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EFFECTIVE MANAGEMENT OF SEWAGE SLUDGE

Techno-economic and environmental assessment of sewage sludge wet oxidation

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Abstract Today, several technologies and management strategies are proposed and applied in wastewater treatment plants (WWTPs) to minimise sludge production and contamination. In order to avoid a shifting of burdens between different areas, their techno-economic and environmental performance has to be carefully evaluated. Wet oxidation (WO) is an alternative solution to incineration for recovering energy in sewage sludge while converting it to mostly inorganic residues. This paper deals with an experimentation carried out within the EU project "ROUTES". A mass balance was made for a WWTP (500,000 person equivalents) in which a WO stage for sludge minimisation was considered to be installed. Both bench- and full-scale test results were used. Design of treatment units and estimation of capital and operational costs were then performed. Subsequently, technical and economic aspects were evaluated by means of a detailed methodology which was developed within the ROUTES project. Finally, an assessment of environmental impacts from a life cycle perspective was performed. The integrated assessment showed that for the specific upgrade considered in this study, WO technology, although requiring a certain increase of technical complexity at the WWTP, may contribute to environmental and economic advantages. The paper provides guidance in terms of which aspects need a more thorough evaluation in relation to the specific case in which an upgrade with WO is considered.

Keywords Anaerobic digestion · Costs · Feasibility · LCA · Mass balance · Technical issues · Wastewater treatment · Wet oxidation

Introduction

Highly important issues in the operation of wastewater treatment plants (WWTPs) are effluent quality and sewage sludge management. Today, the legislative framework in force in Europe (Directive 1991/271/EC, Directive 1999/31/EC, Directive 2000/60/EC, third draft of "Working document on sludge", 2000 etc.) requires the achievement of strict effluent standards for sensitive areas, where nitrogen and phosphorus have to be controlled and also introduces quite severe restrictions on the properties of residual sewage sludge, both if it is landfilled and when it is used in agriculture. These restrictions have resulted in increasing difficulties in finding appropriate recovery/disposal systems at reasonable costs and therefore have pushed operators to find management strategies aimed at the reduction of the amount of residual sludge (Liu and Tay 2001; Wei et al. 2003; Mahmood and Elliott 2006; Pérez-Elvira et al. 2006; Foladori et al. 2010). Nevertheless, the techno-economic feasibility and environmental impact of alternative strategies has to be carefully evaluated. Many variables determine the suitability of a particular solution, and also, these are remarkably site-specific.

The increasing interest in the techno-economic and environmental impacts of wastewater and sludge technologies and

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management strategies is demonstrated by the research financing policies of the European Union. Recently, a project has been funded, with the aim of finding new routes (hence, the project name, ROUTES—Novel processing ROUTES for effective sewage sludge management, http://cordis.europa.eu/fp7/home_it.html) for sludge management and so guiding the members of EU in their future choices. Within this project, wet oxidation (WO) is proposed for a drastic reduction of the volume of sewage sludge to be disposed, obtained by extremely reducing the volatile sludge content. WO has been applied for almost 100 years for the treatment of both sewage sludge and high strength industrial wastewaters (Strehlenert 1911; Zimmermann 1958; Ploos Van Amstel 1971; Ploos Van Amstel and Rietema 1973; Devlin and Harris 1984; Seiler 1987; Foussard et al. 1989; Joglekar et al. 1991; Mishra et al. 1995; Debellefontaine et al. 1996; Duprez et al. 1996; Schmidt and Thomsen 1998; Debellefontaine et al. 1999; Khan et al. 1999; Luck 1999; Zerva et al. 2003), and in recent years, a renewed interest in WO of sewage sludge has emerged, as confirmed by the number of recent publications (Pérez-Elvira et al. 2006; Jaroslaw and Roman 2008; Yang et al. 2010; Abe et al. 2011; Gielen et al. 2011; Strong et al. 2011; Padoley et al. 2012; Strong and Gapes 2012; Baroutian et al. 2013).

