Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.932717

55 (2015) 783–790
July

Taylor & Francis
Taylor & Francis Group

Analysis of real-scale experiences of novel sewage sludge treatments in an Italian pilot region

Marco Ragazzi*, Elena Cristina Rada, Roberta Ferrentino

Civil, Environmental and Mechanical Engineering Department, University of Trento, Via Mesiano 77, I-38123 Trento, Italy, Tel. +39 0461 282609; Fax: +39 0461 282672; email: marco.ragazzi@unitn.it (M. Ragazzi), Tel. +39 0461 282613; Fax: +39 0461 282672; email: elena.rada@unitn.it (E.C. Rada), Tel. +39 0461 282669; Fax: +39 0461 282672; email: ferrentino.roberta@gmail.com (R. Ferrentino)

Received 4 March 2014; Accepted 16 May 2014

ABSTRACT

Four case studies, related to real-scale novel solutions for sewage sludge management are presented. The described experiences concern an Italian region Trentino Alto Adige (TAA). In Italy, few years ago, solutions as landfilling of thermally dried sludge, composting and direct application on land were considered viable options. Today the sector is going quickly towards a crisis, as sludge is no longer accepted for landfilling (because of its biodegradability) and its direct or indirect application on land is more and more restricted in some regions. As a consequence of this situation, in Italy alternative options are studied, and TAA can be considered a pilot region thanks to the presence of multiple interesting case studies. Sludge minimization is widely studied, but in real scale the first Italian plant was constructed in TAA only recently: this plant is based on the principles of solid separation and biological cannibalization of the biomass. The target is the reduction of 50% of the solid load of sludge. The strategy of minimization has been adopted in an activated sludge plant already existing. The wet-oxidation option has been adopted in a civil wastewater treatment plant in TAA. This solution is generally adopted for industrial sludge but the high cost for the management of sewage sludge in TAA made it a viable option too. Pyrolysis of sewage sludge is performed in one real-scale plant in TAA. The pyrolysis gas is combusted and the generated gases are cooled to the operating temperature of the downstream fabric filter. The combustion heat is first used to increase the temperature of the special thermal oil adopted in a sewage sludge thermal drier; then it is used to heat process water for preheating the air of the sewage sludge thermal drier. Concerning the co-combustion of thermally dried sludge in cement works, the real-scale experience that is under discussion in TAA concerns the partial substitution of pet coke in a plant where a SCR (Selective Catalytic Reduction) system is already adopted. SCR in the off-gas treatment line of cement works is not common in Italy. A novelty of this case study concerns the planned adoption of an experimental low-cost system of NO_2 monitoring at the ground level in the territory as an alert system. In the present paper, the four TAA case studies are analyzed and compared.

*Corresponding author.

Presented at the 13th International Conference on Environmental Science and Technology (CEST 2013), 5–7 September 2013, Athens, Greece

Keywords: Co-combustion; Minimization; Pyrolysis; Sewage sludge; Wet oxidation

1. Introduction

The operational costs in a wastewater treatment plant (WWTP) depend on the processing of excess sludge up to half of their amount. Other cost items are conditioning, dewatering, disposal, and odor treatment [1,2]. For that reason, sewage sludge treatment is studied under multiple perspectives.

In Italy, few years ago, viable solutions for sludge disposal were: (a) landfilling of thermally dried sludge, generally at 10% of moisture as a result of the thermal treatment; (b) composting, with the addition of a bulky agent and eventually other discarded biomass; (c) direct application on land with seasonal limitations [2–5].

Today, the sector is going quickly towards a crisis: indeed, in Italy sludge is no longer accepted for landfilling because of its residual biodegradability, as a result of the enforcement of the legislative decree 36/2003; moreover, in some regions as Trentino Alto Adige (TAA) its application on land (direct or indirect through composting) is more and more restricted even in the case of sewage sludge generated from the treatment of civil wastewater; in particular, in Trentino no direct or indirect sewage sludge application on land has been planned in the last waste management plan [6]. These regional restrictions are adopted in spite of the fact that the European Union regulation still allows this option [7]; the local worrying also concerns the potential health impact from this option, as problematic substances can reach the sewerage even if a regulatory system is adopted. This explains the local interest towards researches that open new pathways for the energy exploitation of sludge [8].

