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Overview of sewage sludge minimisation: techniques based on cell lysis-cryptic growth

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ABSTRACT

Sewage sludge production is currently considered as one of the most important problems in wastewater treatment due to the high costs of management and treatment, as well as limitations in its final use. In accordance with the order of priority in waste management options, based on the 3Rs′ (reduce, reuse and recycle), numerous studies are addressing this need to minimize the sewage sludge production. This paper presents a review of recent studies in the field of sewage sludge minimisation, focusing on the techniques based on the cell lysis and cryptic growth mechanism. In addition to reducing sludge, the cell lysis-cryptic growth technologies applied in the sludge return line provide, biodegradable carbonaceous matter that aids denitrification. The promising results obtained in the full-scale application of some of the cell lysis-cryptic growth technologies constitute yet another advantage of this strategy.

Keywords: Sludge reduction; Cell lysis; WWTP; Activated sludge; Cryptic growth

1. Introduction

A huge amount of excess sludge is generated during the biological wastewater treatment process. The treatment of this waste is very costly, supposing around 25–65% of total plant operating costs [1], and may involve major risks to public health if the treatment system fails. Accordingly, current legal constraints, rising costs and public sensitivity to sewage sludge disposal have provided considerable impetus to explore and to develop strategies and technologies for minimising sludge production [2–4]. An ideal way to solve sludge-associated problems is thus to reduce sludge production at wastewater treatment facilities.

The technologies or strategies developed to achieve a reduction in sewage sludge production may be classified into three categories, depending on the unit or treatment line where they are located in the conventional activated sludge plant layout. Strategies belonging to the first category are applied in the wastewater handling units. Strategies included in the second category are employed in the sludge treatment phase. The techniques of this second group aim either to increase the fraction of hydrolyzed sludge in the downstream digestion unit or to achieve more effective dewaterability. In either case, the desired

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Table 1
Main strategies and technologies for sludge reduction

Main strategy	Technology	References
Process whose aim is to reduce the growth yield in the aeration tank (Y, g produced biomass/g consumed substrate)	Lysis-cryptic growth	Extended information in this article
	Control of sludge age and hydraulic retention time	[7,8]
	Uncoupling metabolism	[9–11]
	Predation on bacteria	[12]
Processes with a low-yield coefficient	Anaerobic treatment of sludge	[13]

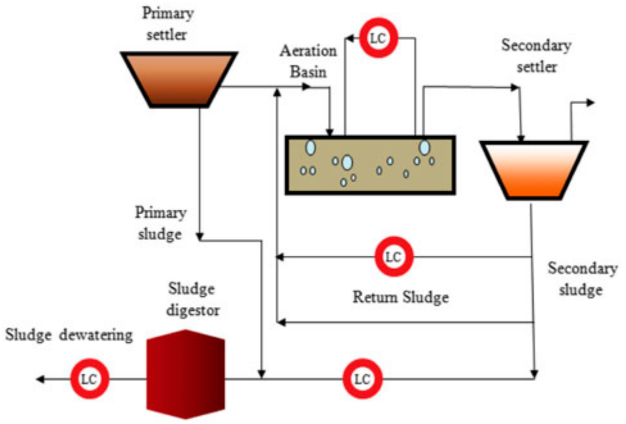

Fig. 1. Possible location for cell lysis and cryptic growth techniques.

reduction in the final stream of sludge is achieved. The third category of strategies focuses on the management of the sludge generated.

Only strategies in the first category pursue a net reduction in sludge production (net biomass growth yield reduction) within the treatment process, following the preferred Waste Management policy strategy (*European Directive 08/98*). At the same time, this reduction in sludge production allows a more marked reduction in sludge management costs [5]. These strategies are classified into two groups according to Pérez-Elvira et al. [6] (see Table 1).

2. Techniques based on cell lysis and cryptic growth

This strategy is based on the reutilisation of intracellular compounds (carbonaceous compounds as well as nutrients) spilled out from the inner contents of cells by viable cells belonging to the same population. When external forces are applied and microbial cells undergo lysis, substrate and nutrients are released. The growth in biomass resulting from the uptake and further biodegradation of this released substrate is called "cryptic growth". Given that a portion of this autochthonous carbonaceous matter is expelled as a product of respiration, this growth results in a net reduction in sludge production [14]. Several techniques are applied to achieve cell lysis and the resulting cryptic growth. The following figure shows where the different cell lysis-cryptic growth techniques can be implemented (red circles).

Besides cell lysis, application of this technique also causes dispersion of sludge flocs, thus enhancing the hydrolysis process. Fig. 1 shows that some cell lysis technologies can be applied in sludge handling units, such as sludge pretreatment before digestion and/or dewatering, thereby increasing biogas production, sludge dewaterability and stability [15–19]. This article does not cover the cell lysis and cryptic growth technologies applied in sludge handling units.

The treatment applied in the recirculation line also produces a notable increase in biodegradable carbonaceous matter that enhances the nitrification–denitrification process in activated sludge process [20].