Also, many reviews on WO process were published (e.g. Mishra et al. 1995; Luck 1999; Bhargava et al. 2006). However, to the authors' knowledge, these publications mainly focus on technical aspects (such as kinetic models, process parameters and their effect on different kinds of matrices), while they seldom discuss advantages/disadvantages of the process application. These are shortly reported as "bullet points" of generic sentences (such as "the main drawbacks of WO process are: high capital and maintenance cost; high ammonia production may be a problem with downstream treatment; high energy-costs, environmental impact is negligible…"), but no detailed estimation has been performed in previous studies even if the quantification of these techno-economic-environmental aspects is crucial for evaluating the real sustainability and applicability of the processes.

In ROUTES project, the innovative matching of WO with anaerobic digestion of the liquid residue is presented. In this way, energetic valorisation (biogas production) and the reduction of chemical oxygen demand (COD) load to be recycled back to the WWTP can be simultaneously achieved. This paper reports on a case study in which a new methodology for technical, economic and environmental assessment has been applied to evaluate the introduction of such innovative WO/anaerobic digestion technology in a conventional WWTP. By means of this integrated, detailed and reliable (i.e. based on full scale experimental data) assessment, advantages and drawbacks of this solution as well as the main factors affecting its applicability have been highlighted and quantified.

Methodology

The techno-economic-environmental evaluation followed in most parts the methodology developed within the ROUTES project and described earlier by Svanström et al. (2014). Since the present paper reports on a case study that was performed in the second cycle of the evaluation within the ROUTES project, the methodology has been slightly modified to account for some issues that were identified in the first cycle (see Svanström et al. 2014 and Bertanza et al. 2014a). In the present paper, only particularly important aspects of or modifications to the methodology are presented; the focus is on the particular case study and its results.

In short, the methodology used for the assessment of technical, economic and environmental features was inspired by systems engineering, using an iterative approach involving several loops of definition and redefinition of systems, data collection and performance assessment.

In the techno-economic assessment, the consequence of changing from a reference scenario into a new scenario was assessed. For the environmental assessment, this was not seen as sufficient since this assessment also aimed at revealing hot spots (dominant activities) in the life cycle. The techno-economic assessment also studied a more narrow system in terms of life cycle stages than the environmental assessment, which was performed using a life cycle perspective.

The methodology involves a preliminary design of WWTPs based on detailed plant-wide mass and energy balances. Secondary sludge production, oxygen consumption and other process parameters were calculated with the support of the WinAscam (Activated Sludge Computer Aided Modelling) software (Tomei et al. 1990; Tomei et al. 1994). Thereafter, the necessary details of the surrounding system, including transport distances, chemicals used and the use of different products (to guide the environmental assessment in what products that can be considered to be replaced) were decided on.

Technical aspects

For the technical evaluation, focusing on the role of the operator, applied assessment parameters can be sorted under the following main aspects:

- Reliability of technology
- Complexity and integration with existing facilities
- Flexibility/Modularity
- Residues and recovered materials
- Consumption of raw materials and reagents
- Electric energy consumption
- Thermal energy consumption
- Energy available for external recovery
- Social and authorisation aspects

Each main aspect contained several different subcategories. The methodology also contains notes on what type of data that is appropriate for each subcategory, e.g. from research activities or from plant monitoring, and site-specific or generic (Svanström et al. 2014; Bertanza et al. 2014a). Data collected was filled into work sheets that had been prepared for calculations, and the results were then analysed.

The final results were eventually expressed by a colour code (Bertanza et al. 2014a, modified), thus avoiding numerical values. A green colour means that the change will not have a significant impact in the operation of the WWTP; yellow indicates a moderate impact; and blue indicates that the impact is significant and should be more thoroughly considered.

Cost estimation

For the economic evaluation, the assessment parameters applied were as follows:

- Depreciation of new equipment (only for the WO scenario)
- Ordinary maintenance cost
- Cost of personnel
- Cost of electric energy
- Income from electric/thermal energy sale
- Cost for additional analyses for process control
- Cost of raw materials and reagents
- Income from recovered materials
- Cost for sludge disposal
- Cost of transportation

Cost items were calculated based on data derived from mass and energy balances. Calculated capital and operating costs refer to average loading conditions, which were considered to correspond to actual (design) loading conditions.

