Sustainable operation of a biological wastewater treatment plant

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Abstract. The sustainable operation of a biological wastewater treatment plant is significantly linked to its removal efficiency, cost of sludge management, energy consumption and monitoring cost. The biological treatment offers high organic removal efficiency, it also entails significant sludge production, which contains active (live) and inactive (dead) microorganisms and must be treated prior to final disposal, in order to prevent adverse impact on public health and environment. The efficiency of the activated sludge treatment process is correlated to an efficient solid-liquid separation, which is strongly depended on the biomass settling properties. The most commonly encountered settling problems in a wastewater treatment plant, which are usually associated with operating conditions and specific microorganisms growth, are sludge bulking, floating sludge, pin point flocs and straggler flocs. Sustainable management of sludge and less energy consumption are the two principal aspects that determine the operational cost of wastewater treatment plants. Sludge treatment and management accumulate more than 50% of the operating cost. Aerobic wastewater treatment plants have high energy requirements for covering the needs of aeration and recirculations. In order to ensure wastewater treatment plants’ effective operation, a large number of physicochemical parameters have to be monitored, thus further increasing the operational cost. As the operational parameters are linked to microbial population, a practical way of wastewater treatment plants’ controlling is the microscopic examination of sludge, which is proved to be an important tool for evaluating plants’ performance and assessing possible problems and symptoms. This study presents a biological wastewater treatment plant with almost zero biomass production, less energy consumption and a practical way for operation control through microbial manipulation and microscopic examination.

1. Introduction

Problems caused by wastewaters: Human activities, such as agricultural including livestock, as well as urban and industrial development, create large quantities of wastewater that have to be treated prior their discharge in water bodies or land. If they are not treated properly, their pollutant load can cause serious environmental deterioration, with direct impact on human health. Agricultural and urban wastewater accumulate large quantities of pollutants, such as organic, nitrogen and phosphorus compounds, in surface waters, underground waters and soils. These pollutants are responsible for eutrophication and are nutrients for a variety of microbial species.

Activated sludge principle: Since decades, a wide range of technologies, processes and techniques has been developed and implemented for the treatment of municipal and/or industrial
wastewaters. The most commonly applied wastewater treatment application is the biological processes, i.e. the use and exploitation of bacteria species for removing pollutants. The principle idea is to cultivate a large number of bacteria colonies (activated sludge, AS), which utilize pollutants for their own needs (growth and energy production), by creating the necessary conditions for their development. Different conditions, such as aerobic, anaerobic or anoxic, enhance the growth of specific bacteria that can be manipulated for the treatment of different substrates. Biological process is followed by solids/liquid separation achieved commonly by gravitational sedimentation. A fraction of the separated solids is recirculated, while the rest is wasted.

The problem of waste sludge: While biological treatment offers significant performance with relatively low cost, it also entails significant sludge production due to the accumulation of biomass and inactive sludge in the wastewater treatment plant (WWTP). The excessive accumulation of sludge hinders sedimentation efficiency and can also create problems concerning mixing and aeration of the bioreactors. Consequently, large quantities of accumulated sludge have to be disposed (waste sludge) frequently from a biological treatment plant, in order to maintain acceptable effluent quality. The quantity of waste sludge depends on influent composition and volumetric load, as well as on WWTP’s operating conditions. Higher loads result in higher biomass yields, while critical operating conditions, such as hydraulic retention time (HRT), solids retention time (SRT), biomass age, food to microorganisms ratio (F/M), dissolved oxygen concentration (DO) and alternating conditions (aerobic, anoxic, anaerobic etc.), significantly affect biomass production.

Landfill disposal of sludge can create negative environmental, economical and social impacts, such as soil and water pollution, threats on human health, land devaluation. Sludge treatment increases wastewater treatment cost more than 50%. Consequently, sludge minimization is a key towards sustainable operation and design of WWTPs.

