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Mesophilic anaerobic digestion of waste activated sludge: influence of the solid retention time in the wastewater treatment process

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Abstract

The performance of mesophilic anaerobic digesters of four large Italian wastewater treatment plants without primary sedimentation were studied. Only the waste activated sludge is stabilised by means of the mesophilic (35–37 °C) anaerobic digestion process. The anaerobic digesters generally worked with a hydraulic retention time in a range of 20–40 days and an organic loading rate of some 1 kg $VS/m^3_{reactor}$ day. The solids content of the sludge fed to the digesters was in the range 2.6–3.9% and the gas produced per kilogram of volatile solids added was in the range 0.07–0.18 m^3/kg VS_{fed}. The specific gas production per kilogram of volatile solids destroyed was in the range 0.5–0.9 m^3/kg $VS_{destroyed}$ and the reduction of the volatile solids concentration was in the range 13–27% (average 18%). These figures are particularly significant when designing anaerobic digesters for the treatment of waste activated sludge as single substrate. Moreover, it was observed that the higher the applied solid retention time in the activated sludge process for wastewater treatment, the lower the gas production. In particular, the specific gas production decreased from 0.18 to 0.07 m^3/kg VS_{fed} when increasing the solid retention time in the wastewater treatment line from 8 to 35 days. Finally, a mathematical model for the prediction of biogas production on the solid retention time applied in the wastewater treatment process was developed.

Keywords: Mesophilic anaerobic digestion; Digester performances; Energetic balance; Solid retention time; Waste activated sludge; Sludge pre-treatment

1. Introduction

The need to fulfil stringent effluent standards for COD (BOD), nitrogen and phosphorous in wastewater treatments, has determined in recent years the adoption of advanced activated sludge processes for nutrients removal. The biological nutrients removal (BNR) processes, either for nitrogen or both nitrogen and phosphorous removal, can be performed only when the necessary amount of carbon in the treated wastewater is available. As a result the primary settling tanks in these wastewater treatment plants (WWTPs) are generally absent to preserve the particulate fraction of the influent COD. Moreover, in order to preserve the nitrification capability of the activated sludge, high solids retention times (SRT) are applied to the biomass in the activated sludge process (>10 days). As a consequence, a partial sludge stabilisation occurs in the activated sludge process and the following anaerobic stabilisation of waste activated sludge can result in low efficiency both from a processing and an economic standpoint [1,2] since this substrate shows a low biomethanisation potential [3]. The specific biogas production determined on the destroyed volatile matter when treating the waste activated sludge is in the range 0.6–0.8 m^3/kg $VSS_{destroyed}$ rather than a typical value of some 1 m^3/kg $VSS_{destroyed}$ observed when digesting mixed sludge (primary and secondary sludges) [4]. This fact results in a decrease in biogas production so that the energetic balance of the anaerobic digester is often negative if sludges are not properly thickened, especially in winter [2].

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Although these problems are well known to technicians and researchers, only some figures for designing anaerobic digesters treating waste activated sludge are reported in literature [4–6] and cited ranges of operational conditions are quite broad. Therefore, some problems may arise when designing the anaerobic digestion section of wastewater treatment plants where the sole waste activated sludge is stabilised. In order to better understand the expected performances and the problems related to the managing of these kind of processes, research was carried out involving four Italian large WWTPs without primary sedimentation (size in the range 50.000–300.000 PE). In three of these WWTPs the anaerobic digestion of secondary sludge is performed in mesophilic anaerobic digesters working with an organic loading rate (OLR) of some 1 kg $VS/m^3_{reactor}$ day and a hydraulic retention time (HRT) in the range 20–40 days. For the fourth plant, where the sludge treatment line was missing (sludge was only dewatered in belt filters), the anaerobic digestion trials were carried out on a lab-scale.

This paper presents the data and performances for both the wastewater and the sludge treatment lines and reports the main figures of the processes. From the figures determined for these plants, a clear relationship between the specific gas production (SGP, $m^3/kg\ VS_{fed}$) and the applied SRT in the wastewater treatment line was demonstrated and a mathematical model of the process was proposed.