Cell lysis and cryptic growth technologies may be divided as follows:

(1) Chemical oxidation.
  (1.1) Ozonation.
  (1.2) Chlorination.
  (1.3) Hydrogen peroxide.
  (1.4) Photo-Fenton reagents.
(2) Chemical and thermo-chemical treatments.
(3) Improved aeration.
(4) Enzymes.
  (4.1) Added enzymes.
  (4.2) Enzymatic hydrolysis by thermophilic bacteria.
(5) Mechanical disintegration.
(6) Ultrasonic disintegration.
(7) Ultraviolet (UV) disintegration.
(8) Electrical treatment.

The different techniques are discussed next, as they are the respective states of their art. A table showing the advantages and drawbacks of each technology is provided in summary form in the discussion section, which also includes several practical clues to help distinguish the most appropriate cell lysis-cryptic growth technology for a particular situation.

3. Chemical oxidation

3.1. Ozonation

This technique is very effective in reducing sludge, but requires a high investment. The ozone molecule first destroys the flocs, leading to the disruption of the compact aggregates and increasing the biodegradability of the inert fraction of sludge [21]. The viability of the cells is not affected at this moment, but the ozone then attacks (>0.02 g O_3/g TSS, [22]) the bacterial cells of the sludge, thus decreasing the cell viability. During ozonation, the carbon, nitrogen and phosphorus contents in the sludge matrix decrease, while the contents of these elements in the micro-solids and supernatant increase gradually [23]. Ozone also decreases the partition coefficients of heavy metals between sludge and supernatant, resulting in most of the released metals from the sludge matrix being found in the micro-solids [24]. The degree of solubilisation ranges from 2.4–5.8 g TSS/g O_3 to 4.1–7.7 g COD/g O_3 [25]. Manterola et al. [26] report that cell lysis takes place rapidly, as experiments varying the hydraulic retention time (HRT) between 10 and 60 min resulted in similar COD solubilisation.

Yasui and Shibata [27] established a required ozone dosage of 50 mg O_3/g TSS to achieve total removal of excess sludge when employing an HRT of 6 h and a recirculation rate of $0.3 d^{-1}$. Deleris et al. [28] obtained a 70% reduction with the same ozone dosage employing a sludge residence time of 10 days. Kamiya and Hirotsuki [29] reported greater efficiency via the use of intermittent ozonation, achieving a 50% higher reduction in sludge production than with continuous treatment, employing only 30% of the required ozone dosage. Chu et al. [30] recommended an ozone dosage ranging from 30 to 50 mg O_3/g TSS [30,31]. Other authors raise the dosage to 80 mg O_3 dose/g TSS [32]. In all cases, the settleability of the treated sludge improved significantly. The ozonation technique can also be implemented in wastewater plants employing membrane technology, likewise improving the quality of the permeate [33–36].

This technology has been successfully tested in full-scale facilities. Yasui et al. [37] achieved zero sludge production in a full-scale activated sludge process via ozonation. Biolysis $O^{®}$ is a process developed by Ondeo–Degrémont based on cell lysis-cryptic growth technology using ozonation. Rewcastle used Biolysis $O^{®}$ to obtain a reduction in generated sludge ranging between 30 and 80% [38]. Ried et al. [39] achieved a 30% decrease in sludge production in a full-scale process employing a solid retention time (SRT) of 15 days, treating 10% of the excess sludge with an ozone dosage of 52 mg O_3/g TSS. Suzuki et al. [40] tested the efficiency of ozonation treatment to reduce sludge production in an anaerobic-oxic-anoxic (A_2O) system, achieving a reduction ranging from 34 to 127%, although T–N and T–P removal efficiencies were slightly lower. Gardoni et al. [41] conducted full-scale trials with industrial wastewater, obtaining a 17% decrease in sludge production over a period of two years. These authors also reported poor phosphorus and nitrogen removal in the effluent.

According to Chu et al. [30], the use of an ozonation unit for sludge reduction via cell lysis and cryptic growth would be economically viable in those wastewater treatment plants whose sludge management costs were high and in which frequent foaming and bulking problems occurred. Böhler and Siegrist [42] estimated that employing 15% of the plant's energy consumption would be sufficient to achieve a 30% reduction in excess sludge production. Exposure to lower dosages of ozone reduced sludge production by an average of 29% in a continuous regime [43]. In this case, the intensity of ozonation was 10.6 mg O_3/(g TSS h) for six hours a day.

In addition to its high cost, a major drawback of this technique is the increasing soluble organic carbon concentration, which could result in a worsening of effluent parameters. One way of solving the problem of nutrient release is to use the ozone-treated sludge (0.1–0.2 g O_3/g TSS) as an external carbon source for phosphorus removal and denitrification processes [44–48]. Nutrient removal would thus be improved at the same time as obtaining savings in the cost of external addition of carbonaceous matter, such as methanol, glucose and acetate, thereby making the use of this technology more profitable. Tsuno et al. [49] achieved an excess sludge reduction of around 90% and recovered 70% of the phosphorus content in the influent without affecting nitrogen removal or COD. The energy required was 40% lower than in a conventional plant.

