



‘Zero energy’ electron beam technology for sludge hygienization

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Abstract. Large quantity of sewage sludge originating from wastewater treatment plants is becoming a growing problem from environmental and human health points of view. One of the ways to use sewage sludge is agricultural purpose due to its nutrients and organic matter content, but the condition is that it should be deprived of pathogenic bacteria and parasite egg contamination. Application of ionizing radiation to hygienize sewage sludge can make it appropriate for agricultural use. The process does not require addition of chemicals to sludge; it is environmentally friendly and effective in removal of biological threats. In the past, successful attempts of sewage sludge treatment using ionizing radiation were made. Pilot plants and commercial ones proved that pathogens can be easily removed from sewage sludge by ionizing radiation. The concept of ‘zero energy’ biogas plant is based on the construction of a complex system consisting of biogas plant and electron accelerator in the biofertilizer manufacturing line. Digestate originating from the methane fermentation of sewage sludge is irradiated to remove all pathogens using electron beam from an accelerator powered by electric energy obtained from burning biogas in a cogenerator. The product is a high-quality, biologically safe fertilizer.

Keywords: biogas • sewage sludge • ionizing radiation • hygienization

Introduction

Nowadays, most of world population is living in big agglomerations and usage of water is growing. As demand for water increases across the globe, the availability of fresh water in many regions is likely to decrease because of climate change. Therefore, for environmental protection of surface water reservoirs and for the need to protect fresh water resources, it becomes necessary to expand the network of municipal wastewater treatment plants. A higher number of infrastructure for wastewater treatment means higher amounts of sewage sludge received every year. One of the useful applications of sewage sludge is in agriculture; nevertheless biological soil contamination due to the presence of pathogens in sewage sludge is a matter of concern. Parasitic eggs and pathogenic bacteria are resistant to soil and can infect humans and animals after consumption of plants grown on sewage sludge fertilized field. Because of this fact, hygienization of sewage sludge purposed for agricultural application is required. Traditional processes of sewage sludge treatment like combustion are energy consuming, generating greenhouse gases and pollutants. Some of them are even not effective enough in the control of parasites and bacteria. Ionizing radiation due to its lethality seems to be appropriate for sewage sludge hygienization. Applications of ionizing radiation for wastewater treatment have been demonstrated in many laborato-

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ries. Industrial wastewater treatment plant based on electron accelerator application was constructed and operated in the Republic of Korea, while sludge hygienization in the biofertilizer manufacturing plant based on gamma source operation has been built in India [1]. Choosing electron accelerators instead of isotopic sources seems to be a better option due to safety while using electron accelerators and lack of need for replenishment of irradiation chamber with the new sources.

Municipal wastewater sludge

Primary municipal wastewater treatment usually involves gravity sedimentation of screened, degritted wastewater to remove settleable solids; slightly more than one-half of the suspended solids are removed ordinarily. Secondary municipal wastewater treatment is almost always accomplished by using a biological treatment process. Microorganisms in suspension (in the 'activated sludge' process), attached to media (in a 'trickling filter' or one of its variations), or in ponds or other processes are used to remove biodegradable organic material. Part of the organic material is oxidized by the microorganisms to produce carbon dioxide and other end products, and the remaining organic material provides the energy and materials needed to support the microorganism community. The microorganisms biologically flocculate to form settleable particles, and, following biological treatment, this excess biomass is separated in sedimentation tanks as a concentrated suspension called secondary sludge (also known as 'biological sludge' or 'waste activated sludge'). Partly, this solid is returned to the biological wastewater treatment reactors and the rest is the so-called excess sludge, whose storage is becoming a problem. Biological sludge, as produced from secondary wastewater treatment processes, often has suspended solid content of less than one percent by weight; that is, each kilogram of activated sludge solids is accompanied by more than 99 kg of water. Primary sludges are more concentrated, but marginally so; typical combined primary and secondary sludges might contain about 3% of solids by weight. Because of the voluminous nature of sludges, processes categorized here as 'thickening', 'dewatering', 'conditioning' and 'drying' (listed in order of decreasing frequency of application) are common in sludge management. Removal of water from sludges improves efficiency of subsequent treatment processes, reduces storage volume and decreases transportation costs. Sludge thickening produces a concentrated product that essentially retains the properties of a liquid. Gravity thickening, or concentration by simple sedimentation, is the thickening process most commonly applied to municipal sludges. The product of gravity sludge thickening often contains 5 to 6% solid material by weight. Alternatives to gravity thickening include flotation thickening (in which a gas is incorporated with sludge solids, causing them to float), as well as the use of gravity drainage belts, perforated ro-

