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Mesophilic and thermophilic anaerobic co-digestion of waste activated sludge and source sorted biowaste in pilot- and full-scale reactors

Cristina Cavinato [a,*], David Bolzonella [b,c], Paolo Pavan [a], Francesco Fatone [b,c], Franco Cecchi [b,c]

[a] Department of Environmental Sciences, Informatics and Statistics, University Ca' Foscari of Venice, Dorsoduro 2137, I-30123 Venice, Italy
[b] Department of Biotechnology, University of Verona, Strada Le Grazie 15, I-37134 Verona, Italy
[c] Interuniversity National Consortium "Chemistry for the Environment", Via delle Industrie, 21/8-30175 Venice, Italy

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ABSTRACT

The paper presents the results of a pilot- and full-scale experimental campaign on the anaerobic co-digestion of waste activated sludge and biowaste both in mesophilic and thermophilic conditions. The study demonstrated the possibility to increase the specific biogas production from 0.34 to 0.49 m^3/kgTVS and the gas production rate from 0.53 to 0.78 m^3per m^3 of reactor per day changing the reactor temperature from the mesophilic (37 °C) to the thermophilic (55 °C) range. The experimental work was carried out at pilot-scale, and the results match the full-scale behaviour. Ammonia nitrogen recycled from the anaerobic digestion section to the wastewater treatment plant accounted for about 4% of the total nitrogen loading. Digestate characteristics in terms of biological stability and heavy metals content suggested the opportunity of a short time post-aerobic stabilisation, leading to a high quality compost product.

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1. Introduction

The efficiency of biological nutrients removal (BNR) processes in wastewater treatment is based on the availability of easily biodegradable carbon in the wastewater to be treated. According to this evidence, primary sedimentation is generally avoided in wastewater treatment plants (WWTPs) adopting the BNR processes to preserve as much COD as possible. Moreover, in order to preserve the nitrification capability of the activated sludge also at low temperatures (winter season), high mean cellular retention times (MCRT) are applied in the activated sludge process (typically greater than 10 days). As a consequence of this high retention time, partial sludge stabilisation occurs in the activated sludge process. Therefore, the anaerobic digestion of waste activated sludge (WAS) can result in low efficiency both from a processing and an economic standpoint: observed values of the specific biogas production (SGP) are generally < 0.2 m^2 $kgVS_{fed}^{-1}$ as the removal efficiency for volatile solids is reported in the range 20–30% [1,2]. Anaerobic digesters treating waste activated sludge are therefore typically low loaded and scarcely efficient: their energy balance is very often negative during winter season [2,3]. In order to improve the performances of under-loaded anaerobic digesters, the co-digestion of waste activated sludge together with other organic wastes is a common practice adopted in wastewater treatment plants [4–8]. After we demonstrated in previous studies the full-scale reliability of the mesophilic co-digestion process, in this paper we report the results of a pilot- and full-scale study dealing with the passage from the mesophilic to thermophilic range of temperature. There are different strategies for changing the working temperature: the first strategy is the direct temperature switch from 35 to 55 °C, while the second one is the gradual temperature increasing in order to acclimatize the microorganism to the new temperature [9]. Some works were carried out on this topic [10–12] comparing this two approach; one of the most important aspect was the feeding strategy, in fact it was necessary to gradually increase the organic waste feeding in order to avoid the overload of the system.

In this experimental work one-step temperature change was tested in a pilot-scale single phase anaerobic digestion process, fed

Abbreviations: BNR, biological nutrient removal; WWTP, wastewater treatment plant; COD, chemical oxygen demand; MCRT, mean cellular retention times; WAS, waste activated sludge; SGP, specific gas production; VS, volatile solids; OFMSW, organic fraction of municipal solid waste; VFA, volatile fatty acid; GPR, gas production rate; OLR, organic loading rate.

* Corresponding author. Tel.: +39 0422 321037; fax: +39 0422 326498.
E-mail addresses: cavinato@unive.it (C. Cavinato), david.bolzonella@univr.it (D. Bolzonella), pavan@unive.it (P. Pavan), francesco.fatone@univr.it (F. Fatone), franco.cecchi@univr.it (F. Cecchi).