Ozonation of sludge can also produce accumulation of inorganic inert matter, which must be removed [50]. Furthermore, continuous sludge ozonation could result in the development of denser and more resistant floc structures in the sludge, thus requiring an increase in ozone dosage [51].

Another issue to take into account is the drop in pH, from seven to five, [52], which results in the release of precipitated metals, especially Ni, Cu and Zn. This hampers solubilisation of the sludge and constitutes a problem due to its high cumulative potential. To avoid this problem, the pH drop in the ozonized sludge should be controlled.

The combination of ultrasound (US) and ozone was shown [53] to be a better technology for improving sludge hydrolysis and reducing sludge production than ozonation and US treatment. US/O_3 treatment achieved 23% higher sludge lysis under the same operating conditions. The aforementioned article argues that this occurs because ozone has a greater reaction in sludge subjected to US/O_3 treatment than in non-sonicated sludge. Another improvement implemented in this technology was introduced by Chu et al. [54] by applying ozone as microbubbles, achieving 99% efficiency in the oxidizing capacity of ozone.

3.2. Chlorination

The technique of chlorination applied to the activated sludge process in order to achieve cell lysis is similar to that of ozonation; the excess sludge is treated in the chlorination unit, with the chlorinated sludge subsequently being returned to the aeration tank. An advantage of chlorination is that the operating costs are only 10% those of the ozonation technique [55].

A 60% reduction in sludge production was achieved [10] employing a 66 mg Cl_2/g TSS chlorine dosage in a membrane bioreactor (MBR) system with an SRT of 11.5 days. Saby et al. [56] observed only a 65% reduction when employing double the above dosage (133 mg Cl_2/g TSS) in an MBR system with an SRT of four days. Hassani et al. [32], however, employing a chlorine dosage of 20 mg Cl_2/g TSS, reported that the depuration efficiency of the pilot plant used in the study was unaffected and no sludge was produced. Besides increasing the SCOD (soluble COD) [57] in the effluent, the chlorination process results in poorer settleability of sludge. It also has the drawback of generating chlorinated organic compounds [56]. Saby et al. [56] proposed as solution for the poor settleability of sludge: the combination of ozonation with a membrane-assisted wastewater treatment process. Recent studies [58] have focused on the use of ClO_2, which does not present problems of biodegradability, unlike Cl_2. A 58% reduction in excess sludge production was achieved using the anhydride form with no detrimental effect on effluent quality in a sequencing batch reactor (SBR) employing an SRT of 11.6 days. The sludge showed better settleability than the sludge treated with Cl_2. The dosage applied was 10 mg ClO_2/g of dry sludge for 40 min with a TSS concentration of 15 g/l. The required dosage is less than that of the molecular chlorine that needs to be used. Lin et al. [59] likewise used ClO_2, though combined with ultrasonication in their study, to treat 70% of the excess sludge in an SBR (SRT: 20 days), reporting a 55% net reduction in the sludge produced. The optimal parameters found for sludge treatment were: 4 mg ClO_2/g dry sludge, 60 min treatment and 0.5 W/ml ultrasonic intensity for six min. The treatment resulted, however, in poorer nutrients removal.

3.3. Hydrogen peroxide

A high enhancement of sludge solubilisation has been achieved by means of hydrogen peroxide oxidation [60]. This method is even more effective when applied after heat treatment of the sludge, because viable aerobic cells segregate catalyses at temperatures below 60˚C, that is, enzymes that impair oxidation by H_2O_2 [61–63]. Wang et al. established that the H_2O_2 dosage used to treat sludge should be in the 0.1–1.0 H_2O_2/TCOD range. Chan et al. [64] reported that a low pH is recommendable for this treatment, since an alkaline medium damages the structural properties of the sludge in the presence of H_2O_2, thereby worsening the efficiency of the dewatering step. Peroxidation was integrated in an activated sludge process (pilot plant, SRT: 10–12 days), treating 17% of the total sludge with a daily dosage of oxidant of 0.12 g H_2O_2/g TSS for 150 min at 93˚C and pH 8.1, obtaining a 50% reduction in sludge production [65].

3.4. Photo–Fenton reagents ($Fe^{2+}/H_2O_2/UV$)

In recent years, Photo–Fenton reagents have also been used to bring about cell lysis. The efficiency of hydrogen peroxide is enhanced in the presence of iron salts [66], while ultraviolet (UV) or visible light radiation is needed to close the iron cycle between Fe^{2+} and Fe^{3+}.

Increasing dosages of both H_2O_2 and the metal catalysts result in the increased levels of sludge solubiliation [66]. In an MBR [67] coupled to a sludge Photo–Fenton oxidation process, the amount of sludge generated was reduced 96%, in addition to improving nitrogen removal without detriment to the quality of the effluent. According to previous studies, the H_2O_2/Fe^{2+}weight ratio to achieve the highest efficiency is 8:1, while the optimal temperature for the Photo–Fenton process is 65–70˚C, operating in an acid medium [68].

Furthermore, there is also a promising line of research aimed at coupling the use of Photo–Fenton reagents with the generation of electricity and H_2 [69]. Tokumura et al. [70] found solar light to be more effective than costly UV light to launch Photo–Fenton reactions and thus achieve greater sludge solubilisation.

