4 The Current Energy Panorama and the Production of Biogas from Sewage Sludge

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Abstract

It is well accepted that no single alternative energy source will be able to meet humanity's growing energy demand. Instead, the trend is for the energy system of the future to be a mix of various renewable energy sources and, at least for the next few decades, still complemented by fossil energy. The growing demand for alternative sources of sustainable energy, coupled with the challenge that the management of waste produced by population growth and the development of the industry represent, has motivated the research for energy generation technologies based on waste biodegradation. Anaerobic digestion (AD) stands out as a promising technology in this area, as it is capable of converting different types of waste into a highly energetic biogas (50–70% of methane). The AD of sewage sludge (SS) is able to produce the highest biogas capacity worldwide and, besides producing renewable energy in the form of methane, stabilizes sludge and aids in odor and pathogen removal present in this type of waste. This chapter will present a review of the global energy landscape, the production of biogas from SS, and the use and improvement of the biogas produced.

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World energy panorama · Renewable energy · Biogas · Anaerobic digestion · Sewage sludge · Pretreatment

4.1 The Current Energy Panorama

The growing demand for energy due to the rapid growth of human population and the depletion of nonrenewable energy resources has been the main cause of the search for alternative sustainable energy resources (Khalil et al. 2019; Li et al. 2019). Fossil fuels are nonrenewable energy sources that comprise coal, oil, and natural gas and provide about 80% of the total energy consumed in the production of electricity used for industrial and domestic purposes worldwide (Aziz et al. 2019). Energy consumption has increased worldwide and should keep rising in the upcoming years, with an estimated growth of almost 50% between 2018 and 2050 (Energy Information Administration (EIA) 2019). However, fossil fuels are finite and consumed by humans faster than they could be replenished (Aziz et al. 2019). Furthermore, the use of fossil fuels is considered to be the main reason for various environmental issues, such as air pollution and global warming (Aziz et al. 2019; Khalil et al. 2019). The world's dependence on a single energy source generates energy insecurity, which can lead to economic and political crises (Hagos et al. 2017). At present, the international energy situation is in a stage of new changes and adjustments. The basic trend of the global energy transition is to realize the transition of the fossil energy system into a low-carbon energy system and finally enter the era of sustainable energy mainly based on renewable energy (Li et al. 2020a).

4.1.1 Renewable Energy

Renewable energy is an effective way of dealing with the dilemma of meeting the growing energy demand and reducing greenhouse gas emissions. It also plays an important role in ensuring energy security, improving environmental protection, and increasing employment in many countries (Li et al. 2020a). Currently, global renewable resource development and its utilization scale have been continuously expanding, and the application costs have decreased (Lu and Gao 2021). Worldwide renewable energy consumption is expected to increase by 3% per year between 2018 and 2050 and become the leading source of primary energy consumption by 2050 (Energy Information Administration (EIA) 2019).

The most important renewable energy sources are wind, solar, and biomass energy. Hydroelectric, geothermal, and marine are also worth mentioning. Increasingly broad sources of wind and photovoltaic energy already provide reasonably cheap energy (Deshmukh et al. 2021), but these systems are characterized by a highly fluctuating and not always predictable production profile. Similarly, hydroelectric energy depends on the rainfall regime, which can compromise a country's energy security. Brazil, for example, whose energy matrix is highly dependent on hydro sources, has already experienced major problems of electricity supply as the result of a great period of drought in 2001, which compromised the capacity of the reservoirs, drastically reducing hydro generation capacity (Freitas et al. 2019). Biomass energy conversion techniques, on the other hand, are capable of producing a constant base load and even balance the gaps between supply and demand in the energy sector (Miltner et al. 2017). Biomass is a carbon-neutral resource as well as a source of C/H/O elements to generate organic carbon-based products, such as bioenergy (biofuel and biogas) and chemicals (biorefinery) (Jung et al. 2021). Thus, the valorization of biomass feedstock has received considerable attention in the last few decades, and biomass-based energy sources are expected to have a representative share in the energy system of the future (Miltner et al. 2017; Jung et al. 2021). From an energetic point of view, biomass can be understood as any renewable resource derived from organic matter (OM) (such as animal and vegetable) that can be used for energy production (Aziz et al. 2019).

Renewable energy has grown strongly, and its competitiveness has increased. According to the statistics of the International Renewable Energy Agency (IRENA) (2020a), the global installed capacity of renewable energy has more than doubled in the last decade, with the development and consolidation of new sources of renewable energy. At the end of 2020, the value of 2,789,061 MW of global installed capacity for renewable energy was reached, of which 43.41% corresponds to hydropower, 25.37% to solar, 26.29% to wind, 4.41% to bioenergy, 0.5% to geothermal, and 0.02% to marine. The evolution of the global installed capacity of renewable energy and the distribution profile of the renewable energy sources for the last decade can be seen in Fig. 4.1.

