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Review

Full-Scale Sewage Sludge Reduction Technologies: A Review with a Focus on Energy Consumption

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Abstract: In recent years, increasing attention has been paid to the problem of sewage sludge management and the relevant energy consumption, which represent the main cost items in wastewater treatment plants. Therefore, implementation of technologies that can reduce sludge production and ensure a positive impact on the energy of the entire sewage treatment plant has gained considerable importance in the scientific and technical community. The objective of this study was thus to screen full-scale sludge reduction technologies integrated into both the water line and the sludge line of a municipal sewage treatment plant with a sustainable impact on the overall balance of the plant. The results showed that, within the water line, ultrasound in the recirculation line of the activated sludge allowed for greater reductions in sludge production than the Cannibal and UTN systems, despite the higher energy consumption. CAMBI™, BioThelys™, Exelys™ and TurboTec® enabled the greatest reductions in sludge production among the technologies integrated into the sludge line, and although they required a large amount of energy, this was partially offset by energy recovery in terms of additional biogas production.

Keywords: sludge reduction; energy consumption; full scale; wastewater treatment; mechanical treatment; biological treatment; chemical treatment

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1. Introduction

Presently, most wastewater treatment plants (WWTPs) use biological processes in both the water line, where the removal of organic compounds and nutrients occurs, and the sludge line, where sludge is treated to reduce its mass and volume. If, on the one hand, biological technologies, such as conventional activated sludge (CAS) and anaerobic digestion (AD), allow high efficiency in the removal of pollutants, on the other hand, they cause the production of large amounts of sewage sludge [1]. The global production of sewage sludge from municipal WWTPs is 45 million dry tons per year [2]. The average annual production of sewage sludge in the European Union, the USA, and China varies between 18 and 33 million tons in dry weight [3]. This amount is expected to increase given the tightening of strict legal limits and population growth. Currently, the main methods for sewage sludge disposal in the European Union are incineration (25%), reuse in agriculture where permitted by law (27%), landfilling (9%), composting (21%) and other methods (18%) [4]. However, incineration removes only 70% of the solids and produces ash with a high metal content, while landfilling is limited in some countries, especially where it is difficult to find new disposal sites [5]. All these approaches result in high disposal costs, which affect the overall cost of sludge management [6]. In addition, for the reuse of sewage sludge in agriculture, strict regulatory requirements must be met to ensure that the sewage sludge does not contain traces of organic compounds, such as pharmaceuticals and pesticides, as well as heavy metals that can leach into the soil and have negative effects on human health [7]. Therefore, this approach has also been restricted and even banned in some countries.

In Europe, the average cost of sewage sludge disposal ranges between EUR 160 and 310 per ton of dry sludge, varying by country and in accordance with the available sludge recovery/disposal alternatives [8]. Therefore, sludge disposal costs have a significant impact on the total operating costs of WWTPs, representing percentages ranging from 20 to 65% [9]. Consequently, the activities related to the management and disposal of sewage sludge have increasingly become an environmental and economic issue, driving scientific research to develop solutions and technologies that could significantly reduce sludge production.

A critical factor in the choice of sludge reduction technology, as with other wastewater treatment technologies, is energy consumption, which, after personnel costs, is the second largest cost factor in the total operating costs of WWTPs, accounting for between 7 and 33% [10]. The more sewage sludge is produced, the more energy is required for its treatment. Therefore, the optimal solution is to use a technology—or combination of technologies—that reduces excess sludge production while limiting the energy consumption of the WWTP.

Sludge reduction technologies can be divided into technologies integrated into the water line and technologies integrated into the sludge line. Generally, they are not used simultaneously in the same WWTP. Technologies integrated into the water line are implemented in small WWTPs where anaerobic digestion (AD) is not present, while technologies integrated into the sludge line are used in medium–large treatment plants, where the AD process is implemented. In recent years, much attention has been paid to technologies that allow sludge reduction directly in the water line, thus directly reducing the amount of sludge sent to and treated in the sludge line of the WWTP. Reductions in sludge production in the water line are achieved by applying reduction technologies in the recirculation line of the activated sludge, which is then sent to the main biological reactor (Figure 1). Sludge reduction is achieved through mechanical, chemical, thermal and biological treatments that include various mechanisms, such as cell lysis–cryptic growth, endogenous metabolism, decoupled metabolism and microbial predation [11].

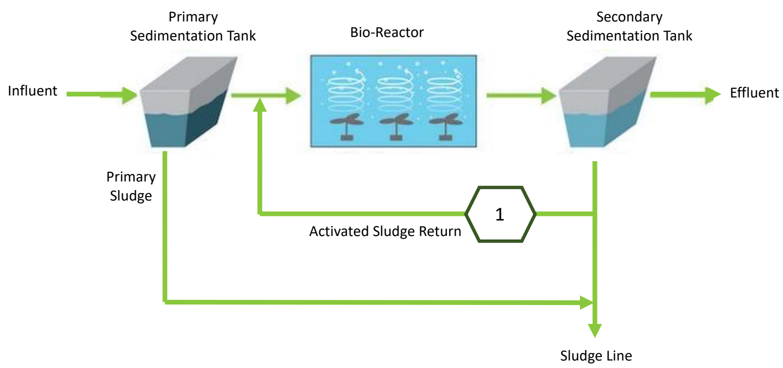

Figure 1. WWTP scheme. The number 1 corresponds to the location of the technologies for reducing the production of sludge integrated into the water line.

Sludge reduction technologies integrated in the sludge line can include sludge treatment before or after the anaerobic digester (Figure 2). In both cases, improved sludge reduction can translate into both improved removal of total solids or volatile solids and improved biogas production [12]. The technologies that are used for sludge reduction are based on physical, thermal, chemical and biological treatments.

As far as we know, there are several studies in the literature describing the state of the art for sludge reduction technologies in wastewater treatment. However, there are not yet any studies in the literature that relate sludge reduction to energy consumption. Therefore, this work aimed to screen the full-scale sludge reduction technologies that have a positive energy impact on the management of a WWTP overall. This means that not only was the energy consumption of each technology considered but the benefits of applying these technologies, such as increases in biogas production, were also evaluated.

