sewage sludge.

Keywords: Sewage sludge; Anaerobic digestion; Alternative energy; Cement clinker; Fertilizer

* Corresponding author.

1. Introduction

The recycling of industrial wastes with the production of valuable materials is of interest [1–4]. Sewage sludge is a complex, multi-component substance consisting of organic and mineral parts. It contains a large number of pathogenic microorganisms [5–8] and toxic compounds, including heavy metal ions [9–11]) and highly toxic organic compounds [12–14]. For large cities with a smaller share of the industry, the composition of sewage sludge is almost the same. It was noted by Sommers et al. [15] that for samples of sewage sludge collected over a 2 y period from eight Indiana cities; their composition contained approximately 50% of organic matter. Organic and inorganic carbon were 19%–27% and 1%–4% respectively, organic and inorganic nitrogen was 1%–4% and 0%–10%, organic and inorganic phosphorus were 0%–1% and 1%–3%. Potassium, calcium, magnesium and iron were found to be present at a relatively constant concentration of 0%–1.5%, 5%–15%, 1%–2%, 1%–4% respectively. Heavy metals levels were found to be quite variable with time. Moreover, from the point of view of environmental impact, not only the general content of heavy metals is important, but also the form of their occurrence. The main conclusion was made that because of the variable nature of heavy metal contents their analysis is essential prior to recommendations of sewage sludge applications on soils used for crop production. A similar component composition was observed for sewage sludge of Belarusian cities based on our examinations for the last 5 y: approximately 60 wt.% of organic matter, and variable heavy metals concentrations depending on city infrastructure (for Minsk in mg/kg of dry matter: Fe – 13552, Ni – 30, Cu – 358, Cr – 235, Pb – 25, Co – 9, Cd – 1.6, Zn – 396). Of course, sewage sludge most likely contains toxic and carcinogenic organic compounds but such substances are not usually controlled in Belarus. According to the calculations [16] it was found that the mass concentration of pharmaceuticals in the raw sludge and thickened activated sludge could vary in a wide range of 1.0×10^{-3} – 215.47 μg/kg d.m., diclofenac is present in the highest amounts – 215.47 μg/kg d.m., drotaverine – 166.08 μg/kg d.m., ketoprofen – 84.20 μg/kg d.m., ciprofloxacin – 60.28 μg/kg d.m., levofloxacin – 32.10 μg/kg d.m., 17β-estradiol – 2.85 μg/kg d.m. and 17α-ethinylestradiol – 0.58 μg/kg d.m.

Legal regulations have a significant impact on shaping the progress in the development of sewage sludge utilization and management technologies, in addition to economic profitability, environmental protection and social acceptance. Based on the Helsinki Convention, HELCOM on March 15, 2017 issued recommendations in accordance with Article 6 of Directive 2008/98/EC [17]. This report includes a possible set of end-of-waste criteria and shows how the proposals were developed based on a comprehensive techno-economic analysis of biodegradable waste derived from compost/digestate production chain and an analysis of the economic, environmental and legal impacts when such compost/digestate ceases to be waste [18]. The purpose of the end-of-waste criteria is to avoid confusion about the waste definition and to clarify when certain waste that has undergone recovery ceases to be waste. Recycling should be supported by creating legal certainty and an equal level playing field and by removing unnecessary administrative burdens. The end-of-waste criteria should provide a high level of environmental protection and an environmental and economic benefit as well as minimizing risks to human safety.

The utilization of sewage sludge generally includes the following basic processes: volume reduction through thickening and dehydration, stabilization (reduction of the organic fraction) and hygienization (elimination of pathogenic organisms). As a result of gravity thickening, excess sludge with the content of 3%–4% of dry matter can be obtained, while mechanical compaction allows for the achievement of 5%–8% dry matter [19,20]. The mechanically thickened sludge is usually subjected to anaerobic biological stabilization (methane fermentation) in order to produce biogas that can be used in the cogeneration process. However, a disadvantage of this process is the incomplete hygienization of the stabilized sewage sludge.

Mechanical dewatering and hygienization of sludge, which are usually performed out by chemical methods, ensure the possibility of its agrotechnical use in the ground. But in this case, the sludge must meet specific bacteriological, parasitological and heavy metal concentration requirements, in particular when it is intended for composting and to be used as digested sludge (Table 1).

Landfilling is another solution for handling of sewage sludge, however, is currently inadvisable, and has already been abandoned in many countries (e.g., Germany, the Netherlands, Austria, Sweden, Denmark, France, Norway, Belgium and Poland), mainly due to the need to limit the landfilling of biodegradable waste and the introduction of the principles of the Circular Economy [21,22].

Hence, an effective solution may be the thermal transformation of sewage sludge through its proper preparation (dehydration) in dryers (solar – allowing for sludge dewatering up to 60%–75% dry matter or high-temperature – allowing for sludge dewatering up to 95% dry matter and further recovery in dedicated sludge incinerators (usually requiring 33%–90% dry matter) [23,24] and/or co-incineration in the cement industry. The plants that are built for thermal treatment of sewage sludge are expensive facilities (in terms of investment and operation) and they can be included in the strategy of sewage sludge management in large agglomerations, in case of smaller agglomerations, the creation of regional thermal sludge treatment stations is being considered.

Against this background, a promising direction for the recovery of sewage sludge, in addition to biogas production, is its recent use as a supplementary fuel in the co-incineration process in the production of cement clinker [25]. Such solutions are already used in many countries [26–28]. In the foreign cement industry, the consumption of alternative fuel and fuel-containing waste reaches 70% of the total amount of fuel consumed [29]. Co-incineration of sewage sludge in cement plants is possible, however, after meeting certain quality requirements set by an industrial recipient, for example, the caloric value for 95% of dry mass (MJ/kg) >14 versus Lafarge Group, and 15 v.s. EURITS (European Cement Producers Association); sulfur <2.5% Lafarge Group, and <0.4% EURITIS [30].