The economic comparison was carried out by calculating the cost difference (gap) between the new and the reference solution. Thus, a positive gap means that an additional cost must be paid in case the new solution is applied to an existing WWTP. Since cost items are variable and depend on many local conditions, a sensitivity analysis was performed in order to reveal critical factors. This was done by calculating variations in the final result due to the assumption of either the most favourable or the worst economic conditions for all cost items.

Environmental assessment

The environmental assessment was performed as a life cycle assessment (LCA), as far as possible following the international standards ISO 14040:2006, ISO 14044:2006 and the International Life Cycle Data Systems (ILCD) Handbook (European Commission Joint Research Centre 2010). An LCA maps the resource use and emissions from a studied system, normally the life cycle of a product or a service and recalculates them into different types of environmental impact, referred to as impact categories. In this study, the environmental impact was calculated "per daily inflow to the WWTP" (the functional unit).

Studied environmental impact categories were as follows:

- Global warming potential (GWP)
- Acidification potential (AP)
- Eutrophication potential (EP) for freshwater, marine and terrestrial systems
- Photochemical oxidant formation potential (POFP)

The environmental impacts from wastewater and sludge treatment as well as the sludge end-of-life and the production of input materials such as electricity, heat and chemicals and sludge transports were included in the studied system (see Fig. 1). However, production capital was not included as the environmental impacts of the assessed kind are typically small

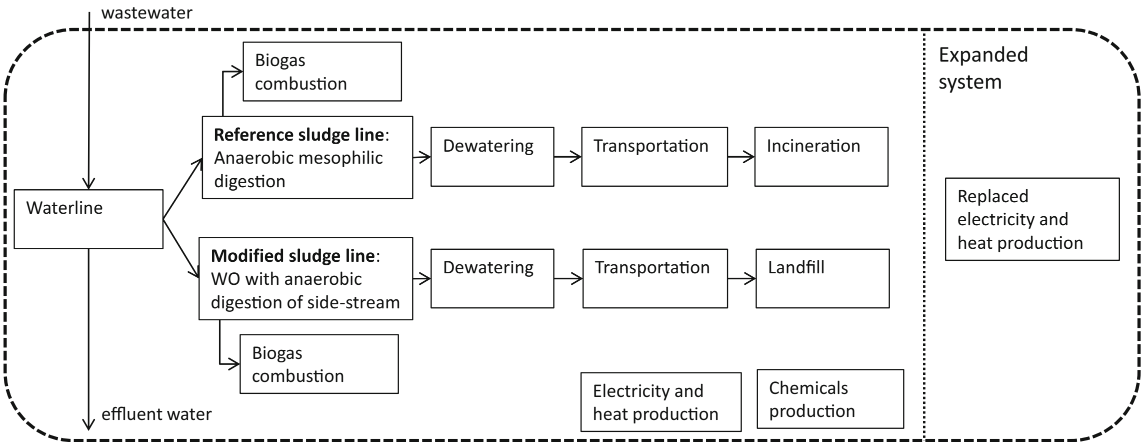


Fig. 1 Process flow chart displaying the system boundaries of the studied reference and modified scenarios

for this part of the system (Corominas et al. 2013). Furthermore, the contribution to the total environmental impact from the production capital in an LCA of wastewater treatment that included WO has been shown to be less than 1 % of studied impacts, which were energy use, GWP, EP and POF (Gielen et al. 2011). In cases where a marketable by-product was generated (electric and thermal energy), a system expansion approach was applied, giving the studied system benefits for the by-products by accounting for avoided production of a similar conventional product. The assessment is made for average EU-25 conditions (important for the selection of data for modelling the background system, for example the electricity production mix). The Gabi software (PE International 2013) was used for modelling the systems, and the characterisation methods recommended by the ILCD Handbook were used in the impact assessment.

