Diagnosis of the anaerobic reject water effects on WWTP operational characteristics as a precursor of bulking and foaming

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ABSTRACT

This study investigates the effects observed on operational parameters in a large and full-scale wastewater treatment plant subjected to anaerobic reject water (ARW) diversion off the main line for a 3-month period and further monitoring for a 2-year period. The plant's secondary unit consists of a two-stage plug-flow-modified Bardenpho process receiving wastewater from both municipal and industrial origins. As a result, ARW was found to have a direct effect on bulking in secondary clarifiers and foaming in anaerobic digesters (AD) despite its relatively small flow rate. During the cut-off period a highly stable sludge volume index at 80 mL g^{-1} level was obtained in the secondary clarifiers, effluent suspended solids concentration was reduced and continuous feeding to AD was recovered. Sludge density increased in the thickeners during hot season. Secondary clarifiers showed good and stable settleability despite low dissolved oxygen, food/microorganism ratio and high sludge retention time and ammonium levels in the biological unit. The bulking and foaming effect was presented on the plant's internal flow balance. ARW needs serious consideration for elimination by appropriate technologies because of its high potential as a multi-dimensional pollutant source, not only as a carrier of nutrients but also as a possible carrier of filamentous bacteria, which might promote chronic seeding and retention in the system.

Key words | anaerobic reject water, Bardenpho, bulking, foaming, operation, wastewater treatment plants

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INTRODUCTION

Anaerobic reject water (ARW) disturbs several mass balances both on the main and sludge lines reaching N overload at 10–30% despite its relatively low flow rate in wastewater treatment plants (WWTPs) (Vandaele *et al.* 2000; EPA 2007). Side-stream treatment applications enable reductions in nitrogen load and sludge production, and savings in aeration on the main line with higher effluent quality for nitrogen (Carrio *et al.* 2003; Joss *et al.* 2009). Other effects of ARW in WWTP operational parameters can be more profound due to the transportation of filamentous bacteria (FB) responsible for foam forming and bulking to the main line as ARW can contain some solids after decantation (Pitt & Jenkins 1990; Pagilla *et al.* 1998). Internal recirculation of ARW to the main line is a possible route for chronic seeding of FB in the activated sludge unit. FB-related foaming in the activated sludge also affects anaerobic digesters (AD) resulting in altered sludge feeding.

In the present study, the aim was to investigate the effects of ARW on settleability and related operational parameters in a large and full-scale WWTP, which experienced excessive foaming in the aerated zones of its Bardenpho Unit (BU) and AD. Aeration and sludge feeding were altered. A more severe problem arose as the sludge that could not be fed to the digesters was carried via the supernatant of the thickeners to the inlet of the plant creating a vicious circle of solids between the primary settlers and sludge thickeners. Added solid load on the primary settlers contributed to the solid rise in the BU during peak flow hours lowering the food to microorganism (F/M) ratio. Primary sludge concentration reached levels well over the design value. As solids consisted mostly of volatile

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structures, another source of pollution was created as they continued to degrade under anaerobic conditions on the sludge line.

In order to sort out the ARW role in several operational disturbances, ARW was cut off the main line flow in Konya WWTP and changes in the operational parameters were examined on settling, solids, N load, thickening, oxygen levels and internal flows including sludge feeding of the digesters on a year (2011) scale. Supporting data from the following year (2012) were also supplied.

MATERIALS AND METHODS

The WWTP located in Konya City (Turkey) is a large-scale treatment plant receiving both industrial and domestic wastewater at a flow rate of 160,000 $m^3\ d^{-1}$ with a million population equivalence in operation since September 2010. The plant is operated by Konya Water and Sewerage Administration (KOSKI) and consists of primary (grit removal and primary sedimentation) and secondary treatment (modified Bardenpho) units for organic matter and partial nitrogen removal. BU (77,000 m^3) consists of two-parallel plug-flow lines with four oxic zones with 56,980 m^3 and anoxic zones of 20,020 m^3 volumes. Four 7,000 m^3 AD receive combined and thickened primary and waste activated sludge (WAS) and are operated with a hydraulic/sludge retention time (HRT = SRT) of 20 days.

Design values for mixed liquor suspended solids (MLSS) in BU inlet zone, F/M ratio, thickened sludge solid content and BU SRT were 3,800 mg L^{-1} MLSS, 0.19 kg BOD_5/kg MLSS d^{-1}, 5% and 9.4–11.2 d, respectively, while obtained levels were 4,200–5,300 mg L^{-1}, 0.11–0.13 d^{-1}, 2.6–2.7% and 17–23 d, respectively, in the beginning of 2011. A lowered F/M ratio and higher SRT were due to excessive suspended solids (SS) concentration in BU. Foaming in the aerated zones of BU and bulking were the operational problems encountered on the main line. On the sludge line, low density of the thickened sludge and foaming in AD caused solid accumulation in the plant. The studied period of the plant was the year of 2011 for the cut-off effect and 2012 for normal plant operation.

