Review Paper

Opportunities regarding the use of technologies of energy recovery from sewage sludge

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Abstract

Based on the global need to efficiently eliminate highly produced amounts of sewage sludge, alternative technologies are required to be practically developed. Reduction of sewage sludge waste quantities with energy recovery is the most important and modern practice, with least possible impact on the environment. Appropriate technologies for treating and disposal sewage sludge are currently considered: incineration, gasification and pyrolysis. The main products generated during the pyrolysis process are bio-gas, bio-oil and bio-residue, providing sustainable fuels/ biofuels and adsorbents. Compared to other disposal methods of sewage sludge, pyrolysis has advantages in terms of the environment: waste in small quantities, low emissions, low level of heavy metals. From a technological point of view, pyrolysis is the most efficient in relation to its final products, pyrolysis oil, pyrolysis gas and solid residue that can be transformed into CO_2 adsorbent with the help of chemical and thermal activation processes. The incineration process of sewage sludge has a number of disadvantages both environmentally and technologically: organic pollutants, heavy metals, toxic pollutants and ash resulting from combustion that needs a disposal process. A comparison of different types of sewage sludge elimination for the energy recovery is described in the present paper.

Article Highlights

- Sewage sludge is a waste in increasing quantities, which requires disposal and energy recovery, in a clean way for the environment.
- The pyrolysis process of sewage sludge is the cleanest method of its recovery. Pyrolysis products, bio-oil, syngas and biochar, can be used as alternative fuels to fossil fuels.
- The pyrolysis process of the sewage sludge is the most advantageous from the point of view of the obtained products and of the environment, in comparison with the incineration and gasification processes.

Keywords Sewage sludge · Valorization · Pyrolysis · Gasification

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1 Introduction

The global production of sewage sludge has increased in recent years and is constantly growing, the sewage sludge (SS) being a by-product resulting from the wastewater treatment process [1]. The main challenge is the removal of sewage sludge, which is a real toxic cocktail due to pollution and heavy metals. At the same time, the world's population is facing another challenge, namely the energy deficit. In order to overcome this energy deficit, alternative energy from renewable sources must be developed, with environmental protection measures. Because of these problems, the sewage sludge is suitable for the development of renewable energy through various processes [2].

Sewage sludge may contain pathogenic microorganisms, parasites or several toxic compounds, such as heavy metals, polycyclic aromatic hydrocarbons, dioxins and furans. High amounts of SS, 60 million tons, of 80% moisture have been reported in China, with potential of increasing by 10% each year [2]. While in EU, the increasing SS amounts can reach about 13 million tons in the 2020 year. In Table 1 is presented the quantity of sewage sludge in different countries for several years.

Table 1 Annual production of sewage sludge (unit of measure in thousand of tonnes) in Europe, by country, during 2016–2018 [3]

Country	2016	2017	2018
Belgium	–	–	–
Bulgaria	65.8	68.6	–
Czech Republic	206.71	223.27	228,22
Denmark	–	–	–
Germany	–	–	–
Estonia	18.34	–	–
Ireland	56.018	58.773	–
Greece	119.768	–	–
Spain	1174.4	–	–
France	1006	1174	-
Croatia	19.72	17.6	19.23
Italy	–	–	–
Cyprus	7.408	7.166	8.406
Latvia	25.923	24.94	24.591
Lithuania	44.422	42.488	44.192
Luxembourg	8.918	8.618	8.28
Hungary	215.078	264.713	217.842
Malta	10.77	10.3	8.28
Netherlands	347.6	–	341.03
Austria	237.938	–	234.481
Poland	568.329	584.454	583.07
Portugal	119.17	–	–
Romania	240.41	283.34	247.76
Slovenia	32.8	36.7	38.1
Slovakia	53.05	54.52	55.93
Finland	–	–	–
Sweden	204.3	205.6	210.9
United Kingdom	–	–	–
Iceland	–	–	–
Liechtenstein	–	–	–
Norway	–	–	147.6
Switzerland	–	177	–
Montenegro	–	–	–
North Macedonia	–	–	–
Albania	94.5	98.12	94.5
Serbia	11.2	13.3	9.6
Bosnia and Herzegovina	9.5	9.5	9.5
Turkey	299.296	–	318.503

