What Advanced Treatments Can Be Used to Minimize the Production of Sewage Sludge in WWTPs?

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Abstract: Similar to other types of waste, sewage sludge (SS) must be minimized, not only to respect the European Directive 2018/851 on waste, but also because the cost of sludge management is approximately 50% of the total running costs of a wastewater treatment plant (WWTP). Usually, minimization technologies can involve sewage sludge production with three different strategies: (i) adopting a process in the water line that reduces the production of sludge; (ii) reducing the water content (dewatering processes) or (iii) reducing the fraction of volatile solids (stabilization). This review, based on more than 130 papers, aims to provide essential information on the process, such as the advantages, the drawbacks and the results of their application. Moreover, significant information on the technologies still under development is provided. Finally, this review reports a discussion on the impact of the application of the proposed processes in the sludge line on a WWTP with a capacity exceeding 100,000 population equivalent (PE).

Keywords: innovative approach; sewage sludge; wastewater; dewatering; minimization; sludge line; stabilization

1. Introduction

Sewage sludge (SS) is a mixture of organic and inorganic matter and its composition strongly depends on the treatment and on the wastewater origin [1]. It can be composed of primary sludge, derived from primary sedimentation and formed by suspended sedimentary materials, secondary sludge, made up of excess biomass and, tertiary sludge, obtained in the advanced wastewater treatment stages, when nutrient (nitrogen and phosphorus) removal is required [2].

In recent years, the population growth and consequent urbanization have increased the number of wastewater treatment plants (WWTPs) and the production of SS [3,4]. Moreover, the application of more stringent requirements for WWTPs effluents quality increases the production, and worsens the quality, of the SS. For instance, in the EU, the implementation of the European Commission Directive 98/15/EC (amending Council Directive 91/271/EEC) led to a strong rise in sludge generation, up to 50% [5], with an estimate of more than 13 million Mg of dry matter in 2020. According to these data, developing urgent and effective approaches to reduce and recover SS becomes a priority [6,7].

Particularly, in order to respect the European Directive 2018/851 on waste, the first aspect to take into consideration is the minimization of the waste produced [8] and therefore, sludge [9]. Furthermore, the economic aspect has become important in recent years. Researchers show that the cost of sludge management is approximately 50% of the total running costs of the WWTP with the conventional activate sludge (CAS) process [10,11]. Moreover, also in the case of the WWTPs,
already suggested in recent years for drinking water treatment plants [12,13], some procedures for evaluating the performance of the plants and for defining optimal solutions for management in order to optimize operation and minimize the production of SS should be studied.

In 2015, 9.7 million MgDM (DM - dry matter) of SS were produced in Europe. More than 60% of the total SS was produced in Germany (around 19%) and the western countries (UK, Italy, Spain and France) (Figure 1). By contrast, eastern countries (such as Poland, Romania, Estonia, Latvia and Lithuania) represent around 12% of SS produced in Europe [14].

Figure 1. Sewage sludge (SS) production in 2015 in Europe [14]. DM: Dry matter. (a): Data referring to 2014. (b): Data referring to 2013. (c): Data referring to 2012. (d): Data referring to 2010. Data from Turkey, Montenegro, Macedonia, Kosovo, Iceland and Norway are not available.

In the last years, in the EU, SS recovery in agricultural use and composting quickly increased from 3 million MgDM in 1995 (42% of total production) to 4.2 million MgDM in 2005 (54% of total production); then, this value increased further (5.2 million MgDM in 2010 to 59% of total production) [14]. The EU issued the Directive 86/278/CEE (recently amended by the EU Decision 2018/853) with the aim of avoiding the application on land of SS that was dangerous for human health. Therefore, every member state has issued a national regulation on this topic [15]. For instance, currently, a high concentration of metals in sludge makes recovery using agriculture impossible [16].

Considering: (i) the framework of the ever-stricter European regulations regarding the recovery of SS in agriculture, (ii) the EU Directive 2018/851 [8] in which minimization is listed as a priority, (iii) the high costs related to SS disposal, it is clear that techniques for minimizing sludge production have become strictly necessary.

In this review, only advanced technologies and treatments are reported. The process description, the advantages, the drawbacks and the results of the literature are presented for each type of treatment. This review provides significant information on the technologies still under development.
2. Bibliometric Analysis

The interest in treatments and technologies in order to minimize the production of SS increased significantly in the last 10 years (Figure 2a). Inserting “minimization sewage sludge” in SCOPUS, only advanced biological treatments were found. Particularly, since 2015, about 83 research papers, reviews, books and conference proceedings on this matter have been published. Among these, biological treatments represent the theme of 39% of publications, while thermal and chemical treatments stop at 14% and 16%, respectively. Moreover, the results of the bibliometric analysis show two different trends: (i) the enhanced interest in the combination of different types of treatments and technologies in order to minimize SS (from 21% to 30%) and (ii) the reduction of the study of treatments exclusively of a physical nature. Considering that electrochemical treatments are generally coupled with the use of pressure, in the two periods examined (Figure 2b,c), they have been inserted in the “mixed” category.

Figure 2. (a) Comparison of the number of research papers, reviews, books and conference proceedings published in the last 20 years and before 2000; (b) Classification of the different types of treatments studied from 2015 to 2019; (c) Classification of the different types of treatments studied from 2010 to 2014. (All data were obtained using the keywords “Minimization sewage sludge” in SCOPUS).

3. Advanced Treatments and Technologies

Usually, minimization technologies can involve SS production in three different ways: (i) adopting a process in the water line that reduces the production of sludge; (ii) reducing the water content (dewatering processes) or (iii) reducing the fraction of volatile solids (stabilization). Both interventions in the sludge line and those in the wastewater line are shown (Figure 3), with their respective advantages and downsides. Technical and economic aspects must be evaluated in order to choose the
most appropriate technology. The advantages and the disadvantages must be considered; not only those direct (i.e., concerning sewage sludge production) but also those indirect (i.e., concerning other aspects of WWTPs). In Figure 4, the suitable advanced treatments available for the minimization of SS production are shown. The patents shown in this document represent, by way of example, those currently on the market. The presence of other patents not mentioned here is not excluded.