2. Materials and methods

The four WWTPs considered in this study did not adopt the primary sedimentation to preserve the available carbon in wastewaters in order to perform the biological removal of either nitrogen or nitrogen and phosphorous. Two of the studied WWTPs (size of 50.000 and 300.000 PE) treated mixed municipal and industrial wastewaters in a pre-denitrification/nitrification process (D–N) for carbon and nitrogen removal. In the third WWTP the carbon and nitrogen removal was carried out by applying two different processes: the Carousel® process, in three tanks working in parallel, and the automatically controlled alternated cycles process® [7]. In the largest of these WWTPs the phosphorous was chemically removed by addition of iron directly in the aerobic tank, while in the other two WWTPs no specific processes for phosphorous removal were present. The fourth WWTP (70.000 PE) treated municipal wastewaters in a nitrogen and phosphorous biological removal process (BNR) [8]. In the three WWTPs where the stabilisation of the waste activated sludge was performed, digesters were fed with pre-thickened sludge and followed by a post-thickening section, before dewatering anaerobic sludges by belt filter presses. The concentration of waste activated sludge before feeding the anaerobic digesters was obtained by means of a gravity thickening step.

Table 1
WWTPs considered in this study

Plant	Applied process	Nominal size (PE)	Design flowrate (m^3/day)
1	D–N	300.000	100.000
2	D–N	50.000	15.000
3	BNR	70.000	12.000
4	D–N	100.000	30.000

D–N: pre-denitrification/nitrification process; BNR: biological nutrients removal process.

The type of applied process, the design size (as people equivalent) and the design flowrate of the four WWTPs considered in this study are reported in Table 1.

The main figures of both the wastewater and the sludge treatment lines of the four WWTPs are reported in Table 2.

The data related to the operational conditions and the performances of both the wastewater treatment line and the sludge treatment line of the period 2000–2002 were recorded and processed for the purposes of this paper. During these 2 years the significant periods, in terms of digesters feeding, were individuated and both the operational conditions and performances were determined. These figures provide the set of data for the following elaborations. With reference to the WWTP number 3, where in last 2 years two different SRT in the wastewater treatment line have been set, the data reported are divided in two different operating periods, one with a SRT of 15 days and another with a SRT of 45 days (Table 3).

Table 2
Main figures of the four studied WWTPs

	Plant			
	1	2	3	4
Wastewater treatment line				
Lines (number)	3	2	1	1 + 1[a]
Anaerobic tank (m^3)	–	–	700–1200[b]	–
Anoxic tank (m^3)	18000	1370	1600–2200[b]	–
Aerobic tank (m^3)	33600	5400	5500	4500 + 2200[a]
Pre-anoxic (m^3)	–	–	400–1200[b]	–
Secondary clarifiers (number)	3	5	2	3
Surface (m^2)	5400	1754	1300	1500
Sludge treatment line				
Anaerobic digesters (m^3)	2 × 3367	Lab-scale	2200	3000 + 1500

[a] This WWTP presents two independent treatment lines, one with three parallel Carousel® basins and one operating the alternate cycles process®.
[b] The volumes can be changed according to the process optimisation.

Table 3
Main figures and performances of the wastewater treatment lines

	Plant				
	1	2	3 (SRT = 15 days)	3 (SRT = 45 days)	4
Loads					
Actual flowrate (m^3/day)	102460	13500	10900	10300	26700
Organic loading (kg COD/day)	39700	2515	2420	2110	9790
Nitrogen loading (kg N/day)	2900	367	129	157	815
Phosphorous loading (kg P/day)	570	40	26	24	95
Solids loading (kg SS/day)	24100	2700	2270	1285	3990
People equivalent (on COD, PE)	330000	23900	23000	20100	93000
Specific volume (l/PE)	150	280	380	440	72
Removal efficiencies					
COD (%)	86	87	95	94	84
Nitrogen (%)	68	65	67	75	57
Phosphorous (%)	77	40	57	58	44
Suspended solids (%)	86	84	95	91	84
Operational parameters					
Biomass (g/l)	4.2	6.5	4	7	4.3
F/M (kg COD/kg ML VSS day)	0.18	0.05	0.06	0.02	0.3
Y_{obs} (kg ML VSS/kg COD day)	0.21	0.44	0.35	0.3	0.3
SRT (days)	16	35	15	45	8

3. Results and discussion

The treated loads of pollutants, the performances as well as the typical operational conditions of the wastewater and the anaerobic digesters of the WWTPs considered are shown in Tables 3 and 4.

