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Sludge reduction by an anaerobic side-stream reactor process: A full-scale application

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ABSTRACT

In the present paper, a new process, whose acronym is UTN (University of Trento) system, is proposed and tested at full scale for reducing the amount of sludge of the wastewater treatment plant. The UTN system allows sludge reduction in conventional activated sludge (CAS) due to the cell lysis, the sludge decay and, above all, to the selection of slow growing microorganism. In this study, the first full-scale UTN system was tested by retrofitting an existing wastewater treatment plant located in Marmirolo (Lombardia, Italy) having a treatment capacity of 6,000 population equivalent (PE). Performances of the UTN system were evaluated in terms of sludge reduction, together with organic carbon and nutrients removal efficiencies. Results obtained over 10 month of monitoring period, divided in period I (7 months) and period II (3 months), characterized by different operative conditions, have reported a specific sludge production of 0.37 and 0.23 kg TSS per kg of COD removed, respectively; which is 50% and 69% lower than that observed in the reference period when the plant worked under conventional activated sludge process. Furthermore, results revealed that the UTN system allows a high removal of wastewater typical pollutants, without causing negative effects on the effluent quality, always ensuring compliance with the regulatory discharge limits.

1. Introduction

The growing number of wastewater treatment plants (WWTPs) built, the expansions of existing ones and more stringent regulation criteria resulted in a sharply increase in the excess sludge production (Collivignarelli et al., 2019). Although the sludge volume produced by WWTPs is only 1% of the volume of sewage flowing in the plants, its treatment and final disposal entail up to 50% of total treatment costs (Turunen et al., 2018). Therefore, finding technological solutions to reduce the production of sludge to be disposed of is a very interesting topic among both researchers and sewage treatment plants operators. In last years, lots of techniques have been developed for sludge minimization, which could be divided into two types: a) reducing sludge production in wastewater treatment line and, b) achieving sludge reduction in sludge treatment line. In general, they are not implemented simultaneously in the same WWTP (Wang et al., 2017). The first option is of great interest because it handles the problem of sludge at its origin, thus reducing the quantity send to the sludge line of the WWTP (Di Iaconi et al., 2020). These sludge reduction technologies include chemical treatments thorough advanced oxidation or uncoupling (Romero et al., 2015), mechanical treatments for cell breakage (Mohammadi et al., 2011), thermal (Camacho et al., 2005) and biological treatments (Ferrentino et al., 2014; Semblante et al., 2014). Most of these technologies are based on cell lysis-cryptic growth and maintenance metabolism mechanism; they cause a release of intracellular and extracellular substances, which become substrate available for biodegradation, whereby sludge reduction is achieved (Van Loosdrecht and Henze, 1999). In addition to this, some technologies for reducing sludge production in wastewater treatment line include the selection of a particular microbial community structure (Cheng et al., 2017; Ferrentino et al., 2016; Wang et al., 2009). Most of these technologies had achieved effective sludge reduction in lab and pilot scale. On the contrary, only few of them have been successfully applied at full scale, due to excessive operating costs or the lack of in-depth knowledge of sludge reduction mechanisms. Compared to mechanical and chemical technologies, biological processes, such as the anaerobic side stream reactor (ASSR) or the oxic-settling anaerobic (OSA) process, received the most attention for their cost-effective and environmental friendly nature (Khursheed and Kazmi, 2011). However, only very few applications at full scale could be found. The first full – scale ASSR in Europe was put into operation in 2008 in the Levico WWTP (Italy), treating a population equivalent of 48,000. The ASSR was build according to the commercial process Cannibal® (Ragazzi et al., 2015). It was in operation

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for more than 5 years and the observed sludge yield (Y_{obs}) was 0.35 g SS g^{-1} COD, as compared to 0.44 g SS g^{-1} COD in the conventional activated sludge (CAS) configuration (Velho et al., 2016). The reduction of Y_{obs} by 20% was lower than those reported in literature, where results were all referred to synthetic wastewater (Chon et al., 2011a, 2011b; Kim et al., 2012; Novak et al., 2007; Saby et al., 2003). Thus, this experience proved that the ASSR – like processes faced some technical obstacles such as long solid retention time (SRT) and negative effects on the effluent quality or larger footprint due to long hydraulic retention time (HRT), bringing many to highlight that the knowledge about the sludge reduction mechanisms were insufficient. In our previous study, we found that there is a combination of biological mechanisms that lead to the reduction in the sludge production in the ASSR process comprising hydrolysis, sludge decay, the extra polymeric substances (EPS) destructuration and, above all, the selection of slow-growing bacteria, such as denitrifying phosphate accumulating organisms (DPAO) and sulfate reducing bacteria (SRB) (Ferrentino et al., 2018). In general, total phosphorous accumulating bacteria (TPAO) are able to release phosphorous in anaerobic conditions and uptake phosphorous in anoxic and oxic conditions. Moreover, DPAO, a particular subgroup of TPAO, are characterized by a low growth yield thus, their selection, could contribute do the reduction of sludge production in the ASSR (Ferrentino et al., 2018). A combination of operative conditions based on the anaerobic solid retention time (SRT_{ASSR}) and interchange ratio (IR) and with new process logics has been proposed at lab scale, to successfully implement the ASSR – like processes (Ferrentino et al., 2019).