tating drums and centrifuges. Sludge dewatering processes produce materials with the properties of a solid, even though the dewatered sludge still contains mostly water. Dewatered sludge can be transported in a dump truck, whereas a tank truck is required to transport thickened sludge. Dewatering may be accomplished on sand drying beds and, occasionally, in lagoons, where gravity drainage and evaporation remove moisture. More often, larger municipal installations use mechanical means for dewatering sludge. Mechanical sludge dewatering equipment includes filter presses, belt filter presses, vacuum filters and centrifuges. The solids content of mechanically dewatered sludge typically ranges from 20% to 45% of solids by weight; most processes produce concentrations of solids at the lower end of this range. Sludge treatment is considered herein to comprise engineered processes for altering sludge quality prior to disposal or reclamation. When sludge is applied to land, inactivation of remaining pathogenic organisms and viruses continues, biological stabilization of residual organic material progresses and biologically mediated and abiotic chemical transformations occur.

The quantity of sewage sludge generated in Europe is constantly increasing; in 2009–2011, it amounted to 9.7 million tons in terms of dry mass (d.m.). In Poland in 2016, the amount of obtained sewage sludge from municipal sewage amounted to 568.3 thousand tons of d.m., of which only 167.9 thousand tons were used for recultivation in agriculture and for crop cultivation. Thermally transformed (burned) sewage sludge was 101.1 thousand tons of d.m. In turn, the amount of sludge from industrial treatment plants using the same technology amounted to 378.9 thousand tons of d.m., which in total gave 947.2 thousand tons of d.m. [2]. It is forecasted that by 2020, 650–800 thousand tons of d.m. from municipal sewage sludge will be produced in Poland.

Organic sludge composition

Sewage sludge obtained from the process of dewatering of municipal wastewater contains various organic origin matters. What are entering the sewers are mostly human and animal excrements, food leftovers, food industry wastes and other organic origin substances. Sewage sludge differs very widely dependently on region. Solid components of sewage wastewater are mostly proteins, fats, oils and carbohydrates. As an example, composition of dewatered to 40.7% d.m. sewage sludge (Inoue *et al.*) can be given as follows: 33.4% of proteins, 6.6% of lipids, 3.3% of carbohydrates, 2574 mg/l of ammonia nitrogen and 16 707 mg/l of total organic carbon (TOC) [3].

Sewage sludge contains nutrients such as S, N, K and P and micronutrients such as Zn, Cu, Fe and Mn [4]. Most of the nitrogen comes from the proteins and urea [5]. Exemplary amount of C, N and S and also halogens in dried sewage sludge is listed in Table 1.

Adam *et al.* carried out experiments using acid leaching of sewage sludge ashes for phosphorus re-

Table 1. Amount of C, N, S, Cl and F in dried sewage sludge [6]

Element	C	N	S	Cl	F
% wt.	30.2 ± 0.1	4.8 ± 0.13	1.2 ± 0.14	0.16 ± 0.005	0.03 ± 0.005

Table 2. Mass fraction of main constituents (in %) in the samples of untreated sewage sludge ashes (SSA) [7]

	SSA 1	SSA 2	SSA 3	SSA 4	SSA 5	SSA 6	SSA 7
SiO ₂	23.8	21.6	19.6	23.3	43.4	23.7	21.2
Al ₂ O ₃	24.9	10.8	15.5	9.3	10.9	10.3	8.9
Fe ₂ O ₃	3.2	16.3	5.7	15.7	8.3	22.6	19.6
MnO	0.09	0.15	0.19	0.35	0.32	0.20	0.09
MgO	1.79	20.85	3.63	3.37	3.51	2.14	2.65
CaO	17.1	15.7	18.5	13.2	14.8	14.4	12.5
Na ₂ O	0.86	1.04	0.98	1.12	0.87	0.43	0.30
K ₂ O	0.95	0.99	2.05	2.77	2.40	1.31	1.08
P ₂ O ₅	19.4	21.3	25.7	23.4	13.7	18.9	24.9

covery. The amount of P₂O₅ was 13.7–25.7%, which depended on the sample. Experimental results are listed in Table 2 [7]. Therefore, sludge may be a rich source of phosphorus, which is not a recoverable element and cannot be obtained like carbonaceous organic compounds from photosynthesis and nitrogen compounds by synthesis via chemical manmade processes.

