Comparison between ozonation and the OSA process: analysis of excess sludge reduction and biomass activity in two different pilot plants

Michele Torregrossa, Gaetano Di Bella and Daniele Di Trapani

ABSTRACT

The excess biomass produced during biological treatment of municipal wastewater represents a major issue worldwide, as its disposal implies environmental, economic and social impacts. Therefore, there has been a growing interest in developing technologies to reduce sludge production. The main proposed strategies can be categorized according to the place inside the wastewater treatment plant (WWTP) where the reduction takes place. In particular, sludge minimization can be achieved in the wastewater line as well as in the sludge line. This paper presents the results of two pilot scale systems, to evaluate their feasibility for sludge reduction and to understand their effect on biomass activity: (1) a pilot plant with an ozone contactor in the return activated sludge (RAS) stream for the exposition of sludge to a low ozone dosage; and (2) an oxic-settling-anaerobic (OSA) process with high retention time in the anaerobic sludge holding tank have been studied. The results showed that both technologies enabled significant excess sludge reduction but produced a slight decrease of biomass respiratory activity.

INTRODUCTION

The conventional activated sludge (CAS) process is the most widely used biological treatment for domestic as well as industrial wastewater. One of the major drawbacks is represented by the fact that CAS processes produce excess biomass, which is characterized by a high fraction of volatile suspended solids (VSS) and retains a large amount of water (>95% by weight). Treatment and disposal of such biomass can account for up to 40–60% of total operation costs of wastewater treatment plants (WWTPs) (Chen et al. 2001; Yan et al. 2009). Hence, the technologies for waste activated sludge (WAS) reduction are gaining interest in the scientific as well as the technical community (Low & Chase 1999; Liu & Tay 2007; Saktaywin et al. 2005; Perez-Elvira et al. 2006; Ye & Li 2010).

Several strategies have been proposed for sludge minimization in biological WWTPs; concerning the position at which sludge reduction takes place, it is possible to list three main strategies, according to Perez-Elvira et al. (2006): (1) process in the water line, with the idea to reduce sludge production during wastewater treatment instead of post-treatment of the generated sludge (ozonation, chemical uncouplers, anaerobic-aerobic processes); (2) processes in the sludge line, which aim is to minimize the sludge stream to be disposed of; in particular, some technologies have been studied to enhance the sludge anaerobic digestion, which represents the standard process to reduce the produced biomass; and (3) processes in the final waste line, with the aim to post-treat the produced sludge; actually, such technologies represent a post-treatment for the final disposal of the sewage solids.

Among the technologies applied in the wastewater line, partial ozonation of return activated sludge (RAS) and oxic-settling-anaerobic (OSA) processes has gained increasing interest in the technical community in recent years (Chudoba et al. 1992; Chen et al. 2001; Ahn et al. 2002; Saby et al. 2002; An & Chen 2008). More in detail, in the ozonation process, the RAS stream (or a fraction of it) passes through an ozone contactor and is further pumped back to the aerobic reactor where it will be again subject to degradation. On the other hand, an OSA process can be classified as a modification of a CAS system, in which the thickened sludge (or a fraction of it) from the final settling
tank is returned to the aerobic reactor through an anaerobic sludge holding tank. In such a reactor, the sludge undergoes anaerobic conditions, characterized by the absence of food and with a low oxidation-reduction potential (ORP). The working principle is quite simple: the alternation of anaerobic–aerobic cycling of activated sludge stimulates the catabolic activity, and makes catabolism dissociate from anabolism, resulting in a minimized sludge yield.

In the present study, two different pilot scale systems were constructed and investigated to evaluate their feasibility for sludge reduction and recycle, as well as to understand their effect on biomass activity by applying respirometric techniques: in particular: (1) a pilot plant with an ozone contactor in the RAS stream for the exposition of the activated sludge to a low ozone dosage; and (2) an OSA process have been studied. The obtained results, in terms of produced sludge, biomass activity and overall performance of the two pilot plants have been compared.

MATERIALS AND METHODS

Description of the pilot plant configurations

The experimental investigations were carried out on a pilot plant built at the Acqua dei Corsari (Palermo) municipal WWTP. The pilot plant was conceived for organic carbon removal only, with the aim to reproduce the CAS scheme of Palermo WWTP, characterized by quite short sludge retention time (SRT) values.