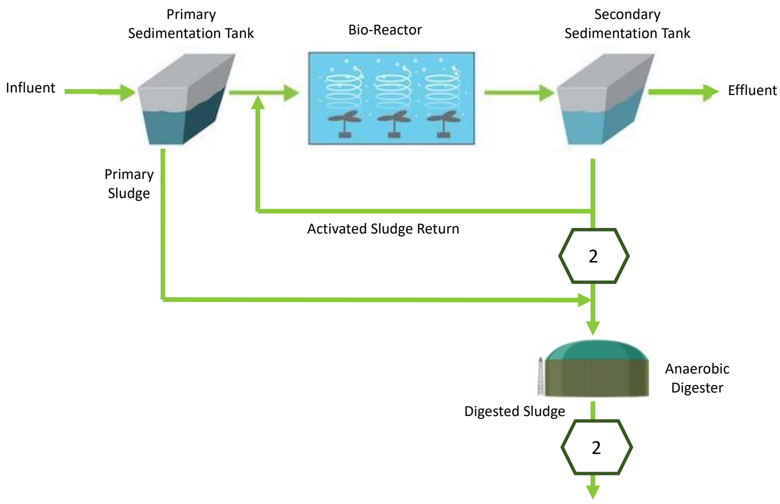

Figure 2. WWTP scheme. The number 2 corresponds to the location of the technologies for reducing the production of sludge integrated into the sludge line.

2. Methodology

The scheme of the WWTP considered as the reference for this review consisted of CAS treatment in the water line and an AD section in the sludge line. Therefore, the sludge reduction technologies that could be integrated into this reference WWTP were considered.

For each technology, the percentages of sludge reduction and energy consumption are highlighted. The observed sludge yield (Y_{obs})—the ratio between the cumulative sludge produced and the cumulative substrate consumed—was used as an indicator of sludge production. In addition to the Y_{obs}, the investigated technology's percentage of sludge reduction compared to conventional treatment is also reported. Furthermore, the energy performance of the technologies was evaluated by considering their energy consumption, expressed in electrical (kWh_{el}) or thermal (kWh_{heat}) energy. Energy consumption is commonly quantified as the organic load removed, expressed in kW/kg $COD_{removed}$; the number of equivalent inhabitants served, expressed in kWh/PE; or the treated volume, reported in kWh/m^3.

Figure 3 depicts the main technologies integrated into the water line and sludge line of a WWTP investigated in this study.

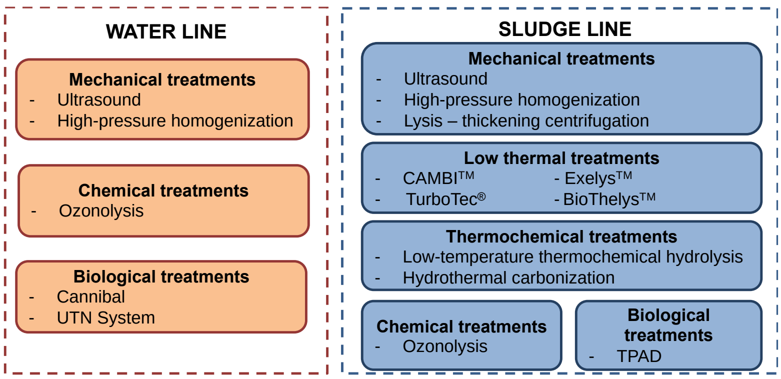

Figure 3. Technologies integrated into the water line and sludge line considered in this study.

3. Mechanical Treatments

The main objective of mechanical treatment is to promote the solubilization of sludge through the disintegration of bacterial cells and disaggregation of sludge flocs. Various devices can be used, such as ball mills, high-pressure homogenizers and other systems, in which energy is supplied in the form of pressure or rotational or translational energy. However, the main mechanical treatment technologies used in full-scale applications are ultrasound, high-pressure homogenization and lysis-thickening centrifugation.

3.1. Ultrasound Treatment

Ultrasound treatment is based on the principle of acoustic cavitation and the formation of hydroxyl radicals. The pressure waves lead to the formation of millions of small bubbles, which, when collapsing, generate high pressures (500 bar) and temperatures (5000 K) and extreme conditions that mechanically attack the sludge and cause its disintegration and the degradation of microbial cells [13,14]. This treatment also generates hydroxyl radicals, which are strongly oxidative and contribute to the degradation of sludge flocs. The chemicophysical effects of lysis induced by ultrasonic treatment facilitate the dissolution of organic substances and increases in biodegradable compounds, which are used by microorganisms as a readily available carbon source.

Ultrasonic treatment is influenced by: (i) the energy applied, since, as the energy increases, the disintegration of the sludge increases; (ii) the ultrasonic frequency, which generally ranges from 9 to 40 kHz, with an optimal value equal to 20 kHz; (iii) the duration of the treatment, which ranges from a few seconds to 2.5 h, with an optimal time of 1 h; and (iv) the characteristics of the sludge, with a good effect on secondary and thickened sludge and no effect on primary sludge.

Neis et al. [15] applied full-scale ultrasound treatment to improve the biological degradation processes in a WWTP (54,000 PE). About 30% of the activated sludge was first thickened, fed through the ultrasonic treatment and finally recirculated into the activated sludge reactor. This approach made it possible to provide an internal carbon source and improve the efficiency of the denitrification process. The use of thickened and, subsequently, sonicated activated sludge as an internal carbon source had several positive effects. First, a significant reduction in total nitrogen was achieved, which meant that the efficiency of the denitrification process was increased. In addition, there were several secondary effects that contributed to improving the overall efficiency of the plant: sludge production was reduced by 25% and sludge dewatering was slightly improved. From an economic point of view, the investment for the installation of the ultrasonic treatment was amortized by the reduction in sludge production and the elimination of the need to add external carbon sources.

Mohammadi et al. [13] studied the application of ultrasound treatment at the pilot scale in a sequencing batch reactor (SBR) to reduce sludge production. The results of the study showed that the reduction in sludge production was influenced by several factors, including the specific energy applied to the treated sludge, the power used to generate the ultrasound, the duration of the ultrasonic treatment and the percentage of sludge treated. Both cell lysis and cryptic growth mechanisms were involved. After increasing the specific energy applied to the treated sludge up to values of 35,000 kJ/kg VSS, an increase in sludge reduction was observed. Beyond this threshold, there was no significant effect in terms of sludge reduction. This demonstrates that it is more beneficial to work with low specific energy values and long treatment times than high specific energies. In addition, the results showed a 78% reduction in sludge production when 30% of the sludge was subjected to ultrasonic treatment.

In some cases, the recirculating sludge is subjected to a dynamic or static thickening process prior to ultrasonic treatment. In this way, the ultrasonic treatment is applied to sludge that has a higher concentration of solids (6–8 g VSS/L), allowing lower energy consumption and optimizing the energy transferred to the sludge. An example is the treatment employed by the German company Ultrawaves at the Bunde WWTP (Germany) [16]. In this case, ultrasound was used to disintegrate the thickened activated sludge, and the treated sludge was used as an internal carbon source to improve the denitrification process. Some of the thickened sludge (about 50%) was fed to the ultrasonic reactor and then the biological reactor of the water treatment plant. The results of the treatment included a significant reduction in the total nitrogen concentration in the effluent wastewater (<3 mg TN/ L), elimination of the need for an external carbon source (e.g., methanol), a reduction of 13% in the sludge to be disposed of and an improvement in the dewatering of the sludge.