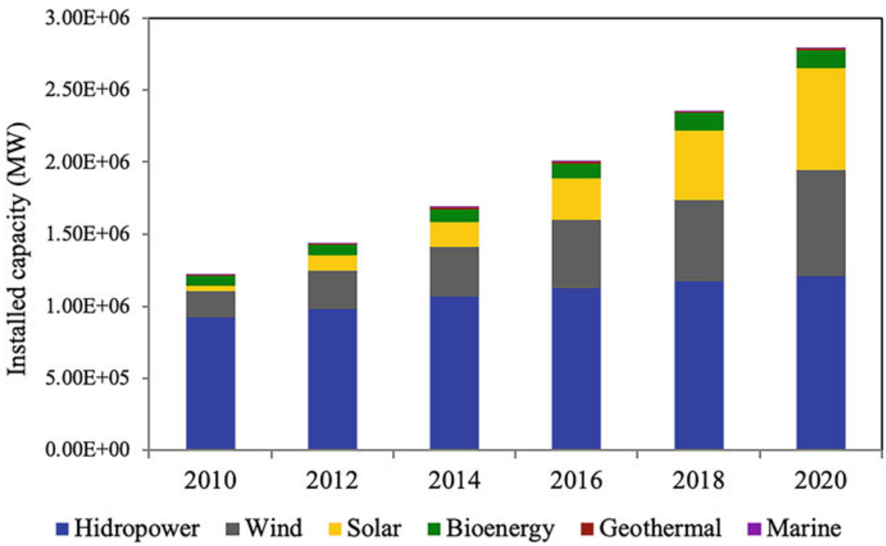


Fig. 4.1 Trends in renewable energy (International Renewable Energy Agency (IRENA) 2020a)

4.1.2 Waste for Energy Production

Waste-to-energy processes comprise any waste treatment technology that generates any form of energy, i.e., heat, electricity, or liquid transport fuels (e.g., diesel, petrol, or kerosene), from a waste material feedstock (Rafiee et al. 2021). The so-called waste-to-energy has multiple advantages. Not only it addresses the waste disposal challenge, but it also offers a good opportunity for energy security, as both the processes for production and consumption of energy can be located in the same geographic location, unlike fossil fuels.

The use of waste as biomass for energy production, such as biogas, has emerged as one of the best options to meet the high global demand for energy consumption (Khalil et al. 2019). In literature, studies have reported that several types of organic waste, such as animal waste (Parralejo et al. 2019; Ramos-Suárez et al. 2019), food waste (FW) (Bozym et al. 2015; Kuczman et al. 2018), urban organic solid waste (Tyagi et al. 2018), industrial waste, SS, and agricultural waste (Onthong and Juntarachat 2017; Momayez et al. 2019; Simioni et al. 2021), can potentially be used as sources for biogas production through AD process (Khalil et al. 2019).

4.2 Anaerobic Digestion

AD is a biochemical process of decomposition of OM, carried out by a consortium of microorganisms that live symbiotically in the absence of oxygen. From a technological point of view, AD is a promising alternative for the management of organic materials, as it is capable of converting practically all biomass sources, including different types of wastes, into a highly energetic biogas. This biogas can be used to produce fuel, chemical compounds, electricity, and heat. AD also gives rise to a by-product. Digestate is the residue of degraded material, a product rich in nitrogen and which has potential to be used as agricultural fertilizer (Seadi et al. 2008; Agustini and Gutterres 2017; Xu et al. 2019).

The AD process basically follows the steps of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, sequentially and synergistically. The steps are linked because the different microbial communities involved in each step work in sequence, with the products from one step serving as substrate for the next step. In general, the OM fed into the bioreactor is composed of different percentages of carbohydrates, proteins, and fats. Anaerobic microorganisms' exoenzymes decompose these complex compounds into simpler and more soluble organic compounds such as sugars, amino acids, and fatty acids, which are absorbed and fermented until they are transformed into simple compounds such as acetic acid, H_2, and CO_2. In the final step, these simple compounds are directly absorbed by methanogenic microorganisms to produce methane (Seadi et al. 2008; Khalid et al. 2011; Hagos et al. 2017; Parsaee et al. 2019; Xu et al. 2019).