The whole experimentation was divided into two experimental periods (100 days each), characterized by a different evolution of the original CAS configuration:

- PERIOD 1: the CAS pilot plant was started-up with sludge inoculum and after 50 days of operation, its configuration was modified by inserting an ozone contactor to treat a portion of the RAS flow; the ozonation configuration was then operated for 50 days.
- PERIOD 2: in this experimental period the CAS pilot plant was again started-up with sludge inoculum, maintaining the same operating conditions of the previous period. Similarly, the plant configuration was changed after 50 days of operation, by inserting an anaerobic sludge holding tank into the RAS line to realize an OSA configuration, which was operated for 50 days.

In Figure 1 the original CAS (Figure 1(a)), the ozonation (Figure 1(b)) and OSA process (Figure 1(c)) schemes are reported.

The CAS scheme consisted of one aerobic tank (mean volume 2 m³) followed by a final settling tank (mean volume 0.98 m³).

The ozonation system consisted of a cylindrical shaped column reactor characterized by a 0.03 m³ volume and a
4 m height; almost 12% of the RAS flow was derived from the sludge return line and fed at the bottom of the ozonation column, characterized by a 35 min contact time. Ozone was applied by bubbling the ozone gas with a dose equal to 0.015 g O₃ g⁻¹ TSSRAS (total suspended solid). The ozonated oxygen-rich stream was then pumped at the inlet of the aeration basin. Ozone was produced from pure compressed oxygen by an ozone generator (TP1/1A, Ozono Elettronica Internazionale Ltd.).

Referring to the OSA process, the anaerobic sludge holding tank was characterized by a 1.3 m³ volume, and was equipped with a slow mixer in order to properly guarantee the sludge mixing. Except for the first experimental days, after configuration change, the amount of the treated sludge was almost equal to the 30% of the RAS stream and the hydraulic retention time (HRT) in the anaerobic tank was almost equal to 9 h, which was high enough to guarantee an ORP level equal to ~180 mV. Indeed, a previous study (Ye et al. 2008) found that the optimum HRT in the anaerobic reactor was near to 7 h; in the present work, however, it was decided to adopt a higher value, in order to enhance the sludge reduction.

It is worthy to observe that, due to the considerable dimensions of the containers, it would be very difficult to operate two different plants in parallel, thus it was decided to operate the different configurations during two separate experimental periods, trying to maintain the same operational conditions in both periods.

Each pilot plant configuration was continuously fed with real municipal wastewater, derived downstream the WWTP screening unit and then pumped into a load equalization basin (volume 1.5 m³). An additional 2 mm screening unit was inserted at the inlet of the pilot plant, to remove coarse and inert material from the raw wastewater. Mixing in the aerobic reactor was guaranteed by the fine-bubble aeration system which also provided the necessary oxygen for the metabolic needs of the biomass.

As confirmed by the data shown in Table 1, the inlet wastewater presented similar characteristics during both experimental periods, in terms of organic matter content as well as biodegradability.

During the overall experimental campaign, the average F/M ratio, HRT and dissolved oxygen (DO) levels were maintained almost equal to 0.3 kg BOD₅ kg⁻¹ TSS d⁻¹, 4.35 h and 2–5 mg L⁻¹, respectively. On the other hand, during the CAS operation of both periods, mixed liquor suspended solid (MLSS) concentrations and SRT were maintained equal to 3 g L⁻¹ and 3.5 d respectively, while, during ozone and OSA operations, the average values of MLSS and SRT were equal to 3.5 g TSS L⁻¹ and 5 d, respectively.

### Analytical methods

Influent and effluent flows, mixed liquors and RAS were sampled and analysed. Composite samples were taken three times a week and analysed for total chemical oxygen demand (TCOD), BOD₅, TSS and VSS.

Further, in order to evaluate any change in sludge settleability the sludge volume index (SVI) in the aeration tank was periodically analysed. All the analyses were carried out according to the Standards Methods (APHA 1995).

Concerning the specific observed heterotrophic yield coefficient (Yobs), referred to the whole system, it was evaluated on the basis of mass balances between sludge withdrawn, sludge production and solids in the effluent, dividing by the cumulated TCOD removed, according to the following expression, similarly to previous experiences (Gardoni et al. 2011):

\[
Y_{obs} = \frac{\Delta M}{\Delta \text{COD}_{\text{rem}}} \text{[kg COD kg}^{-1}\text{COD]} \tag{1}
\]

where \(\Delta M\) represents the overall sludge production, given by:

\[
\Delta M = 1.42 \cdot (x_T \cdot Q_{\text{WAS}} + \Delta x_{\text{AS}} \cdot V_{\text{AS}} + x_c \cdot Q_c)\text{[kg COD d}^{-1}] \tag{2}
\]
where \(x_e\) [kg VSS m\(^{-3}\)] represents the sludge concentration in the RAS stream, \(Q_{WAS}\) [m\(^3\) d\(^{-1}\)] is the waste sludge flow rate, \(\Delta X_{AS}\) [kg VSS m\(^{-3}\)] the variation of the activated sludge concentration, \(V_{AS}\) [m\(^3\)] is the volume of the aerobic tank, \(x_c\) [kg VSS m\(^{-3}\)] is the effluent VSS concentration, \(Q_e\) [m\(^3\) d\(^{-1}\)] is the effluent flow rate and 1.42 represents the COD content of VSS.