Sludge minimization approaches: Recently, approaches for minimizing sludge production have intrigued scientists and engineers, as it can resolve the problem of sludge management at its source. It is well known that WWTP operating conditions are linked to the biological and morphological characteristics of activated sludge and to microbial manipulation that influence sedimentation process, treatment efficiency and net sludge production. High SRT: One approach for minimizing sludge production is the amplification of microbial cell lysis and the growth of biomass from the utilization of cell lysis products, defined as cryptic growth. Starvation conditions that occur in high SRT processes enhance cryptic growth, due to the high biomass concentration and the low F/M. Microbial manipulation: Successful microbial manipulation can minimize sludge production up to where almost no sludge is disposed. Microbial manipulation is the guided growth of desired microbial species by imposing specific operating condition in the bioreactors. The successful microbial manipulation towards the growth of predator microbial species can minimize sludge production, as they feed on bacteria and particulate organics. Growth of predator microbial species can be achieved at high SRT and different operating regimes (extended aeration, cyclic alteration between anaerobic anoxic and oxic conditions etc.) that provoke metabolic changes. Consequently, in high SRT AS processes, the new cells production rate becomes equal to the decay rate. The phenomenon of solids’ accumulation reduction is assisted by the activity of predator species that consume various complex substrates containing influent particulate organics, bacteria, cell debris, etc. In such cases, the net biomass production rate is minimal and tending to zero values.
**Complete solids retention process’ principal idea:** One of the most promising approaches towards sustainable WWTP operation and sludge management is the complete solids retention AS process, which incorporates both high SRT and microbial manipulation for predator microbial species growth. The principal idea of this technology is the almost complete recirculation of sludge in the WWTP, resulting: (a) SRT almost equal to the days of WWTP operation (b) increased sludge age, (c) high biomass concentration in bioreactors, (d) extended starvation conditions (low F/M ratio), (e) low substrate utilization rates (SUR) and (f) growth of predator microbial species. All the above trigger biochemical and biological processes that minimize sludge production, such as bacteria decay/lysis, predation phenomena and the degradation of some of the considered unbiodegradable particulate organics (influent particulate organics and cell debris).9,12 Other studies conducted on membrane bioreactors (MBR) operating at high SRT up to complete retention of solids also indicated that biomass production was equilibrated by biomass loss (endogenous metabolism, death, lysis and predation) or that influent substrate was completely oxidized for cell maintenance (Henze et al., 2000; Spérandio Sperandio et al., 2013).13-14

**Economical footprint:** The sustainable design and operation of a WWTP is inextricably linked to its environmental and economical footprint. High treatment efficiency and low energy consumption are the keys for sustainability. Energy demands for operation of wastewater pumps, air blowers, mixers and separators etc, are analogous to influent load and significantly differ between treatment processes. Energy consumption ranges between 1 to 25 Kwh/kg COD_{removed} and 0,25 to 13 Kwh/kg COD_{removed} for aerobic and anaerobic processes respectively.15-16 Successful microbial manipulation, thus efficient treatment and less sludge production, as well as on low energy consumption should be the goal for engineers towards sustainable wastewater treatment plants’ design and operation.

![Diagram](image)

**Figure 1.** Key parameters towards sustainability of wastewater treatment technologies

This work presents a successful application of a novel activated sludge WWTP, designed for treating high strength wastewaters with minimal waste sludge production. The studied slaughterhouse WWTP operated beyond the typical literature limits concerning biomass concentration, recirculation rates and tank design, while achieving excellent treatment efficiency with low energy cost and negligible waste sludge quantities. The work provides engineers with the information needed for the biological process control through microbial manipulation and offers an opportunity to re-evaluate some critical parameters in WWTP design and operation, towards more efficient and sustainable wastewater treatment.
2. Materials and Methods
The studied activated sludge WWTP is installed in Almopia Prefecture, Pella, Greece. This patented WWTP is designed for treating high strength wastewaters by applying the complete solids retention activated sludge process, with low economical and environmental footprint. The WWTP consists of two subsystems (Figure 1): (a) a preliminary simultaneous nitrification/denitrification system (SNdN) and (b) a pre-anoxic, complete mix, complete SRT, extended aeration system (PCMAS). The preliminary system has a sedimentation tank with internal recycle of solids, ie it operates as a biological selector, where younger biomass that utilizes readily biodegradable organics thrives. The effluent and the waste sludge is transferred (inflow) in PCMAS system. Before the SNdN system, primary treatment, (automated bar screen, decanter, aerated flow and load equalization tank) is performed.