**Figure 3.** Points of possible application of advanced treatments in a conventional WWTP, in order to minimize the production of SS, in the water line (Point A) and in the sludge line: before hypothetical stabilization (Point B), before hypothetical centrifugation (Point C) and at the end of the line (Point D).

**Figure 4.** Suitable advanced treatments available for the minimization of SS production are shown.

### 3.1. Chemical Treatments

The most widespread chemical treatment is chemical oxidation, which differs according to the type of reagent used. In order to minimize the SS production, oxidizing the sludge by conventional and advanced chemical reagents, thus reducing the biomass yield as well as the sewage sludge disposal, is
currently adopted. By chemical oxidation, a part of the activated sludge is mineralized, while another part is solubilized in biodegradable organic compounds which can then be oxidized again in the activated sludge reactor [17–20].

3.1.1. Ozone and Chlorine

Among the conventional chemical reagents, the most common are O₃ and chlorine [21]. Chemical oxidation can be considered an advanced technique applicable both in the water line, directly on the recirculation sludge, and in the sludge line, after the thickener and upstream of the stabilization [22]. The aim of this treatment is the partial oxidation and hydrolysis of the organic matter, which is transformed into smaller molecular-weight compounds and is therefore more easily biodegradable [23]. Among the main advantages there is the best settleability of the SS [24], the reduction of filamentous microorganisms and the simplicity of plant engineering and management. However, the costs related to investment and oxidizing dose, and the formation of by-products, in particular with chlorine, are the main disadvantages. As regards the performance related to ozonation, there is a reduction in SST from 30% to 99% in the water line and from 10% to 60% in the sludge line [25]. This great variability, in terms of performance, is influenced by the dosage of oxidizing agent. However, Torregrossa et al. [22] found that ozonation applied in the water line significantly reduced SS production but resulted in a slight decrease of biomass respiratory activity. Gardoni et al. [26] studied the possible application in the sludge line and demonstrated the (non-linear) inverse relationship between ozone dose and specific particulate chemical oxygen demand (COD) solubilisation in the reactor. As concerns the chlorine dosage, the performances obtained by testing synthetic wastewater were lower than 65% for TSS [25]. Fazelipour et al. [17] studied chlorine application in a sequencing batch reactor (SBR) in order to minimize the SS production. The SBR treatments operate in batch and are composed of five stages: filling, reaction, settling, effluent and idle. The results showed a small dosage of chlorine, equal to 0.26 gCHLORINE gMLSS⁻¹ (MLSS—mixed liquor suspended solids), in return excess sludge to the reactor was able to reduce the yield coefficient by 50%. However, as in the case of ozonation applied in the water line, the COD removal percentage in the biological reactor decreased, particularly from 95% to 56%, due to partial inhibition of biomass caused by the reagent (O₃, chlorine) dosage. Therefore, the application of chemical oxidation in the water line should be carefully evaluated because even with a low concentration of reagents, partial inhibition of biomass could occur.

3.1.2. Wet Oxidation (WO)

Among the chemical oxidation processes, another used and studied is the WO [27–29]. This treatment allows us to obtain a drastic reduction of the organic matter in the SS at certain temperature conditions (150–360 °C), oxygen concentration (or air) and pressure (30–250 bar) and under continuous process conditions (contact time 15–120 min) [25,30,31]. The SS is converted into two products: (i) a gaseous phase and (ii) a liquid phase. This technique can be applied before the dewatering processes because WO can treat sludge with a solid content between 1% and 6% [25]. There are already some applications on the real scale thanks to numerous patents. Many variables influence this process and can act interactively. Oxygen stoichiometry is an important factor, and this is significantly influenced by hydrodynamics. Similarly, temperature influences, reaction kinetics, solubility and gas-liquid mass transfer rates depend on the reactor’s hydrodynamics [29]. The WO has the advantage of requiring relatively low investment and low energy demand [32]. However, it requires highly qualified personnel able to manage a process that takes place under conditions of temperature and pressure that are certainly not usual. Foladori et al. [25] found that the benefits in this case vary from 70% to 80% reduction in terms of TS. Baroutian et al. [28] treated a digested sludge (primary + secondary) for 60 min using WO (T = 220–240 °C; oxygen: biomass ratio of 1:1–2:1). They found that WO was effective at degrading TSS (86%) and VSS (96%). After the experiment, the concentration of oxidizable organic matter was reduced by 98% of the untreated sludge.
3.1.3. Fenton and Photo-Fenton

The Fenton process is an advanced oxidation process (AOP) useful for minimizing the SS production and increase sludge dewaterability [33,34]. This process is composed of four subsequent stages, which are: (i) pH adjustment at low acidic values, (ii) oxidation, (iii) neutralization and (iv) coagulation [35]. The Fenton reaction produces OH• in acidic solutions by iron catalysed decomposition of hydrogen peroxide [36]. During the last decade, the possibility of sludge dewatering by Fenton oxidation has been studied and the experimental results indicated that Fenton oxidation had a positive effect [33,37]. Moreover, the Fenton process allows us to minimize the SS production. In fact, used as pre-treatment, the Fenton process allows us to increase sludge solubilization and biodegradability, degrading extracellular polymeric substances, and breaking the microbial cell walls [34,38]; therefore anaerobic digestion is improved significantly [33,34,39]. As a result of this application, the volatile solids (VSs) are reduced by 27%, and consequently higher biogas production is achieved [34]. In the literature, the combined application of the Fenton process with biological treatments, such as a membrane biological reactor (MBR), are studied. For instance, He and Wei [40] found that the average sludge yield decreased from 0.15 gMLSS gCOD−1 to 0.006 gMLSS gCOD−1 during 60 days of operation when an MBR system was combine with the Fenton process.

During recent years, the integration of the Fenton process with ultraviolet or visible light has been investigated in order to increase the stabilization of organic substances and SS dewatering [36,41]. The use of UV rays stimulates the production of OH• radicals and allows us to re-convert Fe3+ into Fe2+. In this way, the concentration of ferrous ions is increased, and this allows us to further speed up the reaction [42,43]. For instance, Heng et al. [44] tested photo-Fenton pre-treatment followed by anaerobic digestion of secondary sludge and they found 75.7% total VS reduction, 81.5% COD removal, and 0.29–0.31 m3 kgVS−1 d−1 biogas production rate, compared to 40.7% total VS reduction, 54.7% COD removal, and 0.12–0.17 m3 kgVS−1 d−1 biogas production rate without the photo-Fenton pre-treatment. Other applications of photo-Fenton processes for SS are reported in Table 1.