Hydrolysis is the first step of AD, during which complex organic macromolecules (polymers) are converted into simpler and more soluble compounds (monomers and oligomers) (Agustini and Gutterres 2017; Neshat et al. 2017; Li et al. 2019). Lipids, carbohydrates, and proteins are depolymerized through extracellular enzymes from hydrolytic bacteria (lipase, cellulase, amylase, protease) into long-chain fatty acids, sugars, and amino acids (Seadi et al. 2008). Generally, in AD of waste, hydrolysis is the limiting step of the process, determining the rate and efficiency of degradation (Agustini and Gutterres 2017; Mirmohamadsadeghi et al. 2019).

The monomers and oligomers formed during hydrolysis are then degraded by acidogenic bacteria (fermentative) into short-chain fatty acids (propionate, acetate, butyrate, and lactate), alcohols, and gaseous by-products (NH_3, H_2, CO_2, and H_2S), a step that is known as acidogenesis or fermentation (Appels et al. 2008; Li et al. 2019; Mirmohamadsadeghi et al. 2019).

The third stage of AD is acetogenesis. In this step, acetogenic bacteria convert the organic acids and alcohols of high molecular weight produced in the previous step into acetic acid, CO_2, and H_2, which are the direct substrates for the next and final step, methanogenesis (Appels et al. 2008; Mirmohamadsadeghi et al. 2019).

In the final stage of AD, methane is produced by two groups of methanogenic bacteria: the acetoclastic, which are responsible for the decomposition of acetate into methane and carbon dioxide, and the hydrogenotrophic methanogenic, which produce methane using hydrogen as electron donor and carbon dioxide as a receptor (Appels et al. 2008; Neshat et al. 2017; Li et al. 2019).

AD is a highly complex process, and many interfering factors are still not fully understood. To achieve the maximum potential of this technology, the control of some parameters is crucial. Composition and chemical structure of the substrate (C/N ratio, biodegradability, bioaccessibility, and bioavailability), temperature, pH, alkalinity, and VFA concentration are among the most important parameters that affect the performance of an AD system. In addition, there are some compounds and conditions that can have an inhibitory effect on the process (Hagos et al. 2017; Neshat et al. 2017).

4.3 Biogas: Characteristics and World Panorama

Biogas is a mixture of gases produced from the anaerobic degradation of organic compounds (Wu et al. 2015; Khan et al. 2017). Landfill waste, SS, animal manure, corn straw, and agricultural waste, among others, are the main sources of biogas generation (Wu et al. 2015). Biogas mainly consists of methane (CH_4) in a range of 50–70% and carbon dioxide (CO_2) in a concentration of 30–50%. The relative content of CH_4 and CO_2 in biogas is dependent on the nature of the substrate and the parameters employed in the AD process. In addition to these two main gases, biogas may additionally contain smaller amounts of other compounds: nitrogen (N_2) in concentrations of 0–3%, which may originate in the saturated air of the influent; water vapor (H_2O) in concentrations of 5–10% or higher in cases that operate at thermophilic temperatures; oxygen (O_2) at concentrations of 0–1%, which is entering the process from the feed substrate or leaks; hydrogen sulfide (H_2S) at concentrations of 0–10,000 ppmv, which is produced from the reduction of sulfate contained in some wastes; ammonia (NH_3) from the hydrolysis of protein materials;

hydrocarbons in concentrations of 0–200 mg/m^3; and siloxanes in concentrations of 0–41 mg/m^3, originating, for example, from cosmetic industries' effluents (Wu et al. 2015; Khan et al. 2017; Angelidaki et al. 2018; Gao et al. 2018).

In addition to CH_4, all other gases contained in biogas are considered pollutants. The energy content of methane described by the lower heating value (LHV) is 50.4 MJ/kgCH_4 or 36 MJ/m^3CH_4 (CNTP conditions). The higher the CO_2 or N_2 contents in the biogas, the lower its LHV. For example, for biogas with methane content ranging from 60 to 65%, the LHV is approximately 20–25 MJ/m^3 of biogas. There are several treatments to remove undesired compounds from biogas, expanding its range of applications (Angelidaki et al. 2018).

Biogas has characteristics that include low emission of toxic compounds, reduced greenhouse effects, carbon fixation, and other environmental and financial benefits. Its combustion leads to a neutral CO_2, with a rate of 83.6 kg per GJ, well below to 741 kg CO_2 per GJ from diesel, 733 kg CO_2 per GJ from crude oil, 774 kg CO_2 per GJ from fuel oils, and 1096 kg CO_2 per GJ from wood (Giwa et al. 2020).

