Wastewater sludge to energy production. A review

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Abstract. Global economic and social development involves increasing demands for water use for various purposes: domestic, public, industrial. Wastewater treatment in these processes results in increasing volumes of sewage sludge. The elimination of this sludge is a permanent concern at global level because of the dangers to the environment, consisting of the high content of organic pollutants, toxic and heavy metals. However, a significant amount of renewable energy can be recovered from sludge from sewage treatment, with several paths being possible: anaerobic digestion, combustion and co-combustion, pyrolysis, gasification. Each of these pathways is characterized by advantages and disadvantages, benefits and technological limitations. This paper proposes a review of current conversion methods and technologies for energy recovery from sewage sludge, anaerobic digestion, incineration and co-combustion especially.

Processes present in current literature and practice are described, resulting in the influence of the properties of sludge fuels and their impact on the energy recovery process when these fuels are used in combustion plants. There are also scientific researchers conducted to improve operational and environmental performance and cost competitiveness.

1. Introduction

The recovery of energy through current waste management methods is of particular importance due to its impact on the minimization of their storage space and the optimization of alternative energy generation. Energy conversion technologies can be highlighted in Figure 1 [1, 2, 4-6], resulting in the possibility of sludge conversion with natural gas, liquid fuel, chemical, heat and/or electricity generation.

Anaerobic digestion is a widely used method of biological conversion because of its low cost and the ability to use high-humidity organic waste without reducing high calorific value of the produced biogas (methane and carbon dioxide). Sewage sludge is a solid, semi-solid or liquid waste generated by wastewater treatment plants. The physical properties (low ratio of solid matter in the liquid) of the slurry require thickening and dehydration to facilitate transport and logistics during the treatment processes. These processes help to increase the concentration of solid particles in the sludge to about (10-25)% by weight from the predominantly liquid original state (<3% by weight solid) [1-4]. Pretreatment of raw waste water removes large particles such as gravel and stone but also the finest sands in specialized installations. Continued processing with the use of sedimentation tanks where the primary sludge is generated under the gravitational force [2, 5].

Sludge from sedimentation and decantation is sent to digesters where biogas is generated by oxygen-free fermentation. Biogas from the digester can be further cleaned and upgraded to produce...
bio-methane that can be a direct substitute for natural gas or can be converted to thermal and electrical energy by cogeneration using thermal reactors.

On the other hand, thermos-chemical conversion paths, such as burning or incinerating sludge, are characterized by shorter reaction times, ranging from seconds to min. These processes require low-moisture sludge and drying of the sludge can be done with high energy consumption. Fast and controlled decomposition of 80% of the inert, partially or total oxidized organic matter causes these thermal processes to be considered more beneficial compared to anaerobic digestion [7]. However, the cost of thermal technologies is still significantly higher.

Incineration is a process currently used for sewage sludge, but was not intended for energy recovery but is used to reduce the volume of waste and destroy the harmful elements in its composition [8, 9]. The resulting heat recovery from the combustion gases however, converts traditional incinerators into typical combustion systems that use heat from complete oxidation of organic matter at high temperatures (800-1150)°C. Heat extracted is used to heat working fluids (usually water) that can be used directly or are used to generate electricity through a steam turbine.

Unlike combustion, pyrolysis takes place under completely inert (no oxygen) conditions at moderate to high temperatures (300-900)°C to produce pyrolytic oil, carbon dioxide and non-condensable gases (CO, H₂, CO₂, CH₄ and light hydrocarbons) [7, 9].

The operating temperature, heating speed and residence time greatly influence the quality of the product and the energy content of the pyrolytic products. Bio-oil can be processed and used as liquid fuel or converted by synthesis to gas (CO and H₂) for chemical production, while biofuel, non-condensable gases and bio-oil can be used as solid, gaseous and liquid fuels for the production electric and thermal combustion.

Alternatively, the biofuel can be used in adsorption or catalyst applications. Finally, we mention the gasification, the thermo-chemical conversion of the organic compounds by partial oxidation (lower oxidant than stoichiometric requirements) at high temperatures (650-1000)°C to maximize the production of gaseous products, especially synthesis gas (CO and H₂) [10].