Similar trends are beginning to appear in planning the sludge management also in Belarus, where sewage sludge

Table 1
Selected product quality requirements for compost and digestate [18]

Parameter	Value
Minimum organic matter content	15% on dry matter weight
Pathogens	
Salmonella sp.	No *Salmonella* sp. in 25 g sample
E. coli	1,000 CFU/g fresh mass for *E. coli*
Limited content of heavy metals, mg/kg (dry weight)	
Zn	400
Cu	100
Ni	50
Cd	1.5
Pb	120
Hg	1
Cr	100
Limited content of persistent organic compounds, mg/kg except for PCDD/F	
PCB_7 (sum of PCBs – polychlorinated biphenyls)	0.2
PAH_{16} (sum of 16 polycyclic aromatic hydrocarbon)	6
PFC (sum of PFOA and PFOS) [perfluorinated compounds]	0.1
PCDD/F (ng I-TEQ/kg dry weight)	30

is considered as a valuable resource in the economy. A strategic direction of its use as a source of biogas production has been determined, which is also part of the search for alternative energy sources [31–33]. However, this planning does not yet consider options for the use of sewage sludge that are competitive to biogas production, such as co-incineration of sludge in the cement production process. At the same time, an analysis of the current state of sludge management in Belarus shows that, in addition to the above-mentioned biogas production, traditional technologies can also be considered as alternative methods of wastewater sludge management. For example, directions associated with its use in agriculture and for the reclamation of degraded areas. However, the existing legislative base contains almost no normative documents regulating such use.

In Belarus, on average, 180–197 thousand tons of sewage sludge by dry solids are produced annually, among which only 4%–5% is used in the national economy. The largest wastewater treatment plant operating in the capital city of Minsk produces over 4,000 m^3 of wet sludge, which after mechanical dehydration weighs 700–750 tons, the moisture content is 79%–80%. Dehydrated sludge is usually transported to a sludge pond. The total amount of collected sludge has already reached a volume of more than 5.0 million m^3 and poses a significant threat to the environment [34]. The issue of further storage of sludge is a serious unresolved problem, for example, due to the threat to the natural environment and the limited land available in the Minsk region. And also due to the discontinuation of sludge storage technology in many European Union countries [17]. The presence of heavy metals and other toxic chemicals in the sewage sludge is particularly dangerous, as has already been mentioned. This fact almost completely excludes the possibility of using sludge in agriculture [35]. Moreover, hormonally active substances difficult to decompose organic xenobiotics, residues and metabolites of pharmaceuticals and cosmetics are also commonly present in sewage sludge. Taking the above into account, biogas plants could be considered only as a first step in a solution for their utilization.

In connection with the above, a prospective solution may be the implementation of a technology ensuring complete utilization of sewage sludge. Such technology is thermal drying of dehydrated sludge in order to produce alternative fuel (higher heating value 13–14 MJ/kg) and its use in the co-combustion process in the production of cement clinker. When choosing a drying technology, the decisive factor is the amount of processed sludge and its final properties determined by the industrial recipient.

The undeniable advantage of using sewage sludge in cement plants is that there is no need to build special installations and complicated flue gas cleaning systems that are already in use in cement industry enterprises. In addition, the fuel balance is improved, in which alternative fuels based on dried sewage sludge start to play an important role.

Bearing in mind the contemporary conditions of sludge management, this article presents an assessment of the effectiveness of sewage sludge management technology as a fuel used in the co-incineration process in cement clinker production in comparison with other technologies, based on the example of the wastewater treatment plant in Minsk.

2. Methodology

The analysis of alternative options for the treatment of sewage sludge was carried out by evaluating the selected economic (dynamic payback period, internal rate of return, profitability index, etc.), ecological (analysis of the environmental impact of alternative options) and technical (maximum use of the beneficial properties of the sludge taking into account their composition) indicators.

2.1. Economic analysis

For the economic analysis, the following criteria were calculated and considered: estimated capital and operational costs, annual net effect (ANE), simple payback period (SPP), net present value (NPV); internal rate of return (IRR), profitability index (PI), dynamic payback period (DPP).

Annual net effect (ANE) can be determined by Eq. (1):

$$\text{ANE} = P_1 - P_2 - \text{AOC} + \text{AIG} \tag{1}$$

where P_1, P_2 – the annual amount of payments paid by the enterprise before and after the implementation of the option, respectively; AOC – annual operating costs for maintaining fixed assets, euro/y; AIG – annual income growth from improving the production results of the enterprise, euro/y.

Annual income growth was determined by Eq. (2):

$$\text{AIG} = \sum \left(P_i \cdot Z_i \right) \tag{2}$$

where P_i – the amount of the i-th resource involved in reuse after the implementation of the technical option; Z_i – i-th resource unit cost, euro.

Evaluation and comparison of various technical solutions, as well as the decision on their financing is made based on the calculation of NPV, internal rate of return (IRR) and profitability index (PI).

NPV (the excess of income over expenses on an accrual basis for the calculation period t, taking into account the discount) was calculated by Eq. (3):

$$\text{NPV} = \sum \left(\text{ANE}_t - K_t \right) \left(1 + E \right)^{-t} \tag{3}$$

where ANE_t – annual net effect from the implementation of the technical solutions in the t-th year, euros; K_t – capital investments in the t-th year, euros; E – the discount rate (the discount rate was assumed to be 3% per annum).