One of the main disadvantages of the Fenton and Photo-Fenton processes is the production of chemical sludge that must be managed and disposed of. In order to minimize this production, zero valent iron in the form of powder (Fe0, ZVI) can also be used as a catalyst in the Fenton process. The most important advantage of this modified Fenton process is the lower chemical sludge production compared to conventional ones [35].

3.1.4. Thermochemical Hydrolysis (TCH)

Generally, anaerobic digestion is considered to consist of three steps: hydrolysis, acidification and methanogenesis [45]. In order to promote the dissolution of organic particles and the hydrolysis of organic matters, various pre-treatment methods have been [45–47]. The TCH pre-treatment of sludges for anaerobic digestion increases biogas production, enhances volatile solids reduction, and improves dewaterability of digested sludge [48]. TCH is commonly applied in sludge pre-treatment as it is easy to control, stable in performance, and flexible during operation [47]. It is possible to operate both in the water line (with a reactor arranged on the sludge recirculation) and in the sludge line. The alkaline reagents are the most effective ones [25]. The commonly alkali chemicals used in thermo-alkaline pre-treatment are NaOH, KOH, Ca(OH)2 and Mg(OH)2 [45]. As reported by Atay and Akbal [34], in fact, the drawbacks of acidic pre-treatment are: (i) bad odour generation, (ii) possible corrosion of equipment and (iii) potential inhibition to the bacteria involved in digestion. However, in contrast to the alkaline pre-treatment, acidic reagents (e.g., H2SO4) improve the dewaterability of the SS. While the application of the sludge line is decidedly widespread [45,47,48], the application of the water line is not very widely applied at the real scale [25]. In terms of performance, Xie et al. [47] found a higher increase of soluble chemical oxygen demand (SCOD) concentration in the sludge supernatant after TCH pre-treatment, and the biodegradability of sludge was enhanced greatly.

In Table 1, several applications of chemical treatments are reported.
### Table 1. Several applications of chemical treatments.

| Process       | Time [min] | Operative Conditions | Results | Ref. |
|---------------|------------|----------------------|---------|------|
| O$_3$         | 10         | O$_3$ = 268 mg L$^{-1}$ | SSR = 30–35% | [39] |
|               | 1–5        | O$_3$ = 300 mg f.COD$^{-1}$ | SSR = 25–30% | [50] |
| Chlorine      | n.a.       | ClO$_2$ = 2 mg g VS$^{-1}$ | SRR = 28% | [51] |
| WO            | 120        | T = 200-250 °C; P$_{O_2}$ = 8-25 atm; initial TSS = 8% | n.a. | [52] |
|               | 60         | T = 200 °C; pH = 2; P$_{O_2}$ = 30 bar | COD$_{removal}$ = 50–70%; DOC$_{removal}$ = 20–40% | [53] |
|               | 300        | + thermal hydrolysis; T = 180 °C; pH = 3.3 | COD$_{removal}$ = 58%; VSS$_{removal}$ = 20–40% | [54] |
|               | 30         | T = 240 °C; P$_{O_2}$ = 60 bar; | TSS$_{removal}$ = 80% | [55] |
|               | 60         | T = 240 °C | TSS$_{removal}$ = 85%; VSS$_{removal}$ = 95% | [55] |
| Fenton        | n.a.       | Fe$^{2+}$ = 0.067 g Fe$^{2+}$/L; H$_2$O$_2$ = 60 g kg$^{-1}$; pH = 3 | The DM values decreased by 28.2%; The VS values decreased by 26.8% | [34] |
|               | 60         | Fe$^{2+}$ = 200 mg L$^{-1}$; H$_2$O$_2$ = 8 g L$^{-1}$; pH = 3 | Soluble COD increase from 38 to 2213 mg L$^{-1}$ | [34] |
|               | n.a.       | Fe$^{2+}$ = 4 g kg$^{-1}$DM$^{-1}$; H$_2$O$_2$ = 60 g kg$^{-1}$DM$^{-1}$; pH = 3 | SSR = 25% | [39] |
|               | 60         | Fe$^{2+}$ = 4 g kg$^{-1}$TS$^{-1}$; H$_2$O$_2$ = 40 g kg$^{-1}$TS$^{-1}$; pH = 3 | Sludge disintegration increased up to 23.6% and total methane production with anaerobic digestion increased up to 26.9% | [38] |
|               | 360        | Fe$^{2+}$ = 40 mg L$^{-1}$; H$_2$O$_2$ = 4 g L$^{-1}$; pH = 3 | The soluble COD increased to its maximum value. | [34] |
| Photo-Fenton  | 240        | Solar Photo-Fenton; pH = 3; Fe$^{2+}$ = 40 mg L$^{-1}$; H$_2$O$_2$ = 4 g L$^{-1}$ | COD solubilization = 4.62% | [56] |
|               | 45         | Fe$^{2+}$; H$_2$O$_2$ = 1:6; pH = 3 | Solid reduction = 64% | [57] |
|               | 20         | + homogenizer; Fe$^{2+}$; H$_2$O$_2$ = 1:6; pH = 3 | Solid reduction = 73.3% | [57] |
| TCH          | 30         | T = 121 °C; NaOH = 7 g L$^{-1}$ | COD$_{reduction}$ = 89%; Total VS reduction = 77.5%; methane yield = 0.52 m$^3$ kg$^{-1}$; methane biogas content = 79.5% | [44] |
| (+anaerobic stabilization) | 120       | T = 70 °C; NaOH = 5 mol L$^{-1}$; pH = 12 | VFAs production = 7.5 g$_{VFA}$ L$^{-1}$ | [45] |
|               | 120       | T = 70 °C; Ca(OH)$_2$ = 4 mol L$^{-1}$; NaOH = 1 mol L$^{-1}$; pH = 12 | VFAs production = 6.9 g$_{VFA}$ L$^{-1}$ | [45] |
|               | 120       | T = 70 °C; CaO$_2$ = 4 mol L$^{-1}$ | VFAs production = 7.9 g$_{VFA}$ L$^{-1}$ | [45] |
|               | <30       | + H$_2$O$_2$; T = 90–135 °C | VS removal = 46–66% | [58] |