4. Chemical and thermo-chemical treatments

Thermal treatment led to greater cell lysis when the temperature increased from 50 to 95˚C. However, the impact on the floc structure seemed to be limited, with the floc size distribution remaining almost constant above 50˚C [71]. At the early stage of heat treatment, a rapid increase was observed in the population of thermophilic bacteria along with the emergence of protease–secreting bacteria [72]. In addition, protease activity in the supernatant of the sludge increased after 1 h of heat treatment, as proteases were considered to be released from the microbial cells by lysis. Hydrolytic enzymes play an important role in lysis-cryptic growth induced by heat treatment. This trend was also reported by Paul et al. [73]. The same study suggests preferential solubilisation of proteins over carbohydrates after heat treatment. Heat treatment also results in a decrease in the heterotrophic growth rate, giving rise to a higher effluent COD concentration [74]. According to Camacho et al. [75], there are three major issues explaining the observed reduction in sewage sludge: (i) a low release of organics, (ii) an immediate and reversible biological inactivation associated with the additional maintenance energy requirements and (iii) a potential inert production that could reduce sludge biodegradability due to the formation of refractory compounds [20].

High temperatures can be combined with an acid or alkaline treatment. A 60% reduction in excess sludge production was obtained in a membrane system whose recycled sludge was heated to a temperature of 90˚C [76], maintaining both a low hydraulic residence time (1–2 h) and low sludge age (10 h). In another study [77], a fraction of the total volume of the aerobic tank was taken from an MBR pilot plant, specifically 1.5% of the influent volume, and was treated at 80˚C, pH 11 for three hours, obtaining a 33% reduction in the sludge generated. Phosphorus removal was not diminished, whereas nitrogen removal was improved. The enhancement of organic matter solubilisation resulted in a new source of carbon for the denitrification phase [77]. Excess sludge production was reduced by 30% in a continuous system with a sludge age of 15 days, when 20% of the sludge contained in the aeration tank was treated daily at 90˚C [78]. However, removal of COD and TSS worsened 15% compared to the reference system. Moreover, nitrogen removal was impaired due to autotrophic biomass washout, while the presence of heavy metals increased in both the effluent and the sludge (Cd, Cu). This increase in heavy metals depends on the range of temperatures used in the thermal treatment. Up to 95˚C, a significant increase in the biosorption capacity of heavy metals was induced. Above 95˚C, however, the effect of the released soluble ligands and the lower total number of surface functional groups limited the uptake of heavy metals [79,80]. Laurent et al. [78] reported that copper leakage in the effluent increased from 13 to 40% and that the Cd concentration doubled.

Tests carried out in a sequential batch reactor (SRT: 10 days) showed a 27% reduction in sludge production when the temperature rose to 45˚C in the reaction phase. On reaching 60˚C, there was no excess sludge generation. However, COD and turbidity values did not meet the criteria of the American Public Health Association, APHA [81]. When the heat treatment in the same SBR was limited to one hour and was applied to only a fraction of the sludge, reductions in sludge production of 47 and 100% were achieved at 60 and 70˚C, respectively. However, the quality of the effluent was still negatively affected [82].

Camacho et al. [83] applied heat treatment (95˚C, 40 min) to the sludge from the primary settling unit of a wastewater treatment plant located in Evry (France), obtaining a 55% reduction in the sludge production employing a treatment rate of 0.2 d^{-1}. Elliott and Dorica [84] achieved a 26% reduction in the volume of sludge generated in a continuous process sewage treatment plant (pilot plant scale, SRT: 16 days) receiving raw wastewater from a paper mill by treating the recycled sludge in an acid-thermal process (pH: 3.3, 25˚C). Mild treatment with NaOH, (pH = 10, 60˚C, 20 min long) allowed a 37% reduction in excess sludge and resulted in higher biodegradability of the sludge [85,86]. An alkaline-thermal treatment of sludge at pH 13 achieved a 78% reduction in sludge production, while at pH 10 the reduction was 44% [87]. In batch process trials, Tan et al. [88] established an optimum pH for alkaline-thermal treatment of 11 to reduce sludge. In a recent article, a 46% reduction in sludge production was reported when an acidified sludge (9 g/l, 9 h hydrolysis) was recycled back into the wastewater treatment process [89]. Innovative studies have focused on the use of the by-products of the alkaline-thermal treated sludge for both the synthesis of biosurfactants [90,91] and the production of microbial lipid concentrate for further uses, for example, in biodiesel production [92].

5. Improved aeration

The oxygen concentration in the aeration tank has been shown to have an inversely proportional relation to excess sludge production. A higher oxygen concentration might lead to a deeper diffusion of O_2 into the flocs, thus enlarging the aerobic region inside these and consequently leading to a substrate-limiting situation. According to Monod kinetics, this stressed situation results in both lower growth rate and lower sludge production because of the predominant cellular maintenance activities [5]. Nevertheless, the resulting aeration cost is an important factor to be taken into consideration.

