Reducing Sludge Formation in the Activated Sludge Process

M. I. Nelson

Abstract The activated sludge process was discovered by Ardern and Lockett in the years 1913– 1914. In the slightly more than 100 years since its discovery, it has become the most widely used process for the biological treatment of both domestic and industrial wastewaters in developed and developing countries. At its most basic, the process consists of an aerated reactor basin connected to a settling unit. The effluent stream leaving the reactor enters the settling unit where particulate matter settles under the action of gravity to the bottom of the unit. From here, it can be recycled into the reactor unit. The recycling of particulate matter is the key to improving the efficiency of the process, as enmeshed within it are micro-organisms. This particulate matter is known as sludge and consequently sludge is good. However, too much sludge is bad; disposal of excess sludge can account for between 50 and 60% of the typical operating costs of the activated sludge process.This chapter provides a historical overview of the activated sludge process and two methods for reducing the amount of sludge: disintegration through the use of a sludge disintegration unit and a biological approach based upon the use of predators that graze upon the sludge.

Keywords Activated sludge process · Predation · Sludge reduction

1 The History of the Activated Sludge Process

In the first half of the nineteenth century, sewage systems emerged as the primary mechanism for the removal of sewage in cities. These replaced older processes which at one extreme simply involved the emptying of chamber pots into the street. How-

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ever, sewage systems do not treat wastewater; they merely move the waste from one location to another. By the mid-1880s, the role played by untreated wastewater in spreading waterborne diseases had become clear. The need to produce a clean, healthy, water supply was exacerbated by both the large-scale production of wastewaters and increasing population densities, both by-products of the burgeoning industrial world. These problems were particularly acute in England, leading to a Royal Commission on River Pollution being established in 1865 and re-established in 1874. The latter lead to the Rivers Pollution Prevention Act (1876).

Some progress treating wastewaters containing pollutants in the form of waste organic matter was made in the second half of the nineteenth century using physicochemical processes and anaerobic methods. Starting in the 1880s, attempts were made at cleaning wastewater using the biological oxidation of the pollutants. This involves bringing together a wastewater containing pollutants with aerobic microorganisms and oxygen. Biological oxidation has the potential to reduce the organic pollutants to a mixture of carbon dioxide, nitrogen, water, and other compounds. These methods had little success because biological oxidation turned out to be a very slow process.

In the years 1913 and 1914, Edward Ardern and William T. Lockett, working at the Davyhulme wastewater treatment plant (Manchester, UK), carried out a series of lab-scale experiments. During these years, they discovered the key step to making aerobic oxidation work. It was already known that aerobic oxidation produced a suspension, or “sludge”. In earlier work, this sediment had been removed from the reactor vessel. Ardern and Lockett discovered that if the sediment was retained then the process became significantly more efficient. By retaining the sediment over a series of experiments, they were able to reduce the time for the “full oxidation” of sewage from a period of weeks to one of less than 24 h. Arden and Lockett named the sediment “activated sludge”, as it evidently contained an active agent that improved the process, and coined the phrase the “activated sludge process".

At its heart, the activated sludge process essentially entails the use of two units: an aerated biological reactor and a settling unit (or clarifier). In the former, the pollutants are degraded by microorganisms (the active agent that puts the “activated” into “activated sludge”). However, the key to the success of the activated sludge process is the use of a settling unit.

Although not directly realized at the time, aerobic microorganisms flocculate to form settleable solids. These solids are removed from the effluent stream by sedimentation and then returned to the aeration process in a more concentrated culture. It is this recycling of a concentrated activated sludge from the bottom of the clarifier to the biological reactor that drives down the time for “full oxidation” of the wastewater.

Ardern and Lockett presented their findings at a meeting of the Society of Chemical Industry held on the 3rd of April 1914. Following dissemination of their method [1–3] the activated sludge process was rapidly adopted by the wastewater treatment industry. By 1916, during the chaos of the First World War, the first full-scale continuous-flow activated sludge process plant was being used to treat wastewater at Worcester. (Australia’s first activated sludge plant, the Glenelg Wastewater Treatment Plant, was fully operational by December 1932 [10]. It was extended in 1941 to include a winery waste treatment stream).