ARW is produced as the digester supernatant from the decanter at a flow rate of 1,400 $m^3\ d^{-1}$ and is recycled to the inlet of the WWTP. Its characteristics were monitored for a period of 8 months from May to December 2011 and summarized as 335–1,380 mg L^{-1} for chemical oxygen demand, 150–900 mg L^{-1} for biochemical oxygen demand (BOD_5), 607–1,120 mg N L^{-1} for total nitrogen, 580–900 mg L^{-1} for NH_4^+-N and 21–102 mg L^{-1} for total phosphorus. It had a considerable level of BOD_5 in addition to N and P with around a BOD_5/N ratio of 1.1.

ARW was cut off the plant inlet for a period of 3 months between June and August 2011. The study was conducted with routine monitoring of the parameters as SS, volatile solids, MLSS, sludge volume index (SVI), dissolved oxygen (DO) and total solids. Ammonium nitrogen (AN) was monitored in the influent wastewater, primary settler effluent (PSE) and final effluent. All parameters were analyzed according to *Standard Methods* (APHA 2005). DO concentration was monitored via online oxygen meters.

RESULTS AND DISCUSSION

Description of the operational problems

In KOSKI WWTP, excessive biomass concentration in the BU was accompanied by bulking in the secondary clarifiers. Temporary foam production resulted in bubbling over the aerated zones of the BU and was controlled by altering the aeration. Defoam agents were applied periodically with only temporary effect. Severe bulking also increased effluent BOD and SS concentrations to violation level. Foam production also took place in the AD and sludge feed was shut off automatically, resulting in sludge overflow from thickeners, which was also returned to the main line via internal recirculation.

To investigate the cause of bulking and foaming, FB species were examined and Types 0041/0675, 021N, 0092, 1851, 0581, 0803, *N. Limicola* I, II, III, *M. Parvicella*, *Zooglea* and *Thiothrix* II were found as dominating filamentous species in the plant during the winter months, whereas *N. Limicola* II, III, Types, 021N, 0092, 0041/0675, 0581, 0803, *M. Parvicella* and *Nocardia* dominated in the hot season (Aygun *et al.* 2013; Yel *et al.* 2013). Among the foam forming filamentous species, *Nocardia amarae, Nocardia pinensis, Microthrix parvicella* (Goddarao & Forster 1987; Blackall *et al.* 1989; Pitt & Jenkins 1990), *M. parvicella* stands out as the dominant species in both modified Bardenpho (BNR) and Phostrip plants related to foaming and bulking with an F/M ratio lower than 0.2 (a favorable condition for *M. parvicella*) (Baxter-Plant *et al.* 1999) and AD receiving fatty matter (Lienen *et al.* 2014). As many species were present in the studied BU, a cut-off strategy was implemented to sort out the effect of ARW on FB-related operational problems.

Effect on SVI, SS, MLSS and flow rates

During the ARW cut-off period, SVI values were significantly reduced in BU, dropping down to below 100 mL g^{-1} level and stabilizing between 60 and 80 mL g^{-1} ending a severe bulking period (Figure 1(a)). After that period, BU SVI gradually increased to 150–200 mL g^{-1} level returning back to bulking condition. To compare the plant's normal SVI levels in the summer months, SVI data of the year 2012 are provided in Figure 2(b). An earlier decrease in SVI started in the spring months at a fluctuating pattern between 80 and 120 mL g^{-1} and ended in August. Temperature ranged at a similar level during both periods; thus, it was not an influential factor on the results. Elimination of ARW seemed highly efficient in establishing a highly stable and low SVI at 80 mL g^{-1} where its addition bounced it to the 120–130 mL g^{-1} level, indicating a net increase. Data observed in the 2012 summer period started to increase to 130–170 mL g^{-1} level much earlier (in August) despite the high temperature environment. Further rises in SVI with lowering temperature in the following months might be correlated to *M. parvicella* dominance as reported