The energy contained in the product gas varies from 4-28 MJ/Nm³ depending on the gas and temperature agent. The derived gas can be directed to a variety of end uses such as direct heat combustion and electricity generation using a combined cycle gas turbine. By further modernizing the synthesis process or using chemical processes the gas can be converted to liquid fuels by processes such as Fischer-Tropsch synthesis.
2. Anaerobic digestion

By anaerobic digestion we understand a process during which the organic compounds in the mud to be treated are converted into methane and carbon dioxide in microbiological processes. This takes place in four stages: hydrolysis, acidogenesis, acetogenesis and metanogenesis. During hydrolysis insoluble organic compounds and high molecular weight compounds are converted to soluble organic, such as amino acids and fatty acids. The compounds produced by hydrolysis are taken up in the acidogenesis phase where acidogenic bacteria turn into volatile acids, ammonia, carbon dioxide and other byproducts. Acetogenesis further digests the acidogenesis product with acetogens, the final products being acetic acid, carbon dioxide and hydrogen. Hydrogen is the one that, through its partial pressure in the mix, controls this conversion. Finally, in the methanogenesis stage, methane is generated by means of two groups of obligatory anaerobic bacteria.

Therefore, anaerobic digestion is performed by three different groups of bacteria, namely hydrolytic and acetogenic bacteria, the group of hydrogen producing bacteria, acetic hydrogen and carbon dioxide, and the methanogenic methane group producing methane and carbon dioxide. These groups use in their metabolic process the product generated by the previous group.

The whole process of microbial digestion is slow and requires a long retention time (Fig. 2). Throughout it, the whole organic material is digested, less stable woody materials since the anaerobic micro-organisms are unable to degrade lignin.

Figure 2. Stages of anaerobic digestion.

The quantity of methane that can be produced depends on waste composition and in particular the degradable organic content. The theoretical maximum methane yield can be estimated from Eq. (1):

\[ C_{n}H_{b}O_{d}N_{e}S_{s} + y \text{ H}_2\text{O} \rightarrow x \text{ CH}_4 + (c-x)\text{CO}_2 + n \text{ NH}_3 + s \text{ H}_2\text{S} \]  

(1)

where:

\[ x = \frac{(4c + h - 20 - 3n - 2s)}{8} \]

\[ y = \frac{(4c - h - 20 + 3n + 3s)}{4} \]

However, all of the organic content may not actually be able to be degraded by the bacteria. The anaerobic fermentation process can be improved by generating a more intimate contact between biodegradable particles and bacteria. This can be accomplished by finely grinding the particles and making a more homogeneous mixture between finely obtained particles and bacteria. Crushing produces an intimate particle-bacterial contact surface and in this way the organic material is more exposed to the action of the bacteria. This method leads to an increase in the fermentation yield of about 20%.

Another way to increase the efficiency of anaerobic fermentation is to ensure an optimal temperature of the mixture of the material that is degradable with the bacteria involved in the process. This is done by thermal sludge pretreatment, i.e. providing a temperature in the range (150-200) °C and some pressures in the range of (600-2500) kPa. Heat introduced during thermal pretreatment helps solubilize cellular components, accelerating extra cellular enzyme activity acting as a catalyst for
fermentative reactions. The optimum temperature differs depending on the nature and composition of the sludge [51].

Table 1 shows the results obtained by different researchers in the use of thermal pretreatment to improve anaerobic digestion.

| Reference      | Treatment conditions | Comments                                                                 |
|----------------|----------------------|--------------------------------------------------------------------------|
| Hiraoka et al. [11] | (60–100)°C           | -Maximum increase in gas production at 60°C                              |
|                |                      | -Maximum VS reduction at 100°C (only 5–10%)                               |
| Pinnekamp [12]   | (120–220)°C          | -ODS reduction of 10–55% for WAS                                         |
|                |                      | -ODS reduction from 7% to 34% for primary sludge                         |
|                |                      | -Maximum gas yield for treatment temperature of 170 °C                  |
|                |                      | -Positive correlation between gas yield and treatment temperature       |
| Li and Noike [13] | (62–175)°C (30–60) min | -Increase of sludge solubilisation ratio by 25–45% (optimum at 90 °C) for WAS |
|                |                      | -Increase of 30% VSS degradation and of 100% methane production (optimum at 170 °C and 60 min) |
|                |                      | -No further improvement for longer treatment times                      |
|                |                      | -Reduction of retention time in digester by 5 days                      |
| Tanaka et al. [14] | 180°C 60 min         | -90% increase of methane production                                       |
|                |                      | -VSS solubilisation of 30%                                              |
| Zheng et al. [15]  | 220°C 30 s            | -55% VS reduction during digestion                                       |
|                |                      | -Increase in gas production of 200% during first 2 days                 |
|                |                      | -Total increase in gas production of 80%                                |
| Kim et al. [16]   | 121°C 30 min          | -Increase of VS reduction by 30%                                         |
| Valo et al. [17]   | 170°C 90 min          | -59% increase of TS reduction                                            |
|                |                      | -92% higher gas production                                              |
| Ferrer et al. [18] | 70°C 9–72 h           | -Positive effect on gas production                                       |
|                |                      | -Higher temperature (110–134 °C) did not have any effect                |
| Climent et al. [19] | (70–134)°C 90 min–9 h | -Studied thermophilic digestion                                          |
|                |                      | -50% increase of biogas production at 70 °C (9 h)                        |