3.1. Wastewater treatment line

According to the data reported in Table 3, only the WWTPs 1 and 4 treated loads of pollutants similar to the design loadings (in terms of COD), while the WWTPs 2 and 3 treated just one half of the designed people equivalent (PE). Consequently, the WWTPs 1 and 4 show low specific volumes, equal to 150 and 72 l/PE, respectively, whereas WWTPs 2 and 3 have large availability of volumes (specific volumes of some 300–400 l/PE) and greater loads of pollutants than those actually fed could be treated. The latter are clearly low loaded WWTPs, where large SRTs can be applied to the activated sludge process adopting a sort of extended aeration process. The set SRTs for the process were very different for each WWTP, ranging from 8 (WWTP number 4) to 45 days (WWTP number 3, see Table 3). On the other hand, the typical biomass concentrations applied in these WWTPs were quite similar and equal to some 4 g/l, up to 6.5 g/l in WWTP number 2, while the 7 g/l of WWTP number 3 was set for only a relatively brief period. Since the treated organic loadings were very different the consequence

Table 4
Main figures and performances of the anaerobic digesters of the sludge treatment lines

	Plant				
	1	2	3 (SRT = 15 days)	3 (SRT = 45 days)	4
Feed characteristics					
Total solids feed (g/l)	38	26	35	39	27
Total volatile solids feed (g/l)	22	18	22	25	18
Total volatile solids loading (kg TVS/$m^3_{reactor}$ days)	1.0	0.8	0.8	0.7	1.0
Operational conditions					
Digesters temperature (°C)	37.6	35.8	35	34	36
pH	7.3	7.1	7.0	6.9	6.9
Total alkalinity, at pH 4 (mg$CaCO_3$/l)	NA	2000	1700	700	2200
Solid and hydraulic retention time (days)	21	20	33	40	22
GPR (m^3_{biogas}/$m^3_{reactor}$ days)	0.18	0.07	0.08	0.04	0.15
SGP (m^3_{biogas}/kg TVS_{feed})	0.16	0.08	0.16	0.07	0.18
SGP* (m^3_{biogas}/kg $TVS_{destroyed}$)	0.5	0.6	0.6	0.5	0.9
TVS reactor (g/l)	17	15	16	22	15
TVS removal (%)	22	17	27	13	15

was that the WWTPs 1 and 4 showed a food to microorganisms ratio, F/M, equal to 0.18 and 0.3 kg COD/kg ML VSS day, while the WWTPs 2 and 3 showed F/M ratios always lower than 0.1 kg COD/kg ML VSS day. The sludge yields (Y_{obs}), as kg ML VSS/kg $COD_{removed}$, were very different in the four WWTPs considered in the study and seemed not to be tied to the organic loading of the system, but always in the range 0.2–0.4 kg ML VSS/kg $COD_{removed}$ (see Table 3).

The removal efficiencies were good for both the COD and the suspended solids, generally >84%: the WWTP number 3, which treats the lowest loads of pollutants, showed the best results in terms of COD and suspended solids removal (>90%) while the other three plants were very similar in the removal efficiency (some 85% for both the pollutants). The nitrogen removal was quite similar in all the WWTPs, but in plant number 4 was only 56% because of the low efficiency of the Carousel® process. Phosphorous was effectively removed in WWTP number 1, where a chemical precipitation process was adopted (efficiency > 70%) and in WWTP number 3 (efficiency near to 60%) where an anaerobic step, specifically introduced for the biological phosphorous removal, was present. On the other hand, the phosphorous removal in WWTPs 2 and 3, where a specific process for the removal of phosphorous was not present, was very similar in both cases and equal to 40% and 44%, respectively.

3.2. Sludge treatment line

Table 4 summarises the averages of operating data recorded and the performances of the anaerobic digesters of the WWTPs considered in this study. The hydraulic retention time (HRT) ranged between 20 and 40 days, while the organic loading rate (OLR) was some 1 kg TVS/$m^3_{reactor}$·day or less.