![Flowchart of the complete solids retention WWTP and relating operation conditions](image)

This complete solids retention AS treatment system appears significant differences in comparison to conventional AS WWTPs, such as bioreactors’ configuration, settling tank geometry and dimensions, solids and mixed liquor recycle points and rates. The wastewater was treated in alternating anoxic, semi-anoxic and aerobic bioreactors, maintaining low biomass growth yields and increased presence of specific microbial species in activated sludge. In order to control sedimentation process, the WWTP operates with high RAS rate (over 600%), thus causing “forced sedimentation” (Grady et al. 1999; Maine, 2003; Mercalf and Eddy, 2003; Amanatidou et al., 2015a).

Wastewaters of this slaughterhouse have relatively low volumetric load (approximately 35 m$^3$ d$^{-1}$), high organic load (8250 mgCOD L$^{-1}$ and 4538 mgBOD$_5$ L$^{-1}$) and high nitrogen load (1250 mgTKN L$^{-1}$). Due to its origin, the influent organics are highly biodegradable, with an average COD / BOD$_{ultimate}$ ratio of 0.969. Particulate matter in influent is approximately 1100 mgTSS L$^{-1}$, consisting mainly of organics (1008 mgVSS L$^{-1}$) and a small fraction of inert solids (0.027). Not all particulate organic matter is considered biodegradable, but previous studies have demonstrated that under the specific WWTP operating conditions and design, this considered unbiodegradable fraction of particulate organics is eventually utilized by the microorganisms.

3. Results and discussion
In the studied slaughterhouse WWTP, the removal of organic compounds and nitrogen is completed in two stages. An initial removal of COD and TN was achieved in the SNdN system, but the main treatment took place in PCMAS system. Effluent quality was in accordance to the demands of the enforced legislation. The overall WWTP removal efficiency was approximately 99% for organics removal and 90% for nitrogen removal.
Satisfactory solids/liquid separation in sedimentation tank was achieved despite the high MLSS concentrations. This was achieved due to the sedimentation tank’s design and the fact that it operated with high sludge recycling rates (RAS 1000-2000%), thus creating forced sedimentation in the clarifiers and enhancing process efficiency. Worth mentioning that air-pumps were used for sludge and nitrate recirculations instead of electrical pumps, reducing that way the energy requirements of the WWTP. Efficient control of sedimentation efficiency was performed, based on the periodically conducted settling velocity tests and state point analysis. The critical RAS rates were estimated in order to control sludge blanket level, as well as the overall sedimentation process efficiency.

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Energy and labour cost conservation in the studied WWTP is achieved mainly because of the minimized quantities of waste sludge and therefore fewer needs for equipment (sludge dehydration units etc.) and personnel. In conventional activated sludge (CAS) aerobic systems, the observed biomass production rate ($Y_{obs}$) usually ranges between 0.12 and 0.45 kgMLVSS kgCOD$_{removed}^{-1}$. Consequently, in our case one will expect a waste sludge production of 35 to 130 kgMLSS day$^{-1}$ or 12,77 to 47,45 tonnes of sludge annually, corresponding to approximately 546 to 2028 m$^3$ year$^{-1}$. However, the studied system gradually obtained almost negligible $Y_{obs}$ values. At steady state operating conditions, a $Y_{obs}$ mean value of approximately 0.025 kgVSS kgCOD$^{-1}$ was recorded, resulting in an annual sludge disposal of 2.6 tones or 111 m$^3$ year$^{-1}$, corresponding to waste sludge minimization rates between 79,5 to 94,5 %.