The formed biogas has a high calorific value and is considered as a renewable energy source. It is beneficial to produce as much biogas as possible [20].

Despite these advantages of AD, some limitations are inevitable:
- the organic fraction suffers a partial, not total decomposition;
- slow reaction speeds;
- high cost of digesters;
- the process is sensitive to the influence of various reaction inhibitors;
- the presence of other gases along with biogas, CO₂, H₂S, water vapor;
- the possibility of degradation of the biogas combustion boiler pipes due to the presence in the biogas of volatile siloxanes, which generate monocristalline silica which is deposited on the pipes;
- present in important quantities of heavy metals in the residual sludge;
Therefore, microbiology anaerobic digestion is complex and delicate, each of the groups of bacteria with their own optimal working conditions. These groups are sensitive and may optionally be inhibited by a number of waste and environmental factors.

In terms of energy, the anaerobic digestion process is, on the one hand, an important consumer (heating and pumping mixing sludge) and on the other hand it can generate methane-rich biogas as a source of renewable energy for other processes. For this reason, there are various researches that have integrated energy recovery systems in wastewater treatment plants, WWTP-CHP-AD.

Figure 3 shows an example of a WWTP-CHP system integrated with an AD fermentation process (WWTP-CHP-AD). The plant treats 21000 m$^3$ of wastewater per day with the following efficiency figures: 96% for total solids (TSS), 02% for chemical oxygen demand (COD) and 64% for total nitrogen (TN).

![Figure 3. Schematic diagram of the integrated WWTP-CHP-AD system [10].](image)

The process generates excess sludge at primary and secondary decanters. The volume of excess sludge is reduced in the integrated anaerobic fermentation process, which generates significant amounts of methane-rich fermentation gas as a by-product. The anaerobic fermentation and fermentation model is based on the BSM2 simulation model, Benchmark Simulation Model No. 2 [21].

The CHP integrated system covers the heat demand for the AD anaerobic fermentation process and partially the power demand of the plant. In the CHP subsystem, the air is compressed by the AC compressor, then preheated in the PH preheater based on heat recovery from the hot gas stream delivered by the micro gas turbine (MGT). Methane-rich biogas (provided by AD anaerobic fermentation) is injected into a combustion chamber (CC) where it is burnt with compressed air. The high-temperature and high-pressure combustion gases in the CC combustion chamber relax in the MGT gas turbine generating electricity on the one hand with the G generator and on the other hand covering the power consumption of the AC compressor. The flue gas from the MGT passes through the PH to pre-heat compressed air and then passes through the heat recovery steam generator (HRSG) to generate hot steam, which is used to maintain the operational temperature of the heat exchanger, HX, (used as the heat source for the AD process).

3. Combustion

Burning of sewage sludge is similar to combustion of solid fuels. It is about getting heat from the high temperature of fuel oxidation, with the generation of carbon dioxide, water vapour and other gases.

Therefore, combustion technology for residual materials, such as sludge, can be used, mainly for obtaining heat (conventional combustion) or for reducing the amount of waste (incineration). The conventional use of heat generated by combustion technology is heating or generating electricity through thermal engines, while incineration systems may or may not use combustion heat, as their
primary purpose is the combustion destruction of harmful elements waste before final disposal or reuse of residual ash in the construction industry. It has been noticed that by incineration a reduction of up to 90% of the volume of mud can be obtained [22].

The use of incinerators is recommended for the disposal of municipal and municipal solid waste and has been imposed lately due to the need to reduce the use of cultivated land for waste disposal. Combustion of solid fuels involves drying, pyrolysis, volatile combustion, carbon burning, ash melting and agglomeration. These stages occur sequentially or simultaneously, depending on the configuration, the conditions of the reactor and the properties of the fuel. For example, some sludge and biomass can start low-temperature pyrolysis (~ 150°C) typical for fuel drying [25, 26].