In 2019, the maximum biogas generation capacity installed in plants around the world was 19,381 MW, more than twice that observed in 2010, 9519 MW. Germany tops the list of countries with the largest installed capacity (over 7061 MW), followed by the USA (2368 MW), the UK (1775 MW), Italy (1575 MW), China (799 MW), Turkey (534 MW), and Thailand (530 MW) (International Renewable Energy Agency (IRENA) 2020b).

Although it represents only 0.8% of the global renewable energy installed (International Renewable Energy Agency (IRENA) 2020a), compared to other renewable energy sources, biogas production is independent of seasonal fluctuations, can be stably produced, and, therefore, promises a reliable way to produce energy (Koupaie et al. 2019).

4.3.1 Biogas Utilization and Improvement

There are four basic ways of using biogas: heat and steam production, electricity generation/cogeneration, use as fuel in vehicles, and, more recently, production of chemical. However, the use of raw biogas is limited by its contaminants, and, in most cases, purifying treatments are necessary to enable its application (Appels et al. 2008). Currently, there are different treatments to remove undesired compounds from biogas, expanding its range of applications.

The first treatment is related to "biogas cleaning" and includes the removal of harmful and/or toxic compounds (such as H_2S, Si, volatile organic compounds (VOCs), siloxanes, CO, and NH_3) (Angelidaki et al. 2018). Some authors also recommend drying of biogas, since it can be saturated with water vapor when it leaves the digester (Appels et al. 2008).

The second type of the treatment concerns the upgrading of biogas and aims to increase its LHV, converting it into a standard close to that of natural gas fuel. If the biogas is purified according to specifications similar to natural gas, the final product is called biomethane (Angelidaki et al. 2018; Sahota et al. 2018). Currently, the specifications of the natural gas composition depend on national regulations, and, in general, methane content higher to 95% is required (Khan et al. 2021). In the biogas upgrading process, the CO_2 present can be removed or converted to CH_4 through reaction with H_2 (Angelidaki et al. 2018; Sahota et al. 2018). There are many commercial biogas upgrading technologies available that are being used to upgrade the raw biogas such as pressure swing adsorption, chemical scrubbing, water scrubbing, organic solvent scrubbing, membrane separation, and cryogenic separation (Khan et al. 2021). In addition, biogas can also be converted through dry reforming of methane (DRM) into more value-added products, such as H_2, which is considered to be a promising clean energy that is widely used in fuel cells or even used for the synthesis of value-added liquid fuels and chemicals, such as alcohols, plastics, and hydrocarbons (Jung et al. 2021). The selection of the appropriate technology for upgrading the raw biogas depends on the final use of the biogas, the economics involved, and the efficiency of the upgrading process (Khan et al. 2021).

4.4 Biogas from Sewage Sludge

SS is a by-product of wastewater treatment plant (WWTP) generated from the settling (primary treatment) and activated sludge (secondary treatment) processes (Maragkaki et al. 2018; Zhu et al. 2021). Worldwide, the treatment of municipal wastewater produces large amounts of SS (Grosser et al. 2017), and that amount is expected to increase continuously, due to increasing population connected to sewage networks, building new WWTPs, and upgrading existing plants to meet the more stringent local effluent regulations (Dai et al. 2013). It is estimated that the amount of dry sludge produced per capita on a daily basis is around 60–90 g (Appels et al. 2011).

SS is mainly composed of dehydrated microbial biomass, in addition to pathogens, heavy metals, and other hazardous materials (Di Capua et al. 2020), and must be treated prior to disposal for environmental protection (Maragkaki et al. 2018). Although the generated SS represents approximately 2% of the volume of treated sewage (Khanh Nguyen et al. 2021), its disposal is one of the more expensive steps in a WWTP, representing up to 50% of the total operating costs of the plant (Zhen et al. 2017; Ma et al. 2018; Maragkaki et al. 2018). Therefore, progress in cost-effective SS treatment techniques represents an important research area for waste management companies (Khanh Nguyen et al. 2021). Basic SS disposal practices include agricultural use, landfills, composting, AD, recycling as a construction material, and incineration (Dai et al. 2013; Zhen et al. 2017; Maragkaki et al. 2018; Khanh Nguyen et al. 2021).

Among the treatment methods, AD is considered an effective, economical, and eco-friendly technology for treating these huge amounts of SS since it has the ability to reduce (by circa 40%) the overall load of biosolids to be disposed (Appels et al. 2011; Khanh Nguyen et al. 2021). AD stabilizes sludge, aids in odor and pathogen removal, and, more importantly, produces renewable energy in the form of methane

(Zhen et al. 2017; Khanh Nguyen et al. 2021). The AD of SS has the highest biogas production capacity worldwide. The methane yield obtained through AD is very dependent on the sludge composition; however, theoretically, it should be around 0.590 m^3/kg ODS (Appels et al. 2011).