Sewage sludge contains toxic organic and inorganic pollutants. Some of them are washed into sewers by rain from streets and roofs. Pollutants occurring in sewage sludge are: heavy metal ions (Cd, Hg, Pb, Cr(III), Cr(VI) and Cu); polyaromatic hydrocarbons (PAHs) (from incomplete combustion of wood and fossil fuels; waste incineration, especially in household furnaces; fuel and engine oil discharge; solid particles from exhaust fumes and industrial processes, etc.); polychlorinated biphenyls (PCBs) (hydraulic and transformer oils, impregnation agents, flame retardants); dioxins (waste incineration, vehicles' fumes); polychlorinated dibenzofurans or pesticides (used in road and railway weed treatment, gardens, parks) and pharmaceuticals and their metabolites (excreted by humans) [8].

A significant part of organic matter present in sewage sludge comes from human and animal faeces. Excrements are source of pathogenic bacteria and parasite eggs, especially derived from hospitals. Bacteria occurring in sewage sludge such as *Salmonella* spp., *Brucella* spp., *Bacillus anthracis*, *Clostridia* spp. and *Escherichia coli* can cause food poisoning, diarrhoea and other serious diseases. Living eggs of the following species are present in sewage sludge: helminths (e.g. *Ascaris* sp., *Trichuris* sp., *Toxocara* sp., *Fasciola hepatica*) and protozoa (e.g. *Eimeria* sp., *Balantidium* sp.) [9, 10].

Present regulations regarding sludge disposal and utilization

Amount of heavy metals as well as pathogens and living parasite eggs in sewage sludge purposed for agricultural use and other applications is regulated by the law. Also forms of sewage sludge disposal are controlled by law.

Acceptable level of heavy metals in sewage sludge

In each country limits of heavy metal content in sewage sludge destined for agricultural applications are different. In the European Union (EU), law regulations are contained in the EU directive of 12 June 1986 (Table 3), but different EU member states have their own law acts. For example, in Poland, acceptable concentration of heavy metals is given in the Regulation of the Minister of Environment of 13 July 2010 on municipal sewage sludge. In this act, three types of sewage sludge usage are detailed, and the maximum level of heavy metals is different for each application (Table 4) [12].

Table 3. Acceptable heavy metal content in sewage sludge purposed for agricultural use according to the EU directive of 12 June 1986 [11]

Element	Acceptable concentration [mg/kg d.m.]
Cd	20–40
Cu	1000–1750
Ni	300–400
Pb	750–1200
Zn	2500–4000
Hg	16–25

Table 4. Acceptable heavy metal content in sewage sludge purposed for agricultural use according to the Polish Regulation of the Minister of Environment of 13 July 2010 on municipal sewage sludge [12]

Element	Acceptable concentration [mg/kg d.m.]		
	Agricultural use	Land reclamation use	Other*
Cd	20	25	50
Cu	1000	1200	2000
Ni	300	400	500
Pb	750	1000	1500
Zn	2500	3500	5000
Hg	16	20	25
Cr	500	1000	2500

*Needs resulting from waste management purposes, zoning plan, for cultivation of plants used for composting and for cultivation of plants not purposed for food or fodder production.



Fig. 1. Adult forms of parasites, whose eggs are present in sewage sludge and who are detailed in law acts. From the left: human roundworm (*Ascaris* sp.), human whipworm (*Trichuris* sp.) and animal roundworm (*Toxocara* sp.).

Acceptable level of living parasite eggs and pathogenic bacteria

Owing to health threat coming from intestinal parasite eggs and bacteria, the amount of these mentioned pathogens is also regulated by the law. In case of Poland, guidelines are specified in the Regulation of the Minister of Environment of 13 July 2010 on municipal sewage sludge [12], while species detailed in this act are *Salmonella* and parasites such as human whipworm (*Trichuris* sp.) – nematode parasiting in human intestines, human roundworm (*Ascaris* sp.) – human intestinal roundworm and animal (mostly cat and dog) roundworm (*Toxocara* sp.) – pets intestinal roundworm. These species are the most resistant in sludge and soil (Fig. 1) (*Salmonella* can survive up to 1.5 years in soil, while human roundworm eggs can infect even after 6 years of dwelling in soil).

This act says that the overall number of living parasite eggs (*Ascaris* sp., *Trichuris* sp., *Toxocara* sp.) in 1 kg of d.m. of sewage sludge is as follows:

- for agricultural purposes – 0,
- for land reclamation purposes – cannot exceed 300,
- for needs resulting from waste management purposes, zoning plan – cannot exceed 300,
- for cultivation of plants used for composting – cannot exceed 300 and
- for cultivation of plants not purposed for food or fodder production – cannot exceed 300.