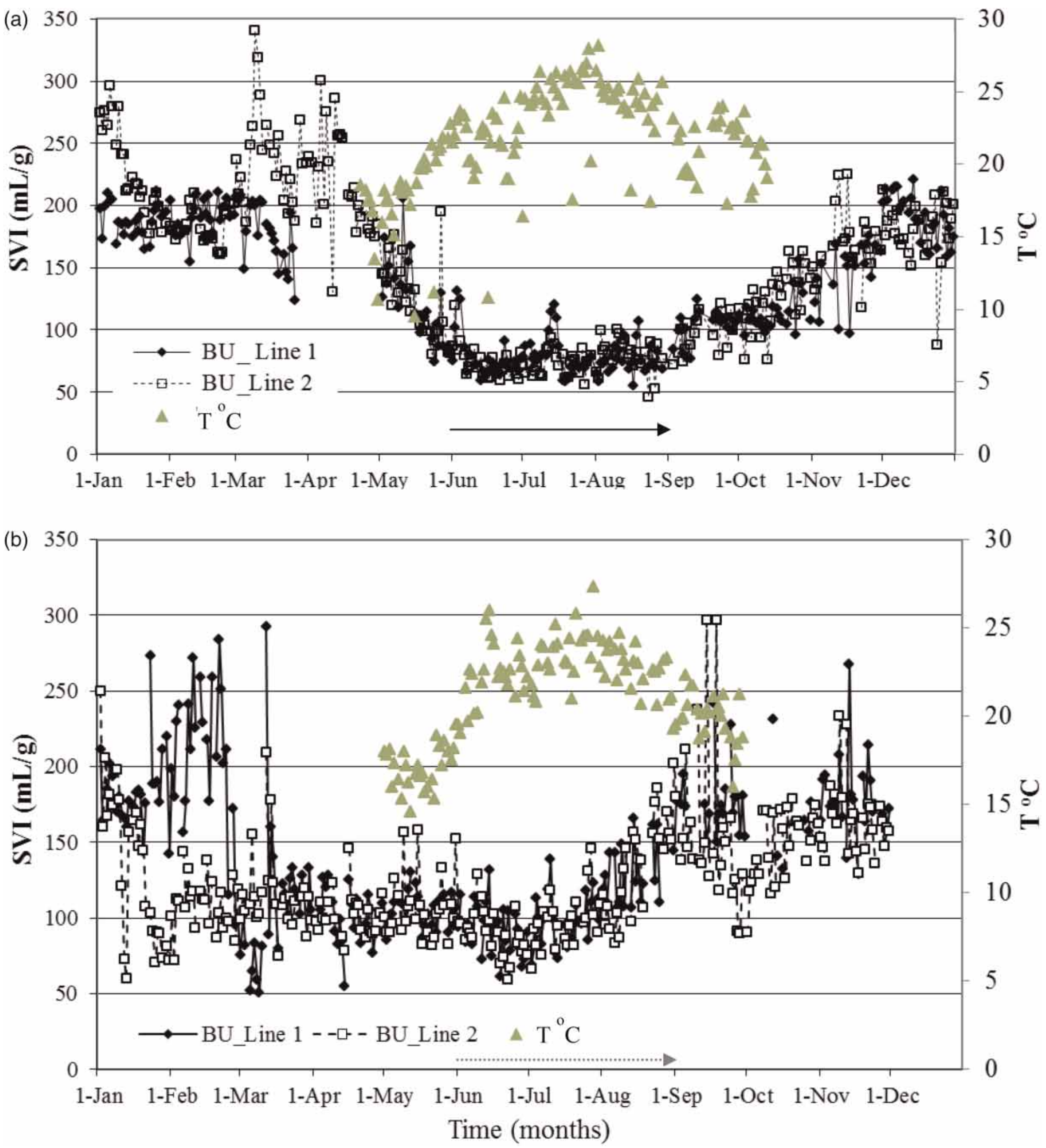

Figure 1 | Sludge volume index data of the biological unit and inlet wastewater temperature in years (a) 2011 and (b) 2012 (solid arrow showing the cut-off period in 2011 and dotted arrow in 2012).