4.4.1 Characteristics of Sewage Sludge

The physical and chemical characteristics of the SS may have different variations depending on the source and geographical location in which it was generated. SS can be a solid, semi-solid, or muddy liquid waste and is generally a mixture of household and industrial waste (Demirbas et al. 2016). The characteristics of SS are listed in Table 4.1.

SS is characterized by the presence of solid and organic compounds, pathogens, microbial aggregates, filamentous bacteria, extracellular polymeric substances (EPSs), nutrients, and heavy metals (Khanh Nguyen et al. 2021). The various types of toxic substances, microorganisms, and OM produce unpleasant odors, cause environmental pollution, and endanger human health. SS may also possess hazardous organic chemicals such as those existing in pesticides, polychlorinated naphthalene, polycyclic-aromatic hydrocarbons, benzene, toluene, trichloroethylene, and nitrobenzene (Khanh Nguyen et al. 2021), besides nonbiodegradable OM, such as endocrine-disrupting compounds (EDCs) and pharmaceutical and personal care products (PPCPs) (Ma et al. 2018).

The inorganic parts of the SS are mainly composed of iron, phosphorus, calcium, aluminum, and sulfur, including traces of heavy metals (such as zinc, chromium, mercury, lead, nickel, cadmium, and copper) (Demirbas et al. 2016). After treatment, SS can be utilized for agricultural purposes because it contains various beneficial nutrients (Khanh Nguyen et al. 2021). Typically, SS contains the following plant nutrients in dry weight: 1–8% nitrogen (N), 0.5–5% phosphorus in the form of P_2O_5, and $<1\%$ potassium (K) as K_2O (LeBlanc et al. 2008).

4.4.2 Pretreatments of Sewage Sludge

Despite the previously mentioned benefits deriving from the anaerobic treatment of SS, AD is generally characterized by long retention times ($\geq$20 days) and low VS degradation (30–50%) (Di Capua et al. 2020). The scientific community has identified that hydrolysis is the rate-limiting step in SSAD because of the large amounts of molecular OM and the complex floc structure, constituted by microorganisms held together by EPS, which are generally composed of proteins, polysaccharides, and humic-like substances (Di Capua et al. 2020; Khanh Nguyen et al. 2021). EPS create a three-dimensional matrix bound to the surface of the cells, generating a shield that protects the microorganisms contained in the aggregate, avoiding the rupture and the lysis of the cells and, consequently, decrease the biodegradability of the flocs (Di Capua et al. 2020).

Table 4.1 Physical and chemical characteristics of SS

Parameter	Value	Reference
Ash	43.4 ± 0.1% (db)	Mu et al. (2020)
Bulk density	1.26–1.38 (kg/L)	Demirbas et al. (2016)
Higher heating value (HHV)	11.3–14.2 (MJ/kg)	Demirbas et al. (2016)
Hydrogen (H)	40–46 (g/kg)	Demirbas et al. (2016)
Organic matter (OM)	418–592 (g/kg)	Demirbas et al. (2016)
Oxygen (O)	185–219 (g/kg)	Demirbas et al. (2016)
Particle density	2.4–2.56 (kg/L)	Demirbas et al. (2016)
pH	7.1–8.2	Demirbas et al. (2016)
Total solids (TS)	2–12% (liquid SS) 12–40% (dewatered SS)	Khanh Nguyen et al. (2021)
Volatile solids (VS)	75–85% (db)	Khanh Nguyen et al. (2021)
Nutrients		
Calcium (Ca)	573.8 (mg/kg TS)	Mu et al. (2020)
Iron (Fe)	5803.2 (mg/kg TS)	Mu et al. (2020)
Magnesium (Mg)	487.5 (mg/kg TS)	Mu et al. (2020)
Nitrogen (N)	5.1 ± 0.0% (db)	Mu et al. (2020)
Organic carbon (OC)	34.8 ± 0.5% (db)	Mu et al. (2020)
Phosphorus (P)	2.5% (db)	Khanh Nguyen et al. (2021)
Potassium (K)	6078.1 (mg/kg TS)	Mu et al. (2020)
Sodium (Na)	731.2 (mg/kg TS)	Mu et al. (2020)
Sulfur (S)	11–17 (g/kg)	Demirbas et al. (2016)
Metals		
Aluminum (Al)	5964.5 (mg/kg TS)	Mu et al. (2020)
Arsenic (As)	9.9 (mg/kg, db)	Khanh Nguyen et al. (2021)
Barium (Ba)	2.8–4.2 (g/kg)	Demirbas et al. (2016)
Cadmium (Cd)	6.94 (mg/kg, db)	Khanh Nguyen et al. (2021)
Chromium (Cr)	119 (mg/kg, db)	Khanh Nguyen et al. (2021)
Cobalt (Co)	18.7 (mg/kg TS)	Mu et al. (2020)
Copper (Cu)	741 (mg/kg, db)	Khanh Nguyen et al. (2021)
Lead (Pb)	134.4 (mg/kg, db)	Khanh Nguyen et al. (2021)
Manganese (Mn)	763.9 (mg/kg TS)	Mu et al. (2020)
Mercury (Hg)	5.2 (mg/kg, db)	Khanh Nguyen et al. (2021)
Molybdenum (Mo)	49.8 (mg/kg TS)	Mu et al. (2020)
Nickel (Ni)	121.3 (mg/kg TS)	Mu et al. (2020)
Selenium (Se)	5 (mg/kg, db)	Khanh Nguyen et al. (2021)
Tim (Sn)	0.1–0.2 (g/kg)	Demirbas et al. (2016)
Titanium (Ti)	0.09–0.13 (g/kg)	Demirbas et al. (2016)
Zinc (Zn)	2.4–3.6 (g/kg)	Demirbas et al. (2016)
Pathogens		
Ascaris lumbricoides – helminth	2×10^2–1×10^3 (N°/100 mL)	Khanh Nguyen et al. (2021)
Fecal coliform bacteria	1×10^9 (N°/100 mL)	Khanh Nguyen et al. (2021)
Salmonella	8×10^3 (N°/100 mL)	Khanh Nguyen et al. (2021)
Virus	2.5×10^3–7×10^4 (N°/100 mL)	Khanh Nguyen et al. (2021)