The positive value of the NPV indicates the economic feasibility of implementing the option.

The profitability index (PI) is defined as the ratio of the difference between income and costs during the implementation of the event to the value of capital investments (cumulative total for the billing period T).

$$\text{PI} = \frac{\sum_{t=0}^{T} \text{ANE}_t \left(1 + E \right)^{-t}}{\sum_{t=0}^{T} K_t \left(1 + E \right)^{-t}} \tag{4}$$

The profitability index is closely related to the NPV. If NPV is positive, then PI > 1, and vice versa. The option is considered cost-effective if PI > 1. When calculating the profitability index, the total value of the column, the present value and the value of capital investments, are used. To select an option from several more effective is an event with a higher index of profitability.

A SPP of capital investments K is used for a preliminary assessment of an option at the stage of a feasibility study for its implementation:

$$\text{SPP} = \frac{K}{\text{ANE}} \tag{5}$$

where K – capital investments, euros, ANE – as in Eq. (1).

When attracting funds (bank loans, borrowed funds) used to finance an option, it is advisable to use the indicator – dynamic payback period (DPP), which determines the actual period of time when capital investments are covered by the total income from the implemented option, that is, the actual term of the possible repayment of a loan or other borrowed investment. The dynamic payback period (DPP) in practice is determined graphically by building the dependence of NPV vs. time (NPV = $f(t)$). The dynamic payback period is at the intersection of the NPV line with the time axis.

$$\text{RV} = \text{ANE} \left(1 + E \right)^{-t} \tag{6}$$

where RV – real value in the t-th year, euro.

The life cycle cost (LCC) for compared options was calculated for 20 y of operation, starting from the stage of purchasing the selected option.

2.2. Ecological analysis

For the environmental analysis, the specific values of emissions, discharges and waste generated during the implementation of the considered technical solutions were used.

2.3. Technical analysis

Technical analysis was carried out according to the following criteria:

- brief description of the option with the main technological parameters;
- technological scheme and mass-balance;
- list of basic and supplementary equipment;
- efficiency of the process in terms of the amount of sludge utilization;
- need for reagents, materials, energy, water;
- operational safety (possible emergencies);
- developer, development stage, where it is currently used;
- possible options for improvement.

2.4. System analysis

Analysis of the options was performed by the ranking method using weighting factors (significance factors). For each criterion, the average numerical values of ranking results performed by individual experts are given. The experts were eight scientists and specialists in the field of industrial ecology and engineers-economists of water and sewage systems from leading technical universities of Belarus.

To select the best option for the disposal of sewage sludge, a ranking method known in expert assessments was used, which is a procedure for ordering objects according to their characteristics.

A comparison of the options was made by the ranking method using weighting factors (significance factors). The best among the three considered options according to the criterion under consideration is assigned a higher rank (for example, 2) the less preferable got a lower rank (for example, 1). For the coefficients of significance, the following relation should be performed:

$$1 = \sum_{i=1}^{n} k_i \quad (7)$$

where – k_i – weight (significance) of each indicator in fractions of a unit; n – the number of criteria by which averaging was performed.

The values of the significance coefficients were determined by experts based on the results of discussion and development of an agreed assessment of the significance coefficient for each criterion. If some objects can be equivalent (identical) according to a given comparison criterion, then the so-called linked ranks were determined for them. Associated ranks are defined as the arithmetic mean. For example, if two methods of utilization of sewage sludge are identical (the same) for some reason, then their ranks will be equal to (1 + 2)/2 = 1.5.

The rank of each object for each criterion is the average of the ranking results by individual experts. The rank for each object r_c taking into account the significance (weight) of each indicator (criterion), was determined by the ratio:

$$r_c = \sum_{i=1}^{n} r_{\text{avi}} k_i \quad (8)$$

where r_{avi} – object rank according to i-criterion as the average value of the ranking results by individual experts; n – and k_i – as in the Eq. (7)

The most preferable option was selected by the highest sum of ranks.

3. Evaluation of options

3.1. Description of options

A comparative analysis of the effectiveness of technical solutions for the disposal of sewage sludge in Minsk was performed for three options (Fig. 1). Option 1 – thermophilic digestion option with the production of biogas and subsequent combustion of the fermented sludge in the territory of treatment facilities. Option 2 – high-temperature drying followed by the use of sludge in cement production. Option 3 – production of fertilizer (soil-improving additives).

As noted in the introduction, the thermophilic digestion option with the production of biogas and subsequent combustion of the fermented sludge (option 1) has recently adopted as the main direction for the use of sewage sludge in the Minsk sewage treatment plant.

In the developed investment feasibility study for the project "Introduction of biogas plants at the treatment facilities in Minsk", the investment volume was 28 million euros. The sludge formed by this technology after anaerobic digestion must be dewatered and used further either as fertilizer, or sent to burial or incineration. This technology clearly does not allow its use in agriculture and land reclamation due to the presence of high concentrations of heavy metal salts, as well as the uncontrolled presence of antibiotics, herbicides, surfactants, and oil products. In this case, the volume of wastewater sludge after the fermentation process decreases only by 7%–10%. At the same time, the volumes of waste disposal sites do not significantly decrease, and it becomes necessary to build a plant for their incineration, which leads to additional capital costs. According to the project documentation, the burning of fermented sediments will generate annually more than 20 thousand tons of ash containing high concentrations of heavy metals, which requires special measures for their use or disposal [36]. There are comments from the Ministry of Natural Resources on this issue, which were not eliminated. The investment justification also indicates that from an economic point of view, the project is not profitable, however, when deciding on the implementation of the project, it was recommended to be guided by the social orientation of the project. In the proposals considered, decisions were made that lead to the formation of new waste, from which it can be concluded that the materials provided were developed in violation of the established requirements in the field of environmental protection,