The case study

The reference plant is a conventional activated sludge WWTP (with primary sedimentation and anaerobic digestion of sewage sludge, nominal size 500,000 person equivalents (PE)). The resulting sludge is considered to be incinerated. The assumed influent and effluent characteristics are reported in Table 1.

The design of the processes of the WWTP was made using the following assumptions:

- Steady-state conditions
- Yearly average performance data
- Wastewater temperature 15 °C
- Average performance (removal efficiency) of primary sedimentation: total suspended solids (TSS)=60 %; COD=30 %; biochemical oxygen demand-5 days (BOD_5)=35 %; N_{tot}=10 %; P_{tot}=10 %

WO is the chemical oxidation of dissolved or suspended components in wastewater or sludge at high temperatures and high pressures, which allows the transformation also of non-biodegradable and toxic organic compounds into biodegradable compounds that can be degraded in a subsequent biological process. The high temperatures and the reaction with oxygen determine the conversion of organic substances into carbon dioxide and water, while the high pressures guarantee the liquid phase in which it is possible to obtain a higher concentration of dissolved oxygen and, therefore, a higher oxidation rate. The WO process allows to obtain a reduction in sludge volume, the partial or full mineralisation of sludge, the reduction of the microbial load and the absence of hazardous gaseous compounds (Collado et al. 2012). The main WO outputs are as follows: a liquid highly biodegradable effluent, a gas outflow (mainly CO_2, N_2 and oxygen) and a residue outflow. During the WO process, many reactions occur at the same time: their detailed understanding is not possible when dealing with complex mixtures, such as sewage sludge. For this reason, Generalised Lumped Kinetic Models (GLKM) may be used to predict WO performance. According to the model described in Bertanza et al. (2014b), the following basic transformations are expected to simultaneously occur: particulate organic compounds are transformed into dissolved intermediate products, and the dissolved organic substance is either mineralised to CO_2 and water or transformed into low molecular weight organic residues (e.g. acetic and propionic acids).

Table 1 Influent and effluent characteristics assumed for the case study

	Influent concentration [mg/L]	Effluent	
		Limit (non-sensitive recipient[a]) [mg/L]	Design assumption (reference scenario) [mg/L]
COD	500	125	50
BOD_5	220	25	–
N_{tot}	40	–	18
P_{tot}	5.5	–	–
TSS	220	35	20

[a] EU Directive 91/271/EEC

In this case study, the reference plant was assumed to be upgraded with a WO process with subsequent anaerobic digestion of the liquid residue. The WO solid residue was considered to be sent to a landfill (non-hazardous wastes). The WO process was considered to operate at temperatures of about 240–250 °C, pressures of about 55–60 bar and reaction times of about 40–80 min. These values correspond to the conditions which are kept at the full-scale plant used as a data source, as reported in Bertanza et al. (2014b) and shortly described below. The sludge fed to the reactor is preheated by means of vapour recycled from flash tanks. In the reactor, pure oxygen and further vapour are added upstream in order to reach the desired treatment conditions.

The performances of both WO and liquid residue anaerobic digestion were derived by experimental activities conducted within the ROUTES project and published in Bertanza et al. (2014b) and Bertanza et al. (2014c), respectively. In summary (see cited references for details), WO tests were carried out on the DUAL TOP® full-scale plant ($V=2.67\ m^3$), which is located at 3V Green Eagle facility, Northern Italy. Four different kinds (depending on their origin) of sewage sludge were fed to the WO plant, which was operated under variable limiting operating conditions (temperature=225–250 °C; reaction time=40–100 min; oxygen dosage with respect to stoichiometric=65–85 %): volatile suspended solids (VSS) and COD removal efficiency varied between 80–97 % and 43–71 %, respectively. The liquid residue obtained during full-scale WO tests on two different types of sludge was submitted to mesophilic anaerobic digestion in a continuous flow pilot reactor (V=5 L). Experimental results showed that after an acclimation period (about 130 days), COD removal efficiency was stably around 60 % for about 120 days, under the following operating conditions: hydraulic retention time (HRT)= 20 days, volumetric organic loading rate (VOLR)=0.75 kg COD/(m^3 day), organic loading rate per VSS (OLRvss)= 0.06 kg COD/(kg VSS day); temperature (T)=36.5 °C, pH=8. In the last phase of the experimental activity, COD removal increased up to 70 %, after changing the feeding mixture (VOLR=0.87 kg COD/(m^3 day)). This final very positive result was indeed not taken into account in the following evaluation, in order to obtain a more conservative general assessment.