Figure 2. Solids accumulation in the studied WWTP and representative microscopic examination images; 
- MLSS concentration;
- MLVSS concentration

The mixed liquor suspended solids (MLSS) concentration, as well as their volatile fraction (MLVSS), were increasing until the 280th day of WWTP operation, a time when plateau phase was reached, considered as steady state operating conditions (Figure 2). At steady state operating conditions, almost zero net biomass production and constant MLVSS to MLSS ratios were observed, attributed to WWTP operating conditions and biomass characteristics. These observations lead to the conclusion that by complete solids retention and specific operating conditions, most of the considered unbiodegradable particulate COD, of influent and of endogenous decay, are consumed by microorganisms. In this study, the microorganisms that are considered responsible for consuming these considered unbiodegradable fractions are rotifer and ciliate species (Figure 2).
Under the imposed WWTP operating conditions, successful microbial manipulation and efficient sedimentation were the keys for achieving efficient treatment and negligible quantities of waste sludge, while the use of air pumps for recirculations and the absence of chemical additives (coagulants, flocculants etc.) minimized energy consumption and operating cost. In our case, more than 90% of WWTP’s operating cost stems from the energy demands of the aeration system, which provides the necessary air oxygen for the highly aerobic bioreactors (DO > 4 mg L\(^{-1}\)) and for the recirculation air pumps. The rest energy demands of the WWTP are because of the submerged anoxic tank mixer, the 2 electrical pumps and of the SCADA system.

Due to the nature of the slaughterhouse wastewater (high organic and nitrogen load) and the high biomass concentrations, the oxygen consumption in the WWTP is relatively high. Oxygen consumption in the WWTP occurs due to organics and nitrogen oxidation, as well as due to biomass respiration. Based on literature\(^1\) and by taking into account the relatively small amount of oxygen that is released in anoxic bioreactors due to denitrification, the calculated oxygen consumption values were approximately 130 kgO\(_2\) d\(^{-1}\), 90 kgO\(_2\) d\(^{-1}\) and 190 kgO\(_2\) d\(^{-1}\) for organics oxidation, ammonia oxidation and biomass respiration respectively, leading to a total oxygen demand of 410 kgO\(_2\) d\(^{-1}\). The actual amount of oxygen required is approximately 940 kgO\(_2\)/d, calculated by taking into account the effects of salinity, surface tension, temperature, elevation, diffused depth, the desired oxygen operating level (4 mg L\(^{-1}\)), the effects of mixing intensity and the basin configuration.

A 7,5 kW electrical air blower is used in order to feed both the aeration system and the recirculation air pumps, consuming approximately 168 kWh d\(^{-1}\). Nitrate and sludge recycle is performed using air pumps connected to the aeration system, thus no additional energy is demanded. The only additional energy consumption is due to the use of two 250 watt submersible electrical feed pumps (maximum consumption of 12 kWh d\(^{-1}\)). Consequently, the total energy consumption is approximately 180 kWh d\(^{-1}\).

It must be noted that energy consumption in a WWTP can be expressed in relation to volumetric feed, to COD or BOD\(_5\) removal as well as to TKN removal (when separate electromechanical equipment is used). In our case, the energy cost is referred to both carbon and nitrogen elimination because carbon oxidation and nitrification processes are performed in the same bioreactor by common electromechanical equipment. Consequently, by expressing kWh kgBOD\(^{-1}\) or kWh kgCOD\(^{-1}\), nitrogen removal is included. In this study, the specific energy consumption is 1,13 kWh kgBOD\(_\text{removed}\)\(^{-1}\) and 0,62 kWh kgCOD\(_\text{removed}\)\(^{-1}\).

These values are lower than most of the reported specific energy consumptions of conventional activated sludge (CAS) processes, which range between 0,95 to 3,3 kWh kgBOD\(_\text{removed}\)\(^{-1}\) or 0,66 to 3,65 kWh kgCOD\(^{-1}\).\(^{1,12\text{3}-\text{25}}\) Furthermore, the studied WWTP consumes significantly lower energy than membrane bioreactors (MBR), which are considered to demand 150% to 300% more energy (Williams, 2007).\(^{1,24\text{3}-\text{25}}\) Only membrane aerated biofilm reactors and anaerobic processes were found to have lower specific energy consumption, with values approximate 0,25 kWh kgCOD\(^{-1}\) and 0,1 kWh kgCOD\(^{-1}\) respectively (Pitas et al., 2010; WEF, 2009; Mizuta and Shimada, 2010; Yand et al., 2010; Bodík and Kubaská, 2013).\(^{15\text{3}-\text{19}}\) Anaerobic treatment can also produce energy by biogas exploitation, thus any comparison with this anaerobic processes is somehow meaningless. Worth mentioning that the SNdN, which is a simultaneous nitrification/denitrification bioreactor, can alternatively be used as an anaerobic bioreactor and thus can utilize a portion of influent organics for biogas valorization, if the necessary electromechanical equipment is installed (membrane cover, biogas filters etc).
Figure 3. Flowchart of WWTP processes control – Logical steps towards the best solution of WWTP operating problems
During the operation of an AS WWTP and depending on imposed operating conditions, biomass biological and morphological characteristics may alternate significantly. The growth of undesired microbial species, such as filamentous bacteria, fungi etc., could create foaming problems, reduce sludge flocs’ cohesiveness (high sludge volume index, SVI) and hinder settling ability of sludge in the clarifiers. The main operating conditions that affect biomass characteristics are activated sludge age (t_c), hydraulic retention time (HRT), DO concentration, food to microorganisms ratio (F/M) and availability of nutrients (C,N,P).