In this frame, the focus and interest in sludge minimization is steadily increasing in Italy. Sludge minimization (mass reduction) options are based on many concepts. It is demonstrated that sludge minimization may be a result of reduced production of sludge and/or disintegration processes that may take place both in the wastewater treatment stage and in the sludge stage. Various sludge disintegration technologies are under discussion, concerning their viability in real scale. They include mechanical methods focusing on stirred ball mill, high-pressure homogenizer, ultrasonic disintegrator [9,10], chemical methods focusing on the use of ozone [11], physical methods focusing on the thermal and thermal/chemical hydrolysis [12,13], and biological methods focusing on enzymatic processes [14]. Some criticalities delayed the full-scale adoption of the above-mentioned options. For instance, stirred ball mill demonstrated to be efficient only for short retention times of anaerobic digestion; high-pressure homogenizer are affected by some difficulties in regulating the cavitation and turbulence mechanisms induced through pressures in the range of 400–900 bars; ultrasonic disintegration demonstrated that sludge has a high susceptibility that depends on its properties [9,10].

Those options decrease the stream of generated waste, thus thermo-chemical treatments of sludge, when adopted, must demonstrate their viability at a smaller scale. To this concern, direct combustion could be disadvantageous compared with the viability of gasification or pyrolysis solutions at smaller scale [15].

In the present paper, four Italian case studies related to real-scale innovative solutions for sewage sludge management are presented and discussed. Innovations in sludge management concern bio-mechanical stream minimization, volatile solids destruction by wet oxidation, energy recovery through pyrolysis, and integrated monitoring applied to co-combustion. The aim is to point out the trend of the sector, presently not yet optimized, in order to develop a preliminary comparison.

2. Case studies principles

The four case studies are based on different processes. A short description of these principles is presented in the following sections, and the reporting data are useful for a discussion.

2.1. Sludge cannibalization

The cannibalization of solids, known as Cannibal® process, is a biological interchange process combined with a conventional activated sludge treatment which allows sludge minimization and a consequent cost decrease for its disposal. This technology can be used for new plant designs or for retrofitting of existing plants. In the TAA's plant, this process has been adopted in an activated sludge plant, already existing, and designed to treat sludge generated from about 100,000 Inhabitants Equivalent. The target is the reduction of 50% of the solid load of sludge (from 740 t_{DM}/year to 370 t_{DM}/year); thus, limiting the electrical extraload under 50% of the existing one, without negative effects on the effluent quality. The adopted cannibalization process (Fig. 1) is composed of the following parts [16]:

- Solids Separation Module.
- Side-Stream Interchange Bioreactor.
- Control Systems.

In this innovative approach, a solid separation module is located on the return sludge line. The module is a patented system that contains an ultra-fine mesh screen with hydrocyclones to remove trash, grit, and inert materials that accumulate in the mixed liquor. This system is essentially a drum screen. These fine materials are not typically removed in the influent screening facilities due to their small size. This module produces a residue that can be disposed of at sanitary landfills. Some of the return sludge flow is directed to the side-stream interchange bioreactor. In this tank, the mixed liquor bacteria are transformed from an aerobic-dominant to a facultative-dominant population by limiting the amount of oxygen. Minimal aeration is applied in the interchange tank: the oxidation reduction potential (ORP) is carefully monitored so that air is supplied for short periods when ORP becomes too low. In the low-dissolved oxygen environment of the bioreactor, the facultative bacteria selectively breakdown and metabolize the remains of the aerobes and their byproducts. The facultative bacteria are subsequently broken down after they are returned to the aeration system. The alternating environments of the oxygen-rich aerobic process and the oxygen-deficient bioreactor result in the destruction of a part of the biological solids, produced in the activated sludge stage.