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with waste activated sludge and the organic fraction of food waste collected in Treviso integrated wastewater treatment plant. During temperature change the feeding was stopped in order to avoid an overload of organic substrate during the microbial shift from mesophilic to thermophilic temperature; on reaching the thermophilic range the organic loading rate was increased gradually to the final value. The results of this pilot-scale trial are reported, and then, according to the evidences coming from this first study, the same process was implemented at the Treviso Municipality full-scale plant (digester volume of 2000 m^3 and working temperature of 35 °C). Finally, the characteristics of the digestate and its possible use for agronomic purposes are discussed.

2. Materials and methods

2.1. Pilot plant

The pilot digester used for the experimental trials was a 380 L AISI 316 stirred tank. Temperature was controlled by an external serpentine, water filled, through a PT100-based thermostat. Reactor temperature, biogas production and composition were monitored continuously by an on-line probe system interfaced with a data logger.

2.2. Treviso wastewater treatment plant features

The full-scale plant, working since 1999, is a 70,000 p.e. system adopting the BNR (Johannesburg scheme) process; volumes of the pre-anaerobic, anaerobic and anoxic zones can be changed according to the necessity. Waste activated sludge produced during the treatment process is thickened to a 3% solids concentration and co-treated with organic fraction of municipal solid wastes (OFMSW) in a 2000 m^3 anaerobic digester. The OFMSW is firstly shredded and screened using a trommel screen after metals removal. Low magnetic permeability materials are then removed and the substrate is shredded using a blade hammer, 15 mm cut size. The biomass is then sent to a wet mixer/separator where the total solid content is diluted to 7–8% using the waste activated sludge coming from the WWTP. The floating residual materials and bottom residues are withdrawn. The mixture is then sent to the digester by a shredding pump, together with the rest of the excess sludge. Produced biogas is stored and used in a 190 kW_{ee} cogeneration unit for heat and power generation (CHP).

2.3. Substrates

The waste activated sludge and biowaste used in the study had the characteristics shown in Table 1.

The dry matter content of the waste activated sludge was 3.7%, 62% volatile. The COD/VS ratio was 0.9 instead of the typical 1.4 [2,3]. All these data confirm that it is a stabilised sludge with poor characteristics in terms of biogas potential. The OFMSW treated in the plant originated from the municipality of Treviso: it was a mixture of food waste from large communities (supermarkets, canteens, restaurants etc.) and separately collected household biowaste. The solids content was 22%, 84% volatile, while the COD/VS ratio was 1. This material present a considerable amount of inert material and some 20% of it is rejected in the sorting line of the full-scale plant. Most of the reject material (up to 90%) is plastic, iron, glass and stones [5,6].

Table 1
OFMSW and activated sludge characteristics.

	Average	Min.	Max.	Std.Dev
Waste activated sludge				
TS, g/kg w.w.	37.5	35.1	38.6	1.37
TVS, g/kg w.w.	23.2	22.7	24.3	0.66
COD, g/kg w.w.	21.6	19.5	24.7	1.96
TKN g/kg w.w.	1.7	1.5	1.8	0.11
Biowaste				
TS, g/kg w.w.	224.1	208.0	243.0	14.38
TVS, g/kg w.w.	189.3	175.0	209.6	14.98
COD, g/kg w.w.	207.8	172.5	233.0	27.09
TKN, g/kg w.w.	6.4	5.4	6.9	0.69

2.4. Analytical methods

The chemical and physical–chemical analyses were performed according to the Standard Methods [13] and other specific methods described elsewhere [14]. VFA analyses were performed using gas-chromatographic methods (Nukol column 0.53 id, 80–150 °C, 30 °C/min, det. Temp. 220 °C, Inj. Temp 220 °C). Respirometric index is evaluated following technical procedure of UNI/TS 11184 [12]. Gas production was monitored continuously by two gas flow meters (Ritter Company, drum-type wet-test volumetric gas meters), while the biogas composition (CO_2–CH_4–H_2S) was defined by a portable infrared gas analyser (Geotechnical Instrument, model. GA2000).