Results and discussion

Mass and energy balances

Detailed mass balances of the case study are reported in Fig. 2 (reference plant) and Fig. 3 (upgraded plant). The comparison of the two mass balances gives evidence of the drastic reduction of sludge production achieved by means of WO (>96 % based on VSS). The very high dry solid content of WO residue after mechanical dewatering (60 %) is in agreement with the one recorded by Luck (1999) in other full-scale experiences (55 %): improvement of sludge dewaterability is an important advantage of WO in view of the amount of residue to be disposed. The residual liquid stream associated with the WO process, even though treated by anaerobic digestion, results in 5–13 % (depending on the considered parameter) of additional mass loading to the biological treatment. This is not considered a relevant drawback if appropriately managed together with the usual loading variability at the WWTP. Therefore, it has been assumed that the effluent quality remains unchanged for all parameters except the COD, for which a certain increase could be found due to the refractory substrates generated during the WO process. From the experimental results, the worst conditions were selected for the COD mass balance (i.e. removal of COD from the digestate stream limited to 35 %), resulting in an increased effluent COD concentration of about 20 mg/L. Hence, it is a valid assumption that better performance and a negligible variation in effluent quality can be obtained under real conditions.

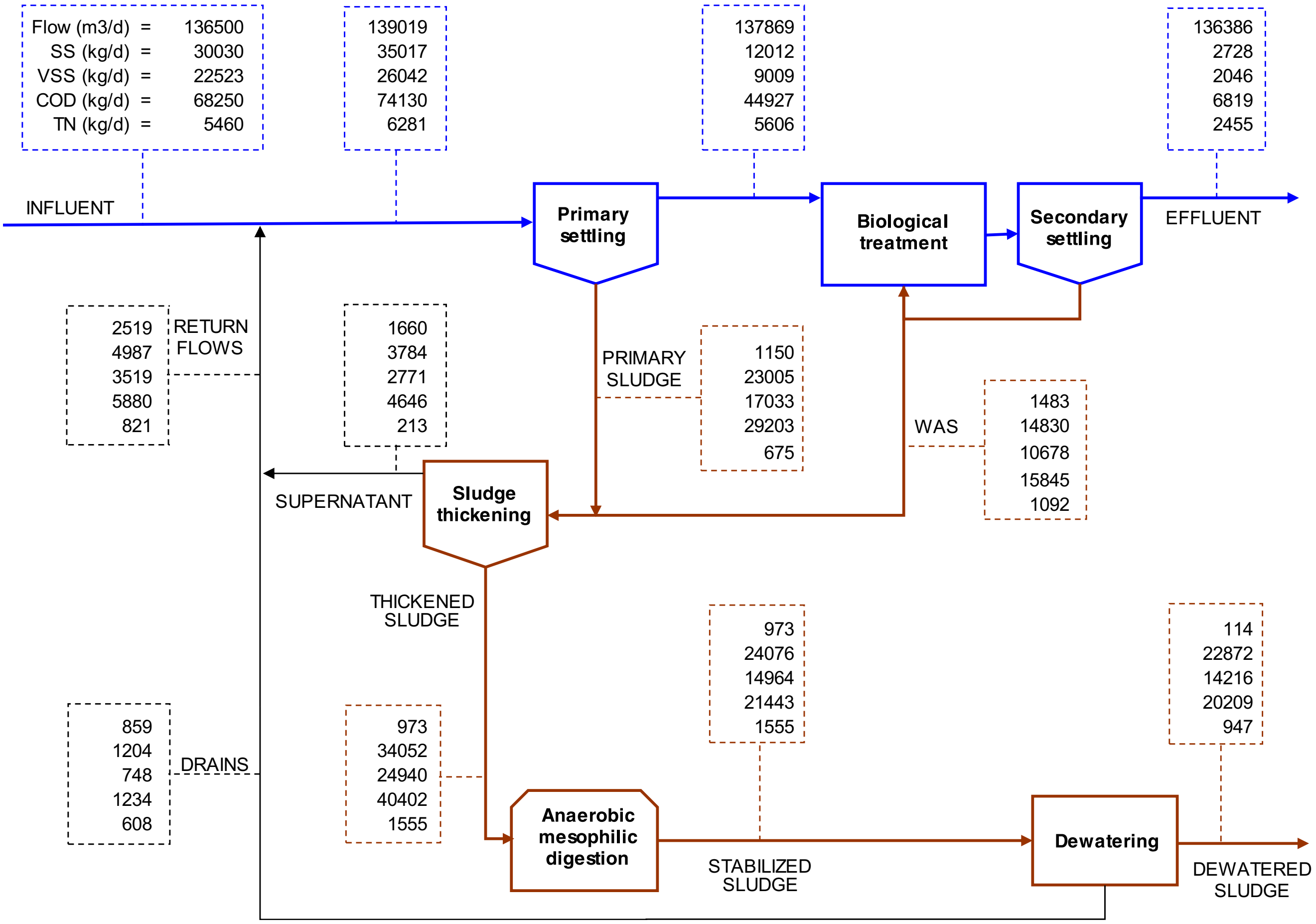


Fig. 2 Mass balance of the reference plant

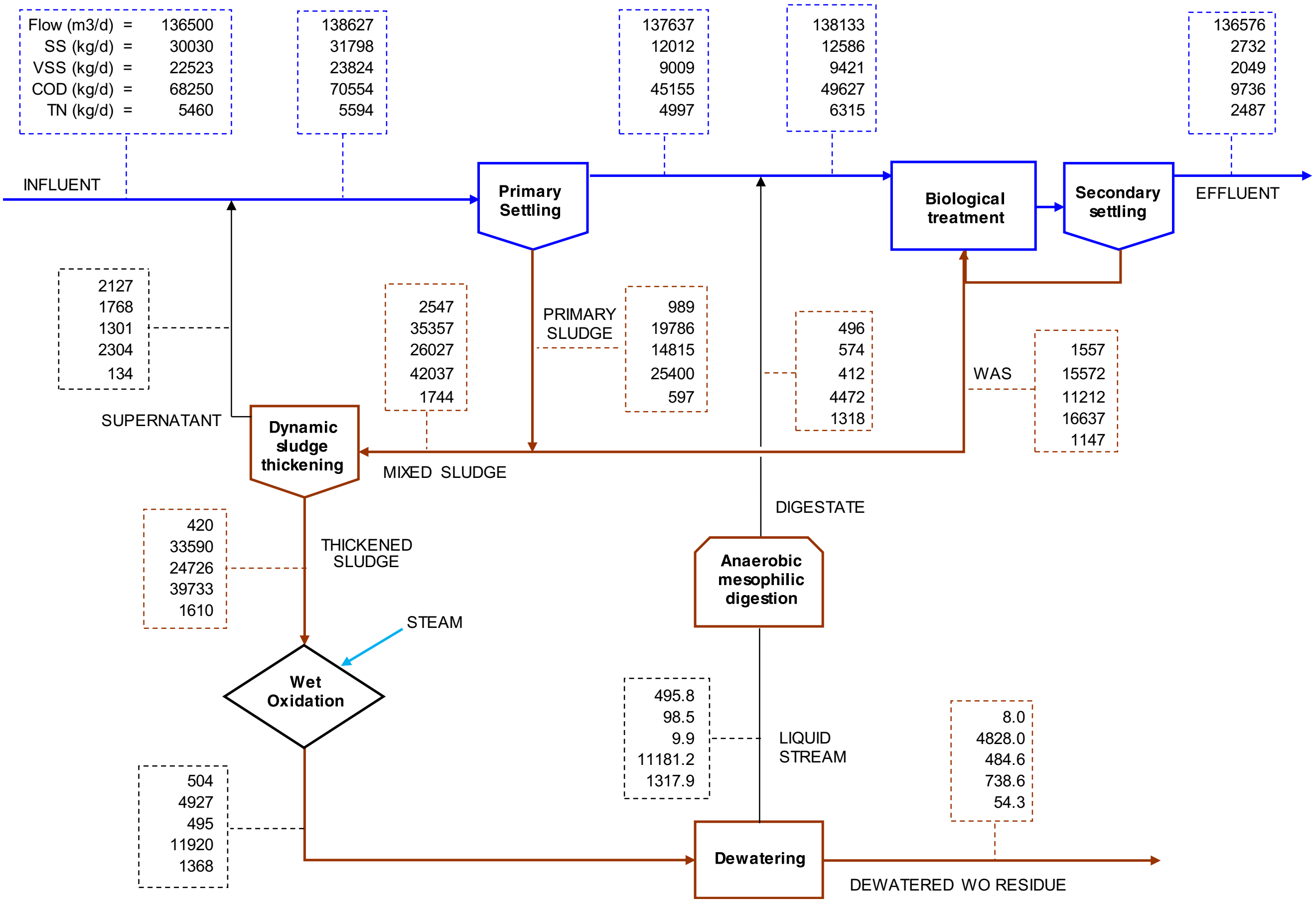


Fig. 3 Mass balance of the modified (with WO+anaerobic digestion) plant

Figure 4 shows the COD transformation pattern for the reference and the upgraded plants. This is drastically changed in the upgraded plant; the sludge COD reduction is significant. Furthermore, COD conversion to methane is reduced, and COD oxidation is very much increased (due to WO). Residual COD in the effluent is also increased, as discussed earlier.

Figure 5 shows the energy demand of the different parts of the process as well as the net for both reference and upgraded plants. It is shown that the introduction of the WO process does not affect the net demand significantly as the additional power consumption in the upgraded system (mainly connected to high-pressure liquid pumping in the WO unit; see the item "Other" in Fig. 5) is