Microscopic observations were carried out for the identification of filamentous bacteria as well as to observe the effects caused by ozone on them. Observations were made under phase contrast at 100× and 1000× magnifications. The filamentous microorganisms were morphologically identified using the Eikelboom classification system. Filamentous microorganism abundance and dominance were estimated using the criteria suggested by Jenkins et al. (2003).

**Description of the respirometric station**

Respirometric batch experiments were conducted using a ‘flowing-gas/static-liquid’ type as batch respirometer (Spanjers et al. 1996). The biomass samples for the evaluation of the heterotrophic growth yield \(Y_{H}\) and biomass activity were taken from the oxidation tank of the pilot plant and eventually diluted with tap water or pilot plant effluent in order to obtain a mixed liquor VSS concentration in the range of 2–5 g VSS L\(^{-1}\). Further, they were moved into the batch respirometer and aerated until endogenous conditions were reached and then the respirometric test was run by adding sodium acetate as synthetic substrate. As a consequence, an increase of biomass oxygen uptake rate (OUR) was immediately recorded, for the oxidation of the external substrate. After the exhaustion of the external substrate the initial endogenous OUR values were restored. Samples were maintained at a constant temperature of 20±1 °C with a thermostatic cryostat. Starting from the obtained respirometry charts, the estimation of \(Y_{H}\) has been carried out from the integral of the exogenous OUR chart, according to the methodology suggested by Vanrolleghem et al. (1999). During each test, the nitrifying biomass has been inhibited by adding allylthiourea to the sample. On the other hand, the activity of the heterotrophic biomass has been derived by measuring the maximum OUR values during sodium acetate consumption under non-limiting conditions, evaluating whether the ozone dosage as well as OSA configuration had sensible effects on the respiratory activity.

**RESULTS AND DISCUSSION**

**Pilot plants removal efficiencies in both periods**

During the ozonation period, the MLSS was in the range between 3 and 3.5 g TSS L\(^{-1}\) with a VSS/TSS ratio almost equal to 70%. On the other hand, during sludge ozonation the biological removal of TCOD was slightly reduced (decreasing from 80 to 75%); this decrease can be attributed to the increase of the COD inert particulate concentration, which is not biodegradable or absorbable within the sludge flocs. Nevertheless, after the configuration change, no reduction of VSS/TSS ratio was observed: this circumstance was probably due to the low ozone dose and to the adopted SRT values, which did not enable inert accumulation or sludge mineralization inside the system.

Contrarily, during the OSA period, the TCOD removal efficiency was equal to 81% in the CAS start-up phase, increasing to 85% during OSA operation, while the VSS/TSS ratio was slightly higher (71%) compared with that in the ozonation period.

Another interesting aspect to be pointed out is related to the effluent biodegradability characteristics in terms of biochemical oxygen demand (BOD\(_5\))/COD ratio variations, which deserves further discussion. Indeed, while the effluent BOD\(_5\)/COD ratio is reduced by about 26% in both CAS systems (with an average inlet value of 0.54, and outlet value of 0.40), on the other hand, such reduction is more significant during ozonation and OSA operations; the explanation of the obtained result is likely due to cell lysis and the consequent intra-cellular material solubilization occurring in such processes. However, it has to be stressed that the BOD\(_5\)/COD ratio reduction is of different magnitude in ozonation and OSA systems, respectively.