In the present paper, this new scheme of the ASSR process, whose acronym is UTN (University of Trento; patent n. 102016000035388) system, is proposed and tested, for the first time, at full scale for reducing the quantity of sludge in an integrated scheme with the wastewater line of a WWTP.

The UTN system is an efficient sludge reduction treatment, consisting of: i) a mainstream reactor in the wastewater line, configured to perform alternate aerobic and anoxic phases and sedimentation connected to ii) an ASSR placed in the return sludge line configured to treat a portion of the settled or thickened sludge and to provide an anaerobic stirred environment; iii) a controller that manages the whole WWTP operations, in particular the alternate phases in the mainstream reactor and the recirculation of the sludge from the mainstream reactor to the ASSR and *viceversa*; iv) eventually, a denitrifying side stream reactor (DSSR), located before the ASSR, configured to both remove the nitrate eventually present in the sludge and to thicken the sludge, increasing the biomass concentration to be fed to the ASSR (Andreottola et al., 2016). The two main operative parameters of the UTN system are the interchange ratio (IR) and the anaerobic sludge retention time (SRT_{ASSR}). The IR defines the amount of sludge to be fed to the ASSR as a mass percentage of the biomass present in the mainstream reactor. The IR value ranges between 10% and 100% while the SRT_{ASSR} is lower than 10 days, preferably lower than 5 days.

In the present paper, the performances of the first UTN system implementation at full-scale, obtained by retrofitting an existing activated sludge WWTP, were evaluated in terms of sludge reduction together with conventional pollutants removal efficiency. Biological activity and energy consumption were also investigated. These performances were compared with the ones of the same WWTP before the installation of the UTN system.

2. Materials and methods

2.1. Plant description and operation

The first UTN demonstrative plant was built in 2018 by retrofitting the existing activated sludge plant of Marmirolo's WWTP, located in northern Italy. The Marmirolo's WWTP treats domestic wastewater and has a design treatment capacity of 6,000 person equivalents (PE), expressed in terms of organic load. The water line consists of preliminary treatments stage for screening, degritting and degreasing operations, biological stage with anoxic (2 tanks, for a total volume of 340 m^3) and aerobic (2 tanks, for a total volume of 595 m^3) compartments for carbon and nitrogen removal, based on activated sludge process, secondary sedimentation (2 clarifiers, total volume 940 m^3) and tertiary treatments for disinfection. The sludge line is based on aerobic digestion (258 m^3 vol.), a post thickening unit of stabilized sludge (3 tanks for a total volume of 39 m^3) and a belt press dewatering unit.

Table 1
Characteristics of the influent wastewater.

Parameter	Reference period	Period I	Period II
COD (mg L^{-1})	194 ± 100	276 ± 163	257 ± 174
NH_4-N (mg L^{-1})	35 ± 20	28 ± 19	15 ± 10
NO_3-N (mg L^{-1})	0.5 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
TN (mg L^{-1})	38 ± 19	35 ± 25	34 ± 16
COD/TN	5.2 ± 1.0	9 ± 3	7 ± 4
N_{org} (mg L^{-1})	3 ± 2	4 ± 4	–
TKN (mg L^{-1})	38 ± 19	35 ± 25	–
TP (mg L^{-1})	4 ± 2	4 ± 3	4 ± 3
TSS (mg L^{-1})	56 ± 40	70 ± 35	210 ± 157

To implement the UTN process, some modifications to the existing WWTP configuration were made (Fig. 1): i) alternate anoxic/aerobic phases were implemented in the biological compartment of the water line; ii) the aerobic digestion was converted in ASSR; iii) a dynamic thickener was installed to thicken the excess sludge prior to fed it into the ASSR; iv) one of the three post-thickening unit was converted both in stored tank, for the subsequent dynamic thickener, and in post-denitrification tank, named DSSR; v) the other two post-thickening units were used both as storage tank upstream of the belt press and as additional DSSR upstream the ASSR.

The main feature of the UTN system is to ensure a solid retention time in the ASSR (SRT_{ASSR}) preferably lower than 5 days and an interchange ratio (IR), defined as the rate of solids that pass through the ASSR from the mainstream reactor (usually expressed as a percentage per day of the total mass present in the water line) at least higher than 50%. Moreover, for a successful application of the UTN process, nitrate and oxygen concentrations in the excess sludge have to be, respectively, lower than 5 mg NO_3-N L^{-1} and close to zero (Ferrentino et al., 2018). The modifications made to Marmirolo's WWTP allowed to obtain a SRT_{ASSR} equal to 2.4 d and a 60% of IR, precisely ensuring a low nitrate concentration and an oxygen content close to zero in the excess sludge. The values of SRT_{ASSR} and IR were fixed according to results obtained at lab scale (Ferrentino et al., 2018, 2019, 2016).

The UTN system was operated for 10 months. The experimental campaign was split in two periods. The first period (period I), which lasted about 7 months (from February to September 2018) and the second period (period II) which lasted about 3 months (from April to July 2019). The main difference between period I and II was in modifications made to the dynamic thickener located before the ASSR. Results of both periods were compared to a reference period (from July 2016 to June 2017) during which Marmirolo's WWTP worked following the CAS process scheme. The characteristics of the influent wastewater in each experimental period are reported in Table 1.