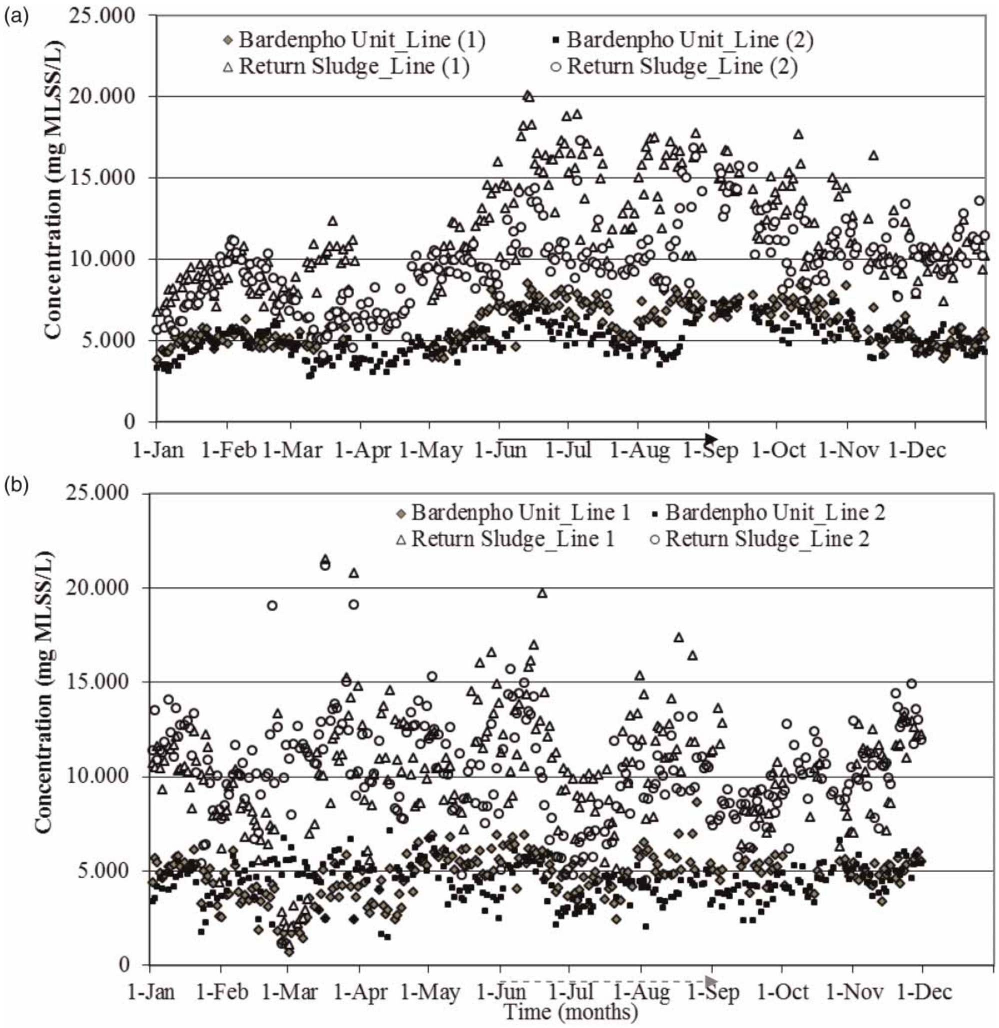

Figure 2 | Suspended solids concentrations of BU and return sludge for the year of 2011 (a) and 2012 (b) (solid arrow showing the cut-off period in 2011 and dotted line in 2012).

more frequently in winter and spring than in summer and autumn (Kristensen *et al*. 1994; Eikelboom *et al*. 1998; Kruit *et al*. 2002). Based on the operational experience in KOSKI WWTP, the temperature difference between day and night exceeding 10 °C acts as a major factor on the dominance of FB as floc-forming bacteria are not tolerant to such conditions and lose their competing ability.

With the start of the ARW cut-off period, there was limited success on the controlling and reduction of MLSS build up in BU (Figure 2(a)). Elevated levels of solids transported to the plant due to heavy rains in May had exceeded the settling capacity of the primary settlers and increased MLSS level in the BU; therefore, the nutrient effect of ARW on biomass growth could not be determined. Nevertheless, return sludge concentration reached a level above 15,000 mg/L as a result of higher settleability obtained in the secondary clarifiers. This phenomenon is crucial in the controlling of BU SRT and increasing sludge density in the thickeners. The unstable and fluctuating pattern of the return sludge concentration at 5,000–15,000 mg/L in 2012 indicated a continuous disturbance in the settling ability (Figure 2(b)).

Improvement in SVI and return sludge concentration was followed by an increasing pattern in the sludge thickening degree and lowering the effluent SS concentration of the WWTP in the summer of 2011 as shown in Table 1. Nevertheless, thickened sludge density showed an opposite pattern compared to the same period under normal operation in 2012. Its density tended to decrease during the summer months despite the same SVI level of the activated sludge and the fluctuating pattern of return sludge from April to August (2012). Observed data supported the fact

Table 1 | Monthly average values for total solid concentration of the thickened sludge in 2011 and 2012 with effluent SS in 2011 (bold numbers indicating the values during the cut-off period)

	Thickened sludge density (2011) (%)	Thickened sludge density (2012) (%)	Effluent SS concentration (2011) (mg L^{-1})
January	2.7		27
February	2.6		58
March	3.1		49
April	4.0	4.9	29
May	3.7	4.8	31
June	4.5	4.3	25
July	3.8	3.5	22
August	3.9	3.1	19
September	3.5	3.0	30
October	3.3	3.3	18
November	3.0	3.3	30
December	3.2		26

that temperature was influential in the thickening performance and showed that the cut-off strategy improved thickening despite the temperature effect in the summer of 2011.