db dry weight basis

In order to accelerate the hydrolysis and enhance subsequent methane productivity, a variety of sludge pretreatment options have been developed to facilitate the release of intracellular substances by rupturing the EPS matrix and cell wall and make them more accessible to subsequent microbial actions (Ma et al. 2018; Khanh Nguyen et al. 2021). By applying different pretreatments (mechanical, thermal, chemical, and/or biological), it is possible to increase the methane yield and to minimize the production of remaining sludge (digestate), but this typically comes with high energy demands and operation cost (Ma et al. 2018).

Physical and mechanical pretreatment (Gil et al. 2018; Nabi et al. 2019) disintegrates the solid particles, reducing their size and thus increasing the particle surface area to enhance the AD process (Khanh Nguyen et al. 2021).

Thermal pretreatment (50–250 °C) (Liao et al. 2016; Neumann et al. 2017; Malhotra and Garg 2019) dissolves the EPS both inside and on the surface of the flocs, thus disintegrating the floc structure and resulting in soluble organic substrates that are easily hydrolyzed during AD (Di Capua et al. 2020; Khanh Nguyen et al. 2021). Thermal pretreatments are beneficial in terms of pathogen sterilization, sludge volume reduction, odor removal, and enhanced sludge dewaterability (Khanh Nguyen et al. 2021). However, they are usually associated with high costs.

Chemical pretreatment (Hallaji et al. 2018; Liu et al. 2018; Wang et al. 2021) is the most promising method for complex organic waste destruction and employs strong reagents to deform the cell wall and membrane, favoring the availability of sludge OM for enzymatic attacks. The major reagents employed in the literature include acids, alkali, and oxidants (ozonation and peroxidation) (Zhen et al. 2017; Khanh Nguyen et al. 2021).

Biological pretreatments (Agabo-garcía et al. 2019) are eco-friendly techniques that utilize aerobic, anaerobic, and enzymatic methods to predigest and enhance the AD hydrolysis stages. These steps can be improved by implementing a complex matrix of microbes that play a synergistic role during the floc structure disintegration of sludge and other organic compounds. Although eco-friendly and cost-effective, this pretreatment technique is time-consuming and requires optimal parameters for microbial proliferation (Khanh Nguyen et al. 2021).

4.4.3 Anaerobic Co-digestion of Sewage Sludge

AD of SS often encountered low methane yields due to the recalcitrant properties of microbial cell wall and extracellular biopolymers. Although the methane production could be improved by mechanical, thermal, chemical, and/or biological pretreatments, the high pretreatment costs limit their applications (Mu et al. 2020). Anaerobic co-digestion (AcoD), which is the AD of two or more different substrates, emerges as a promising option to overcome the disadvantages of mono-digestion and improve the economic viability of AD plants (Hagos et al. 2017). The improved process performance could be attributed to the dilution of potential toxic compounds (heavy metals, pharmaceuticals, and pathogens), balanced macro- and micronutrients, synergistic effects of microorganisms, and increased load of biodegradable OM (Ratanatamskul et al. 2015; Grosser et al. 2017; Li et al. 2020b).