All the parameters for the monitoring of the process stability (pH, alkalinity, gas production and temperature) showed typical values for this kind of process [2,9–11].

Perhaps one of the most significant observations of this study is the relatively low solids content of waste activated sludge fed to anaerobic digesters. The average concentration of total solids in the pre-thickened sludge was 3.3%, with a minimal concentration of 2.6%. This value is a half of the typical concentration of primary and secondary sludge fed to digesters [5]. Dilute feed sludges are a major root cause of several negative impacts on digester and WWTP operations. Among the others also have relative importance: a reduced hydraulic retention time, a reduced capacity in volatile matter stabilisation and methane production, an increase in volumes of digested sludge and supernatants and an increase in heating requirements. The authors have already shown that a sludge concentration >4% should always be preferred when feeding waste activated sludge to the anaerobic digesters [2]. However, despite the variability in total suspended solids concentrations, the volatile solids concentration was generally in the range 18–22 g/l: because of this situation the organic loading rate (OLR) was some 1 kg TVS/$m^3_{reactor}$ day for all the digesters. As regards biogas production performances (see Table 4), the gas production rate, GPR, was in the range 0.04–0.18 m^3_{biogas}/$m^3_{reactor}$ day, the specific gas production, SGP, per kg of volatile solids added to the reactor ranged from 0.07 to 0.18 m^3_{biogas}/kg TVS_{feed} and the specific gas production per kg of volatile solids destroyed was generally equal to 0.5–0.6 m^3_{biogas}/kg $TVS_{destroyed}$ except for WWTP number 4, where it reached a value of 0.9 m^3_{biogas}/kg $TVS_{destroyed}$. The volatile solids removal was always low and in the range 13–27% instead of the typical 50% observed in digesters treating mixed sludges [4–6].

All these figures are in perfect agreement with literature data (see Table 5), but it is important to emphasize that in this study the yields of full scale WWTPs are reported rather than data from lab or pilot scale plants, therefore these can be considered a valuable database for designers and consultants when considering operational conditions and performances of the anaerobic digestion of waste activated sludge as sole substrate.

From the collected data it was clear that a relationship existed between the specific gas production (SGP) and the applied SRT in the activated sludge process. In particular, the highest the applied SRT the lowest the biogas production (see Fig. 1).

From the experimental results collected in this study an empirical relationship can be written

$$SGP = 0.23\,e^{-0.028\,SRT} \quad (1)$$

where SGP is the biogas production per kg of volatile solids fed (m^3/kg VS_{fed}) to the anaerobic digester and SRT is the solid retention time applied to the activated sludge process.

Table 5
Typical data reported in literature for the anaerobic digestion of waste activated sludge

Reference	Scale	SGP* (m^3/kg $VS_{destroyed}$)	TVS removal (%)	HRT digester (days)
[9]	Lab	0.6–0.9	14–30	45
[10]	Full	0.6[a]	29–36	20
[12]	Lab	0.4–0.5[a]	19–35	10–20
[13]	Lab	0.15–0.25[a]	18–27	8–12
[14]	Pilot	0.6	24	20–30

[a] Only methane.

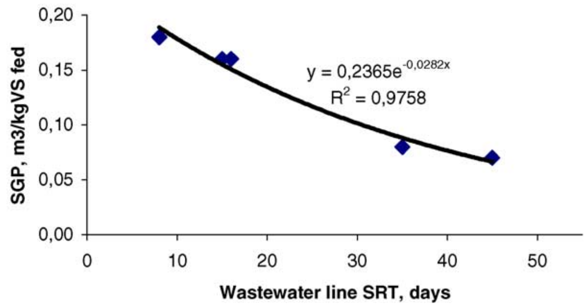

Fig. 1. Dependence of the gas production per kg of volatile solids fed (SGP, m^3/kg VS_{fed}) on the solid retention time (SRT) applied in the wastewater treatment.

According to this equation, passing from 10 to 20 days of SRT in the activated sludge process determines a decrease in the specific gas production (m^3/kg VS_{fed}) of some 25%.