The traditional methods currently used to eliminate SS are composting for use in agriculture, gasification, pyrolysis and incineration. Lately, composting of SS is prohibited due to the strong smell, leachate, spread of pathogenic microorganisms and environmental contamination with toxic compounds [4]. Incineration of SS has a number of negative side effects, among them emissions of greenhouse gas, dioxins and furans being a great concern. Moreover, the resulted ash must also be removed by an additional treatment [5]. This method requires large amounts of energy which limits the development and implementation of such technology. The European Commission task is the reduction of waste by 50% until 2050 [6]. This category also includes SS from the wastewater treatment plants (category 19 of the waste code) in accordance with the Decision no. 856/2002 [7]. EU studies showed that 53% of produced SS is used for the final disposal, used in agriculture/composting, while only 20% is used for incineration.

As shown in Figs. 1a, b and 2, SS can be used in the manufacture of construction materials, land application and incineration. Even if these possible usages have been identified, a significant amount of SS is eliminated by improper discharge. The methods of treatment and disposal of SS varies from one country to another depending on its socio-economic development and the legal requirements [8].

Because of the global need to properly eliminate SS, alternative technologies have been emerged in order to treat, reduce and eliminate such wastes. Pyrolysis represents an appropriate technology, from which bioenergy can be obtained, while harmful organic substances and pathogens may be eliminated [11]. The residue left after the pyrolysis process can be used for the development of efficient adsorbents [12, 13]. These adsorbents can be used to reduce the level of heavy metals or organic pollutants [14, 15]. Thus, pyrolysis can be considered a clean and efficient method of SS disposal [16]. From the

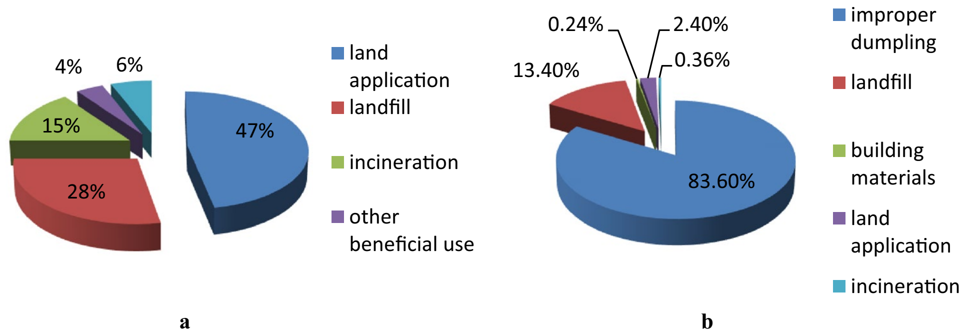

Fig. 1 Data on different methods of elimination of sewage sludge produced in USA (a) and China (b) [9]

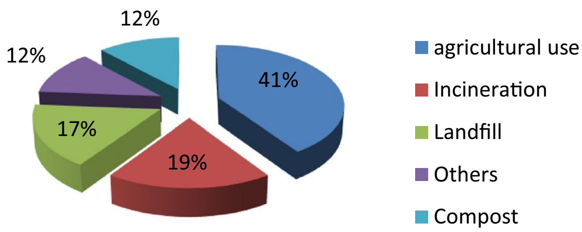

Fig. 2 Sewage sludge usage in Europe according to [10]

pyrolysis process results three types of products: liquid, solid and gaseous. Liquid and gaseous products (bio-oil, bio-gas) can be used as raw or refined materials to obtain chemical fuels, while solid products (bio-residue) can be used as functional materials [17–20]. NOx compounds resulting from the combustion of gases to release energy are considered air pollutants. To reduce air pollution, a nitrogen reduction method for SS pyrolysis must be identified. A number of studies have been conducted to reduce the emission of nitrogen-containing gases during the pyrolysis, as follows: fixation of nitrogen in the solid fraction by pretreatment or roasting [21–26]; mixing the raw material with mineral calcium, CaO, Ca and Na to perform a catalytic pyrolysis [27–30]; changing the conditions under which the pyrolysis process takes place by changing the temperature or atmosphere; transformation of nitrogen-containing gas into N_2 [31].