Elimination of ARW controlled FB and foaming substantially as evidenced by Erdirencelebi & Kucukhemek (2013). Reduction in high SVI and foaming regulated internal flows of primary sludge, WAS, thickener overflow and sludge feeding closer to the design values as illustrated in Figure 3. Excessive overflow from sludge thickeners occurring in May can be mainly attributed to the higher inlet flow rate of the WWTP during this month, when a higher ratio of return sludge flow was directed to the thickeners to reduce SRT and MLSS in BU. WAS flow rate had a design value of 2,936 m^3 d^{-1} and fluctuated at a large scale around this value until the cut-off period. The maximum hydraulic capacity of the plant (200,000 m^3 d^{-1}) was not exceeded, but thickener overflow occurred at levels reaching 9,000 m^3 d^{-1} exceeding considerably its design value of 3,600–4,000 m^3 d^{-1}. The primary sludge flow pattern showed that the drop in the AD feeding also overloaded the primary settlers hydraulically. During the foaming in AD, primary sludge had to be drawn at doubling flow rates. It was possible to reduce it to the design value of 1,942 m^3 d^{-1} in the second half of September. Foaming in the AD could be lowered gradually and sludge feeding was increased over 1,000 m^3 d^{-1} during the cut-off period. With the start of ARW recirculation, sludge feeding was reduced again during September. It recovered and proceeded at its design value during the rest of the year.

Results show that bulking and foaming can unbalance and/or deteriorate a WWTP operation, both in quality and hydraulics. Design characteristics are usually based on normal operation with peak flow consideration, but biological processes can always produce unpredictable conditions that need to be taken into consideration during the design stage.

Overloading of AN

AN was monitored in the PSE to determine the overload of recirculated AN during the winter months (Figure 4). All the

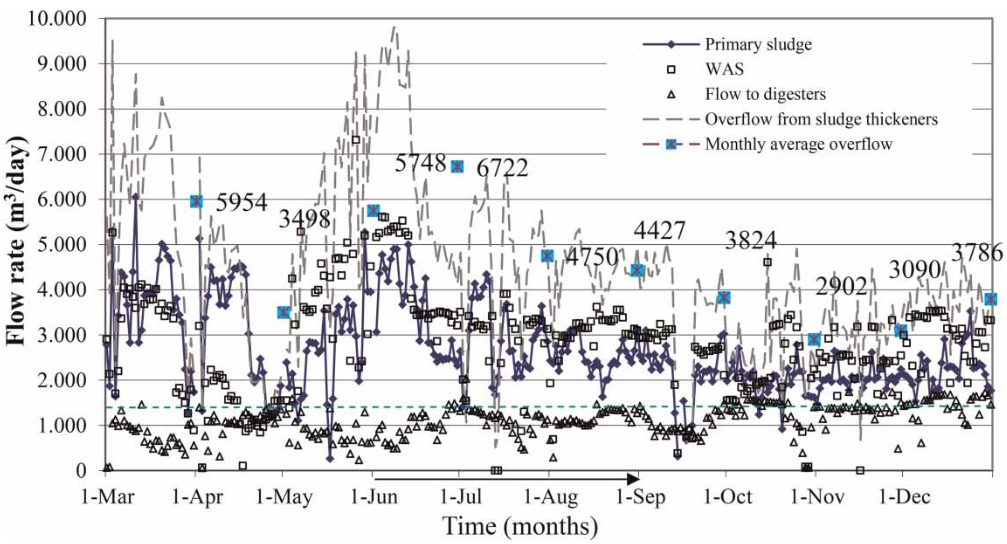

Figure 3 | Flow rate data of the Konya WWTP on the sludge line between March and December 2011 (arrow showing the ARW's cut-off period and dotted line for sludge feeding design value).

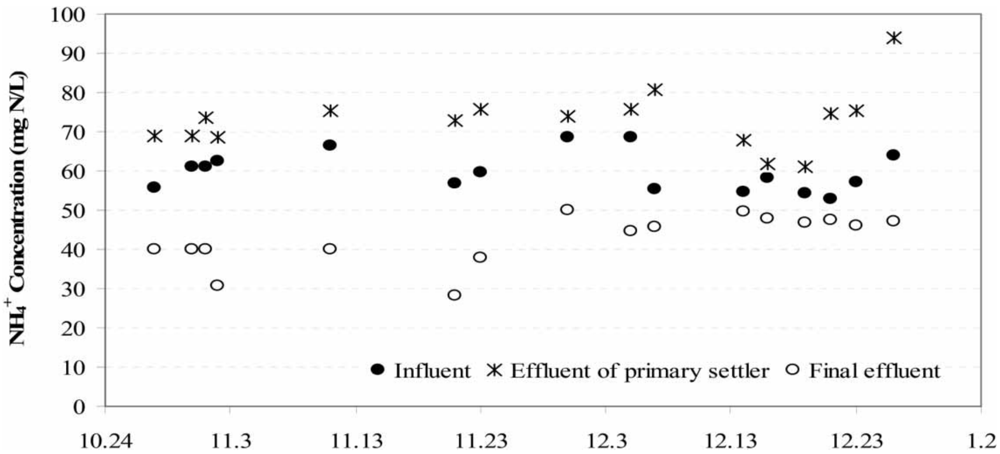

Figure 4 | Nitrogen concentration on the main flow line of WWTP during April–December 2011.