In recent years, ultrasound treatment has been widely used at full scale as a pretreatment in the AD process, which is beneficial for both volatile solids removal and biogas production. This treatment can remove up to 36% of volatile solids and increase methane/biogas production by 24 to 138% [15,17,18]. Several full-scale applications of ultrasonic pretreatment for sewage sludge have demonstrated the many advantages of this technology. First, it can support the biological hydrolysis of sludge: ultrasonic pretreatment of sludge induces the decomposition of complex organic compounds into simpler organic compounds that can be easily degraded in the subsequent AD process. In addition, ultrasonic pretreatment enables reductions in organic matter of up to 25%, increases in biogas production of up to 30%, reductions in sludge production of more than 20%, increases in the dry matter content removed from the sludge dewatering compartment (up to 15%) and reductions in the consumption of flocculants and chemical reagents of up to 30% [19].

Xie et al. [17] studied the effects of ultrasound pretreatment of sludge at a full-scale WWTP in Singapore. The ultrasound was applied at a frequency of 20 kHz and a flow rate of 200 m^3 per day (the percentage of sludge fed to the ultrasonication system was not reported). The results obtained showed a 22% reduction in sludge production (reaching 30% in optimal conditions) and a 45% increase in biogas production with a daily energy consumption of 288 kWh. Furthermore, Hogan et al. [20] evaluated the application of the Sonix™ ultrasonic system in different full-scale WWTPs at a frequency of 20 kHz as a pretreatment for secondary sludge and, in some cases, for thickened sludge before the AD process. The results showed significant removal of volatile solids (between 54 and 70%), a 50% increase in biogas production and a positive impact on sludge dewaterability.

The operating costs of ultrasonic treatment can vary depending on the potential of the system itself, the duration of treatment, the number of ultrasonic units used, the volume of sludge treated and the total solids concentration. Table 1 shows the energy consumption of an ultrasonic pretreatment system (GDS, VTA) with a central mixer with a power of 4 kW and ultrasonic sonicators with a power of up to 4000 W for different WWTP capacities, durations of treatment and numbers of sonicators.

Table 1. Energy consumption for ultrasonic pretreatment [21].

Parameter	WWTP A	WWTP B
Capacity of the plant (PE)	30,000	35,000
Biological sludge treated (%)	50–60	30–40
Treated sludge flow (m^3/h)	0.3	0.75
TSS concentration (g/L)	60	55
Number of sonicators	4	5
Treatment duration (min)	300	120
Specific power intake (kW/kg TSS)	0.35	0.4
Energy consumption (kWh_{el}/m^3)	6.3	16

The data show that energy consumption is strongly correlated with the amount of sludge treated and the treatment duration.

The capital cost of an ultrasound pretreatment system covers the pumping system for feeding the sludge to the ultrasonic reactor, the ultrasonic sonicators, the mixers, the contact reactor and the hardware and software management system. The investment costs are influenced by the capacity of the WWTP and have been estimated to be equal to EUR 7/PE for a WWTP with a treatment capacity of 330,000 PE [15,22].

3.2. High-Pressure Homogenization

High-pressure homogenization is an alternative mechanical treatment to ultrasound. This treatment consists of a high-pressure pump that compresses the sludge to a pressure of several hundred bar (generally between 150 and 660 bar) and a backpressure valve (also called a homogenization valve) through which the sludge is released from the pressure to which it was previously subjected into atmospheric pressure [23].

When the sludge is introduced into the high-pressure homogenizer, it is subjected to an increase in velocity of more than 50-fold (up to 300 m/s), causing hydrodynamic cavitation and collisions that lead to the dissolution of the sludge and the deconstruction of the bacterial cells.

In contrast to ultrasound treatment, high-pressure homogenization has only been applied at the pilot scale in CAS treatment [24]. Continuous tests showed a reduction in the observed sludge yield (Y_{obs}) from 0.36 to 0.29 g TSS/g COD with the application of pressure of 300 bar, which corresponded to a reduction in sludge production of about 20%. In the sludge line, high-pressure homogenization makes it possible to reduce sludge production by up to 30% and increase biogas production by up to 23%, with energy consumption ranging from 0.2 to 0.4 kWh/kg TS [25]. Due to the high energy demand, this technology is quite expensive, so there are few full-scale applications [26].

3.3. Lysis-Thickening Centrifugation

A lysis-thickening centrifuge is a mechanical disintegration system that includes a centrifugal thickener equipped with an additional mechanical ring that breaks up the sludge flocs and cell membranes, promoting the solubilization of the organic matter. The disintegration of the sludge flocs and partial solubilization of the cellular material enhance the anaerobic degradation of the organic matter by reducing sewage sludge production and increasing biogas production. This system has been applied at full scale in semi-continuous mode with variable rotation speeds between 2250 and 3140 rpm. The results of the full-scale application included an increase in biogas production of 15–26% and about 30% dry content in the dewatered sludge [27]. Regarding energy consumption, the estimated power of lysis-thickening centrifuges varies according to the specifications (i.e., the format and treatment capacity of the machine) and generally ranges from 0.75 to 1.1 kW/m^3 [27,28].

4. Chemical Treatments

Chemical treatments that allow sludge production to be reduced are essentially based on oxidation reactions. Ozonolysis is the main oxidative treatment; other oxidative treatments can be performed with chlorine, chlorine dioxide and Fenton reagents. Among these treatments, ozonolysis is the most environmentally friendly method because it does not produce byproducts or residues that can negatively affect the environment and human health. For this reason, ozone is preferred over other oxidizing agents, such as chlorine.

To date, chemical treatments with oxidants such as chlorine, chlorine dioxide and Fenton reagents have only been applied at the laboratory scale, albeit with good sludge reduction percentages. Therefore, these treatments are not included in this review.

The ozonolysis process, in particular, is widely applied in full-scale WWTPs. The sludge treated with ozonolysis is subjected to disintegration, the cells are destructured and solubilization and mineralization of particulate and soluble compounds take place [29]. This process can take place through direct oxidation with ozone; through the formation of hydroxyl radicals, which also have strong oxidizing power; or through the combination of both oxidants.

With regard to applications in the water line, ozonolysis treatment can be carried out with an aliquot of the recirculating sludge using an intermittent ozonation process in a contact reactor. The sludge subjected to this treatment is partially oxidized and partially solubilized; the lysate is sent to the CAS treatment, where it is consumed by bacteria. One full-scale application of ozonolysis treatment is the Biolysis®-O process (Suez Environment, La Défense, France). The ozonated sludge is taken directly from the activated sludge tank rather than from the sludge recirculation line. Déléris et al. [30] showed the results of the Biolysis®-O process applied at full scale, highlighting a reduction in sludge production of up to 80% with ozone consumption of 0.13 kg O_3/kg TS treated.