DM: Dry matter; VS: Volatile solids; SSR: Sludge solubilization rate; SRR: Sludge reduction ratio; WO: Wet oxidation; COD: Chemical oxygen demand; DOC: Dissolved oxygen carbon; VSS: Volatile suspended solids; TSS: Total suspended solids; TS: Total solids; TCH: Thermochemical hydrolysis; VFAs: Volatile fatty acids; n.a.: Not available.
3.2. Biological Treatments

3.2.1. Membrane Biological Reactor (MBR)

In MBR systems, the separation of the sludge from the effluent takes place in highly efficient membrane modules instead of the traditional secondary sedimentation [59,60]. The expected production of sludge in an MBR system is usually lower than in CAS systems, due to the high concentration of biomass in the tank (7–20 g\text{TSS} L\text{−1}), the low Food/Microorganism (F/M) ratio and, consequently, a high sludge retention time (SRT). Therefore, under these conditions, cell growth is not promoted [25].

- Mesophilic Membrane Bioreactor (MMBR)

In recent years, MMBR technology has been proposed as a suitable alternative to CAS because of its higher effluent quality, smaller volumes and a lower amount of sludge production [61–63]. The mesophilic temperature conditions vary in a range between 20 and 45 °C [64]. Being an MBR, this process can be considered a hybrid of a conventional biological treatment system and physical liquid–solid separation using membrane filtration [65]. In MMBR, differently from CAS, the reduction of sludge production appears to be due to the development of predators in the tank, but the opinions on this are discordant [25]. The MMBR technology provides the following advantages over CAS: higher quality effluent for water reuse since bacteria and suspended solids will be retained by membrane, higher volumetric loading rates, shorter hydraulic retention times, longer solid retention times [65–67]. Another advantage of MMBR over CAS systems is the small space required due to the absence of a secondary clarifier and the higher volumetric conversion rates [65,68]. The higher volumetric conversion rates are the result of higher biomass concentrations [68]. However, membrane fouling, attributable to high concentrations of TSS, colloids and sludge flocs, remains a significant drawback of MMBR, as it significantly reduces membrane performance and useful life [25,66,69]. It leads to an increase in operation costs and a limitation in the transfer of oxygen [25].

Moreover, sludge derived from CAS and MMBR systems results in different dewatering efficiency according to Pontoni et al. [70]. This aspect has been studied by Capodici et al. [61]. The achieved results confirmed the complexity of the inter-relationships between many factors affecting the sludge dewaterability. Capodici and Mannina [71] confirmed that the literature reports differ and there are contrasting data on the best or worst sludge dewaterability from MMBR compared to that from CAS. However, Pontoni et al. [70] affirmed that MMBR configuration produced a sludge with a lower mean particle size respect to the CAS and, therefore, worse dewaterability properties. On the contrary, Pontoni et al. [72] tested the effect of anaerobic digestion on dewatering properties in MMBR and CAS. They found that worsening effect due to the post anaerobic digestion is decidedly lower for MMBR sludge with respect to CAS. Several authors also investigated the possibility of adopting suitable sludge retention times in the tank in order to achieve zero net growth [73,74]. Moreover, in the last decade, MMBR systems have been coupled with other disintegration treatments (e.g., ozonation, ultrasonication) in order to increase the biomass decay rate, maintaining a relatively low concentration of TSS in the MMBR system [25,75,76]. Foladori et al. [25] reported that these applications, which can only be used in the water line, make it possible to achieve a reduction of 99% in terms of TSS.

- Thermophilic Membrane Bioreactor (TMBR)

The TMBR represents an evolution of MMBR. In this case, a membrane system (generally ultra or nano-filtration) is coupled to the thermophilic biological process. This aspect allows us to overcome the problem due to the poor settleability characteristics of the thermophilus biomass. Thermophilic microorganisms show optimal growth at temperatures of 50 °C or higher [77]. There is little knowledge about microbiological species in sludge subject to thermophilic processes. In fact, only some species like \textit{Bacillus} have been identified by researchers [78,79]. Moreover, only in recent years has the impact of the operational parameters on the process under thermophilic conditions been investigated [80]. The membrane fouling represents a significant issue in this treatment.
For instance, Collivignarelli et al. [81] found that increasing the SRT, the membrane fouling rate decreased. The operative conditions can be different: (i) aerated, (ii) non-aerated or (iii) alternate [11,81]. In order to reduce the production of SS, this system can be applied both in the water line (replacing the CAS) [80] and sludge line [11,81]. Generally, aerobic conditions are applied if this treatment is used in the water line to treat COD-rich liquid waste (specific lower sludge production) [82–84], while anaerobic or alternate conditions are applied in the sludge line treatment [11]. To date, the application to the real scale concerns two plants in Italy. The reduction in the sludge production varies from 70% to 90% in terms of VS for the treatment of municipal sludge, while from 50% to 65% for those with a strong industrial component [11,25]. This reduction is due to a low specific production of biomass (0.05–0.3 kgVSS produced per kgCOD removed) [83].

3.2.2. Granular Sludge Systems (GSS)

GSS includes anaerobic granular sludge systems (AnGSS) and aerobic granular sludge systems (AeGSS). AnGSS have been largely applied and have achieved good results in the treatment of high concentration organic wastewater [84]. AeGSS are currently under study [84–88]. In granular systems, a specific production of sludge was observed in the order of 0.07–0.15 kgTSS kgCODremoved$^{-1}$, compared to 0.27–0.35 kgTSS kgCODremoved$^{-1}$ of the traditional activated sludge [25]. These results were confirmed by Di Iaconi et al. [89–92], who found a specific production of sludge of 0.16 kgTSS kgCODremoved$^{-1}$ in treating municipal wastewater. An example of a plant of this type has been set by the CNR and is known as the sequencing batch biofilter granular reactor (SBBGR) system [89,90].