Reduction up to 54% in sludge generation has been reported in the activated sludge process when supplying high purity oxygen [93]. Boon and Burges [94] reduced the daily production of sludge to 60% when supplying high purity oxygen to an activated sludge system. Wunderlich et al. [95] considered the decrease in sludge generation to be a consequence of the increased SRT (3.7 vs. 8.7 days), since an aeration basin with higher dissolved oxygen (DO) can support a higher TSS concentration. Abbassi et al. [96] found a 25% decrease in the sludge generated when the DO rose from 2 to 6 mg O_2/l in a reactor. A 10% reduction in secondary sludge production was detected when employing DO values ranging from 1 to 9 mg O_2/l in the aeration unit of a wastewater treatment plant treating the effluent from a paper mill [97]. The increase in DO also improved COD removal and the settling and dewaterability properties of the sludge[5]. Furthermore, the process avoided the proliferation of filamentous bacteria [98].

6. Enzymes

6.1. Added Enzymes

As the vast majority of organic matter present in raw wastewater is composed of proteins (1/3 of chemical oxygen demand, COD), polysaccharides (1/5 of COD) and lipids (1/3 of COD) [99], hydrolytic enzymes (lipases, celluloses and amylases) promote solubilisation of solids and the enhanced biodegradation of sludge.

Although raw wastewater contains enzymes, most of the extracellular hydrolytic enzymes are immobilized by adsorption in the matrix of extracellular polymeric substances (EPS) [100,101]. Commercial enzymes can be used for hydrolytic sludge solubilisation. Parmar et al. [100] used a combination of commercial enzymes (0.1% w/w) to achieve a reduction in sludge of between 30 and 50% and even improved sludge settleability.

The positive synergic effects of different enzymes have been proved. Moreover, the presence of protease has been reported to achieve a better improvement in settleability than lipase or cellulose [100]. Adjustment of the pH of sludge treated with enzymes under acid conditions improves solids reduction, while treatment under alkaline conditions improves settleability. Hydrolysis by enzyme activity [102] can be enhanced through disintegration of the floccular matrix with cation-binding agents [103] or surfactants [104].

Kim and Sim [105] studied the synergy of the hydrolytic action of ozone and commercial enzymes. Their results showed that when proteases were added, maximum solubilisation of sludge was recorded at a dosage of 0.03 g O_3/g TSS. On the other hand, a dosage of 0.04 g O_3/g TSS was needed if enzymes were not added. Enhanced sludge hydrolysis using commercial enzymes has also been shown when metal ions were added at various concentrations [106].

Besides the addition of enzymes, there are other techniques available to achieve sludge reduction that involves the direct release into the recirculation line of two organic matters: Folic Acid [107,108] and Archaea. Two companies market these products: Arkea® (ArchaeaSolutions, Inc.) and Dosfolat®XS (Alpha Chemie Gmbh). The addition of these substances does not truly belong to the main group of lysis-cryptic techniques, as it does not promote cell lysis.

6.2. Enzymatic hydrolysis by thermophilic bacteria (thermophilic aerobic reactor)

In this technique, the activated sludge process is combined with a thermophilic aerobic excess sludge digester (TAESD) in which thermal-enzymatic attack at high temperatures brings about cell lysis [109,110]. The sludge can be mechanically thickened previously so as to save energy. High temperatures promote the growth of the thermophilic bacterial population. These organisms produce enzymes that prevent the reproduction of bacteria present in the sludge and even produce cell lysis. Some of these cells are long lasting and difficult to lyse in the absence of thermophilic bacteria [111]. Seeing as thermophilic bacteria need a temperature above 45°C, these microorganisms generated in the TAESD does not play any role in the aeration tank. However, they do not die either, because they form spores and hence flow back to the aerobic digester. This means that there is no need to add exogenous enzymes. The cost of constructing the digestion unit must be taken into account, as well as the energy required to reach and maintain both thermophilic conditions and correct aeration. Recently, Park et al. [112], coupling a TAESD to the recirculation line, reduced sludge production by 49.6% employing a recirculation ratio of two, and by 69.0% when the ratio was three. Settleability was not affected and the effluent met all the legal requirements. A pilot plant (HRT: one day) achieved a 93% reduction in sludge production and high BOD removal within 270 days of operating [110]. A TAESD was implemented at a wastewater treatment plant treating an influent flow rate of 250 m^3/d. After three years of operating, with a high HRT (1–3 days), the system showed a 75% reduction in sludge production. However, TSS and COD values in the effluent and P removal worsened slightly. A pilot-scale facility of the process has been also operated for a year with wastewater from a petrochemical plant. Excess sludge generation was shown to be completely eliminated in the new process. According to the reported estimates, total operating costs for the new process were reduced to 40–50% of those of the conventional wastewater dewatering process [109].

Biolysis E® (Ondeo-Degrémont) and S-TE Process® (Kobelco Eco-Solutions CO, Ltd) are systems based on the same layout. It thus promotes the proliferation of microorganisms under thermophilic conditions. The Biolysis E® system showed a reduction in sludge production ranging from 30 to 80% depending on the influent. Similarly, a TAESD coupled to a pilot-scale anaerobic-anoxic-oxic (A_2O) process with submerged membrane achieved zero-sludge production with a TAESD with a sludge retention time of two days [113].