2.2. Observed sludge yield and solid retention time

The observed sludge yield (Y_{obs}) was used to evaluate the sludge production in the biological compartment of the WWTP before and after the implementation of the UTN system. Y_{obs} was determined by using a regression method applied to the amount of cumulative sludge generated and the amount of cumulative substrate removed. The cumulative generated sludge consists of all the TSS variation in the plant, considering both the increase of the sludge volume in the water line and the cumulative sewage sludge produced. The cumulative consumed substrate was assessed as the difference between the influent and effluent COD load

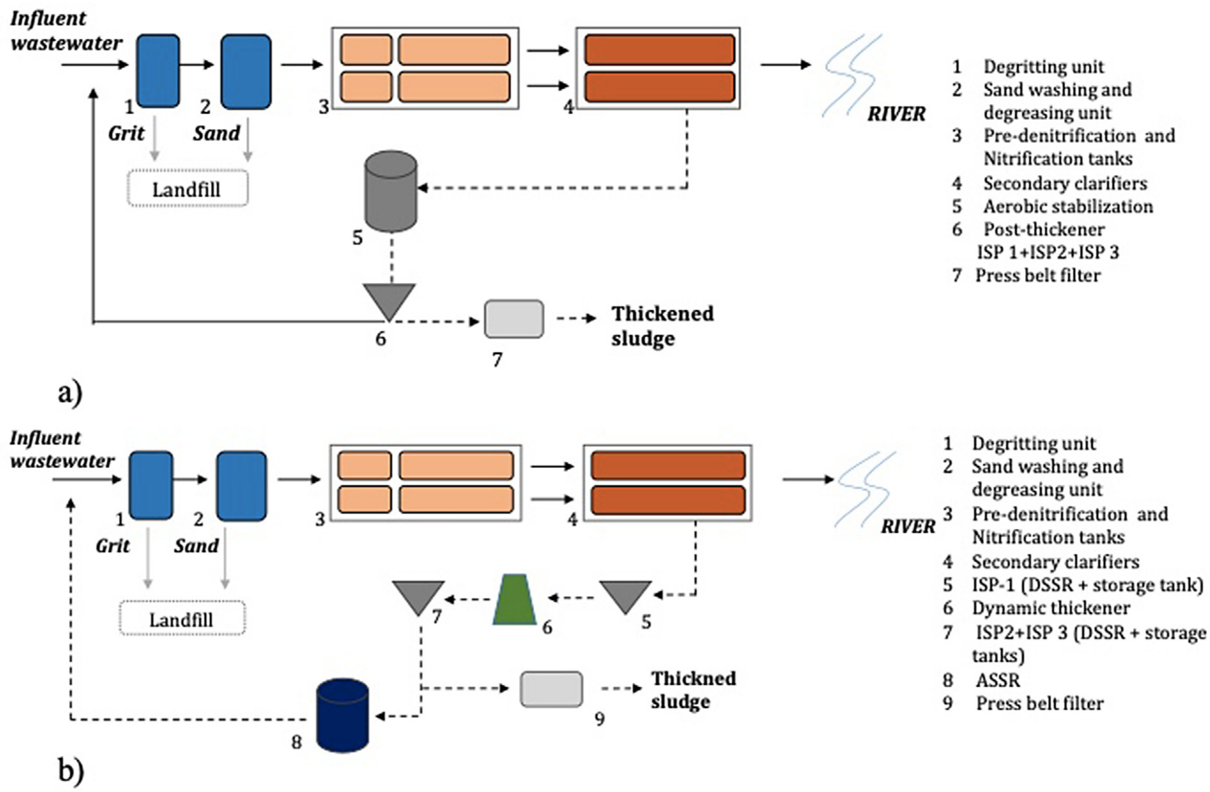

Fig. 1. Flow scheme of the WWTP a) before and b) after the implementation of the UTN system.

(Ferrentino et al., 2018). The value of Y_{obs} for each monitoring period was calculated as the slope of the linear regression curve fitting the cumulative TSS produced vs. the cumulative COD removed. This method takes into account all the changes in both substrates and solid concentrations eventually present during the experimental period giving a careful estimation of the sludge production. Moreover, the Y_{obs} was compared to the specific sludge production of the WWTP (kg TS_{dried} kg $COD^{-1}{}_{removed}$) evaluated on the basis of the amount of the dewatered sludge disposed of before and after the implementation of the UTN system.

The solid retention time (SRT) of the plant was estimated according to Eq. (1). SRT was evaluated as the ratio between the total mass of sludge in the plant and the mass rate of sludge leaving out of the system.

$$SRT = \frac{V_{WL} \cdot X_{WL} + V_{ASSR} \cdot X_{ASSR}}{Q_{eff} \cdot X_{eff} + Q_{qw} \cdot X_{qw}} \quad (1)$$

where V_{WL} (m^3) and X_{WL} (kg TSS m^{-3}) are, respectively, the volume and the TSS concentration of the biological compartment of the water line, V_{ASSR} (m^3) and X_{ASSR} (kg TSS m^{-3}) are, respectively, the volume and the TSS concentration of the ASSR, Q_{eff} (m^3 d^{-1}) and Q_{qw} (m^3 d^{-1}) are the flow rate of effluent and sludge wastage, respectively, and X_{eff} (kg TSS m^{-3}) and X_{qw} (kg TSS m^{-3}) are the TSS concentration in the effluent and in the waste sludge.