This is probably because the application of high SRTs in the activated sludge process determines the aerobic biodegradation of the most biodegradable part of the activated sludge, that is the particulate organic matter in the influent wastewater trapped in sludge flocs and the residues of the cells hydrolysis and part of the viable cells [9]. Recent studies by Novak et al. [15] have shown that exocellular biopolymer rather than cells undergo lysis and produce short chain organic compounds which are then converted into methane. Consequently, cells should break down by some kind of chemical, physical or biological treatments to improve the digester performances [16].

The literature data reported in Table 5, concerning the performances of digesters treating waste activated sludge, are generally taken from studies dealing with some kinds of pre-treatment applications to improve the waste activated sludge digestability. In particular, Lin et al. [12] tried an alkaline solubilisation, Wook et al. [14] verified the possibility of adopting a mechanical pre-treatment (disintegration), Laffitte-Troque and Forster [13] reported the data concerning the use of ultrasounds and gamma-irradiation as pre-treatments to enhance the anaerobic digestion of waste activated sludge. All these pre-treatments generally determine a 15–30% increase in biogas production and a 10–20% increase in volatile matter removal. A number of other studies concerning pre-treatments techniques for mixed or secondary sludge to increase the digesters performances can be found in literature. However, these generally are lab-scale experiences, and data from full scale applications of sludge pre-treatments are still poor.

Clearly, when these methods are applied, other problems should be taken into account: the increased lysis determine an increase in nutrients concentrations in supernatants from the anaerobic digesters and those have to be treated in the wastewater treatment process, moreover, disintegrated sludge generally show a deterioration of dewaterability capacity and an increase in polymer demand should be expected [17].

3.3. Mathematical modelling of the anaerobic digestion process of the waste activated sludge

From the results obtained in this study, a mathematical model was developed starting from that proposed by Gosset and Belser [9] to predict the expected performances, in term of biogas production, of the anaerobic digester, varying the solid retention time applied to the activated sludge in the wastewater treatment process. Generally speaking, biogas production is due to the degradation of the organic matter present in the waste activated sludge:

$$\text{volume biogas} = \alpha Q(S_{\text{in}} - S_{\text{out}}) \tag{2}$$

where α is the conversion coefficient of substrate in biogas, Q the feed flowrate (m^3/day) and S_{in} and S_{out} are the influent and effluent concentrations of substrate (kg/m^3). For methane produced by the degradation of COD as substrate a conversion coefficient $\alpha = 0.35$ applies.

According to these results, the fraction of influent substrate biodegraded in the anaerobic digestion process depends on the applied SRT in the activated sludge process (wastewater treatment line) and to the kinetic of biodegradation within the anaerobic digester, therefore we have to define the influent substrate as a function of these two parameters. The biodegradable fraction of the activated sludge was found to be equal to [9]:

$$f_{\text{d}}^{\text{WAS}} = f_{\text{d}} \frac{X_{\text{active}}}{X} \tag{3}$$

where f_d^{WAS} is the biodegradable fraction of the waste activated sludge, f_d the net biodegradable fraction of the active biomass, X_{active} (kg/m^3), and X the total concentration of the volatile suspended solids (kg/m^3). Since the latter is equal to the sum of the active and the decayed biomass, we will have:

$$X = X_{\text{active}} + X_{\text{active}}(1 - f_{\text{d}})k_{\text{d}}^{\text{AS}}\text{SRT}^{\text{AS}} \tag{4}$$

where k_d^{AS} is the decay coefficient in the activated sludge process and SRT^{AS} is the solid retention time applied in the activated sludge process. Therefore, the biodegradable fraction of the waste activated sludge is

$$f_{\text{d}}^{\text{WAS}} = f_{\text{d}}\left(\frac{X_{\text{active}}}{X}\right) = f_{\text{d}}\left(\frac{1}{1 + (1 - f_{\text{d}})k_{\text{d}}^{\text{AS}}\text{SRT}^{\text{AS}}}\right) \tag{5}$$

According to this equation, the biodegradable fraction of the substrate influent the anaerobic digester, as COD, is

$$S_0 = \text{COD}_{\text{IN}} f_{\text{d}}\left(\frac{X_{\text{biod}}}{X}\right) \tag{6}$$

where X_{biod} is the concentration of the biodegradable part of the activated sludge (kg/m^3).