internal flows were close to their design values during the sampling period. Additional nitrogen load was calculated from the difference between the influent wastewater and PSE ammonium concentrations. It averaged 23% (6–47%) of the influent AN making a load at 2,227 kg N d^{-1}. ARW transported one-third of the extra load where two-thirds were produced from degradation of solids escaping anaerobic digestion.

The actual performance (22–61%) of AN removal was higher than the value calculated (9–51%) between the influent and effluent of the WWTP due to the combined flow and load. (The actual performance went unnoticed). As a result, BU capacity of ammonium oxidation was exceeded considerably as evidenced also by low DO levels in the oxic zones. The capacity was limited during the foaming periods due to altered aeration; therefore, ammonium removal proceeded at a wide range and persisted in the WWTP final effluent at high levels. In ideal sludge feeding, AN overload would have originated only from ARW, which would have returned the organic nitrogen removed in the primary sludge and WAS in the AN form to the main line.

Low DO levels and filamentous growth

Low DO conditions in the activated sludge unit are reported as a promoter of filamentous growth and decreased settleability (Wilen & Balmer 1999). DO profiles in Line-1 BU oxic zones are presented for 2011 and 2012 in Figure 5(a) and 5(b). DO concentration proceeded at low levels during the cut-off period at 0.1, 1.0–2.0, 0.5–2.0 and 0.1–0.8 mg/L in oxic zones 1, 2, 3 and 4, respectively, in 2011. Data for the same period in 2012 present a higher oxygenation level compared with the previous year, especially in oxic zones 2 and 3. This indicates that low SVI values can be obtained at 60–80 mL g^{-1} despite low DO levels. This supports the theory that the plug-flow regime of BU is advantageous in the elimination of filamentous dominance despite low DO F/M and high ammonium levels (Donaldson 1932; Park & Noguera 2004; Guo *et al.* 2010). At this point, ARW's role seemed to be a carrier of FB in Konya WWTP. Aerobic, anoxic, anaerobic zone grower FB as *M. parvicella*, Type 0092, Type 0041/0675 and some species (morphotypes, Type 0961, Type 1863, Type 1851 and *N. limicola*) have been shown to have the capacity to for fermentative metabolism, finding competitive advantages in environments with anaerobic stages or conditions (Horan *et al.* 1988; Nowak & Brown 1990; Martins *et al.* 2004). Anaerobic growth of *M. parvicella* was reported with RNA sequencing in full-scale biogas plants (Lienen *et al.* 2014).

The most frequently identified FB in 964 WWTP in France were Type 0092 followed by *M. parvicella* and *Thiothrix* sp., mainly related to the sludge treatment process (Graveleau *et al.* 2005). Lack of sludge evacuation management was found responsible for high MLSS concentrations; thus, reduced oxygen levels in the aeration tank lead to favorable conditions for FB. Excessive levels of *G. amarae* and *M. parvicella* in anaerobic digestion were found to cause foaming problems not only in the anaerobic digestion process itself but in a preceding activated sludge system due to their presence in the recycle stream from the dewatering facilities (Pitt & Jenkins 1990; Pagilla *et al.* 1998).