In order to produce large quantities of sustainable energy from SS, there are some technological limits. SS has different physico-chemical properties than conventional solid fuels (biomass or coal) which make processing more difficult and complex [32]. The SS contains nitrogen and phosphorus compounds, non-toxic organic compounds, toxic heavy metals (Pb, Ni, Cd, Hg, As), organic pollutants (dioxins, pesticides, polycyclic aromatic hydrocarbons), pathogenic bacteria, inorganic compounds (silicates, calcium and magnesium compounds) and a lot of water [33], composition which may largely vary [34]. To reduce the volume of SS that must be treated or removed, the operation of removing excess water is needed. There are two stages of water removal, performed during dehydration and thickening phases [35, 36]. The moisture content must be considerably reduced so that it can be disposed or used for energy recovery [37]. The SS properties are influenced by the applied technology, season or type of wastewater that enters the treatment plant [38, 39]. Due to its properties, SS is considered a fuel based on its high calorific value (10–14 MJ) and high volatiles [40, 41].

The purpose of this paper is to describe several sustainable technologies currently applied for SS valorization, including those for energy recovery, and to present an overview of the advantages and disadvantages of applying processes such as gasification, pyrolysis and incineration.

2 Agriculture valorization

The sewage sludge used in agriculture has two types of benefits: the recirculation and recycling of important nutrients such as nitrogen and phosphorus and the ecological and adequate disposal of waste from wastewater treatment. The use of sewage sludge as soil fertilizer is beneficial in increasing productivity, but special care must be taken in terms of soil contamination that leads to blockage of ecosystem functions and hence the deterioration of flora, fauna and human health [42–48]

When sewage sludge is used in agriculture, a major problem arises, namely the toxicity of heavy metals that affect the health of humans, animals and plants, which is why the EU has implemented European Council Directive 86/278 /EEC on environmental and soil protection. Before being used in agriculture, sewage sludge goes through a series of biological, chemical, thermal treatment processes, then it is stored for a long time to significantly reduce the sewage sludge fermentation and for safety and health population, plants and animals. After going through a series of processes and stages such as biological stabilization, digestion, composting, the sewage sludge has component nutrients benefical for soil improvement and energy production [49]. The use of SS in agriculture has been done for several beneficial effects: improving the physical, chemical and biological soil properties, and supplementation of soils with essential plant nutrients [50, 51]. Unfortunately, SS is a biological residue with a complex chemical structure [52], which may provide potential toxic components to soil through chemical and biological contamination [53]. Plastics and heavy metals are the main contaminants of the soil after fertilization with SS [54], causing the accumulation and transfer of toxic compounds into the environment [55] which negatively influences microorganisms and plant growth [56, 57]. The risk of contaminating the environment through fertilization soil with sewage sludge is due to the presence of heavy metals, drugs and organic compounds in the sewage sludge. Medicines can reach the environment through several routes, but mainly through sewage, the water from the sewer reaches the treatment plant, and after water treatment they reach the sewage sludge [58–62].

Soil quality and fertility is maintained through microbial activity. From this point of view, sewage sludge has the role and ability to intensify these processes due to the high content of organic matter. The application of a sewage sludge with a low content of heavy metals on the soil has a positive effect on organic carbon, microbial activities and on microbial biomass. On the other hand, if the sewage sludge has large amounts of heavy metals, a negative effect occurs: the decrease of the carbon concentration and activities in the soil [63–66].

Due to the risk of contamination, the EU has issued the Directive 86/278/EEC,which establishes regulations to combat and prevent possible damage to the environment and to human health, and heavy metals admissable levels, as well [67]. The most frequent contaminants are pharmaceutical compounds, especially antibiotics, which are in fairly large amounts in wastewater because they are poorly metabolized by the human body [68, 69]. During the wastewater treatment process, antibiotics are not eliminated, reaching the soils for which SS was used as fertilizer. These antibiotics influence different types of the enzymatic transformations in soil [70].

3 Energy valorization

Reduction of SS waste quantities aiming the energy recovery is one of the most important and modern practice, with the least possible impact on the environment. Valorization of SS through different methods of energy recovery and the obtained products (bio-gas, bio-residues, bio-oil, heat, ash, tar and other chemical compounds) [71–73] is presented in Fig. 3.

The different methods of SS elimination for energy recovery, comparatively illustrated in Table 2 will be further described.