Biolysis®-O technology was also applied in the Broomhaugh (United Kingdom) WWTP, where a 35% reduction in sludge production was achieved at ozone doses of 0.13–0.23 kg O_3/kg TS treated.

In general, ozonolysis treatment allows sludge reductions of at least 35–45% [29,31–34], even reaching zero sludge production [35,36] in some cases, as reported below.

Sakai et al. [35] integrated ozone treatment with CAS treatment. In a full-scale application, three proportions of excess sludge (between 3 and 15%) were fed to the ozonolysis treatment, which was carried out with an ozone dosage of 0.034 kg O_3/kg SS. When 15% of the excess sludge was treated with ozone, zero sludge production was observed. Lee et al. [36] reported zero sludge production in a pilot plant with a treatment capacity of 10 m^3/d. A portion of the recycled sludge (percentage not given) was treated with ozone (0.05 g O_3/g TSS) and then fed into the activated sludge reactor. The authors pointed out that zero sludge production could be achieved when two operating parameters were varied: the percentage of sludge treated with ozone and the daily frequency of ozonation, which in turn depended on the temperature. The results showed that, at a temperature of 15 °C, the frequency of ozonolysis (i.e., how often the same amount of sludge had to be treated) varied between 2.5 and 2.7; at temperatures below 10 °C, the frequency of ozonolysis had to be doubled.

In another case, full-scale application of ozonolysis in a WWTP with a treatment capacity of 50,000 PE showed a reduction in sludge production that was much lower than that obtained in previous studies [29]. In this full-scale application, about 50% of the recirculated sludge was subjected to ozone treatment (0.74 g O_3/g TSS), corresponding to 0.5 kg VSS treated/kg VSS per day, which resulted in only a 10% reduction in sludge production.

Ozone treatment is undoubtedly the most commonly used oxidation pretreatment in the sludge treatment lines of WWTPs [37]. In contrast to aerobic oxidation, which takes place in the water line, the application of ozone in the sludge treatment line increases the recovery of energy from the organic content of the sludge through the production of methane. Pretreatment of the sludge with ozone improves the hydrolysis step in AD, which allows the shortening of the sludge retention time in the digester and significantly reduces sludge production.

In many studies conducted at both the laboratory and pilot scales, ozonolysis has been shown to reduce sludge production much more than physical, thermal and thermochemical treatments [38]. Experimental results have shown that, as the ozone dose increases, the degree of solubilization and disintegration of the organic matter increases. However, when too high a dose of ozone is used, solubilization is reduced due to the oxidation of the solubilized compounds and an increase in the production of inert soluble organic fractions. The optimal ozone dose for oxidation of excess sludge prior to the AD process varies between 0.02 and 0.87 kg O_3/kg TS [28].

Sievers et al. [39] reported a full-scale application of ozone pretreatment in which the ozone system (Wedeco, Xylem) was integrated into the sludge treatment section of the Schermbeck WWTP (17,000 PE) in Germany. The results showed that, with an ozone dosage of 0.05 kg O_3/kg TSS treated, sludge production could be reduced by 55%. Greater reductions in sludge production were observed in laboratory- and pilot-scale applications, reaching percentages of up to 68% (Weemaes et al., 2000). In addition to a 70% reduction in the amount of dewatered sludge and a 12% reduction in water content, ozonolysis improved the biodegradability of polycyclic aromatic hydrocarbons (PAHs) by improving their removal within the AD compartment [37].

The main operating costs for the ozonation process are the costs for the energy consumed for the pumping and aeration system and for ozone generation. The main investment costs for the ozonation process are the costs for the ozone generator, the sludge pumping system inside the ozone reactor, the injection system and the contact tower.

The costs associated with ozone generation, which are given by the sum of the energy and oxygen supply costs, are certainly relevant. Mundy et al. [40] reported a correlation between the total cost of ozone production and ozone concentration. As ozone concentration increases, the specific energy required to produce ozone increases, while the amount of liquid oxygen required decreases. Thus, more energy is required to produce the same amount of ozone. With an average energy cost of 0.08 EUR/kWh_{el} and an average liquid oxygen cost of about 85 EUR/ton, it is possible to define an optimal production value corresponding to about 0.7 EUR/kg ozone, which corresponds to ozone concentrations between 10% and 12%.

In general, the average cost of oxygen is about 0.11 EUR/kg O_2, while the average cost of electricity is 0.15 EUR/kWh_{el} [41]. Considering ozone production using an oxygen system, about 9.67 kg O_2/h and 8.9 kWh_{el} are needed to produce 1 kg O_3/h under standard temperature conditions. Thus, the production cost for 1 kg/h of ozone is about 2.4 EUR/h or 58 EUR/d. If ozone is produced using an air system, about 22 kWh_{el} is needed to produce 1 kg O_3/h at a cost of about 3.3 EUR/h or 80 EUR/d.

The specific dosage for ozone treatment integrated into the water line varies from 0.02 g O_3/kg TSS to a maximum of 1.0 g O_3/kg TSS treated. Therefore, the hourly cost of ozone production varies from 0.05 EUR/kg TSS to 2.4 EUR/kg TSS. In contrast, ozonation integrated into the sludge line requires between 0.05 g O_3/kg TSS and a maximum of 1.0 g O_3/kg TSS treated. Therefore, the maximum ozone production cost of a system integrated into the sludge line is comparable to that of a system integrated into the water line.

In general, the use of ozonolysis as an integrated treatment makes sense where the reduction in the amount of sludge to be disposed of provides greater savings than the cost of ozone production.

The Biolysis®-O process utilizes ozone dosages ranging from 0.13 to 0.23 kg O_3/kg TS treated, with a maximum production cost for the ozone of 0.55 EUR/kg TS treated. Déléris et al. [30] reported that the investment and operating costs for Biolysis®-O in a WWTP with a treatment capacity of 100,000 PE were 140 EUR/ton TSS and 260 EUR/ton TSS, respectively. Thus, the total cost was 400 EUR/ton TSS, which is comparable to the costs of the mechanical and thermal treatment technologies commonly used to reduce sludge production.

In the study conducted by Romero et al. [29], an ozone generation system (Wedeco, Xylem, Herford, Germany) was installed in the sludge treatment line of a WWTP with a capacity of 50,000 PE. The study showed that, during the operation time of the ozonolysis system, the energy consumption of the plant was equal to 567,036 kWh_{el}, while the ozone consumption was 77,194 kWh, which was about 14% of the total energy consumption of the plant. Considering the specific cost of oxygen, which was 0.05 EUR/kg O_2, and the average cost of electricity, which was 0.13 EUR/kWh, the specific cost of ozone production was 1.8 EUR/kg O_3 produced (10 kg O_2 and 10 kWh_{el} electricity per kg O_3 produced). The annual ozone production was 3276 kg O_3 and the operating cost of the system was 5897 EUR/year.