Since it is known that the concentration of the active biomass decreases with the increase of the solid retention time (SRT) [18], the value of f_d was considered as a function of the applied SRT according to the formula: $f'_{\text{d}} = f_{\text{d}}\,e^{-\beta\,\text{SRT}}$, where f_d is 0.8 [9] and β, according to the experimental results, is 0.006. Moreover, as said above, the actually biodegraded fraction of influent substrate is also function of the anaerobic digestion kinetic. For a continuously stirred digester and considering a first-order kinetic:

$$\frac{X_{\text{active IN}} - X_{\text{active OUT}}}{X_{\text{active IN}}} = \frac{K \cdot \text{HRT}^{\text{dig}}}{1 + K \cdot \text{HRT}^{\text{dig}}} \quad (7)$$

where X_{IN} and X_{OUT} are the influent and effluent digester concentrations of active biomass (kg/m^3), K the first-order kinetic constant (day^{-1}) and HRT$^{\text{dig}}$ the hydraulic retention time in the anaerobic digester. S_0, the concentration of potentially biodegradable influent substrate is then:

$$S_0 = \text{COD}_{\text{IN}} \left(\frac{f'_d}{1 + (1 - f'_d) k_d^{\text{AS}} \text{SRT}^{\text{AS}}} \right) \times \left(\frac{K \cdot \text{HRT}^{\text{dig}}}{1 + K \cdot \text{HRT}^{\text{dig}}} \right) \quad (8)$$

And, according to Eq. (2), the produced biogas, as methane, will be:

$$\text{VolCH}_4 = 0.35Q(S_0 - S) = 0.35Q \left[\text{COD}_{\text{IN}} \left(\frac{f'_d}{1 + (1 - f'_d) k_d^{\text{AS}} \text{SRT}^{\text{AS}}} \right) \times \left(\frac{K \cdot \text{HRT}^{\text{dig}}}{1 + K \cdot \text{HRT}^{\text{dig}}} \right) - \text{COD}_{\text{OUT}} \right] \quad (9)$$

From the typical operational conditions and experimental results found in this study, the following values to be introduced in Eq. (9) may be defined: the average influent COD was 30 kg/m^3, the biodegradable fraction of the waste activated sludge, f_d, was chosen equal to 0.8 [9] while the effluent substrate, COD$_{\text{OUT}}$, was assumed equal to average 80% of the treated substrate, k_d^{AS} was equal to 0.06 day^{-1}, from kinetic studies, K, the first-order coefficient, was found to be equal to 0.20 day^{-1}, the hydraulic retention time for the anaerobic digester, HRT$^{\text{dig}}$, was assumed equal to an average value of 25 days. The values of the SGP determined for the different WWTPs using the model were then compared to those observed. Fig. 2 shows the plot of the experimental versus the calculated data. It is possible to observe how the proposed model can predict the expected results in terms of SGP.

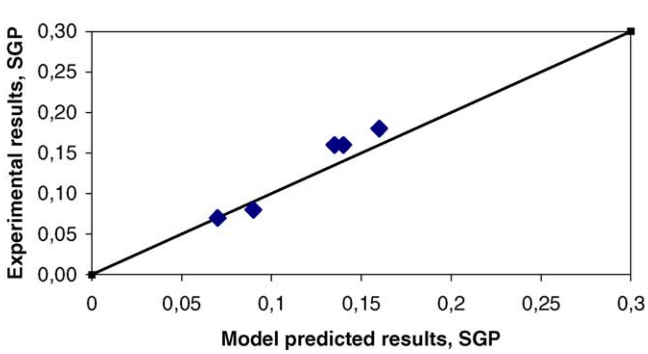

Fig. 2. Experimental vs. calculated data of specific biogas production (m^3/kg VS$_{\text{fed}}$).