3.1 Incineration

SS incineration aims at the complete oxidation of organic compounds at high temperatures. This process has been used very often in the process of energy recovery, but also in order to reduce the amount of waste:for example, Japan incinerates 70% of the SS [75].

The incineration process is an important process in the management of wastewater such as sewage sludge. This process leads to the decomposition of toxic organic substances and to the reduction of waste quantities by 70% -90% [76, 77]. Following the incineration process of the sewage sludge, renewable energy obtained can be used in the form of electricity or heat. After incineration of the sewage sludge, an ash residue results. The resulting ash is considered dangerous due to high concentrations of heavy metals with a negative impact on the environment, and for this reason is used in various fields of industry: in the manufacture of cement and concrete [87] and as road construction materials, for glass and ceramics [78].

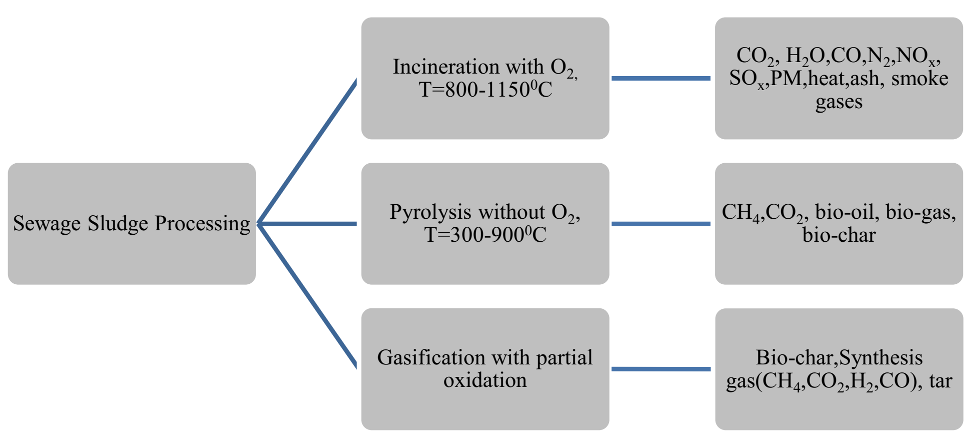

Fig. 3 Different methods of enegy recovery from sewage sludge and their products [74]

Table 2 Comparison of main characteristics of technologies applied for sewage sludge elimination [74]

Parameters	Incineration	Pyrolysis	Gasification	Hydrothermal liquefaction
Process temperature (°C)	> 850	300–900	750–900	250–370
Gas production	No	Bio-gas	Synthesis gas	No
Oil production	No	Bio-oil	Liquid fuel potential	Liquid bio-crude
Char production	No	Bio-char	Tar	
Emissions	CO_2, H_2O, CO, N_2; NO_x, SO_x, PM, Smoke gases	Low emissions of CO_2 and heavy metals	CO, CO_2, H_2, N_2	Hydrocarbons Amines and amides
Costs	High	High	High	
Advantages	Heat Electricity	Low waste Useful Products(oil, gas, char)	Liquid fuel potential	Liquid fuel potential
Disadvantages	Ash waste High moisture of SS	High Moisture of SS	Toxic effects from the mixture of heavy metals and organic pollutants High Moisture of SS	Toxic effects

As described in Fig. 4, mechanically dried SS enters the combustor, where SS turns into an inert ash at temperatures > 850 °C [79]. The incineration process consists in a rapid combustion, chemical reaction with O_2 to produce light, and heat release. Oxidation occurs at any temperature, while combustion occurs only at the ignition temperature. The incineration system consists of the following components: sludge supply, mechanical dehydration, dryer, combustor, ash handling system and control devices for air pollution.