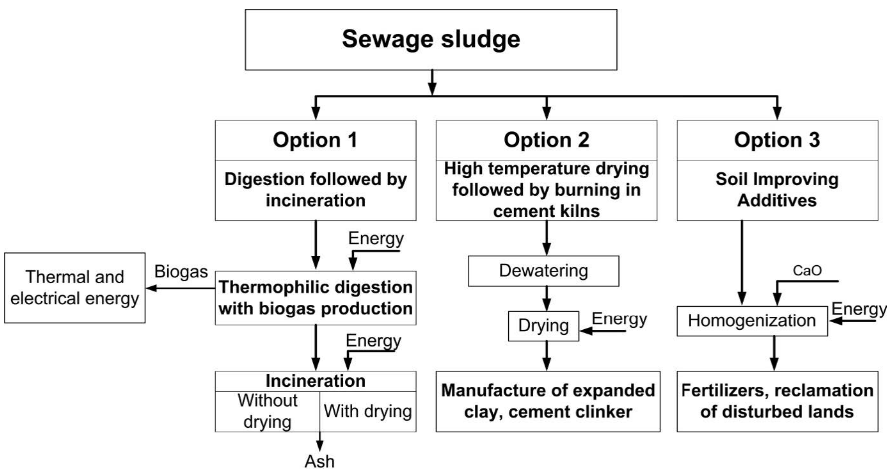

Fig. 1. Alternative options for the sewage sludge treatment covered by the comparative analysis.

namely: alternative options for achieving the goal were not studied, the choice of building biogas plants was not justified and incineration of sewage sludge as the most feasible method, taking into account the economic, environmental and social consequences was not considered.

Option 2 – high-temperature drying followed by the use of sludge in cement production is a technology for the complete utilization of sewage sludge in cement kilns, which is energy and resource-efficient. Organization of sludge drying is envisaged at the site of Minsk wastewater treatment facilities. The proposed technological scheme for the disposal of sewage sludge consists of two main stages: (1) drying the sludge to a moisture content of 10 wt.% and (2) using dried sludge as an alternative fuel in cement kilns.

Rotary cement kilns are an environmentally friendly unit for the disposal of combustible harmful waste due to: (i) high temperature of the material in the furnace (1,450°C); (ii) gas flare and gas flow (1,800–2,000°C); (iii) neutralization of organic pollutants and heavy metals; (iv) highly efficient cleaning of gas emissions in electrostatic precipitators.

This ensures the decomposition of organochlorine compounds such as dioxins and furans [37], the absence of any waste after using alternative fuels, since ash after burning combustible materials is included in the structure of Portland cement clinker. Using the existing infrastructure of cement kilns for joint waste processing saves money and does not invest in the creation of special kilns or landfills. Unlike special waste incinerators, the remains of hazardous waste ash that are processed together in cement kilns are included in the clinker, so there are no end products that require further disposal.

The third option included comparative analysis is production of the soil improving additives. The proposed technology is realized through liming and stabilization, followed by the production of organo-mineral fertilizers using the FuelCal technology [38]. The advantages of this technology are very significant: (i) there is no need to dry and dehydrate the sludge, because the temperature regime (55°C–140°C) is provided due to an exothermic reaction without additional external sources of energy, which ensures drying of the sludge and significantly reduces operating costs and the cost of the final product; (ii) during liming in the course of a thermal reaction, the temperature of the sediment rises, as a result of which the disinfection and neutralization of pathogens occurs; (iii) in the course of the reaction, mobile heavy metals bind and transform into stationary forms. The result of the proposed option is the production of organo-mineral fertilizers.

3.2. Evaluation of options

3.2.1. Evaluation of thermophilic digestion technology with biogas production and further concentration

The precipitate formed by this technology after anaerobic digestion must be dewatered and then sent to the storage places or incineration. This technology does not allow its use in agriculture and in land reclamation due to the presence of large concentrations of heavy metal salts, as well as the uncontrolled presence of antibiotics, herbicides, surfactants, and petroleum products. The volume of sludge after the fermentation process decreases only by 10 wt.%. At the same time, the volume of stored sludge in sludge beds does not decrease significantly, and there is a need to build a plant for their incineration, which leads to additional capital costs.

It should be especially noted that the fermented sludge has significantly worse water discharge properties. This requires additional washing of the fermented sludge with purified water to remove colloids, followed by gravity compaction. After washing, the water is directed to the beginning of the water treatment facilities and leads up to 20% increase of the load by ammonium and phosphate on the biological treatment. This worsens the conditions for the biological removal of phosphates in wastewater treatment plants. Other options for handling the fermented sludge may also be proposed. The sludge can be fermented in two stages, then dehydrated with the addition of polyelectrolytes, then dried and incinerated. There are also technologies for extracting phosphorus from these fluids (struvite precipitation). But all these options will significantly complicate and increase the cost of the technology and were not considered.

The cost of produced biogas is usually higher than the price of natural gas, and the fuel consumption for generating 1 kWh of electricity is 1.4-fold higher than in the whole republic. To operate a mini-CHP plant in the maximum (calculated) mode, the use of natural gas is required. For example, at the Brest Garbage Processing Plant with the production of 2.85 million m^3 of biogas, the design demand for natural gas is 6.36 million m^3/y. Given that in Minsk, the project should produce 11.388 million m^3 of biogas, which will be supplied to the mini-CHP, similar to Brest, at maximum load, it will be necessary to purchase natural gas in an amount of at least 20–25 million m^3/y.

This technology alone does not solve the issue of complete utilization of sludge (additional technologies for utilization are required, for example, the construction of a plant for incineration of fermented sludge).