3.4. Energetic considerations

It is generally accepted that anaerobic digestion is the best solution from an economic and environmental standpoint and should always be chosen when considering different options for the stabilisation of water works sludges [2,19], however some problems related to heat balance may arise when treating waste activated sludge as sole substrate. In particular, two problems have to be considered: the low biogas production (generally < 0.2 m^3/kg VS$_{\text{fed}}$) and the low concentration of volatile solids in the digester feed. These two aspects may upset the heat balance of the digesters. In this study, the hypothetical heat balance of the digesters considered in Table 4, was computed assuming the necessity to heat sludge from its temperature to the digester temperature (37 °C). Actual flow (m^3/day) and solids concentrations (kg/m^3) were considered for the calculations. Since in Italy the temperatures are very different moving from north to south, three different scenarios were considered. In particular, the winter temperatures of sludge were fixed at 12, 15 and 18 °C for north, central and south Italy, respectively, while the set temperatures in summer were equal to 20, 22 and 25 °C, for north, central and south Italy, respectively. A 80% efficiency of the heat transfer system and a heat power of 5500 kcal per m^3 of biogas were chosen. In all the digesters a 10% of heat loss was assumed [20]. The results of the computation are reported in Table 6: here, the percentages of the heat balance covered by the combustion of the produced biogas for the different digesters are reported.

It is clear then, that the anaerobic digesters can generally sustain their operational temperature in summer but they have some trouble in winter. None of the considered digesters was able to self-sustain the mesophilic range of temperature. Speece [5] showed the same results for low loaded digesters treating dilute sludge. The results are clearly better when considering situation in the south, where wintertime is quite temperate. This situation can be found in all the Mediterranean region. Unfortunately, when the operational

Table 6
Percentage of heat balance of the digesters in the studied WWTPs satisfied by the produced biogas

		Plant				
		1	2	3 (SRT = 15 days)	3 (SRT = 45 days)	4
North Italy	Winter	65	56	50	35	28
	Summer	94	83	77	50	43
Central Italy	Winter	73	64	57	37	32
	Summer	106	96	89	59	49
South Italy	Winter	85	74	68	44	38
	Summer	131	122	115	78	62

temperature was not reached, the use of a supplementary fossil fuel was necessary to get the mesophilic range of temperature in the digesters. This problem can mainly be ascribed to the low pre-thickening efficiency. In fact, in all the studied WWTPs the pre-thickening step is carried out using a free sedimentation. This method is strictly related to the gravitational characteristics of the activated sludge and is not very satisfactory, especially in winter, when bulking problems generally arise and may determine a solid concentration <4%. The introduction of dynamic systems for pre-thickening is probably the right solution for these WWTPs to reach high concentrations of volatile solids in the digester feed. Beside thickening improvement, the adoption of pre-treatments processes to increase the sludge biodegradability, which has been discussed above, or the application of the co-digestion of waste activated sludge with organic wastes [21–25] or other substrates [26-28] can be a good solution to improve the biogas production exploiting the available volumes of anaerobic digesters. In these cases, beside heat, also electric power can be generated [2] by applying a unit for the co-generation of heat and power (CHP).

4. Conclusions

In this study the performances of the anaerobic digesters treating waste activated sludge produced in four large Italian wastewater treatment plants were considered. The main conclusions of the study were the following:

- The figures for the design of anaerobic digesters treating waste activated sludge were found. These values were determined on a full scale basis and were only in partial agreement with literature data which are generally determined on a lab-scale basis. The gas produced per kilogram of volatile solids added was in the range 0.07–0.18 $m^3/kg\ VS_{fed}$, the specific gas production per kilogram of volatile solids destroyed was in the range 0.5–0.9 $m^3/kg\ VS_{destroyed}$ and the reduction of the volatile solids concentration was in the range 13–27% (average 18%), when working with a hydraulic retention time in a range of 20–40 days and an organic loading rate of some 1 $kg\ VS/m^3_{reactor}day$. The solids content of the sludge fed to the digesters was in the range 2.6–3.9%.
- The anaerobic digestion process is the best option for the stabilisation of wasted activated sludge from an economic and environmental standpoint when sludge is conveniently thickened. Moreover, some kind of pre-treatment of waste activated sludge should be adopted to improve its biodegradability and thus the heat balance of the digesters. Also co-digestion of sludge with other organic wastes is a good option, but the capability of the wastewater treatment line of facing the increased loads of pollutants originated from the anaerobic surnatants should be verified.
- A relationship between the specific gas production (SGP, in $m^3/kg\ VS_{fed}$) and the applied solid retention time (SRT) in the activated sludge process was found: the higher the SRT the lower the SGP. A model which predicts the digester performances was developed from that proposed by Gosset and Belser [9].

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