Just over 100 years after their landmark experiments, the activated sludge process is now the most widely used process for the biological treatment of both domestic and industrial wastewaters [26]. For example, of the 375 wastewater treatment plants running in the Netherlands in 2007, 366 (97.6%) were activated sludge systems [22]. Wastewater treatment plants based on the activated sludge process are in widespread use in both developed and developing countries. One of the strengths of this process is its versatility, being used to treat wastewaters from both the domestic (sewage) and industrial sectors. In addition to providing a clean and safe water resource as a consequence of its high efficiency in removing organic pollutants, the process has the attraction of being relatively low in operational costs.

2 Too Much of Anything Is Bad

The degradation of organic pollutants by microorganisms produces new sludge. This fact is central to the success of the activated sludge process—sludge is a self-sustaining resource. Sludge that is produced over the requirements to run the process is known as “excess” sludge. Unfortunately, the activated sludge process is too successful at producing new sludge. The costs associated with the disposal of “excess” sludge can run to 50–60% of the total operating costs of a wastewater treatment plant [4, 5, 16]. Disposal of excess sludge imposes a significant burden on operators as it can be more costly than the wastewater treatment process itself.

In addition to containing beneficial biomass, sludge is a complex mixture of bacteria, heavy metals, inorganic matter (such as phosphorus and nitrogen compounds), organic pollutants, pathogens, and water [21]. The removal of heavy metals from the influent stream into the sludge is often regarded as a side benefit of the activated sludge process [11]. However, as a result of the concentration of heavy metals, and other toxic materials, the disposal of sludge has become increasingly governed by environmental regulations.

The first step in conventional methods for the disposal of excess sludge is dewatering, this converts a water disposal problem to a solid waste disposal problem. In the past, excess dried sludge was commonly disposed of by methods such as incineration, landfilling, dumping at sea, and use as a fertilizer in agriculture. However, any toxic elements in the influent stream of the wastewater treatment plant may become concentrated in the dried sludge. Due to increasing environmental concerns, related to the presence of these toxic elements, older disposal methods are being increasingly regulated. More demanding environmental monitoring inevitably leads to increased operating costs. A second factor impacting operating costs is the decreasing availability of land in urban areas, often associated with increasing population densities. The economic costs of landfilling have, therefore, increased due to a combination of these and other factors [26].

Incineration reduces the volume of solid sludge by upto 95%. Thus this process reduces, but does not eliminate, the demand for landfill sites. Unfortunately, the solid residual from incineration, an ash, contains an increased concentration of noncombustible materials, such as heavy metals and many other toxic compounds. Although the reuse of sludge in the agriculture sector is appealing, because it adds an economic premium to a waste product, the transport costs associated with moving the sludge to the end users is often appreciable.

The combination of the increasing restrictions placed upon the discharge of excess sludge and the associated rising treatment costs has created an impetus to develop methods that reduce the volume and mass of excess sludge. It should be noted that in addition to reducing operating costs sludge reduction has other benefits. For example, sludge reduction can prevent filter beds from being clogged with suspended solids. This maintains their treatment efficiency, consequently this provides a secondary mechanism to reduce operating costs.

In Sects. 2.1 and 2.2, two mechanisms for sludge reduction are discussed. The first of these, Sect. 2.1, is to increase sludge biodegradability by disintegrating it. These techniques, particularly chemical treatments and ozonation, have met with some success. However, the costs associated with running these processes have prevented their wide-spread use. The second of these, Sect. 2.2, is to use predators which grow through consumption of the sludge. This is potentially very attractive, since once the predators have been released into the reactor there are no "running" costs.

2.1 Sludge Reduction Through Sludge Disintegration

The ideal solution to eliminate the problems of the posttreatment disposal of excess sludge is to prevent the excess sludge from being formed in the first place. As sufficient sludge must be produced to maintain the viability of the activated sludge process itself, the aim is to minimize the "excess" sludge. Sludge production can be reduced by a variety of proven techniques including biological, chemical, mechanical, and thermal processes [26]. In general, these methods work by breaking open the cell walls of the bacteria, converting the sludge into a mixture of soluble substrate and particulates.