7. Mechanical disintegration

A sufficiently high external stress or pressure must be applied to the sludge to damage microbial cells. If a low energy process is applied, only disintegration of flocs is observed. A sludge thickening unit is often set up prior to mechanical treatment in order to handle a smaller volume of sludge.

Thus far, the influence of mechanical sludge disintegration has mainly been studied as a preliminary treatment prior to digestion with the aim of enhancing the hydrolysis limiting step [114,115]. However, a mechanical disintegration stage can be included in the recirculation flow to promote cell lysis-cryptic growth. Kopp et al. [116] stated that the best techniques for mechanical disintegration of sludge are ball mills and homogenisers. Sano et al. achieved a 52% reduction in sludge production and improved nutrient removal when treating 75% of the recycled sludge from an anaerobic/oxic process (HRT: 12.8 h) using ball mills [117]. Springer and Higgins [118] adapted a wet grinding system (Kady Bio-Lysis System™ (Kady Int. Lc)) to grind sludge, obtaining reductions in biomass growth of 56% in trials conducted in a full-scale pilot study carried out in Maine (SRT: 10–15 days). The aeration costs resulting from the increase in TSS were compensated by the savings generated by the reduction in the final volume of sludge produced. Nolasco et al. [119] tested the effectiveness of this system in a paper mill. In addition to achieving total recycling of the sludge, the effectiveness of the facility was not impaired. Camacho et al. [120] reported only a 20% reduction in sludge production when a high pressure homogenisation unit was implemented in the recirculation line of an activated sludge treatment system operating at a frequency of 0.2 d^{-1}. Slightly poorer SS removal in terms of TSS and an improvement in settleability were observed. In the study by Rai and Rao [114], a high pressure homogenizer (HPH) was employed in a discontinuous process. These authors recommended applying, 6.926 to 10.695 kJ/kg to minimise the microbial growth in the sludge. A 70% reduction in sludge production was achieved when mechanical disintegration of the sludge was combined with a membrane system and high sludge age (54 days) [121]. Another batch process study reported that the degree of disintegration of excess sludge employing an HPH was significantly influenced by the homogenisation pressure, sludge TS and, to a lesser extent, by the number of homogenisation cycles [122]. MicroSludge™ is a patented commercial process that uses an alkaline pretreatment and a high pressure homogeniser to provide an enormous and sudden pressure change to burst cells. At present, it is only applied as a pretreatment before sludge handling units, although its application on a side stream of return activated sludge (RAS) is conceivable [123]. Combined ozone and mechanical disintegration treatments have been also tested by Lee et al. [124], who used a ball mill and ozone dosage in a treatment carried out in acid medium ($pH = 3$) and catalysed by Mn. These authors achieved a 60% reduction in sewage sludge, which meant a twofold increase in efficiency compared to using Mn catalytic ozonation alone.

8. Ultrasonic disintegration

Another technique used to achieve cell lysis-cryptic growth is ultrasonic disintegration [15,125]. An US device, operating at 20–40 kHz, transmits mechanical impulses to the sludge in the form of pressure waves that lead to cavitation bubbles, thereby generating high temperature and pressure located areas, and enhancing disintegration of the sludge and the breakup of cells. This mechanical-type treatment has the highest costs in terms of energy [20]. Two main phases are observed when US treatment is applied. In the first phase, the sludge flocs are divided in micro-floc aggregates, extracellular organic substances are dissolved and microbial activity is enhanced. In the second phase, the micro-floc aggregates are completely broken down into cellular material and subsequently undergo lysis, resulting in a reduction in biomass activity [126].

As regards operating conditions, low power and a long exposure period are preferable for sludge solubilisation [127–129]. The application of US involves the disintegration of the flocs which, depending on the applied intensity, can impair sludge activity [128,130]. US treatment can also reduce the settleability of the treated sludge [131].

Cao et al. [132] reduced the amount of produced sludge in a wastewater treatment process (SRT: six days) by 44% when applying an ultrasonic intensity of 0.25 W/ml for 10 min. Zhang et al. [133] reduced the generated sludge by 91.1% in trials carried out in an SBR (SRT: 10 days), applying an US intensity of 120 kW/kg DS to a sludge fraction comprising 3/14 of the total sludge content. These authors also reported that when the fraction of sonicated sludge exceeded 2/7 of the total sludge content, the SBR became unstable. In trials lasting 56 days, a 25–30% reduction in sludge production was achieved using US on the recycled sludge (initial SRT: 7.5 days) [134] without detriment to the general performance of the facility. In another continuous process plant, employing an initial SRT of six days, [135] a sludge fraction of 1/24 was subjected to ultrasonication with a density of 0.4 W/ml for five minutes, obtaining a reduction in sewage sludge of around 90%. Zhang et al. [136] reported an ultrasonic energy/solubilisation ratio ranging between 102 and 347 kWh/kg ΔS COD. The optimal TS concentration for efficient US treatment was 20 g TS/l, while the minimum intensity was 20–30 W/cm^2. The same authors [137] obtained a 59% reduction in sludge production of in an SBR employing an initial SRT of 12.8 days in a plant fed with real raw wastewater. They concluded that the optimal treatment intensity was 20 kWh/kg DS. A similar reduction was obtained by Li et al. [138]. Poor phosphorous removal was observed in both cases. Neis et al. carried out full-scale trials [139] treating 30% of the thickened sludge from a wastewater treatment plant (WWTP) with US. Lysate was recycled in the aeration tank, achieving a 25% reduction in excess sludge. Recently, Ke et al. [140] obtained a 50% reduction in sludge production in an SBR treating 15% of the total sludge on a daily basis (15 min, 1.2 W/ml). In addition, this system was dosed with eight heavy metals (12.5 mg/L), with bioactivity decreasing to a lesser extent than in a reference system not subjected to sonication.