The experimental results obtained showed that the plant, fed with the effluent exiting the primary sedimentation of an urban WWTP, presented high yields of COD removal, of total suspended solids and of nitrogen (all higher 80%), allowing compliance with the discharge limits established by current legislation. The process was characterized by a very low sludge production (0.12–0.14 kgTSS kgCODremoved$^{-1}$), with respect to CAS, due to the high SRT in the system (>120 d) [91]. A significant advantage of the SBR configuration is that the use of a traditional or integrated settler is not necessary. The separation of sludge and effluent occurs within the reactor during a short settling phase [93]. Therefore, the SBBGR system does not require the presence of a secondary decanter [91,93]. The main disadvantage of these systems is the relatively high investment costs. In fact, de Bruin et al. [93] studied the possible alternative to CAS represented by AeGSS. From an economic point of view, they found that it is very promising technology, and should therefore be further developed, but at the moment has higher costs than CAS. Di Iaconi et al. [91] found that this process allows us to reduce TSS, with yields ranging from 80% to 90%.

3.2.3. Biological Predation (BP)

BP indicates the consumption of excess sludge by higher organisms such as protozoa and metazoa [34,94]. This process can be applied both in the water line and in the sludge line. If it is applied in the water line, it requires a two-stage system: (i) the first has a short hydraulic retention time (HRT), in order to favour the proliferation of rapidly growing bacteria for wastewater treatment; (ii) the second has a long SRT in order to favour the growth of predators [25,95]. For instance, among the protozoa, the ciliate species have a predatory effect on the microfauna of CAS [96]. Wei et al. [95] reported the results of a lab-scale application of a two-stage system with a temperature of 30°C and a pH of 7. Using bacteria Pseudomonas fluorescens and Tetrahymena pyriformis, they observed sludge reduction yields from 12% to 43%. The main disadvantages of this application are the significant volume required for the second stage reactor due to the high SRT [94] and the difficulty controlling the growth and reproduction of protozoa and metazoa in the biological system [25]. Other authors studied the application of this treatment in the sludge line. In this case, metazoa, particularly worms and larvae, are preferred to protozoa. Eisenia fetida and Hermetia illucens are the most used. For instance, Kalová and Borkovcová [97] applied Hermetia illucens in order to minimize the production of primary and secondary SS; after 35 days of process, the wet weight had been reduced by 16%. Guo et al. [98] highlighted that, for a full-scale application, the instability of the worm reactor represents the major
disadvantage. They reported that some researchers have brought up some possible solutions to this problem. For instance, they explained that a 75% decrease in the amount of TSS was observed in an optimized reactor with *Lumbriculus variegatus*.

In Table 2, several applications of biological treatments are presented.

### Table 2. Several applications of biological treatments.

| Process | Application | Operative Conditions | Sludge Reduction/Production | Other Results | Ref. |
|---------|-------------|----------------------|----------------------------|--------------|------|
| MMBR    | Water line  | HRT = 6 h; SRT = 40 d| $SP = 0.23 - 0.32 \frac{kgMLSS}{kgCOD_{removed}^{-1}}$ | n.a. | [99] |
| MMBR    | Water line  | T = 22 °C            | $SP = 0.22 \frac{kgMLSS}{kgCOD_{removed}^{-1}}$ | n.a. | [100] |
| MMBR    | Water line  | Anaerobic; T = 17–33 °C| $SP = 0.16 \frac{kgTSS}{kgCOD_{removed}^{-1}}$ | Energy demand: 0.07 kW h m$^{-3}$ | [101] |
| TMBR    | Sludge line | Intermittent aeration; pH = 8.5; T = 55 °C; HRT = 12–31 d | n.a. | COD removal = 85% | [82] |
| TMBR    | Sludge line | Aerobic; pH = 7; T = 55 °C | VS reduction = 80% | n.a. | [102] |
| GSS     | Water line  | Aerobic; SBR; Municipal wastewater; T = 12–28 °C | $SP = 0.16 \frac{kgTSS}{kgCOD_{removed}^{-1}}$ | COD removal > 90%; TSS removal > 90%; TKN removal > 90% | [92] |
| GSS     | Water line  | Aerobic; SBR; Municipal wastewater | COD removal = 80–90% | n.a. | [103] |
| GSS     | Water line  | Aerobic; SBR; Primary effluent from a tanney WWTP | SP almost one magnitude order lower than commonly reported for conventional treatment plants | COD removal = 80–90% | n.a. | [104] |
| BP      | Water line  | Protozoa; Two-stage system; Treating different pulp and paper industry wastewater | $SP = 0.01 - 0.23 \frac{gTSS_{removed}}{gCOD}$ | n.a. | [95] |
| BP      | Water line  | Protozoa; Two-stage system; Treating synthetic wastewater | $SP = 0.05 - 0.17 \frac{gTSS_{removed}}{gCOD}$ | n.a. | [106] |
| GSS     | Sludge line | Metazoa (*Hermetia illucens*); HRT = 13 d | Dry weight reduction = 31% | n.a. | [107] |
| GSS     | Sludge line | Metazoa (*Eisenia fetida*); HRT = 21 d | TOC reduction = 30.5–62.6% | n.a. | [108] |

HRT: Hydraulic retention time; SRT: Sludge retention time; SP: Sludge production; MLSS: Mixed liquor suspended solids; COD: Chemical oxygen demand; VS: Volatile solid; TOC: Total organic carbon; SBR: Sequencing batch reactor; TKN: Total kjeldahl nitrogen; SR: Sludge reduction; TSS: Total suspended solids; n.a.: Not available.

### 3.3. Thermal Treatments

The thermal treatments (i.e., combustion, pyrolysis and gasification) intervene with the production of SS, reducing the water content and the fraction of volatile solids. In recent years, the applications of these processes within the WWTPs, at the end of the sludge line usually after thermal drying (Figure 3), are increasing. The advantages in this case consist not only of the minimization of the SS, limiting
the amount of generated SS exiting the WWTP, but also in the possibility of recovering the energy produced directly inside the WWTP.