In sewage sludge purposed for agriculture and reclamation of land for agricultural purposes (100 g of examined sludge), *Salmonella* cannot be detected [12].

Another important act in the Polish law is prohibition of sewage sludge storage on landfill sites, which came to be in force on 1 January 2016. This law makes problem of sewage sludge production more significant and contributes to develop new effective methods of sewage sludge use [13].

Conventional technologies for sludge treatment

Owing to the presence of pathogens in sewage sludge hygienization is required. Such processed sludge is safe to use in agriculture and meets law regulations.

One of the main methods of hygienization of sewage sludge is pasteurization. Sewage sludge is heated to a temperature from 65°C to 90°C. Sludge can

be heated by steam, sometimes hot water or primary heated sludge. Effectiveness of the process depends on time and temperature: to achieve removal of required pathogens, a temperature of 65°C must continue for 30 minutes, 70°C for 25 minutes or 80°C for 10 minutes. Because pasteurization temperatures are not enough to kill spore forms (temperature of 100°C and above is required for this), after the first process, sludge is conditioned for 24 h in room temperature, which transforms spore forms into vegetative forms. These spore forms can be killed in the second pasteurization process. This process is highly energy consuming: energy consumption is 11.9 kWh/m³, not considering heat losses.

Other widely used method is composting – the process using aerobic bacteria to stabilize and hygienize sewage sludge at a temperature of about 60°C. This process requires sewage sludge of about 15% d.m.; often some organic matter like dry sawdust is added to decrease the moist content. Composting is also a time-consuming process and requires large area.

Adding calcium compounds (CaO or Ca(OH)₂) is often used to hygienize sewage sludge, both untreated and digested. This process causes pH to increase to about 12. To sewage sludge with low d.m. content, milk of lime (5–10% Ca(OH)₂) is added; in case of sludge with 20–40% of d.m., CaO is used. To stabilize 0.5 to 1.2 kg, CaO or Ca(OH)₂ per 1 kg d.m. is used, whereas to hygienize 0.15 to 0.25 kg, CaO or Ca(OH)₂ per 1 kg d.m. is used. Using sludge treated in such a way is useful when soil alkalization is needed.

Thermal treatment is the process of disintegration of sludge components and hygienization of sludge under a high pressure and temperature. It is fulfilled by heating sludge to 120–150°C, under pressure of 0.5–2.0 MPa during 0.5–1 h. Disintegration obtained in this treatment makes dewatering easier and reduces filtration resistance. Disadvantages of the process are high energy consumption, necessity to use corrosion resistance materials for installation, odour emission and need of frequent installation cleaning [14].

Another form of sewage sludge treatment is incineration. This method reduces volume of wastes – ash volume produced during process is 10 times smaller than mechanically dewatered sludge volume. Incineration also removes completely parasites and disease-causing bacteria. Ways to carry out the pro-

cess are diverse: by using multiple hearth furnaces, fluidized incinerators, electric infrared incinerators or co-combustion in coal-powered power plants, with municipal solid wastes, during clay brick, clinker brick or cement production. The disadvantage of the process is necessity to dry the sludge before burning, which is highly energy consuming. Also emission of significant amount of different pollutants such as solid particles, SO_2 , NO_x , CO, metals, unburned hydrocarbons, volatile organic compounds (VOCs) and dioxins is problematic [15, 16].

Sludge hygienization using ionizing radiation

High-dose ionizing radiation is known for its destroying influence on living organisms. Technologies of sterilizing food or medical equipment are well known and widely used all over the world. Usage of such technology for sewage sludge sterilization can help with removal of pathogens. It is worth considering because it is effective (unlike some of the traditional sewage sludge treatment processes) and does not require chemical additives at the same time.

There are two possible ways of damaging the DNA by irradiation: direct – electron or gamma rays interact directly with DNA chains causing their damage and cell death – or indirect – ionizing radiation interacts with water present in all living organisms; obtained water radiolysis products, which are highly reactive radicals and solvated electrons can then react with DNA chains and damage them, causing effect as mentioned earlier [17]. Irradiation of sewage sludge had already been applied in many countries – commercial as well as pilot installation. Some experiments to evaluate ionizing radiation influence on pathogens in sewage sludge were carried out. Chmielewski *et al.* demonstrated that a dose of 5 kGy can reduce amount of pathogenic bacteria by two orders

of magnitude and a dose of 7 kGy by four orders of magnitude [18]. Another example can be the work of Naign and Lay who reported that a dose of 7 kGy completely eliminates bacteria from sludge [19]. El-Motaïum *et al.* concluded that a dose of 6 kGy removes all living bacteria from the sewage sludge, but to achieve the same effect on untreated wastewater, the dose required is 1.5 kGy. The authors also mentioned that bacterial cells have the tendency to fall to the bottom along with solid particles, which makes the concentration of bacteria higher in sewage sludge due to the fact that hygienization of sewage sludge requires higher doses in comparison to that of wastewater [9].