Energy recovery by incineration of SS has a number of technological, environmental and societal benefits, but also economic. The advantages of this process are: well-established technology, heat generation and electricity; negligible organic pollutants; the possibility of using it together with another solid fuel to reduce greenhouse gases; easy integration of pollutant capture technology; use of existing infrastructure; use together with another solid fuel to reduce costs; energy saving for sewage treatment plants. The disadvantages of this process may include: dehydration of SS as it contains increased

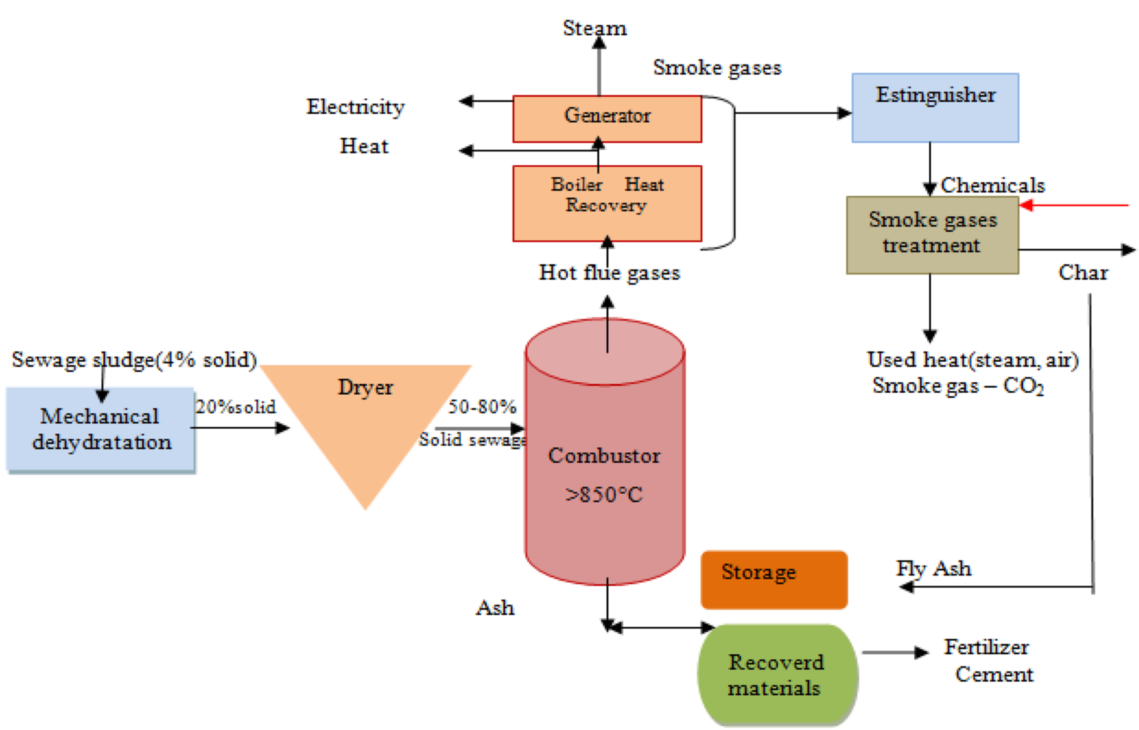

Fig. 4 Incineration of sewage sludge [80]

moisture; requirement for disposal or reuse of ash waste, CO_2, NOx, SOx emissions; public acceptance; high costs for technological cleaning and ash removal; strict control of process pollutants [81].

3.2 Pyrolysis

Pyrolysis is a transformation process of sewage sludge in the absence of oxygen and nitrogen atmosphere, which results in 3 types of pyrolysis products: gaseous product—pyrolysis gas, liquid product—pyrolysis oil and solid product—pyrolysis residue [82–84]. First time in the pyrolysis process the vapors resulting from the volatile components of the sewage sludge are formed, then the non-volatile substance is decomposed and the following are obtained: residue, tar and gases [85, 86]. Pyrolysis can be of several types, depending on temperature ranges and residence time: slow pyrolysis, fast pyrolysis. If the temperature is lower and the residence time is longer, then large amounts of pyrolysis residues are produced, if the temperature is medium and the residence time is short, large amounts of bio-oil are produced [87, 88].

Pyrolysis oil can also be called bio-oil, is dark brown and can be used as an alternative fuel to fossil fuels after a series of refining and water removal processes. Pyrolysis gas is the non-condensable gas obtained from the pyrolysis process of sewage sludge, such as H_2, CO, CO_2, CH_4, C_2H_2, C_2H_6. These gases can be used in different technologies if were separated and purified [89, 90].

Figure 5 shows the pyrolysis process of sewage sludge and products obtained from the process: bio-oil, syngas and bio-char.