5. Low-Temperature Thermal Treatments

Low-temperature thermal treatments are generally carried out at temperatures between 165 and 180 °C with reaction times of 30 to 60 min. The increase in temperature causes the destruction of sludge flocs, the release of extracellular organic compounds and the lysis of bacterial cells with an increase in the concentration of biodegradable organic substances. However, due to their high cost, there are few studies reporting the application of low-temperature thermal treatments in the water lines of WWTPs, and the existing studies only concern pilot-scale applications. In contrast, low-temperature thermal treatments applied as pretreatment for AD in the sludge line particularly favor the hydrolysis of the organic matter, which is the limiting step in the AD process. However, in addition to this, low-temperature thermal treatment prior to the AD process has several advantages, such as reducing total solids by up to 32% [42], with a lower amount of sludge to dispose of; increasing biogas production by up to 90% [43]; reducing the hydraulic retention time (HRT) of the AD compartment, since hydrolysis occurs upstream; and feeding higher concentrations of sludge to AD, with a lower volume required for the anaerobic digester. Low-temperature thermal pretreatment is applied in many real WWTPs and is nowadays the most widely used technology to reduce sludge production within the sludge line. This technology has been commercialized by several companies, including Cambi ASA with the CAMBI™ treatment, Veolia with BioThelys™, Kruger-Veolia with Exelys™, Sustec (DMT Group) with TurboTecTHP™ and Eliquo with LysoTherm™ [12].

The Cambi^{TM} process was the first full-scale implementation of a low-temperature thermal pretreatment of sewage sludge. Today, there are over 70 installations of this technology around the world. The Cambi^{TM} process involves thermal treatment of thickened sludge with a total solids concentration of 16–18%, treatment temperatures from 140 to 165 °C and a pressure of about 6 bar. The reaction time is set at 20–30 min for each reactor to ensure the death of pathogens. This process allows for an increase in biogas production by up to 50% and a reduction in the volume of sludge to be disposed of by up to 65% [44].

Similarly to the Cambi^{TM} process, BioThelys^{TM} technology combines thermal hydrolysis ("Thelys") with AD ("Bio"), ensuring better performance compared to the conventional treatment chain. The thermal hydrolysis is carried out in batch mode at a variable temperature between 150 and 180 °C with reaction times and pressures ranging between 30 and 60 min and 8 and 10 bar, respectively, while the AD process is carried out at 35–38 °C with 15 days of HRT, 6 days less than conventional AD. The BioThelys^{TM} process enables sludge reductions of up to 45% and 50% for biological sludge and mixed sludge, respectively; increases in biogas production of 30–50%; improvements in sludge biodegradability and dewaterability; and the acceleration of methanogenesis. There are three main configurations of the BioThelys^{TM} process: (1) lysis/digestion (LD), in which part or all the sludge is thermally hydrolyzed prior to AD; (2) partial lysis/digestion (partial LD), in which only the biological sludge (secondary sludge) is thermally hydrolyzed; and (3) digestion/lysis/digestion (DLD), which is a Veolia patent. This latter configuration can be implemented when two anaerobic digesters are present. Thermal hydrolysis is applied to all the sludge leaving the first digester. The sludge is then cooled and sent to the second anaerobic digester. This configuration makes it possible to produce up to 80% more biogas and electricity while reducing the amount of sludge by over 45% [45]. This technology was implemented in 2012 at the Monza WWTP, Italy, which has a treatment capacity of 790,000 PE and produces 10,220 tons of TSS per year (28,000 kg SS/d). The implementation of the BioThelys^{TM} process includes the installation of two hydrolysis reactors with volumes of 12.5 m^3 each and a mesophilic anaerobic digester with a volume of 7000 m^3. Results from the Monza WWTP showed an increase in the biodegradability of the VSS—leading to an increase in biogas production of about 80% (daily biogas production: 13,500 Nm^3/d), of which 35% was used to thermally sustain the thermal lysis—and a reduction of 45% in the mass of sludge to be disposed of (sludge produced per day: 22,000 kgSS/d).

The Exelys^{TM} process is a continuous version of the BioThelys^{TM} process. Exelys^{TM} allows reductions in sludge production between 5 and 35% and increases in biogas production between 30 and 50%. The TurboTec^{TM} process developed by Sustec (DMT group) uses direct heating via steam injection. In this process, the hydrolyzed sludge is cooled (to 105 °C) in a heat exchanger and then mixed with the thickened sludge (7–14% TSS) in the patented Mobius mixer to preheat the raw sludge. The mixing unit can separate fluidized hydrolyzed sludge and denser raw sludge based on their different viscosities. The less dense fraction (hydrolyzed sludge) is fed directly into the digester, while the denser fraction, containing a mixture of non-hydrolyzed sludge and untreated raw sludge, is fed into the hydrolysis reactor. Hydrolysis of the biomass in the biological sludge produces up to 35% more biogas in the AD compartment and also improves the dewaterability of the sludge.

Among the various technologies for sludge reduction, low-temperature thermal treatments certainly have significant capital costs due to the reactors, the heating and cooling system, the sludge pumping system and the complex hardware and software required to manage the entire process. The operating costs relate to the energy consumption in terms of electricity and heat. The nature of the thermal treatments themselves means that they are among the technologies that consume the most significant amounts of energy, varying from 7.2 kWh_{el}/m^3 to 24 kWh_{el}/m^3 and, taking into account heat consumption, up to 116 kWh_{heat}/m^3 [46–48]. Nevertheless, as reported by Taboada-Santos et al. [49], low-temperature thermal treatments can have a positive impact on the overall energy consumption of a WWTP since they are able to achieve self-sufficiency from an energy point of view and, with the optimal management and operation strategy, they can ensure an energy surplus that can be used within the WWTP. In fact, thermal treatments allow significant increases in biogas production (up to 50%) and, therefore, energy recovery.

6. Thermochemical Treatments

6.1. Low-Temperature Thermochemical Hydrolysis

Low-temperature thermochemical hydrolysis combines the use of temperatures below 100 °C with chemicals and, when used as a pretreatment for AD, it can significantly reduce sludge while promoting the production of biogas.

The NewLisi® process is a thermochemical hydrolysis treatment that functions at low temperatures (up to 90 °C) and atmospheric pressure in continuous mode. This process allows sludge flocs to be broken up by promoting cell lysis and the release of intracellular water, achieving high solubilization of the sludge. It can reduce the amount of sludge to be disposed of by up to 75%, resulting in a reduction in disposal costs. In addition, biogas production can be increased by over 40% in plants where the AD compartment is present [50]. NewLisi® was applied at full scale in Acquedotto del Fiora (Italy), a municipal WWTP with a capacity of 100,000 PE without an AD compartment. It resulted in a reduction of about 70% in the sludge to be disposed. In addition, an implementation in Acquedotto Pugliese (Italy) in a 195,000 PE WWTP with an AD compartment resulted in sludge production being reduced by 64% and methane production increasing by 44%.