There are numerous examples reporting successful co-digestion of SS and organic fraction of municipal solid wastes (OFMSW). In general, the addition of a protein-rich waste (such as SS) to a carbon-rich waste (such as OFMSW) improves the C/N ratio of the mixtures, and the production of biogas through AD increases (Tyagi et al. 2018).

Ghosh et al. (2020) evaluated the potential of co-digestion of OFMSW and SS for enhanced biogas production. The highest cumulative biogas and methane yield of 586.2 mL biogas/gVS and 377 mL CH_4/gVS, respectively, were observed under an optimum ratio of OFMSW/SS (40:60 w/w). Mono-digested sample of SS showed around 300 mL biogas/gVS of cumulative biogas and CH_4 yield of around 50 mL CH_4/gVS.

Grosser et al. (2017) investigated the efficiency of the AD of a waste mixture consisting of SS, OFMSW, and grease trap sludge (GTS), on the basis of biogas production and VS reduction. The process was carried out at mesophilic conditions (37 °C), 20 days set as hydraulic retention time (HRT), and the reactors (6 L of working liquid) were constantly mixed (180 rpm). Co-digestion of SS, GTS, and OFMSW provided significant benefits for methane yield and VS removal in comparison with digestion of SS alone. The authors found that anaerobic treatment of SS and GTS at a ratio of 30% resulted in increased methane yield of approximately 52% (from 300 to 456 m^3/mgVS) compared to digestion of SS alone. Moreover, the addition of OFMSW as a co-substrate significantly improved the efficiency of the SS AD process by enhancing average methane yield up to 82% (300–547 m^3/mgVS).

FW has also been frequently reported as a co-substrate to improve the AD process of SS. Ratanatamskul et al. (2015) investigated the effect of the AcoDof FW and SS with the mixing ratio (FW/SS) varying to 1:1, 3:1, 5:1, and 7:1. The amounts of biogas production of the mixtures were 761, 998, 1077, and 1504 mL/day, and the methane contents of the obtained biogas were 50.2, 55.5, 55.0, and 60.4%, respectively. The system was operated at total HRT of 33 days, corresponding to organic loading rate (OLR) of 7.0 kg COD/m^3days.

Mu et al. (2020) conducted a series of co-AD of different urban-derived organic wastes (SS, FW, yard waste – YW) in a semicontinuous mode and with a HRT of 20 days. CH_4 yields (mL/gVS) observed were 448.9 ± 6.6, 484.6 ± 32.6, and 413.4 ± 29.3 for the SS + FW, 49.0 ± 5.0 and 149.0 ± 14.9 for SS + YW, and 164.7 ± 22.7, 232.4 ± 46.7, and 314.9 ± 17.1 for co-AD between the three wastes (SS + FW + YW). The CH_4 variations obtained within the same group of experiments are due to different proportions of mixtures adopted and other particularities.

Maragkaki et al. (2018) performed a series of laboratory experiments in an attempt to optimize biogas production from SS by co-digesting with a dried mixture of FW, cheese whey, and olive mill wastewater (FCO). The experiments were carried out in lab-scale continuous stirred-tank reactors (CSTR), operating under mesophilic conditions (37 ± 2 °C) and with a HRT of 24 days. Four types of influent feedstock were utilized – 100% SS; 97% SS + 3% FCO; 95% SS + 5% FCO; and 93% SS + 7% FCO – prepared on a volume (v/v) basis. It was found that FCO addition can boost biogas yields if the mixture exceeds 3% (v/v) concentration in the feed. The reactor treating the SS produced 287 ml CH_4/L/days before the addition of

FCO and 815 ml CH_4/L/days after the addition of 5% FCO (v/v). Any further increase of 5% FCO causes a small increase in biogas production.