In particular, ozonation enabled a greater reduction of settled effluent biodegradability, reaching a BOD\(_5\)/COD value at the effluent almost equal to 0.23 (with BOD\(_5\)/COD ratio reduction as high as 59%), as ozonation induces a strong chemical oxidation of the macromolecules in the RAS stream, which can be then more easily assimilated by microorganisms in the aeration tank. Differently, during OSA operations, the BOD\(_5\)/COD ratio reduction was only slightly higher than that which occurred in the CAS system, reaching an average value equal to about 40%. Indeed, in this case, the alteration of the macromolecules biodegradability is only related to cell lysis due to the starvation conditions in the anaerobic tank, while no chemical oxidation occurs, which is different to the ozonation process.
Regarding the biomass settleability, more discussion is needed to properly differentiate the results obtained in the experimental periods. Figure 2 shows the SVI values in both systems. In particular, as shown in Figure 2(a), during the ozonation process the sludge settleability is slightly better than that in the preliminary stage operated as CAS configuration. In addition, it has to be highlighted that the initial inoculum sludge showed excellent settling characteristics, with an average SVI value lower than 80 mL g\(^{-1}\) TSS. The subsequent improvement of sludge settling property was probably due to the destructive effect of ozone on the filamentous bacterial cells (Caravelli et al. 2006). As a consequence, the average SVI value decreased from 75 to 45 mL g\(^{-1}\) TSS, thus increasing the sludge settling properties. On the contrary, during OSA operation, a reduction of biomass settleability was observed compared with that of CAS operation (Figure 2(b)): indeed, at the end of the start-up phase, and after the pilot plant layout had turned to OSA configuration, the SVI values ranged from about 100 to 200 mL g\(^{-1}\) TSS. This situation, however, was in contrast with previous studies reported in the technical literature (Chen et al. 2003); such behaviour can be likely attributed to operation difficulties during the transition phase after the configuration up-grading as well as to the initial HRT in the anaerobic tank (Müller 2000).

In particular, in the early days of OSA operation, an excessively high HRT was adopted in the anaerobic reactor, equal to 15 h, to enhance sludge reduction, but causing at the same time a rapid growth of mixotrophic filamentous bacteria. However, once the HRT in the anaerobic reactor was decreased to about 9 h, according to previous studies (Ye et al. 2008) the SVI trend was then reversed. Furthermore, the SVI worsening during the first days of OSA operation could be also caused by an accidental and temporary denitrification phenomenon, even if the pilot plant was not designed for nitrification. Such a point cannot be confirmed, as nitrogen monitoring was not planned; however, the rising phenomenon was rarely observed in the settling tank during the overall period.

Effects on heterotrophic biomass activity

The obtained results from the respirometric batch tests showed that the ozone treatment produced a decrease of the biomass respiration rate, in terms of OUR\(_{\text{max}}\). Indeed, the OUR\(_{\text{max}}\) values measured before ozonation, showed an average value equal to 0.48 g O\(_2\) g\(^{-1}\) VSS d\(^{-1}\), while the ozone dosage produced a decrease of the respiration rate to an average value of 0.29 g O\(_2\) g\(^{-1}\) VSS d\(^{-1}\), almost 40% lower than in the CAS start-up phase. The obtained results

![Figure 2](https://iwaponline.com/wst/article-pdf/66/1/185/442877/185.pdf)
are in good agreement with previous experiences reported in the technical literature (Sakai et al. 1997). Such behaviour suggested that the decrease of the respiratory activity after sludge treatment with ozone could derive from the alteration of the membrane permeability following the reaction of ozone with membrane lipids, and to direct reaction of ozone with the proteins involved in respiration, as outlined in Dziurla et al. (2005).

Referring to the OSA period, starting from a value of 0.48 g O₂ g⁻¹ VSS d⁻¹ in the CAS start-up phase, a final value of 0.30 g O₂ g⁻¹ VSS d⁻¹ was obtained, thus confirming a decrease of the biomass respiratory activity even under OSA configuration. The exposure to a low ORP level in the anaerobic tank, coupled to food scarcity, could likely create an environment which was stressful for microorganisms, inducing decomposition of cell bodies to provide additional food during the anaerobic period (Chen et al. 2001).

**Yield heterotrophic growth: **Y<sub>H</sub> and Y<sub>obs</sub>

The obtained Y<sub>H</sub> values were in the range of that ones proposed by the International Water Association (Henze et al. 1987) that vary between 0.38 and 0.75 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub> for a CAS process. Indeed, for the pilot plant under study, the Y<sub>H</sub> of the activated sludge before ozonation presented a mean value equal to 0.63 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub>, while the sludge treatment with ozone had the effect to reduce the heterotrophic growth yield to an average value equal to 0.54 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub>. The lower values for Y<sub>H</sub> suggested that the exposure to ozone could likely favour the selection of a heterotrophic population with a lower growth efficiency, as more energy should be necessary for the synthesis of enzymes to protect the cells from the high oxidation action of ozone as well as to repair cell damage due to ozonation (Gardoni et al. 2011). Similarly, the Y<sub>obs</sub> decreased from an average value of 0.57 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub> during the CAS phase, to 0.38 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub> corresponding to a 32% net reduction.