The incineration of fermented sludge requires the construction of an appropriate production facility with additional investments, which is also not an optimal solution since it does not allow rational use of the calorific value of sewage sludge. When incineration of fermented sludge, more than 20 thousand tons of ash containing high concentrations of heavy metals will be formed annually, which requires special measures for their use or disposal.

The construction costs of the facility for incineration will amount to approximately 28–43 million euros. The investment justification stated that from an economic point of view the project is not profitable, however, when deciding on the implementation of the project, it was recommended to be guided by the social orientation of the project. In fact, in the proposals considered, decisions were made that lead to the generation of new waste, from which it can be concluded that the design documentation were developed in violation of the established requirements in the field of environmental protection, namely: alternative options for achieving the goal were not studied, the choice of construction biogas plants and further incineration of fermented sludge was not justified as the most appropriate methods taking into account economic, environmental and social consequences.

3.2.2. Evaluation of the effectiveness of the technology of using sewage sludge in cement production

The technology of sludge drying with subsequent use as an alternative fuel for cement enterprises ensures its full utilization and rational use creates additional jobs for the production of alternative fuel and allows considering the restoration of sludge ponds. The demand for natural gas for such approach is from 10.75 to 18.8 million m^3/y, depending on the sewage sludge humidity.

When implementing this direction of using sewage sludge, capital costs including taxes (for the purchase of equipment, construction and installation works, development of design and estimate documentation) will amount to 25,240 thousand euros. Fee for loans related to the implementation of investment costs for the project (interest on loans, bank commissions and other costs of loans) will amount to 3,464 thousand euros. Total investment costs will amount to 28,704 thousand euros. At these costs, repayment of the main debt is expected in 20 months from the date of the first tranche and will begin from the moment the equipment is put into operation. Calculations were carried out in euros at a discount rate of 3% per annum. The loan term is 7 y. The loan repayment term is 5 y. The amount of other costs of foreign credit, in addition to interest, will amount to 1,049 thousand euros. Thus, the total debt on the loan, taking into account the repayment of the main debt, interest, as well as other costs for the entire period will amount to 24,306 thousand euros. The dynamic payback period of investments will be 9 y and 10 months. Internal rate of return, or marginal investment efficiency, will be within 5.7%. The project profitability index will have a value of 1.14, which is more than one, therefore, the project is cost-effective by this criterion. Along with this, the feasibility of implementing this investment project is explained by the following circumstances: (i) ensuring the full volume of waste-free utilization of sewage sludge; (ii) additional loading of the rolling stock of the Belarusian Railways, with the partial use of the idle run of hopper-cement trucks; (iii) the creation of additional jobs for the production of alternative fuels; (iv) the realization of the tasks currently facing cement plants on the transfer to local fuels. The use of alternative fuel from dried sewage sludge instead of coal will reduce the cost of cement produced at JSC Belarusian Cement Plant by almost 1%. On a company-wide scale, savings will be about 87 thousand euros annually (alternative fuel from sewage sludge can be used in the production of 123 thousand tons of cement grade 500 DO). The analysis of the financial implementation of the investment project allows us to conclude that the project is feasible and its economic, social and environmental feasibility [39].

3.2.3. Evaluation of the production of organo-mineral fertilizers

The technology is based on the interaction of wet (60%–85%) sludge with quicklime (CaO). As a result of the exothermic reaction, the mixture heats up to 140°C, as a result of which moisture is removed and pathogenic microorganisms are inactivated. As a result of the technological process, the evolved gases (ammonia, mercaptans, etc.) are captured by the mixture, heavy metals are bound into immobile forms. The resulting fertilizer contains organic substances vital for the soil, microelements (K, P, N). Also, the resulting fertilizer contains calcium-containing substances, which are much more effective for deoxidizing of acidic soils in comparison with the use of currently imported dolomite. The annual demand for lime fertilizers in the Republic of Belarus in terms of $CaCO_3$ is 2,199.5 thousand tons [40,41].

3.2.4. Assessment of options

The option to build biogas plants at the Minsk wastewater treatment plant, originally adopted for design, does not ensure compliance with the environmental legislation of the Republic of Belarus, since it aims only at generating electricity and does not take into account the fact that biogas in anaerobic fermentation technology is a by-product of anaerobic digestion processes related to waste disposal. However, for such future use, there is a restriction on the content of a number of toxic substances, like heave metals etc. [42].

Given the above, biogas plants should primarily be a center for the complete processing of organic waste, ensuring that there is no cost for further processing of the fermented mass or its disposal. Accordingly, option 1 is economically and environmentally inefficient and, most importantly, it does not solve the problem of complete disposal of sludge.

The option of obtaining organo-mineral fertilizers from sewage sludge is promising. Such experience is widespread throughout the world. The most important aspect of this direction of use is the presence of heavy metals in sewage sludge. The treatment of sewage sludge with CaO will reduce the cost of moisture removing due to the exothermic reaction and the binding of some of the water with lime. Heating the sludge will additionally lead to its hygienisation. According to technology developers, heavy metals will be bound in sedentary forms. Nevertheless, the implementation of this option in Belarus is practically impossible due to the lack of regulatory documents regulating such handling of sewage sludge (as fertilizer).

In connection with the foregoing, the issue of the application of innovative technologies with 100% disposal of sewage sludge becomes relevant. Such is the technology of thermal drying of dewatered sewage sludge to produce alternative fuels ($Q \approx$ 13–14 MJ/kg) and its use in cement production, which has become widespread in recent years. When deciding on the choice of drying technology, the determining factor is the amount of sludge processed and its final characteristics determined by the consumer in the face of the cement industry (e.g., humidity not more than 10%). These circumstances do not allow considering the use of conveyor dryers. The relevance of such a decision is also indicated by the fact that there is no need to build special furnaces and complex gas purification systems, which are already available at the cement industry enterprises.