The advantages of the pyrolysis process are: minimal amounts of generated waste; production of useful oil, gas and solid residue; use of both raw and digested SS; low emissions and decreased level of heavy metals than from other processes; feasible technology for large treatment plants; low carbon potential for the energy industry. Of course, there are some disadvantages, such as: requirements for dehydration of SS; complex reaction; technology at an early stage, expensive technology with large capital [91–95].

3.3 Gasification

The gasification process involves partial oxidation with different gasifying agents (oxygen, air and steam) (Fig. 6) [96]. The gasification process of the sewage sludge is used to produce electricity, the energy conversion efficiency has a proportion of 14% -30%, but it needs a series of steps to clean the gas of contaminants, which are: tars, heavy metals, dust, acid gases and sulfur. All these cause corrosion and harmful effect for human health and environment [97]. The gas resulting from the gasification process is rich in hydrogen H_2, which means that it can be used as an alternative fuel [98].

The gasification process with the help of air results a mixture of CO, CO_2, H_2, CH_4, N_2 and tar. This mixture has combustion difficulties, especially in a turbine, because the calorific

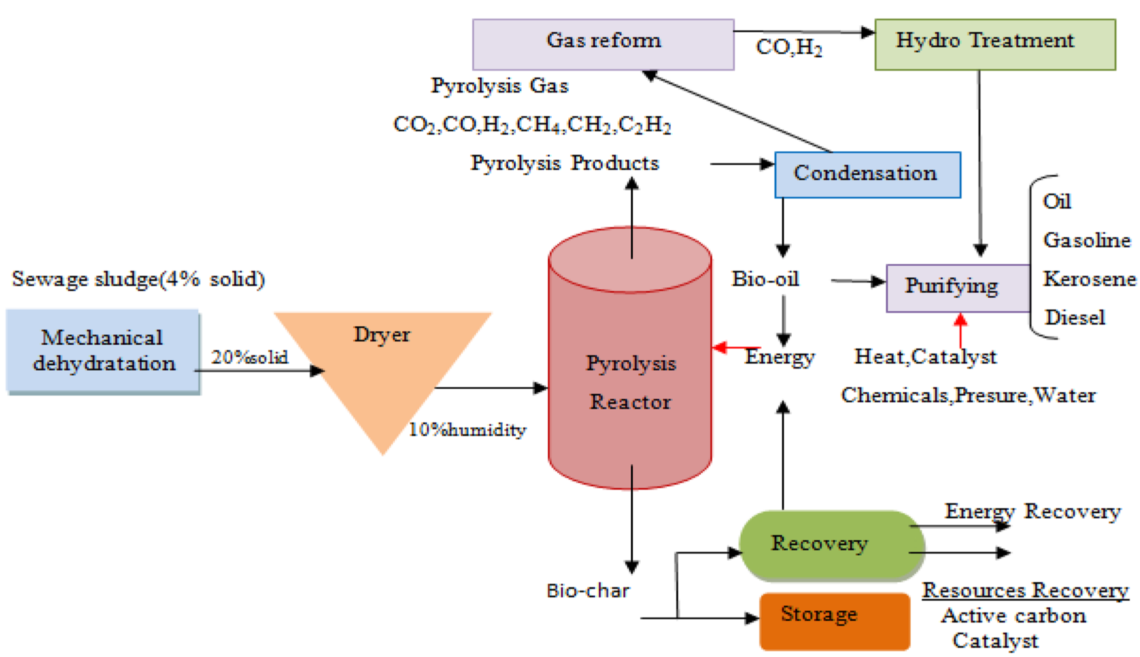

Fig. 5 Pyrolysis of sewage sludge according to [35]