Application of gamma irradiators

Some pilot and commercial facilities using isotope gamma sources were constructed.

As an example, an installation in Geiselbullach, Germany, can be depicted (Fig. 2) [20, 21]. It was built in 1973. First, for test purposes, this installation was able to irradiate 30 m^3 of sewage sludge per day using gamma source with activity of 110 kCi. In 1975, activity of the gamma source was increased to 450 kCi, which allowed to irradiate 120 m^3 of sewage sludge.

This installation was operating periodically using ^{60}Co source (^{137}Cs sources were added later) and was able to irradiate 5.6 m^3 of sewage sludge to 3 kGy in one cycle.

The facility was placed on two levels: ground level and underground level. On the upper level, a silo with a capacity of 5.6 m^3 , a crane, a steering panel and a small laboratory were placed. The lower level, which was 8 m deep, was divided into two separate spaces. The first one was equipped with a thick-walled chamber with radiation sources. The second

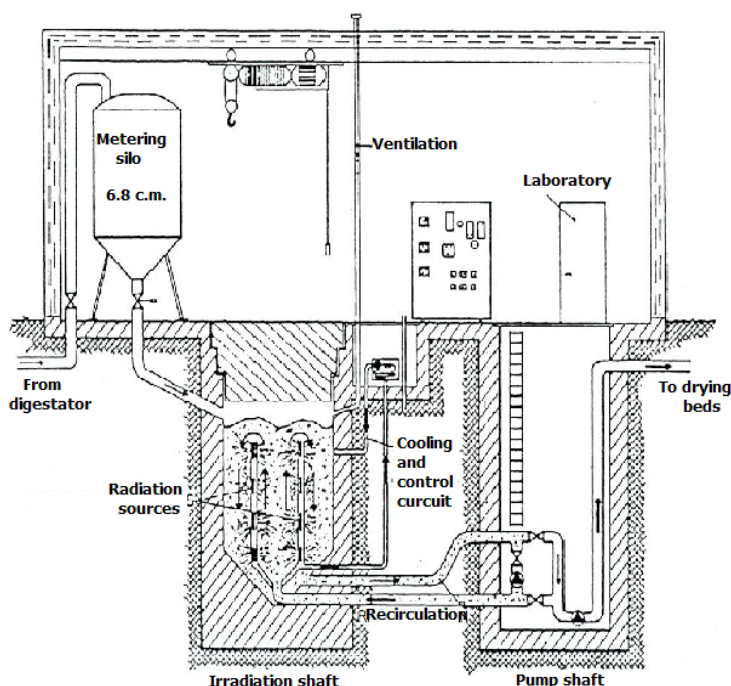


Fig. 2. Scheme of installation for sewage sludge irradiation in Geiselbullach, Germany.

space, isolated from ionizing radiation, contained pumps, valves and other devices. Such a set-up allowed to maintain a pump system without exposing workers to ionizing radiation. The irradiation chamber was designed in the following way: sources were placed in a centrally located double-walled pipe. Sewage sludge was circulated through central and outer sides of the pipe for a certain period of time until the dose was achieved. Then, sludge was pumped out of the chamber. Radioactive sources were cooled all the time with demineralized water, which after cooling were passed through the radiation detector, filtered and were pumped to the buffer tank. The installation operated automatically for 24 h, and only occasional maintenance was necessary. The facility was closed in 1993.