To justify the selection of the best option for the use of sewage sludge, the number of technical and economic indicators and environmental impact indicators were determined. For expert evaluation, the following options were used: thermophilic digestion to produce biogas and subsequent combustion of the fermented sludge, high-temperature drying with burning in cement kilns and production of fertilizer (soil improving additives). The evaluation criteria were as follows: process efficiency, operating costs, environmental impact, operational safety, capital costs, operating experience, possible problems during operation and ensuring operational parameters of the equipment.

Fig. 2 presents the results of a comprehensive assessment of the considered options. In addition, the figure also includes data characterizing the existing state of sludge treatment technology at wastewater treatment plant Minsk in order to present a broader background for the assessment of options. The criteria for evaluation by experts shown in Fig. 2 in the "Criteria" column.

Fig. 3 presents the results of the life cycle cost (discounted) of the compared options over 20 y of operation, starting from the stage of purchasing the selected option.

Comparing the alternatives described above, we can conclude that option 3 requires the lowest investment costs and is the most promising. Nevertheless, in the absence of a number of regulatory documents governing waste management, and in particular with wastewater sludge in the Republic of Belarus, this option becomes practically unreliable. Thus, according to the criteria used to evaluate the options for handling sewage sludge, the best option is high-temperature drying followed by co-incineration in cement kilns.

4. Conclusions

In the process of biogas formation, the absolute amounts of heavy metals will not change and due to the decomposition of organic matter, the content of heavy metals increases after fermentation in relation to dry matter. To ensure the utilization of such sludge, it is necessary to construct a plant to incinerate it, which leads to additional capital costs. To ensure uninterrupted stable operation at the mini thermal power plants and sludge incineration

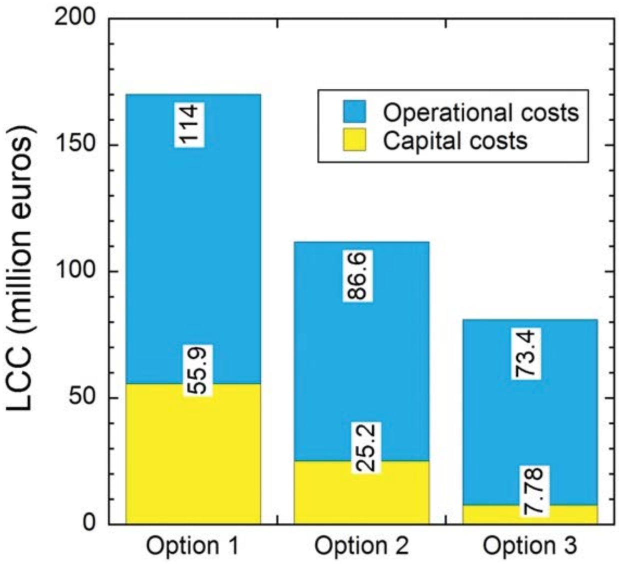

Fig. 3. Comparison of LCC of considered options for 20 y of operation.

Criteria	Sludge ponds (existing state)	Option 1			Option 2	Option 3
		Thermophilic digestion with biogas production	Incineration		High temperature drying followed by burning in cement kilns	Soil Improving Additives
			Without drying	With drying		
The amount of sludge processed	275 891 t/year	730 000 m^3/year	275 891 t/year	275 891 t/year	275 891 t/year	730 000 m^3/year
The amount of waste after processing	275 891 t/year	657 000 m^3/year Fermented sludge	15 600 t/year	15 600 t/year	-	-
Additional expenses	Sludge ponds construction required	Natural gas required	Natural gas required, toxic ash disposal costs	Natural gas required, toxic ash disposal costs	Drying of sludge and delivery to cement plants are required	61250 t/year of lime (CaO) 219 562 MWh/year required
Amount of Alternative Fuel Received	No	Biogas Q=22.34 MJ/m^3x x11.3 million m^3/year = =252442000 MJ	No	No	61 000 t/year 61 000 t/year x 14.3 MJ/kg = =872 300 000 MJ	No
Disadvantages	Alienation of land	Does not solve the disposal problem. Natural gas is required to burn biogas (2:1) i.e. additional 20-25 million m^3 / year	Does not solve the problem of complete disposal	Does not solve the problem of complete disposal	Natural gas required	Additional reagents and energy required
Advantages	-	No prior sludge dewatering required	-	-	100% sludge utilization; use of sludge as an alternative fuel; capital costs in 2.2-2.8 fold lower compared to a biogas plant and further incineration	100% sludge utilization; use of sludge as an organi-mineral fertilizer; minimal capital costs
Environmental impact	Alienation of land, contamination of groundwater (heavy metals, etc.)	Alienation of land for the storage of fermented sludge, contamination of groundwater (heavy metals, etc.)	Pollutant emissions, ash formation with a high concentration of heavy metals	Pollutant emissions, ash formation with a high concentration of heavy metals	Significantly lower pollutant emissions compared to sludge incineration	Significantly lower pollutant emissions compared to the other options
Investment costs (excluding VAT)	-	28 million euros	42.86 million euros	27.854 million euros	25.240 million euros	7.8 million euros
		Total capital expenditures amount to 56-71 million euros				
Expert Assessment Results	-	8.5/1.2			12.5/1.8	13.0/1.9

Fig. 2. Comparative analysis of the effectiveness of technical solutions for the disposal of wastewater sludge in Minsk (marked in red – worst, yellow – medium, green–best option).

plant, the need for natural gas will be in total compared with the needs of gas for drying.