The application of US does not cause accumulation of inorganic matter and enhances the biological activity present in the sludge [141]. He et al. [142] recommend that the fraction of sludge to be subjected to US should be around 15%, applying sonication on a daily basis. US has also been jointly applied along with an alkaline treatment [143], achieving 70% sludge solubilisation. Separate application of the treatments achieved only 50% solubilisation. This treatment was tested in a pilot-scale unit (SRT: 12 days) [144], also combining US /alkaline treatment with hydrolysis/acidogenesis. Sludge production decreased 56.5%. The effectiveness of US can likewise be enhanced if it is jointly applied along with electrolysis [145]. As in other lysis-cryptic growth techniques, the efficacy of US treatment has also been tested for its use in the membrane system [146,147]. Employing an MBR (HRT: four days), Yoon et al. reported complete prevention of excess sludge production when applying an ultrasonic energy of 216 MJ/kg TSS, although the effluent parameter was found to worsen slightly.

Two companies, Ultrawaves–Wasser und Umwelttech Gmbh and Sonico Ltd., manufacture two different US units (Ultrawaves US system® and Sonix™) which have been installed on the recycled sludge line. Trials employing the Ultrawaves device were carried out at Leinetal WWTP (Germany), with an initial SRT of 18 days, achieving a 30% reduction in sludge production and improved settleability [123].

The shear forces generated by ultrasonication, resulting in the disintegration of the sludge, have also been obtained by nozzle-cavitation using a device based on the Venturi effect [148].

9. Freeze-thawing treatment

Freezing-thawing [149] is another novel technique for minimising sludge production. However, it has mainly been employed in the pretreatment of sludge prior to digestion, where it has yielded promising results in terms of dewaterability, biogas production and digested supernatant quality [150–152]. As yet, there are no studies on its application in water processing lines.

10. Ultraviolet (UV) disintegration

At other facilities [153], disintegration of the sludge in the recirculation line is achieved by UV radiation, obtaining a 55% reduction in sludge production. Other authors were able to reduce the average cost of sludge handling by 32% at a plant as a result of decreased sludge production using UV [154]. Elliott et al. [155] likewise achieved reductions in sludge growth of 15, 35 and 43% at a plant treating a TMP-newsprint mill effluent when UV, anoxic conditions and both treatments were respectively applied. This reduction was more pronounced when the treatment operated at a shorter sludge age (9 days vs. 19 days). In another patent, Smith and Hood [156] applied heat and vacuum instead of UV in the recirculation line to reduce excess sludge.

11. Electrical treatment

Studies had previously been carried out to develop a technology based on a pulsed electric current that causes shock waves and induces cell lysis in sludge as pretreatment before digestion [157]. This technology has recently been taken up again by different companies (OpenCEL LLC and EB-Tech) with the aim of also implementing this treatment in the recycled sludge line [123]. Lee et al. [158] focused their study on the use of focused-pulsed treated sludge as an electron donor in denitrification. Data on the reduction in produced sludge were not reported, however.

Discussion

The table below shows the advantages and drawbacks of the different techniques presented in this paper, the scale (full/lab) at which they have been tested, as well as the available commercial processes. There are a number of benefits and drawbacks, present to a greater or lesser extent, which are common to all cell lysis and cryptic growth techniques.

- The intracellular matter released into the medium after lysis provides a source of carbon for the denitrification phase.
- Pathogenic organisms are damaged.
- Increase in SCOD and nutrients in the medium.
- Mineralisation and release of heavy metals.
- Higher oxygen consumption.