3.3.1. Combustion

Combustion means the complete oxidative process that occurs at temperatures between 850 °C and 1000 °C and in over-stoichiometric conditions of O₂. Before subjecting the sludge to a heat treatment, such as combustion (the same concept can then be repeated similarly for pyrolysis and gasification), generally it needs to be subjected to mechanical dewatering and thermal drying: this is in order to have sludge with sufficient calorific value to allow autothermal combustion [109,110]. To date, the full-scale applications of this technology are increasing. If the calorific value is not enough, the combustion of the sludge is problematic: in this case, the appropriate choice is co-combustion, outside the WWTP, with materials having a high lower heating value (LHV) [7,111]. Therefore, SS can be used as auxiliary fuel in coal-fired power plants and cement kilns [7,112]. For some years, co-combustion with other materials has received considerable interest [7,113,114]. The most common co-combustion is sludge with solid urban waste. This allows us to use more conventional plant techniques. This type of treatment acts not only on the water content of the sludge but also on the organic substance, which is then oxidized and transformed, finally allowing a considerable reduction in the volume of sludge produced. To date, the full-scale applications of this technology are significant.

3.3.2. Pyrolysis

The pyrolysis process realizes the thermal degradation of the fuel in an inert atmosphere (i.e., in the absence of oxidizing agents) between 500 °C and 1000 °C and is indicated by the literature as a promising solution [1,112]. In this process, the pyrolyzed material does not undergo combustion, but the structure of the molecules breaks down thanks to the effect of temperature alone [111]. From these thermolytic reactions, three by-products are formed: (i) bituminous coal (solid); (ii) pyrolytic oil (liquid) and (iii) syngas (aeriform). Bituminous coal (char) can then possibly be used as a solid fuel or transformed into activated carbon. Pyrolysis can be aimed at obtaining mainly char, liquid or syngas depending on the operational conditions [112]. There are some advantages associated with this process. For instance, (i) the reduced production of CO₂, (ii) the total reduction of dioxins, (iii) the high flexibility, (iv) the compact installation and of course (v) the minimization of the residue is worthy of mention [115].

3.3.3. Gasification

Gasification consists of converting the carbon content of sewage sludge into ash and a combustible gas. The process takes place at higher temperatures compared to pyrolysis (typically above 500 °C) [1,111]. The oxidizing agent is dosed lower than the stoichiometric value compared to the amount of organic carbon (sub-stoichiometric conditions). Oxidation is therefore to be considered partial [111]. In addition to obtaining the removal of water from the sludge and the reduction of the content of volatile substance, there is also the production of a fuel in the gaseous phase (Syngas), which can then be reused for energy production.

In Table 3, several applications of thermal treatments, with literature information, are reported.
Table 3. Several applications of thermal treatments.

| Process                  | Temperature [°C] | Results                                                                                                                                                                                                 | Ref.   |
|-------------------------|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| Combustion              | 800              | The main decomposition during the combustion process is in the 180–580 °C temperature range. The highest mass loss is caused mainly by the decomposition of carbohydrates and lipids. After this process, c.a. 77%, of total mass is degraded. | [116]  |
| Combustion              | n.a.             | High reduction of sludge volume by about 90% and nearly complete elimination of the organic materials.                                                                                                       | [110]  |
| Pyrolysis               | 460–600          | In pyrolysis, the second stage finishes at ~540 °C, with an average 55 wt.% mass loss. The final decomposition is of inorganic matter.                                                                           | [116]  |
| Pyrolysis               | 300              | Pyrolysis temperature was the most important factor affecting the yield of biochars produced. Sewage sludge pyrolysis at 300 °C maximized biochar yield.                                                             | [117]  |
| Pyrolysis               | 500–900          | Biophysical dried sludge was rapidly pyrolyzed at temperatures from 500 °C to 900 °C. With the temperature rising, the yield of biochars decreased, the ash content and microstructure development of biochars were promoted. | [118]  |
| Pyrolysis               | n.a.             | Volume reduction by as much as 90% and production of a sterile carbon char high efficiency and energy self-sufficient.                                                                                           | [110]  |
| Drying + Gasification   | 120 (Drying) + 550–900 (Gasification) | SS was partially dried in an oven at 120 °C for 2 h. The drying reduced the moisture content from 43% to 3.5%. After gasification, the moisture content in the char was 2.1–2.8%. | [119]  |

n.a. = Not available.

3.4. Electrochemical Treatments

For minimizing the production of SS, electrochemical treatments are generally coupled with the use of pressure. Among the pressurized electro-dewatering treatments, electro-osmosis is arousing a growing interest [120–122].

Electro-Osmosis

In this case, the osmosis process is combined with the use of electric current [120]. Gronchi et al. [123] have recently tested this type of treatment. They obtained up to 40–45% of dry substance content compared to 20–25% obtainable by conventional physical/mechanical processes [123]. This type of process can be applied in the sludge line, before or after the phase of stabilization, with very low energy consumption: 0.12–0.5 kWh kg\textsuperscript{-1} water\textsuperscript{-1} for activated sludge and 0.14–0.55 kWh kg\textsuperscript{-1} water\textsuperscript{-1} for digested sludge [124,125]. Moreover, other advantages, such as the removal of pathogens and reduction of the final transportation cost, can be highlighted [125]. Therefore, the application of an electric field, combined with pressure, tends to increase the dehydration of the sludge. Many experimental factors can influence the reduction of water content and consequently, the process yields: (i) the electric voltage, (ii) the pressure, (iii) the contact time, (iv) the characteristics of the polyelectrolyte dosed, (v) the temperature, etc. The electrode reactions are not only influenced by the material of which the electrode is made but also by the ions contained in the sludge. The process could therefore be hindered by the characteristics of the sludge [123,126], although the action mechanism has not yet been fully clarified [126]. Other experiments confirmed these results, and 38–45% of dry matter has been obtained [122,127]. In Table 4, some applications and results of electro-dewatering processes are reported.
Table 4. Several applications of electro-osmosis processes.

| Initial DM [%] | Final DM [%] | Time [min] | Pressure [kPa] | Voltage [V] | Energy Consumption [kWh kg<sub>water</sub> −1] | References |
|---------------|-------------|------------|----------------|-------------|---------------------------------|------------|
| 16.6          | 40          | 7.5        | 100            | 20          | 0.065                           | [121]      |
| 20–25         | 40–50       | 10–14      | 25.5           | 30–40       | 0.06–0.18                       | [125]      |
| 22            | 37.5        | 30         | n.a.           | 15          | n.a.                            | [128]      |
|               | 40          |            |                | 25          | n.a.                            |            |
|               | 46          |            |                | 35          | n.a.                            |            |
| n.a.          | 40          | 16         | n.a.           | 25          | n.a.                            | [129]      |
|               | 45          |            |                | 35          | n.a.                            |            |
| 18            | 40          | 25         | 300            | 10–20       | 0.123                           | [122]      |
| 9–10          | 40–50       | 120        |                | n.a.        | n.a.                            | [124]      |

DM: Dry matter; n.a.: Not available.