Amongst a wide variety of techniques, chemical treatments and the use of ozone have become the most widely used in commercial activated sludge plants [17]. Ozone treatments involve moving sludge from the main bioreactor into a separate unit, known as the "sludge disintegrator", where ozone ruptures the cell walls. The treated mixture is then returned to the main bioreactor. Ozonation has been established as a technique that reduces the amount of excess sludge. However, the initial high capital costs and associated ongoing operational costs has restricted its use to niche commercial applications.

2.2 Sludge Reduction Through Predation

A promising alternative to chemical, mechanical, and thermal treatments is sludge reduction through predation by higher organisms, such as protozoa, metazoan, or fungi, upon sludge bacteria [7, 26]. This approach is attractive because it requires little energy and is therefore low cost. Furthermore, unlike chemical treatments this method does not introduce secondary pollutants into the wastewater treatment system [21].

Why does predation reduce sludge? The activated sludge process can be considered to be a food-chain, in which the biomass extracts mass and energy from the substrate. The introduction of a predator introduces a new layer into the food chain: mass and energy are now transferred from the microorganisms to the predator. At each step in the food chain not all of the available energy and material are transferred to the next level: some energy, a significant proportion of the energy, is used for maintenance processes, respiration, and reproduction. Thus predation on microorganisms may lead to a lower total biomass, i.e., sludge reduction.

Some wastewater treatment plants may naturally contain suitable predators. Predators such as metazoan organisms, chiefly Annelida but also including Nematoda and Rotifera, have been found to be present in wastewater treatment plants. It has been suggested that they can enter wastewater treatment plants from surrounding water bodies, or that they can be transported into aeration tanks by birds [15]. Be this as it may, research has focussed on the introduction of 'foreign' predators as a mechanism to control sludge production.

Predation has been shown to be an effective technique in lab-scale experiments [7, 9, 12, 13, 18, 24, 26, 28, 29] and pilot-scale systems [23, 30]. The main thrust in these papers is to quantify the effect that predators have upon process characteristics, in particular to determine the sludge reduction capacity of predators. Although a variety of predators could be used, much attention has focused on the use of worms. Worm growth is clearly a prerequisite for sludge reduction through predation. Relatively little is known about the growth and development of worms during sludge predation. However, it has been shown that the wrong choice of aeration rate, temperature, and predator (worm) density can adversely effect worm growth and consequently sludge reduction [29].

A variety of continuous flow reactor configurations have been used in these investigations. These include: a hydrolyzation food chain reactor [30], a single reactor [12], a single reactor connected to a recycle sludge reactor [9], a membrane bioreactor without biomass discharge [8], a two-stage reactor [7], and a six-stage reactor consisting of alternating aerobic and anaerobic compartments [18].

Despite promising results obtained at lab scale, the role that predictors play in full-scale wastewater treatment plants has rarely been investigated—perhaps because such experiments typically require long-term study carried out over a period of years. The feasibility of using worms to reduce sludge reduction in wastewater treatment plants has been reviewed by Ratsak and Verkuijlen [20]. Experimental investigations at the treatment plant level include [6, 14].

There are two main barriers to the adoption of predation as a cost-effective mechanism to reduce sludge formation. The first of these is the uncontrollable growth of predators [6]. Predator density in full-scale plants can often reach very high densities. Associated with this is a well-known phenomenon in wastewater treatment plants, the so-called "worm blooms", in which predator population densities display peaks followed by a sudden disappearance of the population [19]. The development of methods to control worm proliferation is a challenging problem that needs to be overcome [25]. The second problem is that the use of predators increases the amount of phosphorus, nitrogen, and soluble chemical oxygen demand in both the effluent and waste streams from a treatment plant [26]. This can cause undesirable consequences in receiving waters downstream of treatment plants, i.e., eutrophication and deoxygenation. The release of nutrients and phosphorus into effluent streams is exasperated by predator blooms. Consequently, the release of nutrients and phosphorus due to predation has been investigated [24, 27]. It is essential to know the operating conditions that maintain stable predator populations and which reduce nutrient release.