In order to avoid problems related to undesired microbial species growth, such as sludge bulking due to filamentous bacteria growth, successful microbial manipulation and regular monitoring of biomass characteristics had to be performed. It is well known that high concentrations of soluble readily biodegradable organics enhance filamentous bacteria growth.26 The excessive growth of filamentous bacteria hinders sedimentation efficiency and deteriorates effluent quality. Therefore, the utilization of influent soluble, readily biodegradable COD in SNdN system prevented filamentous growth in the WWTP, thus SNdN system operated as a microbial selector. The monitoring of biomass by microscopic analysis proved to be a rapid and accurate tool for controlling microbiological characteristics of biomass. Alternations of biomass characteristics can be easily observed with microscopic examination, which in turn can help identify their cause and rapidly suggest a WWTP operating conditions related solution. In Figure 3, a flowchart of the WWTP processes control, with the logical steps towards the best solution, is presented.

4. Conclusions
By successfully imposing complete solids retention AS process, through microbial manipulation, extended starvation conditions, highly aerobic bioreactors, high recirculation rates and controlled sedimentation efficiency, efficient treatment of high strength wastewaters can be performed with negligible waste sludge production. Sludge minimization can reach up to 95%, leading to an over 50% reduction of WWTP construction and operational cost. Furthermore, the limited use of electrical pumps reduces energy consumption resulting in a highly energy efficient WWTP, having lowest specific energy consumption than most of the treatment systems. While energy consumption of the studied WWTP is comparable even with the considered more energy efficient anaerobic processes, the environmental and economic benefit of minimizing waste sludge production renders this technology sustainable.