2.3. Batch tests

The phosphate uptake rate (PUR) tests were performed during the entire experimental period as an indirect and simple way to evaluate the activity of total phosphate accumulating organisms (TPAO) and denitrifying phosphate accumulating organism (DPAO). The PUR tests were performed according to the procedure reported in Ferrentino et al., 2018. The specific phosphorous uptake rate of TPAO ($SPUR_{tot}$) was determined in a 2-stage batch assay, initially under strictly anaerobic conditions (first stage) and then under aerobic conditions (second stage). The specific phosphorous uptake rate of DPAOs ($SPUR_{DPAO}$) was determined in a 2-stage batch assay as for TPAO, initially under strictly anaerobic conditions (first stage) and then under anoxic conditions (second stage). Both the specific TPAO and DPAO activities were calculated from the slope of the initial section of PO_4-P curves in the first and second stage, divided by the TSS concentration in the batch reactor. Results were expressed as release rate (v_P) of phosphorous in anaerobic condition for TPAO, uptake rate of phosphorous in anoxic condition for DPAO ($v_{S,\ DPAO}$) and uptake rate in aerobic condition for TPAO ($v_{s,\ TPAO}$) and used to evaluate the percentage for DPAO over TPAO. Batch tests were performed in duplicate once a month.

2.4. Analytical methods

Plant performances were evaluated in terms of traditional parameters to express the main pollutants removal efficiency and the sludge production. Chemical oxygen demand (COD), soluble chemical oxygen demand (COD_{sol}), total suspended solids (TSS), volatile suspended solids (VSS), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), nitrate (NO_3–N), nitrite (NO_2-N), total nitrogen (TN), soluble phosphorous (PO_4-P) and total phosphorous (TP) were determined according to Standard Methods (APHA et al., 2012). These parameters were measured one times a week in the influent and effluent samples of the WWTP, in the main biological compartment in the water line, in the recycling activated sludge line, in the excess sludge sample and in the influent and effluent sample of the ASSR.

2.5. Energy consumption

The total energy consumption of the WWTP has been collected by an automatic meter reading system. This evaluation has been done considering the reference period and period I. The energy consumption has been referred to the average influent flow considering both the consumption of electromechanical equipment associated with the water and air treatment chain, and the consumption of auxiliary machines, such as lighting, cooling and electrical panels.

3. Results and discussion

3.1. WWTP performances

After a microbial acclimatation period of 60 days, the UTN system was continuously operated and monitored with chemical analysis. The COD removal efficiency of the WWTP was almost high and stable during all the monitoring period. The average COD in the effluent concentrations were 16 ± 5 mg L^{-1}, 18 ± 7 mg L^{-1} and 24 ± 22 mg L^{1}, respectively, during the reference period, period I and period II, obtaining efficient COD removal of 90%, 92% and 82%, respectively. The COD removal efficiencies in the reference period and during period I were almost equal; on the contrary, the average COD removal in period II was lower than the previous monitoring periods. Considering this latter period, the COD removal efficiency was on average above 94% except for three samples where low influent COD concentrations were measured, highlighting a higher variability in the COD influent and effluent concentrations compared to the reference period and period I. However, the COD removal efficiencies were in the common range for OSA and ASSR process (84 – 91%) treating real wastewater (Ferrentino et al., 2019; Velho et al., 2019; Zhou et al., 2015a).

With influent NH_4-N concentration of 35 ± 5 mg L^{-1}, 28 ± 19 mg L^{-1} and 15 ± 10 mg L^{-1}, respectively in the reference period, period I and period II, the WWTP was equally effective in NH_4-N removal during the reference period and period I, obtaining a high nitrification efficiency, accounting for 97% and 98%, respectively in period I and II. A slight lower NH_4-N removal efficiency was observed in the reference period, accounting for 87%. Efficient COD and NH_4-N removal efficiencies were attributed to the high heterotrophic and autotrophic activities in the WWTP.

TN removal efficiency increased from 66% in the reference period to 90% and 81% in period I and II. Both nitrification and denitrification processes of the WWTP were improved ensuring lower concentrations of ammonium nitrogen and nitrate in the effluent. The improvement was attributed to the implementation of anoxic/aerobic alternate phases in the water line, together with the presence of the ASSR, which contributed to the selection of a particular denitrifying biomass and to the release in the ASSR of additional carbon source from the degradation of secondary organic substrates (Cheng et al., 2017).

The TP removal increased from 79% in the reference period up to 92% in both period I and II, after the implementation of the UTN system. TP removals were relatively higher than previous literature studies on ASSR. Cheng et al. (2017), investigating the effects of different side-stream ratio (IR equal to 20%, 50% and 100%) on sludge reduction of ASSR coupled with membrane bioreactors, obtained an insignificant effects on TP removal which fluctuated in a narrow range from 15% to 20%. The authors attributed the low TP removal obtained to the long SRT of the whole ASSR coupled membrane system and the low concentration of COD in the influent. Also Huang et al. (2020), who investigated the biological nutrient removal in the ASSR coupled with membrane bioreactors, obtained a low TP removal, ranging between 37% and 50%.,

The present results, in terms of COD, NH_4-N, TN and TP removal obtained at full scale, confirmed what has been demonstrated in lab-scale applications (Ferrentino et al., 2019). The insertion of an ASSR in a conventional activated sludge scheme using the UTN configuration had no adverse effects on organic degradation and nutrients removal but, on the contrary, improves the WWTP performances. Thus, no negative effects on wastewater quality were found, because the effluent concentrations of the common pollutants present in wastewater were always lower than the regulatory discharge limits. Moreover, results revealed that the UTN system allows to obtain a better performance of the whole plant, or at the most equal to the reference scheme.