Combustion of volatile matter dominates heat production from sludge burning, with carbon burning being relatively negligible. Increasing the temperature at the surface of the fuel due to the burning of volatiles may result in the melting of the ash covering the surface of the particles at temperatures of 900 °C. Carbon combustion occurs with increasing temperature and increases the proportion of gaseous compounds until the combustion takes place rapidly (in an equivalent time or less with that of the devolatilization stage) due to the low carbon content of the sludge [27, 28].

Finally, agglomeration of ash particles is facilitated by the heat from the combustion of carbon, and after reaching the maximum surface temperature the gradual cooling begins, indicating complete firing [29]. This suggests that the burning of all organic matter and the ash melting are necessary to reduce the volume of sludge during incineration while drying, devolatilization and burning of volatile substances are more important for the conventional combustion system for heat generation. Hence, the necessary considerations regarding the efficiency of combustion and incineration can be derived. These systems must be equipped with flue gas cleaning installations to minimize fly ash or hazardous gas emissions.

Different combustion installations such as multiple hearth furnaces, rotary furnaces and cyclones, and fluidized bed furnace, which have a different fuel supply regime, other mode of operation, with its advantages and disadvantages are used. However, the fluidized bed furnace is quite popular for burning wet sludge (35-59% humidity) and dry, due to its simplicity, of low cost, uniform heating, low-pollutant combustion gases (50% CO and NOₓ, 40% CO₂), lower residence time and high combustion efficiency [30-32]. Such technologies are also known to reduce the costs associated with extra fuel (about $ 0.2-1 million annually at operational facilities) [33]). Recent studies focus mainly on three areas:
- improving combustion and optimizing reaction parameters by using catalysts and co-mixing with other fuels such as coal, crude oil and biomass [34-39];
- the use of ash and fly ash generated by the process as a fertilizer or in the cement industry [40-42];
- reduction of toxic emissions and CO, NOx, SOx and PAH pollutants, prevention of heavy metal emissions [45].

3.1. Sludge incineration

Different methods are used for the thermal treatment of sludge:
- combustion or mono-incineration using multiple-hearth furnace, fluidized bed, combined MHF-FBC, cyclone furnace, smelting furnace, rotary furnace;
- co-combustion with coal in power plants, with coal in FBC power plants, with other fuels, with MSW;
- alternative processes such as wet oxidation, pyrolysis, oil from sludge, fuel from sludge, gasification;

Combustion and co-firing are recommended because the processes can be well controlled during the course of the reactions, and various combustion products purification techniques are possible. If only incineration is used as a method of destroying sludge, it is also not possible to obtain energy that can be utilized because of their low calorific value.
Figure 4 shows a simple sludge incineration scheme. This, with a low solid content (about 1-4%) is introduced into the mixing and homogenization tank. Thereafter, the stage of thickening and removal of the supernatant follows, at which end the solids content reaches volumes of 3-8%.

The dried sludge is then dehydrated using plate or band filters. In this process organic and inorganic additives are added which increase the calorific value of the sludge while reducing the ash content generated. At the end of this stage the solids content increases to 18-35%. The combustion is carried out in a fluidized bed with the introduction of combustion air at temperatures (500-600)°C. Thus, an area with temperatures (800-900)°C is generated in the furnace where the water vaporizes and the volatile metals and the compounds organic burns and turns into combustion gases. The resulting inorganic ash is discharged from the furnace with the hot combustion gases.

After yielding a significant amount of heat to the steam boiler, the gases are cleaned by passing through an electrostatic filter and a wet scrubber. The remaining particles from the gas generate significant amounts of sewage sludge and then the clean gases are evacuated to the stack [43].

3.2. Sludge co-combustion

The construction of a sludge incineration plant is an important investment, given the high costs for the boiler plant and for the flue gas treatment plant. The idea was to use existing coal-fired power plants for incineration of dry co-combustion sludge. In this way, a special sludge incinerator is no longer required, but existing coal combustion plants and combustion exhaust systems are used. The small amount of dry mud compared to the large amount of coal to be burned in the plant makes the sludge incineration effects on air and ash qualities insignificant.

Co-combustion of coal-purification sludge thus becomes a viable option for destroying sludge but also for obtaining significant amounts of renewable energy. In this way, a higher efficiency of the combustion plant is obtained from an economic point of view under approximately similar environmental protection conditions.