3. Results and discussion

3.1. Pilot-scale trials

The pilot-scale reactor was inoculated with the effluent of the full-scale mesophilic digester. During the start-up phase, from day 1 to 40 (run I), the digester was maintained in mesophilic conditions, while the applied OLR was 1.2 kgTVS/m^3 d. In a second run, from day 40 to 60, the reactor was fed with WAS mixed with the OFMSW for a resulting OLR of 1.60 kgVS/m^3 d. After one HRT (settled at 22 days as applied at full-scale) of steady state conditions, we stopped the reactor feeding and changed the temperature from 37 to 55 °C. The change occurred in 24 h. After 1 week without feeding, the digester was fed with an OLR equal to half of the original (0.8 kgVS/m^3 d same WAS/OFMSW ratio) in order to support microorganism adaptation. After 1 week, the OLR was raised to the full initial value (OLR 1.66 kgVS/m^3 d, run III). The new steady state conditions (SSC) were reached after 20 days and maintained for another complete HRT. A further period was studied, increasing the OLR to 2.21 kgVS/m^3 d using the same quantity of WAS and doubling the quantity of OFMSW fed to the system so to reproduce the design operational conditions of the full-scale digester (20 tonnes of OFMSW per day). Fig. 1 shows the patterns of the stability parameter during the time.

According to the profiles reported in the figures, the temperature change was performed without any problem of process stability and in a very short time: the only evidence of minimal instability was related to the VFA pattern during the first days after the temperature change (from <100 mg/l up to 350 mg/l), however also this situation was completely recovered in a few days. In general, VFA and pH showed the same levels for both mesophilic and thermophilic conditions while, on the other hand, alkalinity and ammonia concentrations increased constantly along the experimentation: this behaviour was strictly related to the different substrate [14–16] in fact, the high degradation of OFMSW leads to a quick release of ammonia in liquid phase due to proteins demolition. Table 2 compares the main results obtained (as average values) in the different experimental runs. Both the stability parameters and the yields are reported. The percentage of OFMSW indicated for each experimental run is related to the total design load (20 tonnes per day): this was 50% for runs II and III, and 100% for run IV.