References
[1] Metcalf and Eddy, 2003. Wastewater Engineering: Treatment and Reuse. Metcalf and Eddy Inc., McGraw Hill, Boston, USA (revised by: Tchobanoglous G., Burton L.F., Stensel H.D.).
[2] Guo, W.Q., Yang, S.S., Xiang, W.S., Wang, X.J., Ren, N.-Q., 2013. Minimization of excess sludge production by in-situ activated sludge treatment processes - a comprehensive review. Biotechnol. Adv. 31, pp. 1386-1396.
[3] Amanatidou Elisavet, Samiotis Georgios, Trikoilidou Eleni, Pekridis George, Taousanidis Nikolaos, 2015. Evaluating sedimentation problems in activated sludge treatment plants operating at complete sludge retention time. Water Research J, Volume 69, pp. 20–29.
[4] Y. Wei, R.T. van Houten, A.R. Borger, D.H. Eikelboom, and Y. Fan, 2003. Minimization of excess sludge production for biological wastewater treatment, Water Research 37, pp. 4453–4467.
[5] Amanatidou Elisavet, Samiotis Georgios, Bellos Dimitrios, Pekridis George, Trikoilidou Eleni, 2015. Net biomass production under complete solids retention in high organic load activated
sludge process. Bioresource Technology J., 182, pp. 193–199.
[6] Rocher, M., Goma, G., Begue, A.P., Louvel, L., Rols, J.L., 1999. Towards a reduction in excess sludge production in activated sludge processes: biomass physicochemical treatment and biodegradation. Appl. Microbiol. Biotechnol. 51, pp. 883-890.
[7] Liu, Y., Tay, J.H., 2001. Strategy for minimization of excess sludge production from the activated sludge process. Biotechnology Advances 19, pp. 97-107.
[8] Loosdrecht, M. and Henze, M. 1999. Maintenance, endogenous respiration, lysis, decay and predation, Water Sci. Technol. 39, pp. 107–117.
[9] Amanatidou Elisavet, Samiotis Georgios, Trikoilidou Eleni, Tsikritzis Lazaros, 2016. Particulate organics degradation and sludge minimization in aerobic, complete SRT bioreactors. Water Research (94), pp. 288–295.
[10] Foladori, P., Andreottola, G., Ziglio, G., 2010. Sludge Reduction Technologies in Wastewater Treatment Plants. IWA Publishing.
[11] Amanatidou Elisavet, Samiotis Georgios, Trikoilidou Eleni, Pekridis George, Tsikritzis Lazaros, 2016. Complete Solids Retention Activated Sludge Process. Water Science and Technology, 73.6, pp. 1364–1369.
[12] M. Henze, M.C.M. van Loosdrecht, G.A. Ekama, and D. Brdjanovic, 2008. Biological Wastewater Treatment: Principles, Modelling and Design. IWA Publishing.
[13] Henze, M., Gujer, W., Mino, T., van Loosdrecht, M.C.M., 2000. Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. Scientific and Technical Report No.9. IWA Publishing.
[14] Sperandio, M., Labelle, M.-A., Ramdani, A., Gadbois, A., Paul, E., Comeau, Y., Dold, P.L., 2013. Modelling the degradation of endogenous residue and unbiodegradable influent organic suspended solids to predict sludge production. Water Science & Technology 67, pp. 789-796.
[15] Pitas, V.; Fazekas, B.; Banyai, Z.S.; Karpati, A., 2010. Energy efficiency of the municipal wastewater treatment. Journal of Biotechnology 150, pp. 163-164.
[16] Water Environment Federation (WEF), 2009. Energy conservation in water and waste water facilities, 1st Ed., WEF Press, McGraw Hill, New York.
[17] Mizuta, K.; Shimada, M., 2010. Benchmarking energy consumption in municipal wastewater treatment plants in Japan, Water Science and Technology 62, pp. 2256-2262.
[18] Yang, L.; Zeng. S.; Chen, J.; He, M.; Yang W., 2010. Operational energy performance assessment system of municipal waste water treatment plants. Water Science and Technology 62, pp. 1361-1370.
[19] Bodik, I.; Kubáská, M., 2013. Energy and sustainability of operation of a wastewater treatment plant. Environment Protection Engineering 39, pp. 15-24.
[20] Bellos, D., 2012. Special compact activated sludge wastewater treatment plant for large and medium size applications. Patent number: 1007711, International Classification (INT.CL8):C02F 9/00, C02F 11/00.
[21] Grady, C.P.L., Daigger Jr., G.T., Lim, H.C., 1999. Biological Wastewater Treatment, second ed. Marcel Dekker, Inc. Revised and expanded.
[22] Maine department of environmental protection, (USA), 2003. Document Describing the State-point Analysis Process. Maine DMR O&M News.
[23] Williams, R., Schuler, P., Comstock, K., Pope R., 2008. Large Membrane Bioreactors of Georgia: A Guide and Comparison. Water Environment Federation Membrane Technology Conference. Atlanta Georgia. pp 548-561.
[24] Chudoba P., Rosenbergová R., Beneš O., 2010. Benchmarking of large wastewater treatment plants, Proc. from Conference Wastewater, STU Bratislava, I. Bodík (Ed.), pp. 385.
[25] Malcolm B., Middleton R., Wheale G., Schulting F., 2011. Energy efficiency in the water industry, a global research project, Wat. Proc. Techn. 6, pp. 221.
[26] Amanatidou Elisavet, Samiotis Georgios, Trikoilidou Eleni, & Michailidis Avraam, 2016. Influence of Wastewater Treatment Plants’ Operational Conditions on Activated Sludge Microbiological and Morphological Characteristics. Environmental Technology J. 37, pp. 265-278.