6.2. Hydrothermal Carbonization

In recent years, the thermochemical process known as hydrothermal carbonization (HTC) has gained considerable attention in the treatment of sewage sludge. The HTC process can be applied at full scale as a pre- or post-treatment for the AD process [51,52]. The HTC process converts residual biomasses at temperatures in the range of 180–250 °C and pressures in the range of 10–50 bar and operates in a reaction environment characterized by the presence of liquid water. HTC is a weakly exothermic process. Once the temperature at which the process is activated is reached, the reaction is then supported by the energy released during the process itself. During the HTC reaction, water, carbon dioxide and other compounds are broken down from the biomass. The results are a carbonaceous solid called hydrochar with properties very similar to lignite and a liquid residue called HTC liquor, which is rich in nutrients and biodegradable organic compounds [53,54]. The advantage of this technology over others is that the process takes place in liquid water, making HTC suitable for treating biomasses with high moisture content without the need for prior dewatering or drying of the feedstock. The HTC process has been commercialized by several companies, such as TerraNova Energy GmbH (Düsseldorf, Germany), Ingelia (Valencia, Spain), AVA CO2 (Zug, Switzerland) and Carborem (Trento, Italy), for full-scale treatment of sewage sludge, organic fractions of municipal solid waste (OFMSW) and green waste.

TerraNova Energy GmbH (Germany) constructed the first plant with a continuous HTC process that uses biological sludge as feedstock in China. Biological sludge is carbonized during the TerraNova® Ultra process for a reaction period of between two and three hours at a temperature of about 200 °C and pressures from 20 to 35 bar. The dehydrated sewage sludge (dry matter content: 5–30%) is preheated in a heat exchanger. At the end of the HTC reaction, the HTC liquor is separated from the hydrochar using a filter press, which makes it possible to obtain hydrochar with a dry matter concentration of between 65% and 70%. As a result, the hydrochar that is produced can be employed as a useful material in technological applications and as a solid fuel, fertilizer and adsorbent. In addition, HTC liquor has valuable nutrients, such as phosphorus and nitrogen, that can be recovered and used as valuable products added to fertilizers. The TerraNova® Ultra process, when applied at full scale, reduces the volume of sludge that needs to be disposed of by more than two thirds, uses 80% less energy than the drying treatment, produces 10% more biogas and can even be implemented to recover phosphorus. This technology requires 100 kWh_{heat} and 15 kWh_{el} per ton of biological sludge treated. In contrast, it is possible to recover 425 kWh per ton of treated sludge when using hydrochar as a fuel. Therefore, the TerraNova® Ultra process can provide about 3400 MWh of energy annually, which can be used for energy self-sufficiency in WWTPs with a capacity of 100,000 PE [55]. In 2022, the TerraNova® Ultra process was employed for treating municipal biowaste in Mexico City.

Two HTC plants have been developed by Ingelia (Spain) for the treatment of OFMSW and green waste, and two more plants for the treatment of biological sludge have been commissioned, but no data relating to sludge reductions, biogas production or energy consumption are available [56]. AVA CO2, a company acquired in 2016 by International Power Invest AG, built the first industrial-scale HTC process plant in Relzow, Germany. The plant, initially consisting of two HTC reactors and later six reactors, was built to treat 8000 tons per year of reeds from agricultural lake areas and produces roughly 2664 t/year of biocarbon [57]. A full-scale HTC plant was recently built by the Italian start-up Carborem in Trento (Italy) for the post-treatment of sludge derived from the AD of agro-industrial wastewaters (from the wine industry, alcoholic distillate production, dairies, etc.). The technology, known as C700, consists of a thermal process that operates at up to 200 °C and 20 bar with a reaction time of less than 60 min to valorize organic waste, such as sewage sludge, digestate, OFMSW, and manure. Application of the C700 technology resulted in a 43% decrease in TSS (concentration of TSS before the HTC process: 44.5 g/L; after HTC: 25.1 g/L), which had a positive effect on sludge transport and disposal costs. Additionally, by recycling some of the HTC liquor back into the AD, a twofold increase in biogas production compared to that in the traditional AD process was achieved. Moreover, for the treatment of 760 L of sludge, consumption of 3.5 kWh_{el} and 63.0 kWh_{heat} was certified [58]. Regarding the costs of HTC, Lucian and Fiori [59] highlighted an investment cost of EUR 1,774,000 for the treatment of 44,000 tons of sludge per year, with a final product consisting of dry pelletized hydrochar. The total annual operating cost, which included the costs of thermal and electrical energy, equaled EUR 833,000. The overall production cost was approximately 157 EUR/ton of dry hydrochar produced, with thermal and electrical consumption of 1170 and 160 kWh/ton of dry hydrochar generated, respectively.

7. Biological Treatments

Biological treatments for the reduction of sludge production are based on the selection and activity of bacteria that are generally anaerobic and, under certain operating conditions, able to break down organic matter. Generally, in this type of processes, an anaerobic side-stream reactor (ASSR) is inserted into the sludge recirculation line of the activated sludge reactor for sludge treatment. In this way, the sludge is exposed to alternating aerobic and possibly anoxic conditions in the activated sludge reactor and anaerobic conditions in the side-stream reactor, which is also known as "sludge fasting/feasting", a feast–famine alternation [60]. This treatment, commonly known as an oxic-settling-anaerobic (OSA) and/or anaerobic side-stream reactor (ASSR) process, has been studied in many configurations, especially at the laboratory scale, and allows reductions in sludge production of up to 70% [61]. However, there are only a few full-scale applications because it is difficult to clearly understand the mechanisms whereby sludge production is reduced [62]. Among the various proposed technologies for sludge reduction, biological treatments are certainly the least demanding from an energy point of view. Their major advantage is the relatively low operating cost compared to mechanical or chemical sludge reduction technologies. Investment costs are also limited, especially if existing volumes can be converted into sludge treatment reactors. Therefore, biological treatments are also easy to implement in existing WWTPs.

7.1. The Cannibal Process

The Cannibal® process was the first full-scale application of an ASSR process that combines biological and physical approaches to reduce sludge production [61]. According to the Cannibal® process scheme, a portion of the recirculating sludge (typically about 10% of the recirculation flow rate) is sent to a pre-accumulation tank, which consists of a drum screen and a hydrocyclone, for physical treatment and then discharged into the ASSR with a retention time of 10 days [63]. In the study by Novak et al. [61], the Cannibal® process was applied at the laboratory scale and obtained a reduction in sludge production of 60% compared to CAS treatment. However, the application of this process at the full scale resulted in lower percentages of sludge reduction. Velho et al. [62] evaluated the performance of the Cannibal® process by monitoring a full-scale WWTP for 5 years (Levico, Italy). The results of this study showed that the sludge production rate decreased from 0.44 kg TSS/kg COD in the reference activated sludge plant to 0.35 kg TSS/kg COD when the Cannibal® process was used, which corresponded to a reduction in sludge production of only 20%. In addition, the study showed that increasing the volume of the ASSR by 45% had no positive effects on the reduction of sludge production. The authors concluded that the mechanisms involved in sludge reduction are not only related to the endogenous decay within the ASSR and that several other aspects, such as the interchange ratio (IR) and the sludge age of the ASSR (SRT_{ASSR}), must be considered.