3.2. Evaluation of sludge reduction

The cumulative biomass production was plotted against the cumulative organic matter removed in order to evaluate the observed sludge yield (Y_{obs}) of the biological compartment referred to the reference period, period I and II post the implementation of the UTN system. The slope of the linear regression curves for each experimental period was determined. In the reference period, the Y_{obs} was equal to 0.7703 kg SST kg^{-1} COD ($R^2 = 0.9909$). The Y_{obs} of a small WWTP ranges between 0.30 – 0.45 kg SST kg^{-1} COD (Foladori et al., 2010), without considering the contribution of the sludge post-treatment (i.e. anaerobic or aerobic digestion). Thus, the Y_{obs} referred to the reference period was higher than reported values of typical domestic wastewater.

Furthermore, the specific sludge production in terms of amount of dried sludge disposed of was evaluated. In the reference period, the mass of total solid sludge flooded by the plant as waste accounted for 38,525 kg TS_{dried}, while the amount of substrate removed was 66,629 kg COD. Thus, the overall specific sludge production in the reference period was estimated to be 0.58 kg TS_{dried} kg^{-1} $COD_{removed}$. The comparison between this result and the biological Y_{obs} suggested that, during the reference period, the aerobic digestion of sludge contributed for 24% to sludge reduction. As for the biological Y_{obs}, the value of the specific production of dried sludge was higher than that reported in literature for typical domestic WWTPs, equal to 0.30 ± 0.07 kg TS_{dried} kg^{-1} COD (Foladori et al., 2010). These findings contributed to demonstrate that the sludge production of Marmirolo's WWTP is high as compared with other small WWTPs. Thus, some modifications to the Marmirolo's WWTP could be useful to ensure an improvement of the whole WWTP scheme in order to achieve a lower sludge production.

The same evaluation of the Y_{obs}, referred only to the biological compartment of the WWTP, was performed after the implementation of the UTN system for both period I and II. The Y_{obs} of period I and II was 0.3864 kg SST kg^{-1} COD ($R^2 = 0.9616$) and 0.2344 kg SST kg^{-1} COD ($R^2 = 0.9898$), respectively (Fig. 2), both lower than the Y_{obs} calculated in the reference period.

Results showed that the implementation of the UTN system contributed to 50% and 69% in the biological sludge reduction, respectively, in period I and II, as compared to the reference period. Furthermore, the mass of total solid sludge flooded by the WWTP as a waste was equal to 19,702 kg TS_{dried} and 9200 kg TS_{dried} during period I and II respectively, while the amount of substrate removed was 51,896 kg COD in period I and 325 kg COD in period II. Thus, the overall sludge production in period I was estimated to be 0.38 kg TS_{dried} kg^{-1} COD and 0.24 kg TS_{dried} kg^{-1} COD in period II. These data highlighted that, in both periods, the sludge production of dried sludge was equal to the specific sludge production of the biological compartment since, after the implementation of the UTN system, the sludge line only comprised the belt press filter, without any other treatment for sludge reduction such as anaerobic/aerobic digestion.

Moreover, considering the contribution of the aerobic digestion in the reference period and the overall sludge production of 0.58 kg TS_{dried} kg^{-1} COD, the implementation of the UTN system allows to obtain a reduction in the total sludge production of the WWTP equal to 34% and 59% in period I and II, respectively.

Despite the sludge reduction obtained in this full scale application after the UTN implementation, the obtained results were lower than those reported in our lab-scale previous studies (Ferrentino et al., 2018, 2016), where for a SBR-ASSR system working at 2.5 days of SRT and 100% IR a Y_{obs} of 0.12 g TSS g^{-1} COD was obtained, accounting for a sludge reduction of 66%. This was probably linked to the lower SRT_{ASSR}, fixed at 2.4 days in the full scale application, and to the lower design IR that was about 60%. Moreover, at full scale applications, it should be considered that the influent wastewater characteristics, and as a consequence the recycling sludge characteristics, are variable, thus causing a fluctuation on the IR value. In this study, the actual IR was indeed lower than the design one due a variation in the TSS concentration of sludge,

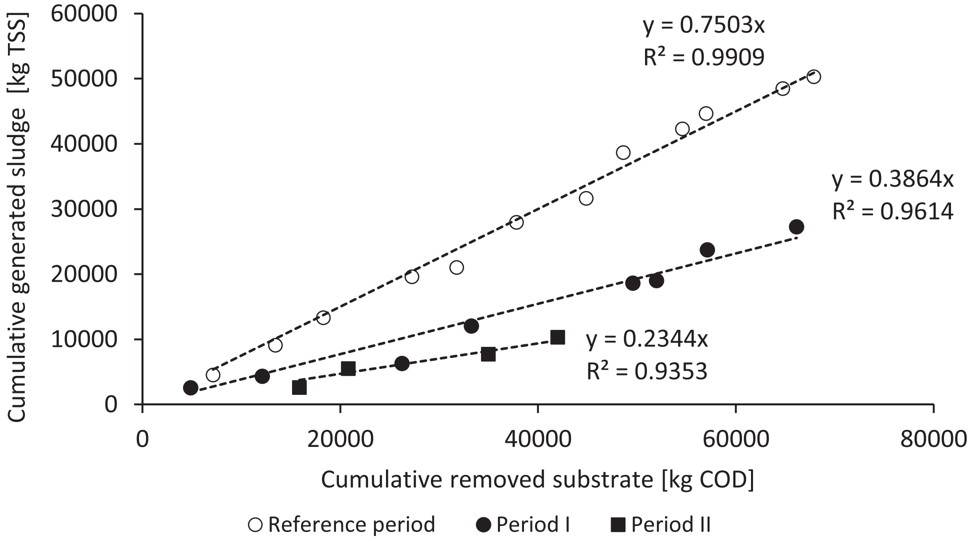

Fig. 2. Cumulative sludge production.

varying from 24% to 55%. This variation in the IR value could negative influence the performance of the UTN process, leading to a lower sludge reduction compared to than expected by project.