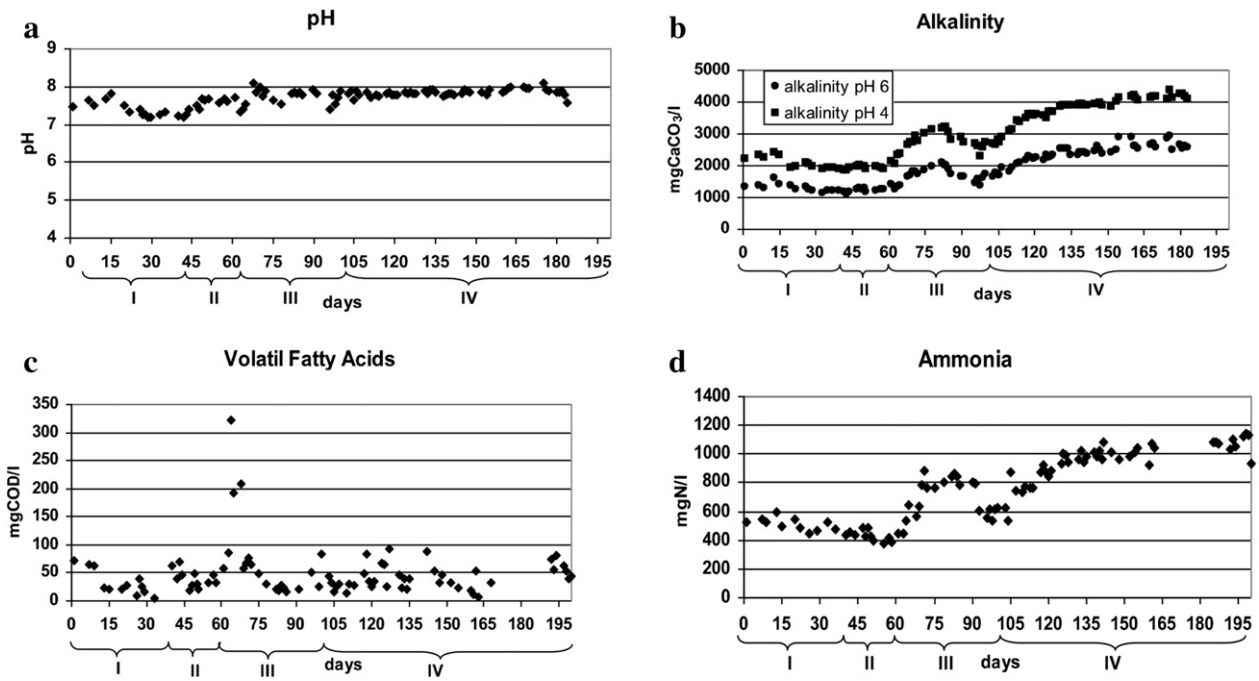

Fig. 1. Stability parameters patterns in pilot-scale experiment: a) pH; b) alkalinity; c) volatile fatty acid; d) ammonia.

According to the data reported in Table 2 and Fig. 2, a clear increase of yields was obtained by changing the temperature to the thermophilic range: GPR values changed from 0.53 to 0.78 m^3/m^3 d, while SGP from 0.34 to 0.49 m^3/kgVS (47 and 44% increase respectively) despite the same OLR being applied.

This evidence confirms previous literature results where the superior performances of the thermophilic processes were reported [14,17–21].

3.2. Full-scale trials

Considering the positive results obtained, the same approach was then applied to the full-scale reactor, obtaining very interesting confirmations of the pilot-scale study. The temperature change was carried out in 15 days thanks to the heating capacity of the heating exchangers, while the applied loading rate followed the same pattern as the pilot-scale trial. The final OFMSW load was limited to 50% of the design load (operational conditions equivalent to period III in pilot test), due to the administrative limitation to the amount of waste treatable in the plant. The process showed the same behaviour observed in the pilot-scale trials: the stability parameters showed similar patterns and levels along about 6 HRT after temperature increasing. Only VFA showed higher concentration values in the full-scale trial compared to the pilot-scale, but values were even low (<300 mgCOD/l) and don't affect the stability of the process.

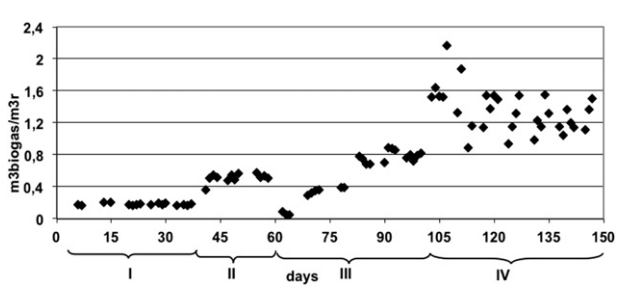

Fig. 2. Biogas production profile at pilot-scale.

Also the yield values, in terms of both GPR and SGP, replicated the results observed at pilot-scale: while in mesophilic conditions the observed yields in pilot- and full-scale were practically the same (GPR, 0.53 vs. 0.56 m^3/m^3 d, SGP, 0.34 vs. 0.35 m^3/kgVS), when considering the thermophilic conditions, the full-scale results were even better. In fact, it should be kept in mind that the OLR applied at full-scale was lower than the one at pilot-scale (1.28 vs. 1.66 kgVS/m^3 d) (see Table 3). Because of this situation the GPR value was lower than the one observed at pilot-scale (0.70 vs. 0.78 m^3/m^3 d) while the SGP was higher: 0.55 vs. 0.49 m^3/kgVS.

Considering the obtained results, a further improvement can be expected in reaching the full loading conditions.