The implementation of the economically, environmentally and socially beneficial option both for the Republic of Belarus and for the city of Minsk for drying sludge with its further use in cement production is due to the following:

- solves the main task – complete waste-free utilization of the entire volume of sewage sludge in Minsk;
- creates additional jobs for the production of alternative fuel;
- allows you to consider the restoration of existing sludge ponds;
- the mineral fraction contained in sediments is a useful technological component that used as a mineral part in cement clinker, and therefore does not require separate utilization;
- sewage sludge co-incinerated in cement kilns possesses not only the properties of alternative fuels, but also renewable fuels.

The calculations showed that when producing of 123,000 tons of cement of grade 500 DO using of the alternative fuel from dried sewage sludge during the year, about 15 284 tons of coal is replaced. In monetary terms, this amounts to approximately 3,484,741 euro.

The analysis of the financial feasibility of the investment project allows us to conclude the economic and social feasibility of its implementation. This option is cost-effective and financially feasible.

A promising direction of using sewage sludge as an organo-mineral fertilizer in Belarus is impossible due to the lack of regulatory documents in this area.

Funding: Ministry of Science and Higher Education of the Russian Federation in the framework of Increase Competitiveness Program of NUST "MISiS" (№ K2–2020–024), implemented by a governmental decree dated 16th of March 2013, N 211.

References

[1] V. Romanovski, Chapter 25 – Agricultural Waste Based-Nanomaterials: Green Technology for Water Purification, K.A. Abd-Elsalam, M. Zahid, Aquananotechnology: Applications of Nanomaterials for Water Purification Micro and Nano Technologies, Elsevier, Cambridge, United States, 2020, pp. 567–585.

[2] E. Romanovskaia, V. Romanovski, W. Kwapinski, I. Kurilo, Selective recovery of vanadium pentoxide from spent catalysts of sulfuric acid production: sustainable approach, Hydrometallurgy, 200 (2021) 105568, doi: 10.1016/j.hydromet.2021.105568.

[3] V. Romanovski, New approach for inert filtering media modification by using precipitates of deironing filters for underground water treatment, Environ. Sci. Pollut. Res., 27 (2020) 31706–31714.

[4] M. Kamarou, M. Kuzmenkov, N. Korob, W. Kwapinski, V. Romanovski, Structurally controlled synthesis of calcium sulphate dihydrate from industrial wastes of spent sulphuric acid and limestone, Environ. Technol. Innovation, 17 (2020) 100582, doi: 10.1016/j.eti.2019.100582.

[5] J.M.J. Mathney, A critical review of the U.S. EPA's risk assessment for the land application of sewage sludge, New Solutions, J. Environ. Occup. Health Policy, 21 (2011) 43–56.

[6] National Research Council, Biosolids Applied to Land: Advancing Standards and Practices, National Academies Press, Washington, United States, 2002.

[7] M. Reilly, The case against land application of sewage sludge pathogens, Can. J. Infect. Dis. Med. Microbiol., 12 (2001) 205–207.

[8] C. Snyder, The dirty work of promoting "recycling" of America's sewage sludge, J. Environ. Occup. Health Policy, 11 (2005) 415–427.

[9] A. Pathak, M.G. Dastidar, T.R. Sreekrishnan, Bioleaching of heavy metals from sewage sludge: a review, J. Environ. Manage., 90 (2009) 2343–2353.

[10] USEPA, Biosolids: Targeted National Sewage Sludge Survey Report, United States Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, Washington, United States, 2009.

[11] P.S. Kidd, M.J. Domínguez-Rodríguez, J. Díez, C. Monterroso, Bioavailability and plant accumulation of heavy metals and phosphorus in agricultural soils amended by long-term application of sewage sludge, Chemosphere, 66 (2007) 1458–1467.

[12] T.L. Jones-Lepp, R. Stevens, Pharmaceuticals and personal care products in biosolids/sewage sludge: the interface between analytical chemistry and regulation, Anal. Bioanal. Chem., 387 (2007) 1173–1183.

[13] L.H.M.L.M. Santos, A.N. Araújo, A. Fachini, A. Pena, C. Delerue-Matos, M.C.B.S.M. Montenegro, Ecotoxicological aspects related to the presence of pharmaceuticals in the aquatic environment, J. Hazard. Mater., 175 (2010) 45–95.

[14] J. Sipma, B. Osuna, N. Collado, H. Monclús, G. Ferrero, J. Comas, I. Rodriguez-Roda, Comparison of removal of pharmaceuticals in MBR and activated sludge systems, Desalination, 250 (2010) 653–659.

[15] L.E. Sommers, D.W. Nelson, K.J. Yost, Variable nature of chemical composition of sewage sludges, J. Environ. Qual., 5 (1976) 303–306.

[16] N. Shepeleva, Sewage Sludge Handling for Environmental Impact Minimization, State Scientific Institution "Institute for Environmental Use of the National Academy of Sciences of Belarus", Minsk, 2018. Available at: https://vak.gov.by/sites/default/files/2018–09/%D0%9A-Shepeleva_%D0%B8%D1%81%D0%BF%D1%80.pdf – Date of access 22.01.2021.

[17] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (the Waste Framework Directive), The Stationery Office Limited, Norwich, UK. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN.

[18] H. Saveyn, P. Eder, End-of-Waste Criteria for Biodegradable Waste Subjected to Biological Treatment (Compost & Digestate): Technical Proposals EUR 26425, Publications Office of the European Union, Joint Research Centre, Institute for Prospective Technological Studies, 2014. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC87124/eow%20biodegradable%20waste%20final%20report.pdf – Date of access 12.01.2021.