4. Summary

In the following review, advanced treatments for the minimization of SS production have been analysed. Chemical, biological, thermal and electrochemical processes have been reported (Table 5).

Table 5. Uses and yields of advanced treatments and technology for the minimization of SS and maturity of technology [7,11,21,25,45,82,83,115,123,130,131].

| Technique | Use | Maturity of Technology | Effect |
|-----------|-----|------------------------|--------|
| Chemical  |     |                        |        |
| (O<sub>3</sub>) | X  | Real                   | (B)    |
| WO        | X  | Real (B) (C)           |        |
| Fenton    | X  | Real (Laboratory) (B)  |        |
| TCH (<sup>1</sup>) | X  | Laboratory (in water line) | (B)    |
| Biological |     |                        |        |
| MMBR      | X  | Real (A)               |        |
| TMBR      | X  | Real (in the water line) (A) | In the sludge line (B) |
| GSS       | X  | Real (A)               |        |
| BP        | X  | Real (in water line) (C) | Laboratory (in sludge line) |
| Thermal   |     |                        |        |
| Combustion| X  | Real (B) (C)           |        |
| Pyrolysis | X  | Laboratory (B) (C)     |        |
| Gasification | X  | Laboratory (B) (C)     |        |
| Electrochemical | Electro-Osmosis | X | Laboratory (C) | |

(<sup>1</sup>) In the sludge line, it must be coupled with anaerobic digestion.

Chemical treatments such as ozonation or the use of chlorine certainly have the advantage of representing a mature technology. However, if adopted in the water line, they can easily alter the balance within the biological sector. WO is one of the most interesting of the advanced chemical processes from the point of view of performance (in terms of sludge reduction). However, it should be remembered that it requires highly qualified personnel for its management. The Fenton and Photo-Fenton processes are still applied to the pilot scale only. The great disadvantage is that chemical sludge is inevitably produced, which must then be properly disposed of. TCH is currently adopted at the real scale, as pre-treatment before the anaerobic digestion in the sludge line, in order to maximize the stabilization of the SS. One of the main disadvantages is due to the cost for chemical reagents for enhancing the hydrolysis pre-treatment.

Among the biological processes, interesting results are given, for example, by the application of the MMBRs in the water line that allow a significant reduction of the sludge produced compared to the CAS. For these systems, which are already widely adopted at the real scale, fouling remains the main problem. On the other hand, despite having shown significant results, especially if applied in the sludge line, the
TMBRs do not yet have a high diffusion. Finally, among the advanced biological processes, the BP is presented. This has given interesting results in terms of minimization yields of SS but nevertheless there are not yet a significant number of applications at the real scale (mostly examples exist on a pilot scale).

The research has shown increasing interest in recent years for thermal processes. Combustion treatments are widely applied to the real scale, while pyrolysis and gasification present more difficulty in plant engineering and are currently applied only to the pilot scale.

Among the electrochemical dewatering processes, electro-osmosis is the most significant. It does not present a considerable number of applications to real plants; however, it allows an important reduction of the water content in SS. Given that in recent years the research has allowed us to optimize energy consumption, the first important disadvantage of this process, a considerable development of this type of treatment in the coming years can be expected.

Therefore, in order to minimize the production of SS, there is not a best solution for every situation, but the optimal treatments and technologies must be evaluated on a case-by-case basis. For having a complete and objective evaluation, a comparative analysis of different applicable solutions should be carried out as reported in different works [132–134].

Moreover, by way of example, a list of several patents available on the market is shown (Table 6). The presence of other patents not mentioned in the table is not excluded.

| Process | Patent Name | Description |
|---------|-------------|-------------|
| Chemical processes | O₃ Biolysis-O® | In this technology, the mixed liquor extracted from the CAS reactor is in contact with ozone into another reactor and returned to the CAS tank. |
| | WO TOP® | Suitable for mixtures consisting of at least two phases, one dense (SS) and one liquid (WW). The solid residue that leaves the plant can be recovered by conventional decantation and filtration. This can be converted into a primary-secondary material. This material obtained the CE mark as a filler according to UNI EN 13043. |
| | WO DUAL TOP® | The technology can simultaneously process: (i) activated sludge derived from industrial or municipal biological plants, (ii) industrial wastewater, (iii) landfill leachates with high levels of COD and (iv) highly contaminated sediments (marine, fluvial, etc.). |
| | WO Athos® | It is a solution based on the principle of WO, but which operates at more moderate temperatures (240 °C) and lower pressures (45 bar). It is a compact process that performs almost complete oxidation of the organic matter with a minimum retention time of the sludge (less than 1 h). |
| | WO Zimpro® | Most of these systems are low-temperature and low-pressure designs, commonly referred to as low pressure oxidation. These systems use temperatures and pressures of less than 220 °C and 35 bar, respectively. |
| TCH | Cambi THP® | Without the use of chemical reagents, it improves both digestion and dewaterability after digestion with up to 45% DM. The mass reduction is around 40–70%. |
| TCH | HCHS® | It allows us to obtain up to 22% dehydration by operating with saturated steam at 6 bar at a temperature between 150 and 170 °C. |
| TCH | TurboTec® | Before entering the system, the raw biomass is screened. After being sieved, the biomass is partially heated using the heat of the outgoing biomass. The temperature is increased by using steam at 140–160 °C introduced into the reactor. The reactor is a continuous mixing system (CSRF). Following hydrolysis, the biomass is cooled through contact with heat exchangers. |
| TCH | Bio Thelys® | Without the use of chemical reagents and coupled with anaerobic digestion, it offers better performance than conventional digestion and optimizes sludge treatment by producing: (i) ~25-35% DM and (ii) +30–50% biogas. |
Table 6. Cont.