3 Conclusions

Over the past century, the activated sludge process has emerged to become the most widely used method for the biological treatment of contaminated wastewaters under aerobic conditions. The success of this technique can be ascribed to the use of a settling unit which "captures" particulate matter, allowing it to be recycled into the reactor. This vastly improves the efficiency of the process, since the particulate matter contains entrapped micro-organisms. Consequently, recycling sludge increases the concentration of biomass inside the reactor.

Alas! Too much of a good thing is a bad thing—the disposal of excess sludge imposes a significant overhead on the running of a wastewater treatment plant. Two mechanisms for reducing the amount of sludge produced by the process have been discussed. The first of these is to disintegrate the sludge in situ, converting it into a supply of nutrients. Although this method has been shown to give excellent results on a lab scale, its use in practice are restricted to niche applications. The reason for this is that there are significant costs associated with the use of chemicals and the building and operating of sludge disintegration units. The decrease in costs due to sludge reduction must be balanced by the increase in costs due to the operation of the sludge disintegration unit.

A promising alternative is to introduce predators into the activated sludge plant. The predators grow through consumption of the active biomass, which in turn reduces sludge production. There are conflicting reports in the literature as to whether predation can be successfully implemented as a sludge reduction strategy. If conditions can be found which can guarantee successful operation, then it promises a low-cost route to sludge reduction.

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References

1. E. Ardern, W.T. Lockett, Experiments on the oxidation of sewage without the aid of filters. J. Soc. Chem. Ind. **33**, 523–539 (1914)
2. E. Ardern, W.T. Lockett, The oxidation of sewage without the aid of filters. Part II. J. Soc. Chem. Ind. **33**, 122–1124 (1914b)
3. E. Ardern, W.T. Lockett, The oxidation of sewage without the aid of filters. Part III. J. Soc. Chem. Ind. **34**, 937–943 (1915)
4. A.P. Canales, J.L. Poles, Decreased sludge production strategy for domestic wastewater treatment. Water Sci. Technol. **30**, 97–106 (1994)
5. E. Egemen, J. Corpening, N. Nirmalakhandan, Evaluation of an ozonation system for reduced waste sludge generation. Water Sci. Technol. **44**, 445–52 (2001)
6. H.J.H. Elissen, E.T.H.M. Peters, B.R. Buys, A. Klapwijk, Population dynamics of free-swimming Annelida in four Dutch wastewater treatment plants in relation to process characteristics. Hydrobiologia **605**, 131–142 (2008)
7. W. Ghyoot, W. Verstraete, Reduced sludge production in a two-stage membrane-assisted bioreactor. Water Res. **34**, 205–215 (1999)
8. M. Heran, C. Wisniewski, J. Orantes, A. Grasmick, Measurement of kinetic parameters in a submerged aerobic membrane bioreactor fed on acetate and operated without biomass discharge. Biochem. Eng. J. **38**, 70–77 (2008)
9. X. Huang, P. Liang, Y. Qian, Excess sludge reduction induced by Tubifex tubifex in a recycled sludge reactor. J. Biotechnol. **127**, 443–451 (2007)
10. B. Kent, *Special Treatment: Australia's Pioneering Wastewater Plant*. Chemistry in Australia. pp. 24–25 (Dec 2014–Jan 2015)
11. L. Lazzari, P. Sperni, P. Bertin, B. Pavoni, Correlation between inorganic (heavy metals) and organic (PCBs and PAHs) micropollutant concentrations during sewage sludge composting processes. Chemosphere **41**, 427–435 (2000)
12. P. Liang, X. Huang, Y. Qian, Excess sludge reduction in activated sludge process through predation of Aeolosoma hemprichi. Biochem. Eng. J. **28**, 117–122 (2006)
13. P. Liang, X. Huang, Y. Qian, Y. Wei, G. Ding, Determination and comparison of sludge reduction rates caused by microfaunas' predation. Bioresour. Technol. **97**, 854–861 (2006)
14. J. Lou, P. Sun, M. Guo, G. Wu, Y. Song, Simultaneous sludge reduction and nutrient removal (SSRNR) with interaction between Tubificidae and microorganisms: a full-scale study. Bioresour. Technol. **102**, 11132–11136 (2011)
15. G. Milbrink, T. Timm, Distribution and dispersal capacity of the Ponto-Caspian tubificid oligochaete Potamothrix moldaviensis Vejdovský et Mràzek, 1903 in the Baltic Sea Region. Hydrobiologia **463**, 93–102 (2001)
16. O. Nowak, Optimizing the use of sludge treatment facilities at municipal WWTPs. J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. **41**, 1807–1817 (2006)
17. Y.-K. Oh, K.-R. Lee, K.-B. Ko, I.-T. Yeom, Effects of chemical sludge disintegration on the performance of wastewater treatment by membrane bioreactor. Water Res. **41**, 2665–2671 (2007)
18. F. Quan, Y. Anfeng, C. Libing, C. Hongzhang, C.-H. Xing, Mechanistic study of on-site sludge reduction in a baffled bioreactor consisting of three series of alternating aerobic and anaerobic compartments. Biochem. Eng. J. **67**, 45–51 (2012)