3.3. Energy balance considerations

On the basis of the results obtained, a complete analysis of energy and mass balances of the proposed approach was carried out. In particular, considering the energy aspects, it was determined the minimum condition of OFMSW load which allows a complete autothermal management of the process in thermophilic conditions. The evaluation was performed considering the typical working conditions of a municipal WWTP (specific hydraulic load 0.25 m^3/equivalent inhabitant p.e. d, inlet wastewater COD 250 mg/l). For the calculation were used: a specific heat request of 1 kCal/kg °C; a temperature of sludge of 12 °C; a combustion heat for biogas of 5500 kCal/m^3; a combustion yield of the heater of 90%; a total heat loss from the digester walls of 10%. The temperature used for calculation was 55 °C for the thermophilic digester, 4 °C for environmental temperature and 5 °C for soil. The size ranges for this simulation considered a digester volume between 1500 and 2500 m^3 and a plant size between 50,000 and 100,000 p.e. (with a 100 m^3 of digester volume increase every 5000 p.e.). A standard cogeneration unit (CHP) was considered for energy and heat recovery (40% electrical yield, 50% of thermal yield, 10% losses). Considering the energy and mass balances results, it was shown that it was possible to reach a complete autothermal condition treating 6.5 tonnes of OFMSW per day in a 50,000 p.e. WWTP. If we consider that the normal production of selected OFMSW (after

Table 2
Main results obtained in pilot-scale experiments.

Parameter (referred to reactor content)	Period I	Period II	Period III	Period IV
	Start-up (sludge)	Mix, 50% OFMSW[a]	Mix, 50% OFMSW[a]	Mix, 100% OFMSW[a]
T, °C	37	37	55	55
OLR, kgTVS/m^3 d	1.22	1.60	1.66	2.21
HRT, d	22.1	23.5	22.3	21.6
NH_3 gN/l	0.48	0.39	0.59	0.99
Alkalinity pH 6, mgCaCO$_3$/l	1223	1233	1544	2439
Alkalinity pH 4, mgCaCO$_3$/l	1973	1940	2570	3903
pH	7.3	7.6	7.7	7.8
VFA tot, mgCOD/l	19.0	36.4	52.6	43.0
TKN out gN/l	1.4	1.4	1.1	1.3
Ptot out g/l	0.8	0.6	0.8	0.7
SGP, m^3/kgTVS$_{fed}$	0.15	0.34	0.49	0.57
GPR, m^3/m^3 d	0.18	0.53	0.78	1.24
CH_4, %	61.0	60.4	61.6	62.2

[a] As simulated percentage of the total load foreseen for the service of the whole city.

sorting) can be assumed equal to 0.25 kg per person per day, it is clear that the system can work in autothermal conditions even if only 50% of the OFMSW produced in a given basin is treated through the thermophilic co-digestion approach. It is important then to emphasise that, at the same time, about 850 MWh per year of electric energy are produced. Considering the typical values for the green certificates for Italy this gives some 180,000 € per year.

3.4. Nitrogen feedback to the wastewater treatment

Two streams are produced after digestate dewatering: the supernatant (reject water), which is recycled to the wastewater treatment plant, and the dewatered digestate (solid fraction). As for the supernatant, it is clear that nutrients released during the hydrolysis process in the anaerobic digester are recycled to the activated sludge process, determining an extra-load to be treated. A typical belt-press dewatering is considered, with a solids capture efficiency of 90%. In particular, to define the relationship between the ammonia concentration in the supernatant vs. the OFMSW OLR applied to the digester, the data collected in several OLR conditions are considered. The data were elaborated and a linear interpolation was applied, leading to the equation below:

$$\mathrm{N-NH_4,\ in\ reject\ water(gN/l)} = 0.132\,\mathrm{OLR}\left(\mathrm{kgVS/m^3d}\right) + 0.48(\mathrm{gN/l}) \quad (1)$$

Increasing the amount of OFMSW from 50% of treatment plant capacity to 100% (total OFMSW produced from the same basin) the WWTP extra-load of total N is only the 3.7%.

Table 3
Results obtained in full-scale application.

	Full-scale, mesophilic	Full-scale, thermophilic
OLR, kgTVS/m^3 d	1.62	1.28
SGP, m^3/kgTVS$_{fed}$	0.35	0.55
GPR, m^3/m^3 d	0.56	0.70
CH_4, %	60.0	60.0
TVS % removed	39.5	47.2
pH	7.2	7.6
TA (pH 6), mgCaCO$_3$/l	1073	1444
TA (pH 4), mgCaCO$_3$/l	1775	2533
VFA, mgCOD/l	270.1	267.8
N–NH_4^+, mgN/l	0.42	0.69

This minimal extra-load can be treated at relatively low costs, which are largely counterbalanced by the extra incomes related to the renewable energy produced. Considering a conventional nitrification/denitrification system without external carbon source, the cost estimated to treat 1 kg N is 0.66 € [22], as consequence the extra N-load doesn't play an expensive element on the WWTP economy.