Currently co-combustion of coal with sewage sludge is applied, but there are co-incineration plants for combustion of a classic fuel in combination with municipal waste [44]. Co-combustion is agreed to the disadvantage of incineration due to advantages, of which:
- reduction of carbon dioxide emissions;
- a more efficient use of fuels in the location of the installation;
- the use of biomass as a high efficiency residual fuel under controlled environmental conditions;
As potential disadvantages can be enumerated:
- additional investments in combustion gas treatment equipment;
- higher costs in sludge drying installations;
- the possibility of the occurrence of toxic combustion compounds due to the composition and the properties of some sludges, [45].

Combined combustion of fossil fuels with sewage sludge and with different types of biomass is the most efficient way of using waste for energy purposes.

Like any method, the possibilities of application and use can be hampered by different aspects:
- Fueling problems of combustion plants (difficulty in homogenising the fuel mixture before combustion);
- the combined use of several types of fuel in the same combustion plant is difficult to control;
- correlation of combustion quality control with variation of composition of fuel-waste mixtures;

To overcome these difficulties, combustion plants have to be equipped with advanced combustion control systems and advanced exploitation technologies, especially in the handling and fuelling area [46].

Of the most known types of co-combustion plants that are used, some can be highlighted:
- adaptation of an existing coal-fired or suspended coal combustion plant to combined coal-sewage sludge combustion by additional direct feeding of the pulverized sludge [47, 48];
- additional supply by introducing sludge onto the combustion grill of a fluid bed combustion plant [49];
- separate burning of sludge by steam injection coupled to the main charcoal burner;
- using sludge as additional fuel for recharging the combustion plant;
- the use of sludge as a fuel in a post-combustion installation to reduce nitrogen oxide emissions [50].

Although recommended as a method of destroying sewage sludge and other types of waste, co-incineration can generate a series of unintended exploits. Some of these are:
- Energy and volatile production: The use of additional low calorific fuels, obtained on the basis of various additives during preliminary thermal treatments, can cause thermal imbalance of the boiler, with consequences for its operation and reliability;
- Effects on air pollution: substances that generate pollutant emissions, nitrogen, sulphur, chlorine can be converted into pollutants, NOx, SO2, HCl to a greater or lesser extent depending on the concentrations in the respective substances of the basic fuels and extra. If the concentration is higher in the additional fuel the emissions will be higher and vice versa;
- Ashes generation: The presence of ash-generating elements may favour the formation of deposits which will reduce the flue gas flow and will contribute to the occurrence of corrosion phenomena;
- Heavy metals: pollutes the atmosphere by volatilizing poisons and soil and waters by ashes poisoning.

4. Conclusion
Anaerobic digestion is a proven technical success and is currently being applied to a variety of wastewater and waste streams, but worldwide application is still limited, thus negating an important renewable energy source. Furthermore, some potential sources that are currently being treated are an excellent substrate for anaerobic treatment and could contribute to the production of renewable energy rather than energy consumption during treatment. Applying anaerobic digestion to produce energy from sludge and solid waste can help to obtain low-cost fuels compared to natural gas. During anaerobic treatment, biodegradable compounds are effectively eliminated, leaving a small number of compounds in the effluent, such as ammonium, organic N compounds, sulphides, organic P compounds and pathogens. Depending on subsequent use, a complementary treatment step is required. Anaerobic treatment is an ecologically and economically proven technique. Technology is relatively new, and in many countries application is still at an early stage. It is extremely important to establish
demonstration projects in many parts of the world to show the environmental and economic benefits and to provide the necessary confidence in the technique.

Biomass is a viable alternative to energy fuel for a good time. Studies in the use of biomass as renewable energy can be successfully applied in the energy sector and other categories of organic waste, such as sludge from sewage treatment.

The combined combustion technique of sludge with a conventional fuel in energy steam generators is a way to follow, given the simplicity of technology and the fossil fuel economy. However, prior to being introduced into the combustion plant, the sludge undergoes a variety of thermal, mechanical, ultrasound, filtration, etc. treatments, whereby organic materials in the source water, including suspended and colloidal are concentrated in a small volume, processed mud. It contains with more than 100% more energy that can be recovered compared to sludge from a classic installation without pretreatment.

Although combined combustion has a number of advantages, so the process is efficient, the sludge must be autothermic. For this reason, before choosing the sludge treatment solution, its energy characteristics, such as calorific power and ignition temperature, must be determined. For this we must first establish the energy balance of the mud burning based on the values of the burning heat present in the literature, from which it is to be determined how much it should be dehydrated to become self-thermally and at what costs.

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