For this process, capital costs include the costs of the sand and the inert removal system (hydrocyclone and rotating drum), the cost of constructing the anaerobic/anoxic reactor and the cost of the pumping system. The operating costs only relate to the energy consumed by the pumping and mixing system in the sludge treatment tank. As far as we know, there is no information in the literature on capital and operating costs. For a plant that treats approximately 1.5 MGD (millions of gallons per day) of wastewater (approximately 6000 m^3/d), it is possible to obtain annual savings in the plant operating and management costs equal to approximately EUR 200,000 [64].

7.2. The UTN Process

Recently, the implementation of a new ASSR treatment scheme, called the UTN System, which originated at the laboratory scale, has been successfully applied at the full scale [63].

Unlike the Cannibal® process, in the UTN System, the method of sludge reduction is related to a combination of different mechanisms, including cell lysis and cryptic growth and the selection of slow-growing bacteria in the ASSR. The activated sludge is first sent to a denitrification side-stream reactor (DSSR) to complete the denitrification process where necessary and ensure a nitrate concentration below 5 mg/L in the sludge fed to the ASSR, as well as to thicken the sludge to be fed into the ASSR. From the DSSR reactor, the sludge is then sent to the ASSR, which operates with an SRT_{ASSR} of 2.5 d (or <5 days) and an IR between 30% and 100%.

The UTN System has been applied at the full scale in a municipal WWTP with a capacity of 6000 PE (Mantova, Italy), replacing the existing aerobic digestion process [63]. The results showed sludge removal equal to 0.37 and 0.23 kg TSS/kg COD removed for two monitoring periods with the UTN process compared to sludge removal of 0.75 kg TSS/kg COD with the conventional treatment. Data showed reductions in sludge production of 50% and 69% compared to the conventional treatment. The energy consumption of the UTN treatment was also estimated. The ASSR in the UTN process contributes only 15% of the overall consumption of the sludge line compared to 24% with aerobic digestion. The average annual energy consumption is 84 kWh_{el}/PE, which is slightly lower than the 90 kWh_{el}/PE of the CAS system. A deeper analysis considering the nominal powers of the individual pieces of electromechanical equipment, the absorbed powers and the numbers of operating hours per day of the individual pieces of electromechanical equipment showed that the consumption of the UTN process was slightly higher than that of CAS due to the use of a dynamic sludge thickening system.

7.3. Temperature-Phased Anaerobic Digestion (TPAD) Process

The two-stage temperature treatment, known as TPAD, is a biological pretreatment technology commonly used to reduce sludge production. In this treatment, a thermophilic stage with low retention times is combined with a mesophilic stage with longer retention times [65,66]. In this way, the initial phases of the AD process—i.e., hydrolysis, acidogenesis and acetogenesis—are separated from the methanogenesis phase.

The temperature in the pretreatment digester is usually between 60 and 70 °C and the HRT is between 9 and 48 h [67,68].

Despite extensive testing in the laboratory, there are few applications of the TPAD method with thermophilic–mesophilic sequencing. In 1997, ten plants in Germany were reported to use TPAD, of which only five were highly efficient [69]. More recently, a plant in Norway combined the TPAD process with the CAMBI™ process [70], and other plants have been built in the United States [71]. The results of full-scale applications showed an increase in biogas production between 7 and 11% and a reduction in sludge production between 26 and 50%.

The investment costs are related to the construction of the digestion compartment and the pumping system. The operating costs mainly relate to the energy needed to heat the thermophilic and mesophilic reactors. Krugel et al. [71] reported energy consumption of 0.04 kWh_{el}/kg VS (electrical consumption) and 0.5 kWh_{heat}/kg VS (heat consumption), corresponding to VS removal of 45% and biogas production of 454 Nm^3/ton VS treated.

8. Performance Overview

Table 2 summarizes the main advantages and disadvantages of all the technologies respectively integrated into the water line and sludge line previously described.

Table 2. Advantages and disadvantages of sludge reduction technologies applied in the water and sludge lines.

Technology			Advantages	Disadvantages
Water Line	Mechanical treatment	Ultrasound	Low investment costs Low space requirements No production of odor	Erosion of sonotrodes High operating costs Increase in effluent COD
	Chemical treatment	Ozonolysis	Improved sludge settleability	High investment and operating costs Increase in effluent COD and phosphorous
	Biological treatment	Cannibal	Easy to apply in existing plants	Increase in effluent phosphorous
		UTN	Low investment and operating costs Improved sludge settleability	Only one full-scale application
Sludge Line	Mechanical treatment	Ultrasound	Low investment costs Low space requirements No production of odor Improved sludge settleability	Erosion of sonotrodes High operating costs
		High-pressure homogenization	Improved sludge settleability at high disintegration intensity Short contact time No production of odor Lower sludge viscosity	Deterioration of equipment High investment and operating costs No pathogen inactivation
		Lysis-thickening centrifuge	Short contact time No production of odor	Deterioration of equipment High investment and operating costs No pathogen inactivation
	Chemical treatment	Ozonolysis	Lower sludge viscosity Improved sludge settleability	High investment and operating costs Increase in the wastewater nitrogen and phosphorous Worsening of settleability at high ozone dosages

Table 2. *Cont.*

Technology			Advantages	Disadvantages
Sludge Line	Low-temperature thermal treatment	CAMBI™ Exelys™ BioThelys™ TurboTec®	Pathogen inactivation Improved sludge settleability Thermal synergies increasing biogas production	Production of odor Deterioration of equipment
	Thermochemical treatment	NewLisi HTC	Pathogen inactivation Improved sludge settleability Thermal synergies increasing biogas production	Deterioration and erosion of equipment High operating and maintenance costs High chemical consumption Production of odor
	Biological treatment	TPAD	Pathogen inactivation Improved sludge settleability Low management costs	High investment costs Production of odor

Table 3 shows the performances of the main sewage sludge reduction technologies integrated in the water lines of WWTPs and applied at full scale in terms of sludge reduction, energy consumption and investment costs.

Table 3. Performance of sludge reduction technologies integrated in the water line.