3.5. The fate of the digestate

The last aspect to consider in the co-digestion option refers to the quality of the dewatered digestate and the possibility to produce high quality compost from this. Two aspects have to be considered in this topic: a) the real need of a stabilisation treatment after an anaerobic digestion step, b) the content of heavy metals in the final product, considering the fact that sludge is normally richer than OFMSW in these compounds. About the first question, several tests of respirometric index [23] were carried out using the dewatered digestate coming from the Treviso full-scale plant. All the tests show an index lower than 1000 mgO$_2$/kgVS h, which is lower than the minimum required for a stable compost following the Italian regulation system. Thus, it is clear that the integration among A.D. process and composting process, leads to a single process where composting assumes the role of a curing step, such as demonstrated previously by Vallini and co-workers [24] and also recently by Di Stefano and co-workers [25], who also showed the possibility to overcome the digestate phytotoxicity limit for VFA and NH_3 after 4 and 8 days of treatment, respectively.

Concerning the heavy metals content, a complete mass balance simulation of the system was carried out, considering the metals concentration values shown in Table 4.

The heavy metals mass balances were evaluated in an integrated approach (anaerobic co-digestion and composting) treating the total flow rate of sludge, OFMSW and green waste (usually used as a bulking agent in the composting process) calculated considering the pro-capita production.

Data reported for biowaste (OFMSW) are the average values obtained from the data of some Swedish's city [26], of the Directorate General Environment [27] and of the Regional Agency for Environment Protection of Veneto (2006). The characteristics of the green waste are the average values of data collected by the Directorate General Environment and the Regional Agency for Environment Protection of Veneto.

Due to the variability of values observed, the metals concentrations in the activated sludge considered were both data of metals specific load [28] and analytical data of Regional Agency for Environment Protection of Veneto and Emilia Romagna. Fig. 3 shows the metals mass balance in the co-digestion approach implemented with a composting process.

In this mass balance the organic content loss was considered for each substrate, taking into account the composting process: OFMSW, green waste and sludge typically show 60%, 30% and 10%

Table 4
Metal content of sludge, OFMSW and bulking agent considered for the mass balance.

Metal	Sludge (Balmèr P. 2001) Min.	Sludge (ARPA Veneto and Emilia Romagna) Max.	OFMSW	Bulking agent
Cd, mg/kgTS	0.41	1.82	0.24	0.38
Cr, mg/kgTS	8.89	84.47	9.49	15.67
Hg, mg/kgTS	1.59	2.74	0.13	0.13
Ni, mg/kgTS	9.52	52.40	8.46	11.23
Pb, mg/kgTS	3.81	72.85	7.04	15.13
Cu, mg/kgTS	79.37	261.61	34.73	28.53
Zn, mg/kgTS	444.44	876.40	107.86	103.93