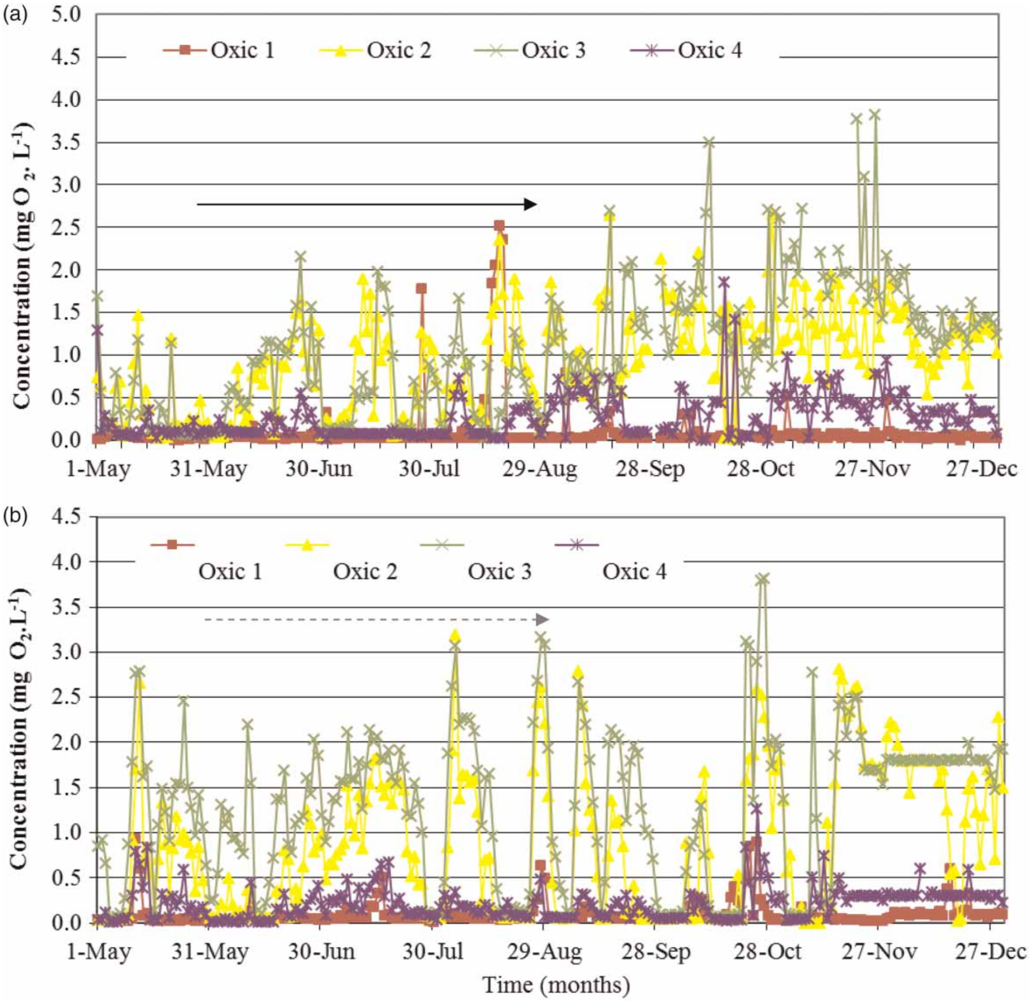

Figure 5 | BU Line-1 oxic zones DO concentration profiles in 2011 (a) and 2012 (b) (solid line showing the cut-off period in 2011 and dotted arrow in 2012).

CONCLUSIONS

Elimination of ARW in a full and large-scale WWTP with a modified Bardenpho process had a direct and rapid effect on the reduction of bulking and SVI improving the settling ability in the secondary clarifiers and effluent SS quality. It was shown that low SVI levels can be obtained even at low DO F/M and high ammonium levels. High SVI was found to correlate to lower sludge thickening. AN load added on the main line via internal recirculation averaged 23% of the influent AN, which persisted at high levels in the effluent.

Foaming in the activated sludge has been a pre-alarm for AD operation as parallel foaming occurred and sludge feeding was disrupted. Improvement was obtained gradually after the ARW cut-off. Regarding the experience and research on biological treatment, bulking and foaming phenomena can be a severe burden on WWTP operation. ARW treatment toward its nutrient load and possible FB content needs further consideration. The Bardenpho process suffered from filamentous growth despite its favorable environment for floc-forming bacteria. More serious disturbance occurred on the sludge line when AD operation was disrupted. Efficiency of the sludge thickening process has an eminent role on the recirculation flow pollutant load and mechanical systems would be a better choice compared to conventional gravity thickeners to provide lower sensitivity to changes in SVI.

REFERENCES

APHA 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Aygun, A., Kucukcongar, S., Gok, Z., Sogancioglu, M., Yel, E. & Kucukhemek, M. 2013 Bulking and foaming filamentous in modified Bardenpho process during hot season. In: *2nd International Conference and Chemical, Environmental and Biological Sciences, Proceedings ICCEBS–2013*, 17–18 March, PSR Centre Org., Dubai, UAE, pp. 56–60.

Baxter-Plant, V. S., Hayes, E. & Forster, C. F. 1999 Problems caused by filamentous bacteria in pilot-scale nutrient-removal activated-sludge plants. *J. CIWEM* **13**, 131–136.

Blackall, L., Parletti, H., Hawnd, A. C., Minnikin, D. E., Greenfield, F. & Harberas, E. 1989 *Nocardia pinensis* sp. Nov, an actinomycete found in activated-sludge foams in Australia. *J. Gen. Microbiol.* 135, 1547.

Carrio, L., Sexton, J., Lopez, A., Gopalakrishnam, K. & Sapienza, V. 2003 Ammonia-nitrogen removal from centrate, 10 years of testing and operating experience in New York City, WEFTEC 2003, *Water Environ. Fed. Sess.* **42** (14), 140–153.