Another example is the pilot plant located in Albuquerque, New Mexico, USA operating from 1979 to 1985, equipped with ^{137}Cs source with a maximum activity of 1 MCi. Sewage sludge in an amount of 8 tons per day was moved on the conveyor under the source of radiation and received dose of 10 kGy [22, 23]. In Vadodara, India, since 1992, installation based on ^{60}Co source is in service. The irradiation chamber (Fig. 3) can be easily transported and attached to standard waste water plant, and the achievable efficiency is 110 m³ per day. Sewage sludge is recirculated through the chamber until it

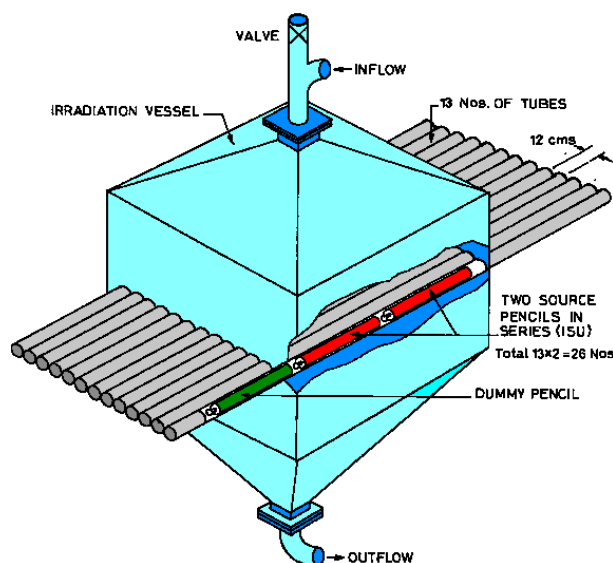


Fig. 3. Scheme of irradiation chamber used in WWTP Vadodara, India [22].

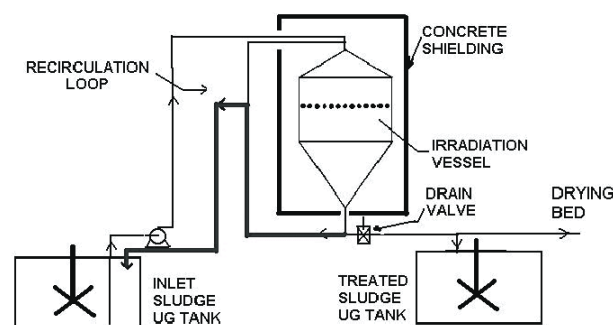


Fig. 4. Scheme of installation for sewage sludge irradiation in Vadodara, India [22].

gets required dose, and then, it is pumped to the container for irradiated sludge (Fig. 4) [23].

Application of electron accelerators

In 1976 in Boston, USA, installation for sewage sludge irradiation using an electron accelerator was built. It was possible to irradiate 655 m³ of sewage sludge per day with a dose of 5 kGy. The electron beam (EB) energy was 1.5 MeV. Sewage sludge was pumped through the 1200 mm wide nozzle, which formed 4 mm thick layer falling vertically passing the electron accelerator [22].

Similar facility was located in Takasaki, Japan. Efficiency of this installation was 300 kg/h, and the absorbed dose was 5 kGy. Sludge was coming out from the nozzle as a 10 mm thick layer, and then, it passed the electron accelerator. After irradiation, sludge was aerated and composted in determined conditions [22].

There was also a pilot plant in 2005 in South Korea. A 100 MW, 2.5 MeV electron accelerator with a maximum dose rate of 40 kGy/s was used. Sewage sludge came out from the 300 × 7 mm nozzle onto the stainless steel conveyor in the form of 6 mm thick layer. The conveyor carried sewage sludge layer under the electron accelerator, and after irradiation, sewage sludge was collected in the container. It was possible to irradiate 500 kg/h of sludge. A dose of 3 kGy was enough for complete elimination of *Salmonella* and reduction of coliforms by three to four orders of magnitude [1, 23].

'Zero energy' EB technology for sludge hygienization

Nowadays, municipal sewage is being cleaned mostly with the use of the method of activated sludge. Excess of activated sludge constitutes biomass, which can be utilized to produce energy and at the same time has a value as a fertilizer. However, the problem is that the sludge is microbiologically contaminated by human and animal parasites, their eggs and also pathogenic bacteria. One of the methods for sludge treatment consists of drying and burning, which is not an environmentally friendly method due to greenhouse gas and dioxin emissions. The energy yield of this method, which uses a burning process, is reduced due to high levels of hydration of the biomass, which requires the moisture to be evaporated unproductively. Thus, the preferred method is methane fermentation whereby biogas is produced. Excess sludge from municipal sewage treatment plants contain organic and inorganic components valuable as a soil fertilizer; so if disinfected, they can be beneficial – recycled in agriculture instead of being burdensome waste.