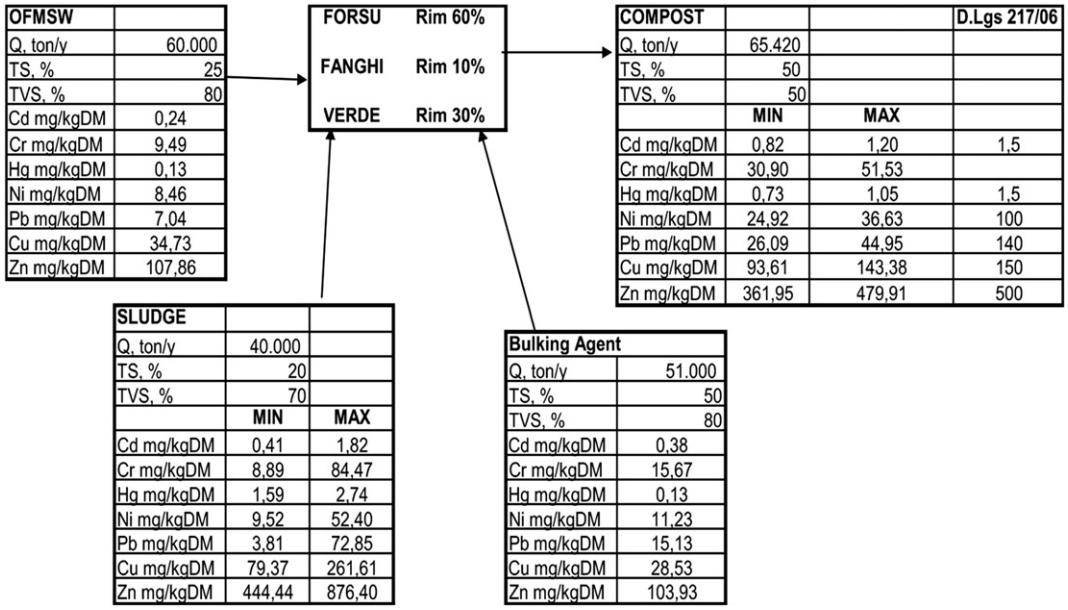

Fig. 3. Heavy metal's mass balance in the integrated WWTP.

Table 5
Heavy metals concentration resulting in final compost using co-digestion.

Metal	A.D. compost Min.	A.D. compost Max.	Italy (D.lgs 75/2010)	Germany (RAL GZ 245)	UK (BSI 2005)	France (NF–U44-051, 2006)	Sweden (SPCR 120)	Europe (IPTS 3rd draft EoW) compost/digestate limit
Cd, mg/kgTS	0.82	1.20	1.5	1.5	1.5	3.0	1.0	1.5
Hg, mg/kgTS	0.73	1.05	1.5	1.0	1.0	2.0	1.0	1.0
Ni, mg/kgTS	24.9	36.6	100	50	50	60	50	50
Pb, mg/kgTS	26.1	44.9	140	150	200	180	100	120
Cu, mg/kgTS	93.6	143.4	230	100	200	300	600	100
Zn, mg/kgTS	361.9	479.9	500	400	400	600	800	400

respectively of organic matter removed at the end of the process. It is possible to observe that the characteristics of the final product are compatible with the Italian definition of "quality compost" but for zinc the values are strictly near limit low (IT D.lgs 75/2010).

The legal limits for various countries resulting from a voluntary certification system are reported in Table 5. Among all countries, Germany adopts extremely restrictive limits, that cause problems in utilising activated sludge in the composting processes. These limits are similar with those proposed by the third draft of the IPTS 2012 on biodegradable waste subject to biological treatment (compost/digestate) [29].

After all, it appears that laws limit the treatment of sludge from the municipal wastewater treatment, thus precluding the recovery of an important carbon source of good quality.

In fact, it is necessary also to consider, besides the legal limit, the fact that in reality the major part of the analytically quantifiable metals are not bio-available, as evidenced by several studies in Holland [30,31]. In particular, it has been demonstrated that the inorganic fractions (0.05–0.2 mm), deriving from residual of heart, have higher levels of heavy metals concentration than the organic fractions, in particular for Cd, Cu, Pb and Zn, and that these fractions are practically not bio-available. The results for both conditions are reported in Table 5 and compared with the Italian and E.U. limits for quality compost.

4. Conclusions

The experiments carried out and the simulation performed on the basis of the data collected allows some important conclusion on the feasibility of the approach suggested:

- the thermophilic option can be considered as the best condition in a co-digestion process for the treatment of sludge/biowaste mixtures: improvements in terms of biogas yields around 45–50% are proven;
- the energy balance of the thermophilic process, although demanding a higher heat capacity compared to a mesophilic process, can be easily supported even when treating only 50% of the biowaste produced in a given basin;
- nitrogen feedbacks to the activated sludge process derived from biowaste treatment are very low: less than 4% of the total N normally entering the plant;
- digestate characteristics are adequate for the production of good quality compost using a simple aerobic post stabilisation step, considering a very short HRT due to the high biological stability already reached in the anaerobic step. Metal contents are within the more stringent limit used in Europe for high quality amendants.

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