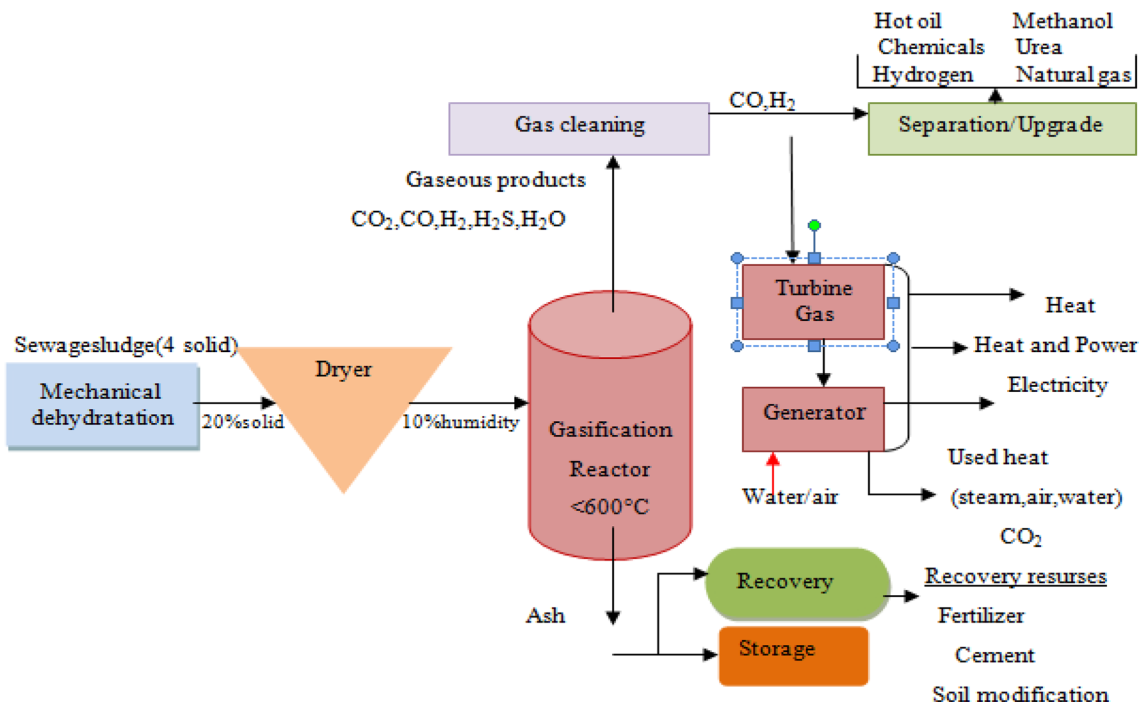

Fig. 6 Gasification processof sewage sludge [96]

value of the gas is 5 MJ/m^3 [99, 100]. If oxygen is used in the gasification process, the calorific value of the resulting gas can reach a value of 10 MJ/m^3 up to 12 MJ/m^3, and nitrogen is missing from the gaseous product. The difference between using oxygen or air is both in quality and cost. Oxygen is more expensive, but the quality of the resulting gas is clearly superior. If steam is used, the concentration of methane and hydrocarbons increases, thus changing the proportions of the components. The gas obtained from the gasification process has a calorific value of 15 MJ/m^3 up to 20 MJ/m^3. The sequence of events during the gasification process is as follows: evaporation of moisture from the raw material, gas production, oil production and then the solid residue [101–103].

The advantages of the gasification process are: energy efficient technology; liquid fuel potential; stand-alone technology; waste in small quantities; low emissions; favoring the treatment plants from an economic point of view; low carbon potential for the energy industry. The disadvantages are the following: requirements for dehydration of SS; complex reaction; release of heavy metals and organic pollutants having toxic effects; expensive technology with high capital and operating costs [104].

4 Conclusions and future remarks

Sewage sludge is a complex matrix consisting of several residual products, such as biomass waste, paper and cardboard, microplastics, textiles, waste oils, traces of fossil fuels, human and animal feces, traces of drugs. This viscous matrix has an extremely high moisture content > 80%. However, the organic composition makes it attractive for the energy sector.

From an environmental point of view, the pyrolysis process provides more advantages because it produces minimal amounts of waste, low emissions, low level of heavy metals than those resulted from the gasification and incineration processes. In terms of technology, the pyrolysis process is the most efficient due to its final products, oil, gas and solid residues that can be used as catalysts. Instead, the combustion process generates heat, the gasification process is energy efficient, but the reaction is complex and releases organic pollutants, heavy metals and other toxic pollutants. Considering incineration, the resulting ash requires its elimination. Also, during this process CO_2, NOx, and SOx are released.

The economic advantages of low carbon potential for the energy industry advocates for the use of pyrolysis and gasification processes. An economic advantage for incineration is the existing infrastructure that can be used. But incineration may become expensive due to the requirement for the ash removal, pollutant control and technological cleaning. Gasification and pyrolysis processes also require a large investment capital.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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