2.2. Wet oxidation

Wet oxidation is another thermal treatment that consists a partial oxidation of organic species which are suspended in water, like sludge. This is pre-mixed with air, under pressure, and pre-heated at 200–300˚C, in a heating exchanger. After this step, the mixture is sent to an adiabatic reactor, where the oxidative demolition of organic species takes place. This oxidation also produces the heat suitable for the maintenance in temperature of the overall process. Steam is also used when the heat produced by the oxidative reaction is not sufficient for the maintenance of temperature. The oxidation degree of the suspended organic species is a function of temperature, pressure, and time. Reaction products are cooled in the heat exchanger, and then separated. Exhausted gases are discharged, while the suspended oxidized solids are selected by filtration. This solution is generally adopted for industrial sludge, but the high cost for the management of sewage sludge in TAA made it a viable option too. Wet oxidation is performed in the civil WWTP of Rovereto (TAA). This process can be classified depending on the presence or absence of the catalyst and on air or pure oxygen utilization. This plant has a not catalyzed configuration and works with the addition of pure oxygen, treating about 3,000 t_{DM}/year and 24 h per day when operating. This plant needs about three millions of cubic meters

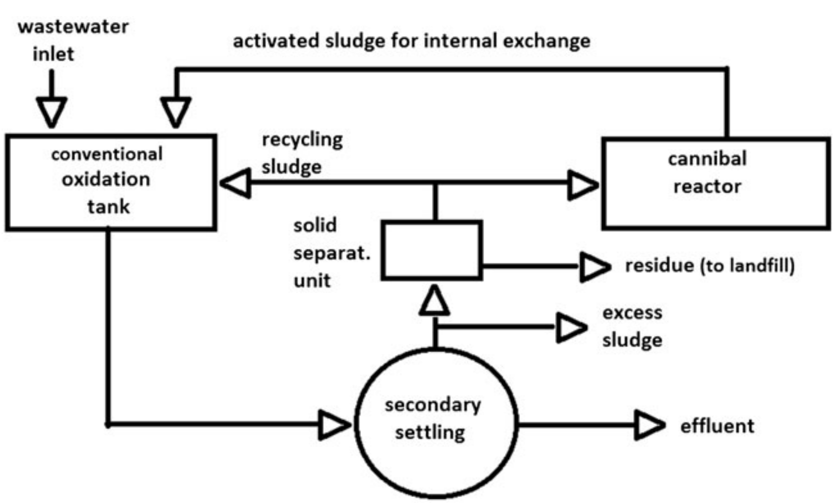

Fig. 1. Scheme of the Cannibal® process operating in Levico (TAA) WWTP.

of oxygen per year. The plant activity started in 2012 but its operation is not yet optimized because of some criticalities of the overall balance of nitrogen in the integrated WWTP.

2.3. Pyrolysis

Pyrolysis of sewage sludge [17] is performed in one real-scale plant in TAA. The pyro-combustor for dried sewage sludge with a calorific value of up to 12,000 kJ/kg and 10% of residual moisture is designed for a throughput rate of 550 kg/h (operating 7,500 h/y). In the first chamber, the material is pyrolyzed. And directly following that, in second chamber, the pyrolysis char is oxidized to ash, thanks to an auxiliary burner. Flue gases from the combustion process go in counter current of sludge, in order to deliver the heat required for the pyrolysis. After exiting the pyro-combustor, flue gases are treated in a cyclone. The generated gas is combusted at a minimum temperature of 850˚C in a dedicated chamber (Fig. 2). The hot flue gases are cooled to the operating temperature of the downstream fabric filter. The combustion heat is first used to heat a special thermal oil that heats the sewage sludge thermal drier. Then, it is used to heat the process water for preheating the air of the sewage sludge thermal drier. The fabric filter removes fine dust from the flue gases. In addition, adsorbents are added into the flue gases before they enter the filter to separate acid gas and heavy metals. The residual product is used as a filler in a brick work.