| Process Type | Name   | Patent Name       | Description                                                                 |
|--------------|--------|-------------------|-----------------------------------------------------------------------------|
| Biological   | TMBR   | Biorime®          | Biorime consists of a Thermophilic Aerobic Membrane Reactor (TAMR). TAMR works at temperatures around 54 °C. Pure oxygen is insufflated inside the reactor. |
|             | BP     | Cannibal®         | It allows a reduction in secondary sludge production. The technology is applicable both to new plants and to up-grade existing plants. The technology is based on the retention of a part of recirculating sludge in a tank subject to micro-aeration. |
| Thermal      | Combustion | HELIOSOLIDS® | It can be applied to: (i) municipal and industrial SS, (ii) oily sludge and slurry, (iii) spent grains, (iv) paint and paint sludge, (v) shredded wood and pellets, (vi) meat and bone meal, (vii) acid oils and (viii) soap stock. |
|             | Pyrolysis | PyroBoiler® | By combining the pyrolysis treatment with the drying treatment, it allows a reduction in the output flow up to 80% in weight and 60% in volume. |

DM: Dry matter; WW: Wastewater; COD: Chemical oxygen demand.

5. Discussion

The proposed treatments (Table 5) lead to a reduction in sludge production, not only in agricultural but also in urban and industrial areas. Assuming the application of proposed processes, for example, on the urban WWTPs with a capacity higher than 100,000 population equivalent (PE), this would cover more than 50% of the total load (expressed in PE) treated in EU28 [135]. In Table 7, the SS disposal options and costs in Europe are reported.

Table 7. Sewage sludge (SS) disposal options and costs in Europe.

| Type of Disposal | SS Disposal [%] (a) | Disposal Costs [€ M\textsubscript{DM}^{-1}] (b) |
|------------------|----------------------|-----------------------------------------------|
| Agriculture      | 28.3                 | 150 (min) 400 (max)                          |
| Compost          | 14.8                 | 250 (min) 600 (max)                          |
| Incineration      | 37.7                 | 450 (min) 800 (max)                          |
| Landfill         | 7.1                  | 200 (min) 600 (max)                          |
| Other            | 12.1                 | 90 (min) 260 (max)                           |
| Transport        | 100                  | 50 (min) 160 (max)                           |

(a): [14]; (b): [25,136].

As reported by Foladori et al. [25], the transport is indicated as 100% because all the disposal options require the SS transport from the WWTP where it is produced. Currently in Europe, about 9.7 million M\textsubscript{DM} year\textsuperscript{-1} of SS are produced [14]. As previously reported (e.g., Sections 3.1 and 3.2), interventions in the wastewater line present greater risks of the balance alteration in the biological reactor (i.e., CAS) and partial inhibition of biomass. Considering minimization technologies only in the sludge line, a precautionary minimization yield of 50% can be assumed. Therefore, by adopting these criteria only in the WWTPs with over 100,000 PE (i.e., about 50% of the total SS produced in Europe) makes it possible to reduce the SS produced each year to around 7.28 million M\textsubscript{DM} year\textsuperscript{-1}. This would significantly reduce the costs related to the different disposal options currently adopted in Europe, as shown in Figure 5.
Figure 5. Comparison between the total costs of the different SS disposal options in Europe in 2015, before and after the hypothetical application of minimization techniques in the plants with more than 100,000 PE. A range of SS disposal costs, between a minimum and maximum value, was determined considering the high variability within the different EU countries.

Furthermore, as reported by Kalderis et al. [136], costs vary. Minimizing the production of SS has the disadvantage of the costs of implementing the WWTPs (not subject to analysis here) but it would allow reducing the costs of disposal of the SS and would eliminate the variable given by the SS disposal price fluctuation.

6. Conclusions

This paper presents a review of the various treatments applicable for the minimization of SS. Only advanced technologies and treatments are reported. This work is based on about 130 papers, reviews, books and conference proceedings. A description of the process, the advantages, the drawbacks, and the results of the literature are presented for each type of technology. Both the interventions on the sludge line and those on the water line are shown. In order to minimize the SS production, the results of the bibliometric analysis show the increased interest in the combination of different types of treatments and technologies and the reduction of the study of treatments exclusively of a chemical nature. Among the biological treatments, while MMBR and TMBR allow us to obtain encouraging results, the BP must be studied even before possible intensive application at a real scale. In order to minimize the SS, thermal treatments have gained interest in recent years. However, while combustion and co-combustion of SS are already applied at the real scale, pyrolysis and gasification are currently under study and development. Finally, electro-osmosis is arousing a growing interest. The results are encouraging, but the maturity of the technology is not yet developed, and other studies are needed before a real-scale application. Assuming the application of proposed processes in the sludge line in WWTPs with a capacity higher than 100,000 PE, this would significantly reduce the costs related to the different disposal options currently adopted in Europe.
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Nomenclature

| Abbreviation | Description                  |
|--------------|------------------------------|
| AeGSS        | Aerobic granular sludge systems |
| AnGSS        | Anaerobic granular sludge systems |
| AOP          | Advanced oxidation process    |
| BP           | Biological predation          |
| CAS          | Conventional activate sludge  |
| COD          | Chemical oxygen demand        |
| DM           | Dry matter                    |
| DOC          | Dissolved oxygen carbon       |
| GSS          | Granular sludge systems       |
| HRT          | Hydraulic retention time      |
| MBR          | Membrane biological reactor   |
| MLSS         | Mixed liquor suspended solids |
| MMBR         | Mesophilic membrane bioreactor|
| SBBGR        | Sequencing batch biofilter granular reactor |
| SBR          | Sequencing batch reactor      |
| SRR          | Sludge reduction ratio        |
| SRT          | Sludge retention time         |
| SS           | Sewage sludge                 |
| SSR          | Sludge solubilization rate    |
| TCH          | Thermochemical hydrolysis     |
| TKN          | Total kjeldahl nitrogen       |
| TMBR         | Thermophilic membrane bioreactor|
| TS           | Total solids                  |
| TSS          | Total suspended solids        |
| VFAs         | Volatile fatty acids          |
| VS           | Volatile solids               |
| VSS          | Volatile suspended solids     |
| WO           | Wet oxidation                 |
| WW           | Wastewater                    |
| WWTP         | Wastewater treatment plant    |

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