On the contrary, the sludge reduction obtained in this full-scale application was higher than that reported by Velho et al. (2019, 2016), who investigated in both studies the performances of a full-scale ASSR, where the IR was equal to 7 - 10%, the anaerobic hydraulic retention time was 7 d and the ORP values was equal to −250 mV. Velho et al. (2016) reported, in the ASSR configuration, a value of Y_{obs} equal to 0.35 kg TSS kg^{-1} COD, 20% lower than that of the conventional activated process (0.44 kg TSS kg^{-1} COD). In Velho et al. (2019) the sludge reduction, however, was slightly higher (28%) than that reported in the previous study (20%), probably due to the smaller monitoring period. These results are referred to an ASSR configuration.

Moreover, in the present full-scale application, the introduction of the ASSR promoted an increase in the SRT of the whole WWPTP (biological compartment and ASSR) from 29 days up to 75 days. Even if some literature studies have reported that long SRT could contribute to the reduction of sludge production, however results obtained in this study cannot be linked exclusively to this aspect confirming what has been addressed by Salehiziri et al. (2018).

3.3. ASSR performances

Fig. 3a and b shows the concentration of soluble COD influent and effluent the ASSR. The average value of soluble COD in the influent stream of the ASSR was equal to 58 ± 30 mg L^{-1} and 20 ± 13 mg L^{-1}, respectively, during period I and period II, while it was equal to 120 ± 50 mg L^{-1} and 36 ± 20 mg L^{-1} in the effluent stream of the ASSR highlighting the substrate solubilization. For ammonium nitrogen, the increase in the concentration was even more pronounced (Fig. 3c and d).

The mean value of NH_4-N in the water line was 4.3 ± 1.5 mg L^{-1} and 2.9 ± 1.0 mg L^{-1}, respectively, during period I and II while it reached 25 ± 12 mg L^{-1} and 18 ± 8 mg L^{-1} in the effluent of the ASSR. These results are consistent with previous studies (Wang et al., 2008), where the release of soluble COD and NH_4-N in the anaerobic reactor was observed. Soluble compounds in supernatant of sludge after the ASSR may come from the hydrolysis of organic components of wastewater, cell lysis or extracellular enzymes (McSwain et al., 2005). In the ASSR some particulate organic compounds were hydrolysed to simple monomers and then, these simple organic substrates were degraded further to volatile fatty acids (VFAs) such as acetate, ethanol, propionate and butyrate (Wang et al., 2008). Moreover, the solubilized compounds could be used as cryptic substrates for aerobic microorganisms growth, denitrification and anaerobic phosphorous release meaning that most of these are biodegradable and, thus, do not cause negative effects on the removal efficiency (Semblante et al., 2017).

Furthermore, the increase in NH_4-N and total organic nitrogen was also observed by Zhou et al. (2015b) where the release of soluble microbial products was associated with the hydrolysis of particulate organic matters and cell lysis in the sludge holding tank, demonstrating the effects of the sludge decay under anaerobic conditions. The concentrations of orthophosphate (Fig. 3e and f) in the influent of the ASSR were always lower than that of the effluent. In period I the average PO_4-P concentration in the water line was equal to 39 ± 14 mg L^{-1} while, after the anaerobic treatment, reached an average value of 54 ± 7 mg L^{-1}. The increase in the PO_4-P concentration, after the ASSR treatment, was even more pronounced in period II where the average influent concentration to the ASSR was 79 ± 43 mg L^{-1} while the effluent concentration was 251 ± 127 mg L^{-1}. The rise of PO_4-P released under anaerobic conditions could be related to the increase of the selection of poly-P organisms (de Oliveira et al., 2018). These results are consistent with those reported by Goel and Noguera (2006), where an increase in the PO_4-P concentration was detected under anaerobic conditions. The authors highlighted that the alternation between aerobic and anaerobic environments may favor the selection and growth of phosphate accumulating organisms (PAOs) and denitrifying phosphate accumulating organisms (DPAOs), which, using the biodegradable compounds generated by cell lysis, contribute to the reduction of sludge production and to the biological phosphorous removal.

To evaluate the presence of PAO and DPAO in the ASSR sludge, PUR tests were used. The results of batch tests on TPAO, in the first monitoring of the UTN system (period I), showed that the average specific phosphorous uptake rate in aerobic conditions was equal to 1.58 mg PO_4-P g^{-1} TSS h^{-1}, while the average specific phosphorous uptake rate of DPAO in anoxic conditions was equal to 0.71 mg PO_4-P g^{-1} TSS h^{-1}. These results allowed to calculate the percentage of DPAO over TPAO that varied from 34 to 54% with an average value of 41%.