2.4. Co-combustion

Co-combustion of thermally dried sludge in cement works is a well-known option, but the real-scale experience that is under discussion in TAA concerns the partial substitution of pet coke in a plant where a SCR (Selective Catalytic Reduction) system is already adopted. SCR in the off-gas treatment line of cement works in Italy is not common. A novelty of this case study concerns the planning of an experimental low-cost system of NO_2 monitoring at the ground level in the territory [19]. This system should act as a sentinel aimed to detect in real time the presence of NO_2 anomalies in the air quality in strategic sites close to the plant (the substitution of pet coke with sewage sludge can increase the emissions of NO_x because of the high N content of sludge). In case of peak events, the addition of sludge could be suspended until the air quality conditions come back to normal values. The worry about the impact of nitrogen oxides emitted by the cement works are related to the location of it: the plant is located in a narrow alpine valley. The interest is concentrated on NO_2 because of its direct effects on the human health [20]. Moreover, the NO_x emission limit in the sector of cement works is not stringent (800 mg_{NO_x} Nm^{-3} in this case) and the off-gas flow rates are generally high giving a significant stream of NO_x all over the year. The additional feeding of nitrogen, consequence of sludge co-combustion, can cause criticalities that can affect the local environment impact in some periods of the year.

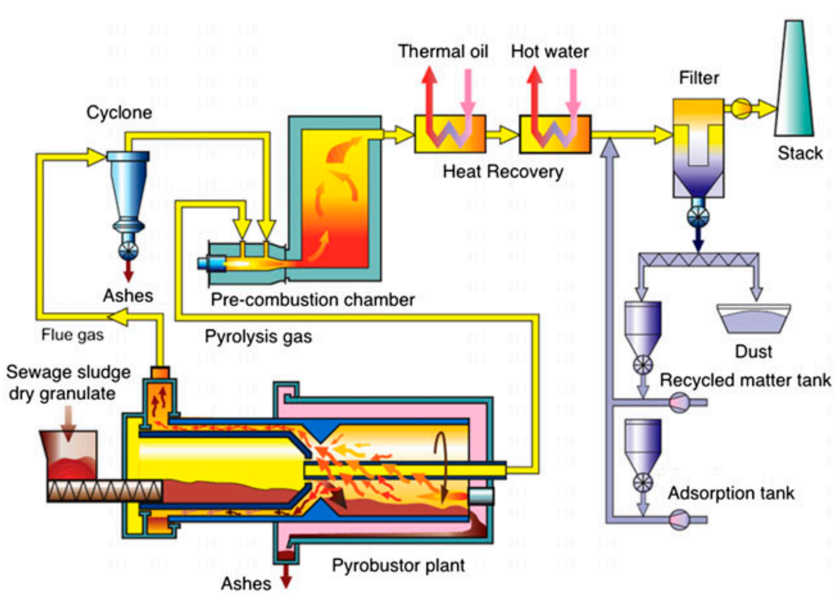

Fig. 2. Sludge pyrolyzer scheme [18].

3. Discussion and proposals

3.1. Sludge cannibalization

The solids separation module performances can give interesting perspectives for alternative uses. Indeed, the module produces a quantity of material as trash, grit, and inert of about 700 kg/d that corresponds to 25% of solids removal (the same value indicated by Siemens Water Technologies [16]). Thanks to this positive performance, it could be planned to apply the solid separation module as pre-treatment also for other sludge reduction technologies.

For instance, considering a conventional anaerobic digester for sewage sludge, if the above-mentioned solid separation module were used as pre-treatment, it could be possible to keep away materials that are not involved in the production process of biogas; their separation would induce an increase of the process performance thanks to the consequent lower volume needed for sludge treatment (resulting also in a decrease of energy consumption in the reactor, because of a reduced amount of inert to be mixed). Of course, an estimation about the cost effectiveness of the solid separation module as anaerobic digestion pre-treatment should be performed.

Moreover, a research developed in China [21] draws the attention on the suitability of sewage sludge as input of a process to be converted in activated carbon for specific uses. The results of that research were limited because of the excessive presence of inert in the solids of the sludge. The above-presented separation process could be a potential solution to this limitation.