		Advantages	Drawbacks	Operational experience	Commercial technologies
Chemical oxidation	Ozonation	• Full-scale trials • Improved settleability • Depuration efficiency not impaired • Persistent pollutant removal	• Slightly lower TN-TP removal • High investment and operating costs. • Inorganic matter may accumulate (optimal dosage) • Progressive formation of an ozone-resistant floc structure • pH drop • More highly qualified personnel needed	Full-scale	• Bioleader™ (Kurita Water Industries Ltd, Japan) • Lyso™ (Praxair) • Halia® (Air Products) • Biolysis O® (Ondeo-Degrémont)
	Chlorination	• Cheaper than ozonation • No mineralisation • Easy to apply	• Increased SCOD in effluent • Poorer settleability • Generation of chlorinated compounds (use of ClO_2)	Lab-scale	

(Continued)

(*Continued*)

		Advantages	Drawbacks	Operational experience	Commercial technologies
	Hydrogen peroxide	• Cheaper than ozonation • No harmful by-products (versus chlorination)	• Increased SCOD in effluent • More expensive equipment and reagents (versus chlorination)	Lab-scale	
			• Technically complicated	Lab-scale	
Chemical and thermo-chemical treatments	Photo–Fenton reagents	• Future possible application of the alkaline-heat treated sludge for by-products • Pathogen inactivation • Simple operation	• Nutrient removal impaired in some trials (NaOH toxic to some organisms) • Release of heavy metals • Turbidity and SCOD may worsen • High energy consumption • Subsequent neutralisation required • Corrosion	Full-scale	
Improved aeration		• Avoidance of filamentous bacteria • Full-scale trials • No additional unit required • High solids content in aeration tank	• High operating costs (Energy)	Full-scale	
Enzymes	Added enzymes	• Low equipment costs • Easy to apply	• High operating costs for commercial enzymes • Enzymatic proportions and complex mechanisms unknown	Lab-scale	
	Enzymatic hydrolysis by thermophilic bacteria	• Full-scale trials • Pathogen inactivation	• Slightly lower TP removal • High energy consumption (aeration of reactor, high TSS)	Full-scale	• S-TE Process$^{®}$ (Kobelco Eco-Solutions CO, Ltd) • Biolysis E$^{®}$ (Ondeo-Degrémont)

(*Continued*)

(*Continued*)

	Advantages	Drawbacks	Operational experience	Commercial technologies
Mechanical disintegration	• Full-scale trials • No reagents needed	• Prior sludge thickening desirable • High investment and operating costs (corrosion, wear, additional aeration)	Full-scale	• Kady Bio-Lysis System^{TM} (Kady Int. Lc)
Ultrasonic disintegration	• Full-scale experiences • Reduced treatment time • No reagents needed	• High investment, and high operating and maintenance costs • Settleability may be impaired	Full-scale	• Ultrawaves Ultrasound System$^{®}$ (Ultrawaves-Wasser und Umwelttech.Gmbh) • Sonix^{TM} (Sonico Ltd)
UV disintegration	• No instrument wear • Pathogen inhibition • No reagents needed	• No recent publications • High operating costs	Full-scale	
Electrical treatment	• Full-scale trials • Compact device • Reduced treatment time • No reagents needed	• Not extensively researched • Energy consumption	Full-scale	• Opencel, LLC • EB Tech Co. Ltd

This paper has presented a state-of-the-art review of the techniques comprising the cell lysis-cryptic growth strategy for sewage sludge reduction with the aim of providing readers with a comprehensive overview of these techniques. Nonetheless, comparison with the techniques based on the other three sludge reducing strategies is recommended before choosing a concrete technique.

As many authors confess, each WWTP is different from the next. Specific factors concerning wastewater treatment facilities (e.g. budget, characteristics of the influent, land availability, etc.) make the implementing of techniques that might otherwise not be considered suitable. Therefore, it is not possible to define a universal solution for every WWTP; at least at this point in time. As an aid to research into the "most optimal" technology, a number of general recommendations drawn from the extensive bibliography concerning the technologies discussed here are set out below with the aim of making the choice of the most suitable cell lysis-cryptic growth technique as clear as possible.

Note: The references refer the reader to the text from which information has been drawn to put together the chart, without these necessarily being implicitly mentioned.

WWTP circumstance	Cell lysis-cryptic growth technology	Reference
Sludge disposal cost not very high	Disintegration techniques not recommended	[42]
Existing digester and cogeneration equipment	Thermophilic bacteria not recommended	[122]
No possibility of adapting the plant	Thermal, chemical and thermo-chemical' techniques not recommended	[20]
No possibility of high investment	Thermophilic bacteria, mechanical, thermal, chemical, thermo-chemical and ozonation not recommended	[20]
Fully experimented technique desired	Strong oxidants (not ozone), added enzymes, electrical treatment not recommended	[20]
Operating costs/ Investment costs as low as possible required	Mechanical, chemical and thermo-chemical treatment suitable	[20]
Aeration equipment oversized	Improved aeration suitable	[5]
Availability of some existing (industrial) acid or alkaline stream	Chemical and thermo-chemical treatment suitable	[84]
High sludge management costs and frequent bulking and foaming problems	Ozonation suitable	[30]
High disposal costs and sludge with low degradability	Mechanical treatment suitable	[18]
No qualified personnel	Mechanical (homogenizers), chemical, and thermo-chemical treatment not suitable	[20]
Stability required (heterogeneous influent)	Thermal and mechanical treatment and ozonation suitable	[19]
Population close to WWTP (odour)	Ozonation and thermal treatment not recommended	[19]
Low temperatures	Freeze-thawing treatment suitable	[19]

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