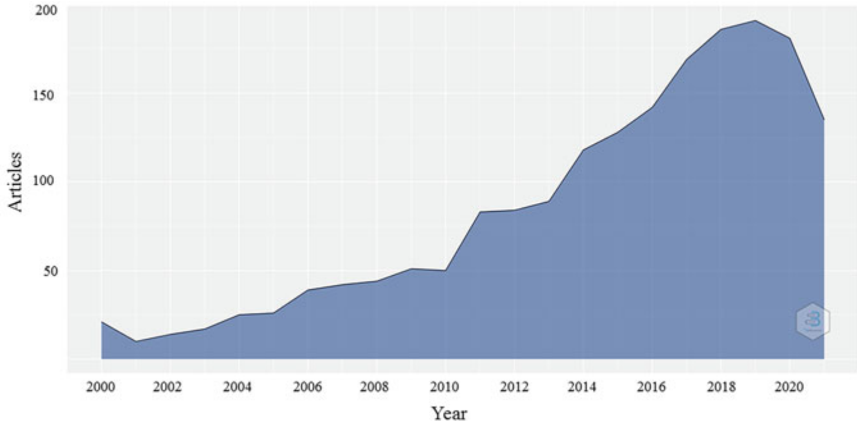
Other types of wastes have also been reported as co-substrates for SS in successful AcoD processes. Zhu et al. (2021) assessed the effects on the biogas production of thermophilic AcoD of SS with paper waste (PW) in a continuous experiment with the fixed HRT in 30 days. The mixture ratios of SS/PW content used in this experiment were 4:0, 4:2, 4:4, 4:6, and 4:8 based on the TS. The optimal performance was obtained at the ratio of SS/PW equal to 4:6, where the biogas production increased from 438 $\pm$ 53 to 594 $\pm$ 72 mL/gVS (+35.6%) compared to the monodigestion. Vassalle et al. (2020) aimed in their study to evaluate co-digestion between raw sewage and microalgal biomass in terms of biogas production. The results showed that methane yield was increased by 25% after AcoD with microalgae, from 156 to 211 $NLCH_4$/kgVS. Considering biogas production, the increase after co-digesting was 10% (from 304.42 to 331.12 NL/kgVS).

Another type of biodegradable wastes, which can be used as co-substrates for SS co-digestion, is fat-rich materials. For example, fat, oil, and grease (FOG) have been reported to increase methane yield in almost threefold when added to the anaerobic digester (Kabouris et al. 2009). However, there can be process inhibition by long-chain fatty acids, sludge flotation, digester foaming, blockades of pipes, and clogging of gas collector (Grosser et al. 2017).

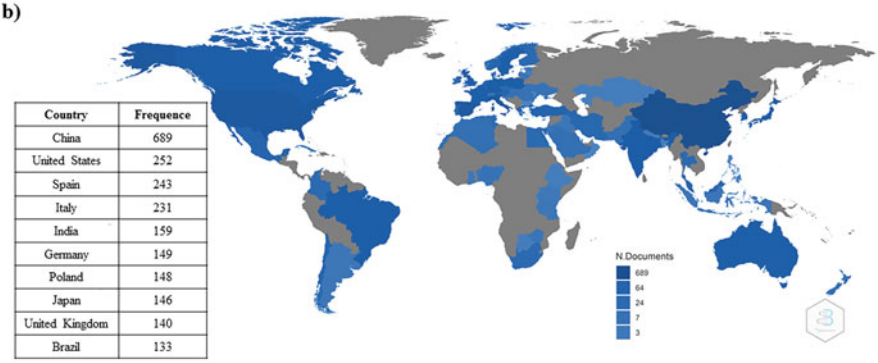
4.4.4 State of the Art

In order to systematize the state of the art and carry out a macroanalysis of the work that has been developed on the production of biogas from sewage, the articles reported in the literature were explored using the “Bibliometrix,” a tool in the RStudio® software version 4.1.0. The articles used in this analysis were found by inserting the terms “biogas” and “sewage” and “sludge” and “anaerobic” and “digestion” in the Scopus database, including title, abstract, and keyword. The period delimited for the research was from 2000 to July 2021, resulting in 1845 published articles. According to the bibliometric analysis performed, it was observed that there is a growing interest in the topic in question especially after 2013 and with the peak of publications in 2019 (Fig. 4.2a). China is the country that publishes the most articles on biogas production from SS, followed by the USA and the Spain (Fig. 4.2b). It is worth mentioning the large participation of North America and Europe, with several countries among those that publish the most on the topic, possibly motivated by the stricter environmental policies in these regions. In addition, a WordCloud was generated with the main titles included in the articles that address the topic (Fig. 4.2c). In addition to the words directly related to the theme, some others can be highlighted, such as “chemical oxygen demand,” related to the most used characterization technique, and “municipal solid waste” and “food waste,” as the most studied co-substrate.

a)



b)



Country	Frequence
China	689
United States	252
Spain	243
Italy	231
India	159
Germany	149
Poland	148
Japan	146
United Kingdom	140
Brazil	133

c)

Fig. 4.2 (**a**) Annual global scientific production of articles that address the theme biogas from sewage. (**b**) Scientific production by country of articles, addressing the theme biogas from sewage. (**c**) WordCloud with the 50 most cited words in the titles of the articles studied

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