3.2. Wet oxidation

The WWTP in Rovereto is designed to treat an influent with an amount of nitrogen of about 1,140 kg_N/d. Every day it receives a total amount of 798 kg_N/d of municipal wastewater. It is easy to understand that its remaining capacity to treat nitrogen is about 342 kg_N/d. To avoid problems in the biological WWTP, it is necessary not to overcome this value which corresponds to a need of the removal of the nitrogen in the liquid byproduct load from wet oxidation (a load of 444 kg_N/d to be reduced before recycling it in the local WWTP). To solve this problem, the liquid effluent is sent to an air-stripping column that allows an "extraction" of nitrogen in the form of ammonia. In Table 1, an estimation of the load of nitrogen that should be sent to the WWTP, depending on the percentage of reduction made by post-treatment, is reported. Setting a target of not exceeding 90% of the WWTP design load, nitrogen removal of about 50% is needed. The potential problems of nitrogen overloading must not be underestimated: indeed the wet oxidation plant is presently not fully operating because of the difficulties of complying with the stringent limits of nitrogen discharge into the surface water.

Table 1
Amount of nitrogen recycled and to be treated depending on %N removal

%N Removal	kg_N/d sent to WWTP
0	444
25	333
50	222
75	111
95	23

3.3. Pyrolysis

The pyro-combustor present in TAA has three aspects that can be discussed:

- The thermal drier had to be substituted recently in order to generate a well granulated sludge suitable for pelletization; after that modification, the plant operates with no technical problems, but this demonstrates that the process is very sensible to the pre-treatment stage.
- The processed sludge comes from a group of WWTPs generating sewage sludge with variable and not fully optimized characteristics; as a consequence, the treatment capacity of the dryer is not fully exploited; on the contrary, it can be demonstrated that coupling this pyrolyzer with a well mechanically dehydratated sludge, (possibly from only one WWTP) the same dryer could treat sludge suitable to be the input of two pyrolyzers of the same power; that means an optimized integration of the couple dryer–pyrolyzer could significantly decrease the cost of treatment. Table 2 reports a demonstration referred to the increase of sewage sludge dry matter from 14% to 23% to be performed at the WWTPs. This modification can almost double the population serviced.
- The pyrolyzer uses natural gas for supporting one of the thermal steps. It is clear that the evolution of the system should put to zero this consumption.

The expected health impact of this approach is similar to the one from direct combustion [20].

Table 2
Potential modifications of pyro-combustion configuration

	Reference configuration	Modified configuration	Measurement units
Wet sludge	28,000	32,000	Mg/y
Operating hours	8,000	8,000	h/y
Hourly flow rate	3.5	4	Mg/h
Wet sludge moisture	14%	23%	%
Dried sludge (10% solids)	544	1,022	kg/h
Evaporated water	2,956	2,978	kg/h
Per capita generation of sludge (solids)	60	60	kg inh^{-1} d^{-1}
Serviced inhabitants	178,995	336,073	inh

Indeed, a recent research has demonstrated that pyro-combustors and incinerators have similar emission factors when fed with similar inputs [15].

3.4. Co-combustion

The presented case study does not point out technical problems and is locally seen as an opportunity for introducing the concept of integrated control of the environment: the alert sensors to be placed in the territory could help the local environmental protection agency to check for potential anomalies that the conventional monitoring network could not detect. The recent cost decrease of NO_2 thick-film sensors [14] opens to new perspectives for other sectors that could be affected by high streams of nitrogen oxides. A preliminary study of the territory for the correct positioning of the sensors (location and number) should always be based on a dispersion and deposition modeling. The selected sensor for this case study is SENS 3,000 [22] having a range of 0.1–500 $\mu g\, m^{-3}$. It can be kept on field for six months before recalibration. Its range is compatible with the threshold limit for hourly NO_2 concentration, according to the European Union air quality regulation (200 $\mu g\, m^{-3}$). It can be coupled with an internal data logger and a transmission box in order to guarantee a continuous monitoring [19]. Moving average of NO_2 can be easily calculated using software in order to support decision-makers in preventing critical conditions on the territory where a set of sensors act as sentinels.