High-efficiency biogas plant

Biogas is created by anaerobic methane fermentation, with the participation of a diverse population

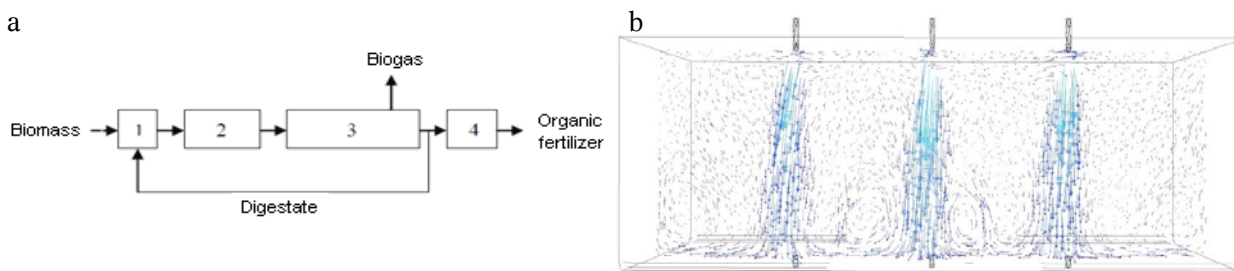


Fig. 5. Scheme of two-stage biogas plant (a) and CFD model of biomass mixing in bioreactor (b). 1 – biomass tank, 2 – hydrolyser, 3 – fermentor and 4 – digestate reservoir.

of microorganisms, during which the decomposition of complex organic matter into a reduced gas product occurs. Biogas in its composition contains mainly methane and carbon dioxide. The biogas production process consists of four main stages. In the first stage, water-insoluble organic fraction is hydrolyzed to water-soluble monomers (amino acids, simple sugars, fatty acids). Then, a group of microorganisms – anaerobes – decomposes hydrolysis products to volatile fatty acids, alcohols, hydrogen and carbon dioxide (acidogenesis). The next stage is acetogenesis, thanks to methanogenic substrates, i.e. acetic acid, hydrogen and carbon dioxide, that are produced from acidogenesis products. The last stage of the process is methanogenesis, proceeding in two ways: in the first one, acetic acid is used as a substrate, and in the second one, hydrogen and carbon dioxide. Acetogenic bacteria are hydrogen producers. Methanogens, in turn, responsible for the production of methane during the last stage of methane fermentation, require the presence of hydrogen for the survival. The above environmental requirements make these two groups of microorganisms coexist in symbiosis. The biogas plant developed by the Institute of Nuclear Chemistry and Technology (INCT) and its collaborators uses the technology of anaerobic biomass processing that is carried out in a two-stage manner – separation of hydrolysis from fermentation (Fig. 5) and hydraulic mixing applied in bioreactors [24].

This technology introduces a cascade system of tanks and devices in the anaerobic fermentation system, i.e. hydrolysers, fermenters, press or decanter centrifuge and composter. The post-fermentation effluent along with the methane bacteria returned through the pipeline to the biomass preparation system and to the hydrolyser causes the acceleration of the hydrolysis process and allows you to obtain the right amount of dry matter in the suspension. In addition, it allows for proper water management.

These patented [25] solutions allow to combine the system to:

- a heat and power plant generating electricity and heat or a plant generating electricity and gas fuel or
- a high-efficiency power plant with an electricity generation efficiency of 60%.

Thus, the preferred method is methane fermentation, whereby biogas is produced. Recently, Institute of Nuclear Chemistry and Technology has developed a new technology regarding two-stage biogas plant engineering, and two 1.2 MW units have been constructed.

Electron accelerator unit for biofertilizer hygienization

Experiments have been performed at INCT to test influence of 10 MeV EB on bacteria, parasites and parasite eggs content in municipal sewage sludges from different locations in Poland. Double-bagged samples of sludges (1 kg weight and 2.5–3 cm thick) were irradiated with the doses of 5–7 kGy in Russian electron accelerator of LAE 13/9 type. Total bacteria content, spore-forming bacteria content, *Coliform* counts and *Clostridium perfringens* counts, as well as the number of parasites and their eggs were determined. The dose of 6 kGy kills all parasite eggs and decreases total bacteria content by 3 logs, spore-forming bacteria and *Coliform* counts by 2 logs and *Clostridium perfringens* counts by 1 log. It should be added that all adult parasites are being killed too, as they are much more radiosensitive than their eggs. On the basis of experiments, the concept of installation has been designed for disinfection of dewatered sewage sludges (Fig. 6).