Donaldson, W. 1932 Use of activated sludge increasing. *Civ. Eng.* **2** (3), 167–169.

Eikelboom, D. H., Andreadakis, A. & Andreasen, K. 1998 Survey of filamentous populations in nutrient removal plants in four European countries. *Water Sci. Technol.* **37** (4/5), 281–289.

EPA 2007 Wastewater Technology Fact Sheet, Side Stream Nutrient Removal, EPA 832-F-07-017.

Erdirencelebi, D. & Kucukhemek, M. 2013 Effect of the anaerobic digester filtrate to WWTP performance in the controlling the biomass and thickening, Istanbul International Solid Waste, Water and Wastewater Congress. In: *3W Congress Proceedings*, Istanbul, ISTAC Inc., pp. 1005–1010.

Goddarao, J. & Forster, C. F. 1987 Stable foams in activated sludge plants. *Fnz Microbiol. Technol.*, **9**, 164.

Graveleau, L., Cotteux, E. & Duchene, P. 2005 Bulking and foaming in France: The 1999–2001 survey. *Acta Hydrochim. Hydrobiol.* **33**, 223–231.

Guo, J.-H., Peng, Y.-Z., Peng, C.-Y., Wang, S.-Y., Chen, Y., Huang, H.-J. & Sun, Z.-R. 2010 Energy saving achieved by limited filamentous bulking sludge under low dissolved oxygen. *Bioresour. Technol.* **101** (4), 1120–1126.

Horan, N. J., Bu'Ali, A. M. & Eccles, C. R. 1988 Isolation, identification and characterisation of filamentous and floc-forming bacteria from activated sludge flocs. *Environ. Technol. Lett.* **9**, 449–457.

Joss, A., Salzgeber, D., Eugster, J., Konig, R., Rottermann, K., Burger, S., Fabijan, P., Leumann, S., Mohn, J. & Siegrist, H. 2009 Full-scale nitrogen removal from digester liquid with partial nitrification and anammox in one SBR. *Environ. Sci. Technol.* **43** (14), 5301–5306.

Kristensen, G. H., Jorgensen, P. E. & Nielsen, P. H. 1994 Settling characteristics of activated sludge in Danish treatment plants with biological nutrient removal. *Water Sci. Technol.* **29** (7), 157–165.

Kruit, J., Hulsbeek, J. & Visser, A. 2002 Bulking sludge solved?! *Water Sci. Technol.* **46** (1/2), 457–464.

Lienen, T., Kleyböcker, A., Verstraete, W. & Würdemann, H. 2014 Foam formation in a downstream digester of a cascade running full-scale biogas plant: Influence of fat, oil and grease addition and abundance of the filamentous bacterium *Microthrix parvicella*. *Bioresour. Technol.* **153**, 1–7.

Martins, A. M. P., Pagillac, K., Heijnena, J. J. & van Loosdrecht, M. C. M. 2004 Filamentous bulking sludge – a critical review. *Water Res.* **38**, 793–817.

Nowak, G. & Brown, G. D. 1990 Characteristics of *Nostocoida limicola* and its activity in activated sludge suspension. *Res. J. Water Pollut. Control Fed.* **62**, 137–142.

Pagilla, K. R., Jenkins, D. & Kido, W. 1998 *Nocardia* effects in waste activated sludge. *Water Sci. Technol.* **38**, 49–54.

Park, H.-.D. & Noguera, D. R. 2004 Evaluating the effect of dissolved oxygen on ammonia-oxidizing bacterial communities in activated sludge, *Water Res.* **38** (14–15), 3275–3286.

Pitt, P. & Jenkins, D. 1990 Causes and control of *Nocardia* in activated sludge. *J. Water Pollut. Control Fed.* **62**, 143–150.

Vandaele, S., Bollen, F., Thoeye, C., November, E., Verachtert, H. & van Impe, J. F. 2000 Ammonia removal from centrate of anaerobically digested sludge: state of the art biological methods. In: *1st World Water Congress of IWA*, Operation and management, landfill and sludge management, July 3–7 2000, Paris, IWA Publishing, London, pp. 280–287.

Wilen, B.-M. & Balmer, P. 1999 The effect of dissolved oxygen concentration on the structure, size and size distribution of activated sludge flocs. *Water Res.*, **33**, 391–400.

Yel, E., Kucukcongar, S., Gok, Z., Sogancioglu, M., Aygun, A. & Kucukhemek, M. 2013 Identification of winter bulking and foaming filaments in the Konya Wastewater Treatment Plant. In: *Istanbul International Solid Waste, Water and Wastewater Proceedings 3W*, ISTAC Inc., Istanbul, pp. 1027–1033.

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