3.5. Comparative considerations

In Table 3, a quick comparison form the energy, environmental, and economic point of views is presented. Energy balance is negative for cannibalization and wet oxidation as no net ouput is obtained. Indeed, both cannibalization and wet oxidation need an electricity consumption for their operations without generating any net output. From the environmental point of view, assumed in terms of local impact, the cannibalization option seems to be the less impacting. Capital costs are low for cannibalization compared to more technological options.

In Table 4, a comparative vision of the technological difficulties, post-treatment needs, and real-scale experience on sewage sludge is presented. The first parameter is related to high pressure and temperature values in the processes. The transport effects for cannibalization are interesting even if a significant part of sludge remains after the treatment: indeed, a reduction in volume is obtained at the WWTP, giving a direct advantage in terms of transport organization. The real-scale experiences in the sector of sewage sludge are generally few.

In Table 5, considerations on landfilling volumes, transport interaction, and flexibility to sludge

Table 3
Comparison from the energy, environmental, and economic point of views

	Energy balance	Environment	Capital costs
Cannibalization	−	+	+
Pyrolysis	−/+	−/+	−/+
Co-combustion	−/+	−/+	+
Wet oxidation	−	−/+	−

Table 4
Technological complexity, transport effects and sector experiences comparison

	Complexity	Transport effects	Experiences
Cannibalization	+	−/+	−
Pyrolysis	−/+	−/+	−/+
Co-combustion	+	−/+	−/+
Wet oxidation	−	+	−

Table 5
Comparison about landfilling needs, output fate, and flexibility

	Landfilling	Post-treatments	Flexibility
Cannibalization	−	−	−
Pyrolysis	−/+	−/+	−/+
Co-combustion	+	+	−/+
Wet oxidation	+	+	−

characteristics in the input are reported. Landfilling for wet oxidation residues is minimized also thanks to the shape of the output, similar to sand. Cannibalization treats only partially the sludge stream, thus a post-treatment is compulsory. The input conditions must be steady in the case of cannibalization as the biological process must not be stressed. In the case of wet oxidation, the moisture of the stream entering the plant must be kept constant.

4. Conclusions

The sector of sewage sludge management in developed economies as Italy shows a delay in finding optimized solutions. This problem is related to the lack of implementation of complete sludge treatments during the stage of WWTP construction. Regarding the cannibalization process, the attention was focused on the solid separation module. In the Levico WWTP, this unit allows about 25% of solid reduction, which is in accord with the value expected by the proposers. Based on these results, the unit could be applied as a pre-treatment for conventional sludge producing several advantages in terms of lower volumes and energy consumption and opening to alternative options (activated carbon generation). Regarding wet oxidation technologies, it is important to take into account some problems linked to its solid, liquid, and gaseous byproducts. The results presented in this study show that is necessary to design a post-treatment unit for liquid effluents that must ensure a high percentage of nitrogen reduction. This important aspect affects the management costs of the technology, which are already high. The analyzed pyrolysis offers interesting results but some improvements should be set for its energy optimization. Co-combustion could be more accepted when, as in the case study, a SCR was implemented for the process air treatment and an additional control of the local air pollution was adopted.

References

[1] S.S. Yang, W.Q. Guo, X.J. Zhou, Z.H. Meng, B. Liu, N.Q. Ren, Optimization of operating parameters for sludge process reduction under alternating aerobic/oxygen-limited conditions by response surface methodology, Bioresource Technol. 102(21) (2011) 9843–9851.
[2] M. Ragazzi, Production, treatment and disposal of sludge in Italy, Eur. Water Pollut. Control. 7(2) (1997) 42–46.
[3] L. Vecchietti, B. De Lucia, G. Russo, E. Rea, A. Leone, Environmental and agronomic evaluation of containerized substrates developed from sewage sludge compost for ornamental plant production, Acta. Horticulture 1013 (2013) 431–440.
[4] M. Fumagalli, A. Perego, M. Acutis, Modelling nitrogen leaching from sewage sludge application to arable land in the Lombardy region (Northern Italy), Sci. Total Environ. 461–462 (2013) 509–518.
[5] C. Collivignarelli, V. Riganti, G. Andreottola, G. Bertanza, R. Canziani, M. Ragazzi, Essiccamento termico dei fanghi di depurazione: Aspetti tecnico-economici, normativi e ambientali (Sewage sludge thermal drying: Techno-economic, regulatory and environmental aspects), Quaderno, Ingegneria Ambientale, Inquinamento e depurazione 18 (1993).
[6] PAT Provincia Autonoma di Trento, Piano Provinciale di Smaltimento dei Rifiuti—Terzo aggiornamento (Provincial Waste Management Plan—III update), Waste Office, Trento, 2006.
[7] Commission of the European Communities, Report from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions on Implementation of the Community Waste Legislation, SEC 1586, Bruxelles, 2009.
[8] E.C. Rada, M. Ragazzi, L. Fiori, D. Antolini, Bio-drying of grape marc and other biomass: A comparison, Water Sci. Technol. 60(4) (2009) 1065–1070.
[9] G.W. Strunkmann, J.A. Muller, F. Albert, J. Schwedes, Reduction of excess sludge production using mechanical disintegration devices, Water Sci. Technol. 54(5) (2006) 69–76.