The selection of TPAO and DPAO was even more evident in period II, where the specific phosphorous uptake rate in aerobic conditions was equal to 1.95 mg PO_4-P g^{-1} TSS h^{-1} while the average specific phosphorous uptake rate of DPAO in anoxic conditions was equal to 0.76 mg PO_4-P g^{-1} TSS h^{-1}. Thus, the percentage of DPAO over TPAO ranged between 45 and 77%, with an average value of 61%. The obtained phosphorous uptake rate as well as the percentage of DPAO over TPAO are consistent with results obtained at lab-scale (Ferrentino et al., 2018), meaning that a selection of DPAO was obtained also in the full scale implementation of the UTN system.

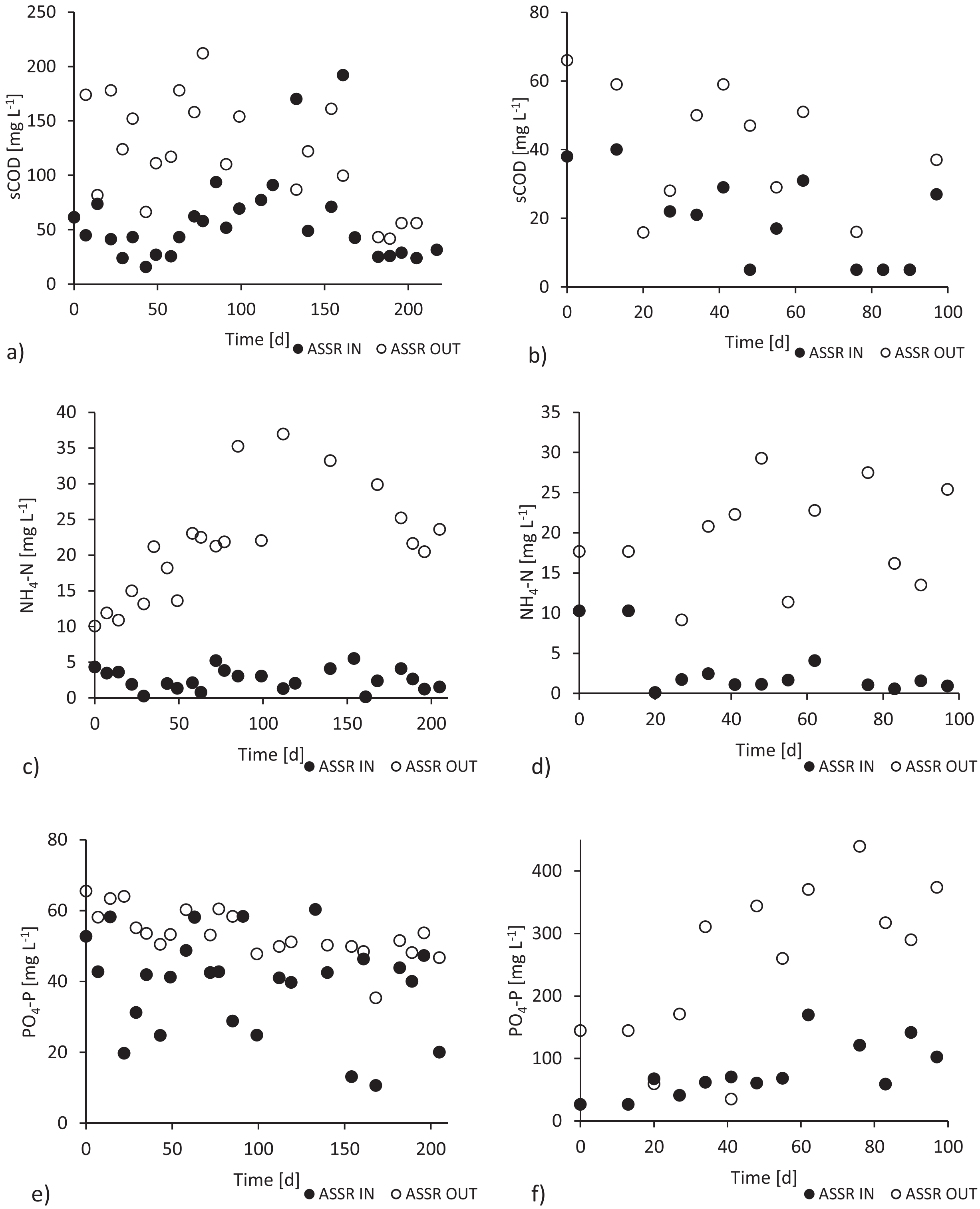

Fig. 3. Profile of sCOD during a) period I and b) period II, NH_4-N during c) period I and d) period II, PO_4-P during e) period I and f) period II.

3.4. Energy consumption

The daily energy consumption of the WWTP was equal to 457 ± 44 kWh d^{-1} and 550 ± 50 kWh d^{-1}, respectively, during the reference period and period I, revealing that the overall energy consumption after the implementation of the UTN system was higher than that of the reference period.

However, in order to make a pair comparison between the two monitoring periods, specific energy consumptions were assessed with respect to the amount of COD removed, expressed in kg, and to the PE.