Referring to the OSA period, the Y<sub>H</sub> during the CAS start-up phase showed an average value equal to 0.64 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub> similar to that evaluated in the start-up phase of the ozonazion period; on the other hand, under the OSA configuration, the Y<sub>H</sub> values decreased to 0.58 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub>. Concerning the observed sludge yield, the net sludge reduction was about 35% and the Y<sub>obs</sub> decreased from 0.58 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub> to 0.37 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub>.

It is worthy to note that the Y<sub>H</sub> values obtained through respirometry significantly differ from the Y<sub>obs</sub> values; the explanation of such a discrepancy could likely be related to the fact that the observed yield coefficient, calculated on the basis of mass balances, naturally takes into account the biomass decay (differently from a respirometric batch test, whose length is limited in time), leading to a much lower net growth. Further, a possible explanation of the above mentioned discrepancy could be found in the different biomass behaviour with real wastewater and synthetic substrate, like sodium acetate, used in the respirometric batch test.

Despite the overall Y<sub>obs</sub> reduction in both periods being comparable, it showed different rates, as outlined in Figure 3, which shows that the time span needed to reach a new steady-state condition was smaller for ozonation than for the OSA process. In other words, the ozone dosage in the RAS stream allowed a very rapid Y<sub>obs</sub> reduction reaching after only 12–13 days a steady-state value equal to 0.38 mg COD<sub>cell</sub> mg⁻¹ COD<sub>ox</sub>. On the contrary, in the OSA system, the time span needed to reach a steady-state condition was about 20–22 days.

In addition, it should be noted that the adopted ozone dose was relatively low compared with the ones suggested in the technical literature (Chu et al. 2009) and this choice

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**Figure 3** | Y<sub>obs</sub> trend in the 'CAS—Ozonation' system (a) and in the 'CAS—OSA' system (b).
could limit the excess sludge net reduction. However, it was decided to investigate the process behaviour with a low ozone dose as, according to Yan et al. (2009), no alteration in bacterial DNA was detected at an ozone dosage lower than 0.02 g O_3 g\(^{-1}\) TSS.

**Sludge production**

A mass balance of solids in each system has been calculated from excess sludge wastage and variation of biomass concentration in the biological tanks.

In particular, a comprehensive sludge mass balance was undertaken to ensure that all the solids in the process were accounted for, in accordance with Equation (3). As previously discussed, the net sludge withdrawals from the pilot plants were carefully measured by daily measurements of the discharged solid quantities. The net WAS production in both pilot plants, before and after the configuration change, is reported in Figure 4.

As shown in Figure 4, after the change of plant configuration, the net sludge production was almost equal to 5.47 kg TSS week\(^{-1}\) and 5.39 kg TSS week\(^{-1}\) for the ozonation and OSA processes, respectively. On the other hand, the biomass production in both CAS systems was about 1.5 times higher than that observed in the ozonation and in the OSA processes.

**CONCLUSION**

The present work reports the analysis of two case studies dealing with excess sludge reduction in CAS systems. In particular, the authors compared the effects of a chemical oxidation with ozone and the uncoupled metabolism induced by the OSA process, in terms of both excess sludge reduction and biomass activity. In the following the main experimental results are listed:

- The OSA process showed a slightly higher reduction of suspended solids (average value of excess sludge reduction under stationary conditions equal to 38%, with a maximum value of 42%) compared with that of ozone (32% as average, maximum value of 38%); however, sludge reduction after ozone treatment is proportional to the ozone dose and, in the present study, it was decided to use a low dose (0.015 g O_3 g\(^{-1}\) TSS\(_{RAS}\)).
- Neither technology significantly affected the effluent quality in terms of TCOD removal efficiency. Referring to sludge settleability, while ozonation improved the settling properties of sludge, the OSA configuration caused a worsening of sludge settleability with a significant increase of SVI values, likely due to a too high HRT in the anaerobic tank.
- Respirometric tests showed that both technologies caused a decrease in biomass activity with a reduction of the
OUR$_{\text{max}}$ values to 0.29 and 0.30 g O$_2$ g$^{-1}$ VSS d$^{-1}$ after the ozonation and OSA process, respectively.

To conclude, the results obtained in the ozonation period suggested that the use of a low ozone dose allows at one time considerable excess sludge. On the other hand, referring to the OSA process, high retention times in the anaerobic sludge holding tank can increase the excess sludge reduction but cause a worsening in the sludge settleability.

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