[10] G. Andreottola, P. Foladori, M. Vian, An integrated approach for the evaluation of bacteria damage and biodegradability increase in sonication of excess sludge, in: Proceedings of Sustainable Sludge Management: State of Art, Challenges and Perspectives, 2006.
[11] K.H. Ahn, K.Y. Park, S.K. Maeng, J.H. Hwang, J.W. Lee, K.G. Song, S. Choi, Ozonation of wastewater sludge for reduction and recycling, Water Sci. Technol. 46(10) (2002) 71–77.
[12] J. Chauzy, S. Graja, F. Gerardin, D. Crétenot, L. Patria, P. Fernandes, Minimization of excess sludge production in a WWTP by coupling thermal hydrolysis and rapid anaerobic digestion, Water Sci. Technol. 52(10–11) (2005) 255–263.
[13] E. Nayems, J. Baeyens, C. Creemers, Alkaline thermal sludge hydrolysis, J. Hazard Mater. 97 (2003) 295–314.
[14] J. La Cour Jansen, A. Davidsson, E.S. Dey, Norrlow, in: H.H. Hahn, E. Hoffmann, H. Odegaard (Eds.), Chemical Water and Wastewater Treatment VIII, IWA, London, 2004, pp. 345–353.
[15] M. Ragazzi, E.C. Rada, Multi-step approach for comparing the local air pollution contributions of conventional and innovative MSW thermo-chemical treatments, Chemosphere 89(6) (2012) 694–701.
[16] Siemens, 2011. Available from: www.water.sismens.com (accessed January 2013).
[17] M. Grigiante, M. Ischia, M. Baratieri, R.D. Maschio, M. Ragazzi, Pyrolysis analysis and solid residue stabilization of polymers, waste tyres, spruce sawdust and sewage sludge, Waste Biomass Valoriz 1/4 (2010) 381–393.
[18] Eisenmann, Thermal Treatment of Sewage Sludge in Municipal Water Treatment, Böblingen, Technical report, Germany, 2005. Available from: www.eisenmann.de (accessed January 2013).
[19] E.C. Rada, M. Ragazzi, M. Brini, L. Marmo, P. Zambelli, M. Chelodi, M. Ciolli, Perspectives of low-cost sensors adoption for air quality monitoring, UPB Sci. Bull. 74/2 (2012) 243–250.
[20] M. Ragazzi, M. Grigoriu, E.C. Rada, E. Malloci, F. Natolino, Health risk assessment from combustion of sewage sludge: A case-study with comparison of three sites, in: Proceedings from RIMA'10, Bucharest, Romania, 2010, pp. 176–180.
[21] W.H. Li, Q.Y. Yue, Z.H. Ma, B.Y. Gao, Y.J. Li, H.X. Zhao, Effect of preparation conditions and washing of activated carbon from paper mill sewage sludge on its adsorptive properties, Water Sci. Technol. 67(2) (2013) 284–292.
[22] UNITEC, 2013. Available from: www.unitec-srl.com, 2013 (accessed January 2014).