Technology	Sludge Treated	Treatment Conditions	Performance Indicators			References
			Sludge Reduction (%)	Energy Consumption	Investment Cost	
Ultrasound	Biological sludge	20–40 kHz	25–78%	2.4 kWh_{el}/m^3	0.97 EUR/PE	[15,22]
		>90 s		28.1 kWh_{el}/m^3	7 EUR/PE	
Ozonolysis		0.01–0.15 kg O_3/kg TS	35–45%	30 kWh_{el}/kg O_3	45–67 EUR/ton 10–30 EUR/PE	[28,34,72]
Cannibal		HRT 10 d	20%	N.A.	N.A.	[62]
UTN		HRT 2.5 d	50–69%	84 kWh_{el}/PE	N.A.	[63]

Note: N.A. = not available.

The data presented in Table 3 could be useful for a comparison between the various technologies. In particular, in terms of sludge reduction, the integration of the ultrasonic process in the water line of a WWTP could enable a sludge reduction of 78%, which is slightly higher than the value obtained from the application of the UTN process (up to 69%). However, the latter consumes less energy than the former. Nevertheless, further full-scale applications are needed to confirm these data. Integration of the ozone process into the water line still enables good reductions in sludge production (up to 45%), but it is economically less convenient than the previous solutions. The Cannibal process is definitely the less convenient process in terms of the sludge reduction achieved. Table 3 shows the performances of the main sludge reduction technologies integrated in the sewage sludge lines of WWTPs and applied at full scale in terms of sludge reduction, biogas production, energy consumption and investment cost.

The data reported in Table 4 show that the processes that enable greater reductions in sludge production are the low-temperature thermal and mechanical treatments. Low-temperature thermal processes not only allow reductions in sludge production of up to 75% but also facilitate increases in biogas production, which may reach up to 50%. Mechanical processes can enable reductions in sludge production of up to 60% but with a smaller increase in biogas production (up to 30%).

Table 4. Performances of sludge reduction technologies integrated into the sludge line.

Technology	Sludge Treated	Treatment Conditions	Performance Indicators					PE	References
			Sludge Reduction (%)	Increase in Biogas Production (%)	Biogas Produced (Nm^3/ t VS)	Energy Consumption	Investment Cost		
Ultrasound	Mixed sludge	20–40 kHz 90–300 s	10–60%	20–30%	442	2.4 kWh_{el}/m^3 28.1 kWhel/m3	0.97 EUR/PE 7 EUR/PE	17,000 330,000	[15,22]
Lysis-thickening centrifugation	Mixed sludge	2250 rpm 3140 rpm	60%	15–26%	362	11.4 kWh_{el}/m^3	1.22 EUR/PE	650,000 100,000 70,000	[27,28]
High-pressure homogenizer	Mixed sludge	150 bar 36–38 °C	23–57%	30%	478	5.5 kWh_{el}/m^3 0.2–0.4 kWh/kg TS	2 EUR/PE	55,000 100,000	[25,73]
CAMBI®	Thickened sludge	160–180 °C 5–6 bar 20–30 min	65	50	252–442	7.2 kWh_{el}/m^3 116 kWh_{heat}/m^3	20.38 EUR/PE	100,000 250,000	[44,46–48]
BioThelys®	Secondary sludge	150–180 °C 8–10 bar 30–60 min	40–60%	30–50%	286	N.A.	N.A.	760,000	[74]
Exelys®	Secondary sludge	130–150 °C 8–15 bar Continuous	64%	30–50%	600	6.4 kWh_{el}/m^3	N.A.	630,000	[75–77]
TurboTec®	Thickened sludge	140 °C	41%	35%	350–410	52 kWh_{el}/t TS 620 kWh_{heat}/t TS	N.A.	300,000	[78]
TerraNova® Ultra	Thickened sludge Digested sludge	200 °C 20–35 bar 2 h	75%	10%	N.A.	15 kWh_{el}/t 100 kWh_{heat}/t	N.A.	N.A.	[55]
C700	Thickened sludge Digested sludge	200°C 20 bar <60 min	43%	50%	N.A.	4.60 kWh_{el}/m^3 83 kWh_{heat}/m^3	N.A.	N.A.	[58]
NewLisi	Mixed sludge	pH 1–3 pH 8–12 70–90 °C	64%	43%	N.A.	N.A.	N.A.	195,000	[50]

Table 4. *Cont.*

Technology	Sludge Treated	Treatment Conditions	Performance Indicators					PE	Reference
			Sludge Reduction (%)	Increase in Biogas Production (%)	Biogas Produced (Nm^3/ t VS)	Energy Consumption	Investment Cost		
Ozone	Activated sludge Digested sludge	0.01−0.15 O_3/kg TS 0.02−0.87 O_3/kg TS	55%	20–30%	550	23.8 kWh_{el}/m^3	18 EUR/PE	17,000	[73]
TPAD (thermophilic–mesophilic)	Secondary sludge	60–70 °C 9–48 h $HRT_{55\,°C}$: 9 d $HRT_{35\,°C}$: 18 d	26–50%	7–11%	454	N.A.	N.A.	N.A.	[67,68,71]

Note: N.A. = not available.

Ozone treatment provides a good reduction in sludge production that is comparable to physical treatments, but it requires higher energy consumption. Finally, the biological TPAD process allows for a moderate reduction in sludge production without significantly increasing biogas production.

9. Conclusions

Reductions in sludge production and energy consumption in WWTPs are issues of great interest in the scientific field and, even more so, in the technical field.

With regard to the reduction technologies integrated into the water line, the analysis carried out led to the identification of three types of processes that are applied in the recirculation line of activated sludge: mechanical, chemical and biological. Among them, the mechanical treatments—in particular, those using ultrasound—showed the greatest reductions in sludge production of between 25 and 78%, followed by the biological treatments and, finally, the chemical ones. However, ultrasonic treatment and ozonolysis entail higher energy consumption than biological treatments, which, unlike with technologies integrated in the sludge line, cannot be compensated for by possible energy or resource recovery. The processes that could facilitate the double goal of saving energy and reducing sludge production are the biological processes, but they require further real-scale applications for the full definition of site-specific operational and capital costs.

Among all the possible treatments integrated into the sludge line, low-temperature thermal treatments are the most promising, as they allow both a strong reduction in sludge production and a significant increase in biogas production. This last aspect is of utmost importance. Although low-temperature thermal processes are highly demanding from an energy point of view, their ability to recover energy in the form of biogas has a positive impact on the total energy and cost balances of WWTPs. In addition, these processes also allow for the possible recovery of material, facilitating the valorization of the sludge and its subsequent use as a soil conditioner, adsorbent or fuel material. Low-temperature thermal treatments are followed by mechanical treatments, which also make it possible to obtain a good percentage reduction in the production of sludge and a moderate increase in the production of biogas. For all these treatments, high-pressure homogenization and disintegrating centrifuges are preferred, which involve lower energy consumption than ultrasound-based processes. The least appealing option is represented by the biological treatments, which do not allow the achievement of a significant increase in biogas production and are, therefore, less economically sustainable.

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