[19] PURE, Project on Urban Reduction of Eutrophication, Vanha Suurtori 7, FIN–20500 Turku, Finland 2012. Available at: http://zwik.szczecin.pl/uploads/dokumenty/PURE_dobre_praktyki_zwi%C4%85zane_z_gospodark%C4%85_osadow%C4%85.pdf – Date of access 12.01.2021.

[20] B. Wu, X. Dai, X. Chai, Critical review on dewatering of sewage sludge: influential mechanism, conditioning technologies and implications to sludge re-utilizations, Water Res., 180 (2020) 115912, doi: 10.1016/j.watres.2020.115912.

[21] Council Directive 1999/31/EC of 26 April 1999 on the Landfill of Waste (the Landfill Framework Directive) , The Stationery Office Limited, Norwich, UK. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=LEGISSUM:l21208.

[22] Closing the Loop – An EU Action Plan for the Circular Economy, The Stationery Office Limited, Norwich, UK. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

[23] J. Bień, B. Bień, Sludge Thermal Utilization, and the Circular Economy, Civil and Environmental Engineering Reports 29, 2019. Available at: https://doi.org/10.2478/ceer-2019–0052.

[24] J. Bień, B. Bień, Utilisation of municipal sewage sludge by thermal methods in the face of storage disallowing, Inzynieria Ekologiczna, 45 (2015) 36–43 (in Polish).

[25] Z. Chang, G. Long, J.L. Zhou, C. Ma, Valorization of sewage sludge in the fabrication of construction and building materials: a review, Resour. Conserv. Recycl., 154 (2020) 104606, doi: 10.1016/j.resconrec.2019.104606.

[26] A. Hasanbeigi, H. Lu, C. Williams, L. Price, International Best Practices for Pre-Processing and Co-Processing Municipal Solid Waste and Sewage Sludge in the Cement Industry(No. LBNL–5581E), Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (United States), 2012.

[27] Y. Li, H. Wang, J. Zhang, J. Wang, O. Lan, Co-processing sewage sludge in cement kiln in China, J. Water Resour. Prot., 5 (2013) 906–910.

[28] Z. Yang, Y. Zhang, L. Liu, X. Wang, Z. Zhang, Using Sewage Sludge as Alternative Fuel and Raw Material to Produce Cement Clinker, International Proceedings of Chemical, Biological and Environmental Engineering (IPCBEE), Vol. 94, 2016, pp. 88–93, doi: 10.7763/IPCBEE.2016.V94.14.

[29] D. Bernard, D. Lemarchand, N. Tétreault, C. Theévenet, Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice, Technical Report, International Finance Corporation, Washington, DC, 2017. Available at: https://www.ifc.org/wps/wcm/connect/33180042-b8c1-4797–ac82–cd5167689d39/Alternative_Fuels_08+04.pdf?MOD=AJPERES&CVID=lT3Bm3Z – Date of access 12.01.2021.

[30] M. Borzym, Sewage sludge quality standards required by Polish cement plants, Chemik, 67 (2013) 1019–1024.

[31] https://veres.schools.by/pages/energeticheskaja-politika-respubliki-Belarus – Date of access 12.01.2021.

[32] S. Werle, S. Sobek, Gasification of sewage sludge within a circular economy perspective: a Polish case study, Environ. Sci. Pollut. Res., 26 (2019) 35422–35432.

[33] http://www.ecoinfo.by/wp-content/uploads/2020/12/%D0%A0%D0%9E%D0%98%D0%9E–%D0%A7%D0%B0%D1%81%D1%82%D1%8C–2.pdf – Date of access 12.01.2021.

[34] https://rep.bntu.by/bitstream/handle/data/31208/Vybor_napravleniya_ispolzovaniya_osadkov_stochnyh_vod_g_Minska.pdf – Date of access 12.01.2021.

[35] M. Schnell, T. Horst, P. Quicker, Thermal treatment of sewage sludge in Germany: a review, J. Environ. Manage., 263 (2020) 110367, doi: 10.1016/j.jenvman.2020.110367.

[36] M. Smol, J. Kulczycka, A. Henclik, K. Gorazda, Z. Wzorek, The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy, J. Cleaner Prod., 95 (2015) 45–54.

[37] R. Jin, J. Zhan, G. Liu, Y. Zhao, M. Zheng, L. Yang, M. Wang, Profiles of polychlorinated biphenyls (PCBs) in cement kilns co-processing solid waste, Chemosphere, 174 (2017) 165–172.

[38] Fuelcal® Technology. Available at: https://evergreensolutions.pl/en/ – Date of access 17.12.2020.

[39] https://www.researchgate.net/publication/281826184_Organizacia_proizvodstva_alternativnogo_topliva_iz_osadkov_stocnyh_vod_ocistnyh_sooruzenij_g_Minska_i_ispolzovanie_ego_v_proizvodstve_cementnogo_klinkera_na_OAO_Belorusskij_cementnyj_zavod – Date of access 12.01.2021.

[40] https://elib.bsu.by/bitstream/123456789/161967/1/%D0%9A%D0%BB%D0%B5%D0%B1%D0%B0%D0%BD%D0%BE%D0%B2%D0%B8%D1%87%D0%92%D0%B0%D1%81%D0%B8%D0%BB%D1%8E%D0%BA2003.pdf – Date of access 12.01.2021.

[41] https://mshp.gov.by/documents/plant/protection/a95709b40a025b68.html – Date of access 12.01.2021.

[42] A. Mudhoo, S. Kumar, Effects of heavy metals as stress factors on anaerobic digestion processes and biogas production from biomass, Int. J. Environ. Sci. Technol., 10 (2013) 1383–1398.