The specific energy consumption based on the COD removed was similar during both monitored periods, equal to 2.50 ± 1.1 kg Wh kg^{-1} COD and 2.52 ± 1.4 kg Wh kg^{-1} COD, respectively, indicating that in the Period I a higher load of COD has been treated by the WWTP, as

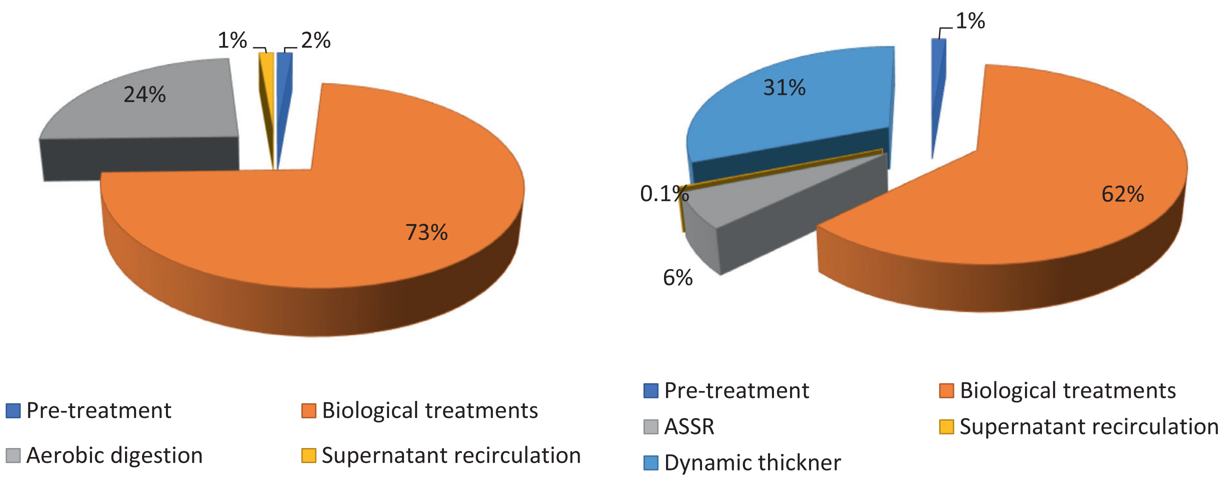

Fig. 4. Energy consumption of different treatment units in the a) reference period and b) period I.

compared to the reference period. Similarly, the specific energy consumption based on the PE, accounted for 90 ± 30 kWh PE^{-1} $year^{-1}$ and 84 ± 43 kWh PE^{-1} $year^{-1}$, respectively, in the reference period and in period I. The values reported are in the range with those reported in the literature for small WWTPs (55 – 90 kWh PE^{-1} $year^{-1}$) (Campanelli et al., 2013). Thus, a slight increase in the energy consumption of the WWPT has been registered.

Thus, energy consumption was analysed in detail. Fig. 4 summarizes the consumption, in percentage, of the different treatment units on the overall energy consumption of the WWTP.

After the implementation of the UTN system, the consumption of the water line, comprising pre-treatments and the biological compartments, accounted for 63% of the total energy consumption against 73% of the reference period. Thus, a decrease of 10% was observed mainly ascribed to a better management of the aeration phases in the biological compartments due to the implementation of alternated anoxic/aerobic phases. Considering the sludge treatment, in the reference period, the energy consumption accounted for 24% (aerobic digestion) against 37% after the implementation of the UTN system (ASSR + dynamic thickener). However, it must be highlighted that in the UTN system, the ASSR only contribute for 15% of total energy consumption of the sludge line, while the higher energy consumption was due to the solid separation unit used before the ASSR reactor, that is a very energy-intensive unit. Consequently, other solid separation units, besides dynamic thickener, may be considered in the implementation of UTN system, in order to optimize energy consumptions.

3.5. Research limitations and future implications

The main limitation of this study was the implementation of the UTN System to an existing WWTP. Thus, there was no possibility of building a plant with optimal reactors volume for the process, but all the existing compartments were adapted to the proposed scheme. This implied the need to make design choices that best matched the parameters of the UTN process, with the awareness that the process was not applied do its maximum potential.

Furthermore, specific details about costs and benefits of the process are lacking. Costs could be attributed to the construction, operation and maintenance and management of the process. On the contrary, benefits could be ascribed to a smaller amount of sludge to be disposed of and, consequently, to a lower incidence of this cost item on the overall plant management costs and, moreover, to the need not to add chemicals for nutrients removal.

However, this first full scale application has clearly revealed the feasibility of UTN system implementation, in both new and existing WWTP. In the European Union sludge production is around 13.5 Mt SS $year^{-1}$ (Eurostat, 2020). Considering a sludge disposal cost of about 100 € ton, the application of the UTN system could reduce the sludge production up to 6.75 Mt $year^{-1}$ and save you up to 675 milion per year.

4. Conclusions

A new sludge reduction system, whose acronym is UTN (University of Trento), was proposed and tested at full scale for reducing the amount of sludge in an integrated water line – sludge line configuration of the wastewater treatment plant. Full-scale adoption of a new cost-effective treatment for sludge reduction contributes to the innovation and technology management. The UTN system was monitored for 10 months; sludge production and typical pollutants parameters of 6000 PE WWTP were evaluated to assess the effectiveness of the process. Depending on the UTN operative conditions, the cumulative sludge production was equal to 0.23 - 0.37 kg TSS per kg of COD removed, 50% - 69% lower than that observed in the reference period. Furthermore, high and stable performances in terms of COD, NH_4-N, TN and PO_4-P removal efficiency were obtained, accounting respectively up to 92%, 98%, 90% and 92%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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