19. C.H. Ratsak, Effects of Nais elinguis on the performance of an activated sludge plant. Hydrobiologia **463**, 217–222 (2001)
20. C.H. Ratsak, J. Verkuijlen, Sludge reduction by predatory activity of aquatic oligochaetes in wastewater treatment plants: science or fiction? A review. Hydrobiologia **564**, 197–211 (2006)
21. J.H. Rensink, W.H. Rulkens, Using metazoan to reduce sludge production. Water Sci. Technol. **36**, 171–179 (1997)
22. Statistics Netherlands (CBS), 'CBS Statline' webpage. Quoted in [6] (2007), http://statline.cbs.nrl
23. J. Tamis, G. van Schouwenburg, R. Kleerebezem, M.C.M. van Loosdrecht, A full scale work reactor for efficient sludge reduction by predation in a wastewater treatment plant. Water Res. **45**, 5916–5924 (2011)
24. Y. Tian, Y. Lu, Simultaneous nitrification and denitrification process in a new Tubificidae-reactor for minimizing nutrient release during sludge reduction. Water Res. **44**, 6031–6040 (2010)
25. Z. Wang, H. Yu, J. Ma, X. Zheng, Z. Wu, Recent advances in membrane bio-technologies for sludge reduction and treatment. Biotechnol. Adv. **31**, 1187–1199 (2013)
26. Y. Wei, R.T. Van Houten, A.R. Borger, D.H. Eikelboom, Y. Fan, Minimization of excess sludge production for biological wastewater treatment. Water Res. **37**, 4453–4467 (2003)
27. Y. Wei, H. Zhu, Y. Wang, J. Li, P. Zhang, J. Hu, J. Liu, Nutrients release and phosphorus distribution during oligochaetes predation on activated sludge. Biochem. Eng. J. **43**, 239–245 (2009)
28. Q. Zhang, S. Wang, W. Wang, P. Bao, B. Li, Y. Peng, Achieving one-stage sludge reduction by adding Chironomid larvae in wastewater treatment systems. Ecol. Eng. **83**, 291–295 (2015)
29. X. Zhang, Y. Tian, Q. Wang, H. Liu, Waste sludge reduction using Limnodrilus hoffmeisteri: growth, development and sludge predation potential of aquatic worm correlate with process conditions. Ecol. Eng. **58**, 406–413 (2013)
30. T. Zheng, P. Li, Q. Wang, X. Li, H. Ai, K. Gan, A. Sharavsambuu, Pilot-scale experiments on brewery wastewater treatment and sludge reduction based on food chain predation. Desalin. Water Treat. **55**, 1142–1151 (2015)