A typical EB sludge treatment plant consists of sludge feeding system, an electron accelerator with a shield structure. Dewatered sludge is spread through a flat wide nozzle onto a stainless steel

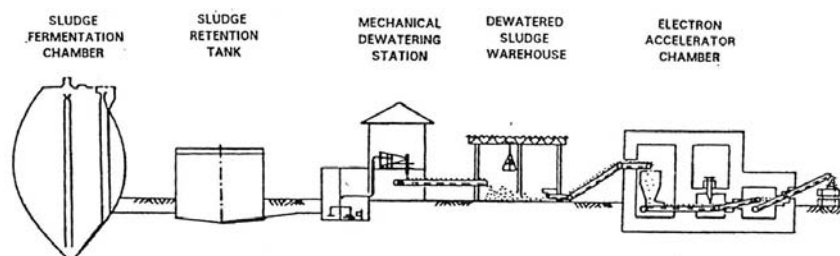


Fig. 6. Concept of sludge hygienization plant with 10 MeV, 10 kW accelerator.

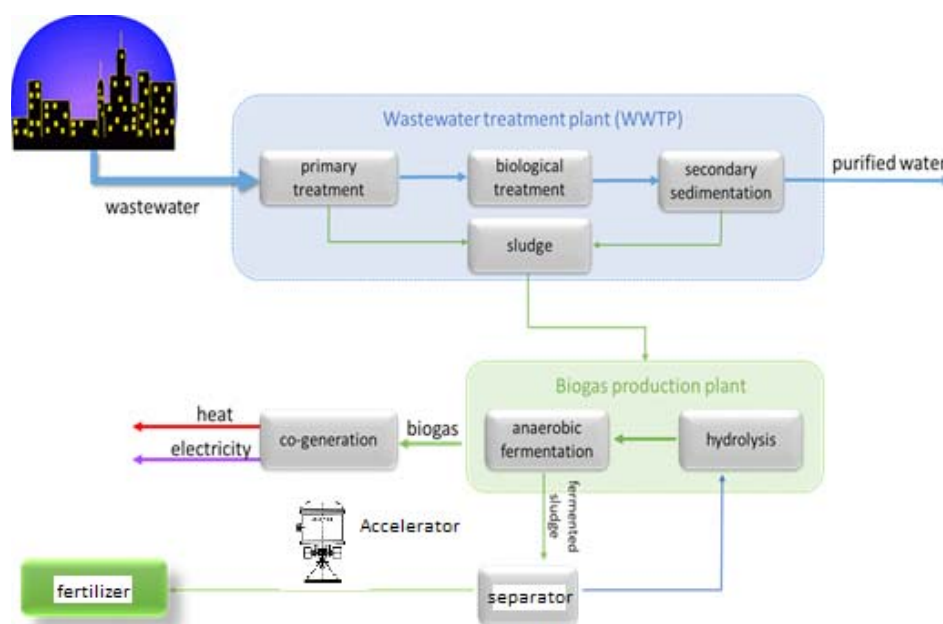


Fig. 7. Principle of 'zero energy' sludge hygienization technology.

conveyor belt and fed past the EB in an 8–40 mm thick layer at a rate that provides an absorbed dose of 5–10 kGy; the maximum feed rate is 3 ton/h. The thickness of sludge depends on the energy of EB. After irradiation, the sludge is moved to a conveyor belt where it is composted under conditions of controlled aeration and frequent mixing. The irradiated sludge, being pathogen free, can be beneficially used as manure in agricultural fields, as it is rich in required soil nutrients.

Hybrid system – biogas plant and accelerator system

On the basis of above-described developments, a new concept of 'zero energy' sludge hygienization technology was elaborated [26]. According to the invention, biomass originating from waste prior to its fermentation or digestate derived in the process of methane fermentation is irradiated with EBs that use energies from 1 MeV to 10 MeV, preferably 1–3 MeV. For a digestate derived in the process of fermenting biomass originating from waste and having a liquid form with the content of dry matter less than 5%, the radiation dose is from 1 kGy to 5 kGy, whereas for a digestate from which the aqueous phase has been filtered out and which has a dry matter content up to 30%, the radiation dose is from 5 kGy to 20 kGy.

An electron accelerator is favourably powered with energy provided by a cogenerator fuelled by biogas produced in the process of methane fermentation (Fig. 7).

Conclusions

The advantage of the method according to the invention consists of the fact that the energy is generated from renewable waste materials, which

is widely available. The method according to the invention does not require energy from external sources (thanks to the fact that irradiated digestate is utilized as a fertilizer) and does not generate waste. The method allows pathogens to be eliminated from sludge and does not have a negative impact on the environment. The plant due to own electricity source may be installed in the remote site, providing electricity for accelerator, wastewater treatment plant and village. The heat from the cogenerator may be used for fertilizer drying.

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