compensated for by energy production. Note that a CHP unit is installed in the upgraded plant, while in the reference one, according to the energy balance, all produced biogas is used for digester heating.

As reported by Hii et al. (2014), it must be taken into account that WO process typically becomes energetically self-sufficient at medium-high temperature (>200 °C) which corresponds to the typical working conditions for sludge treatment.

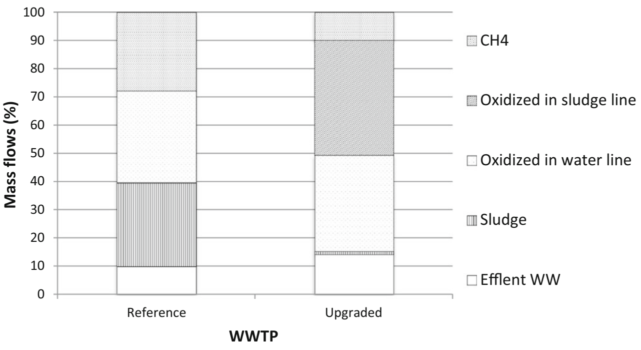


Fig. 4 COD transformation pattern for reference and modified plants

Technical assessment

Final results from the technical evaluation are shown in Table 2. Note that the technical evaluation here reported aims at reflecting the viewpoint of the technical manager operating the plant. However, when evaluating the technical assessment for real case studies, further general aspects that contribute to the overall opinion of the technical manager should be taken into account, such as the site-specific sludge management conditions, that could not be quantified in the presented methodology. Economic and environmental benefits and drawbacks are considered elsewhere.

Fig. 5 Energy demand inventory for reference and upgraded plants (electric energy (EE))

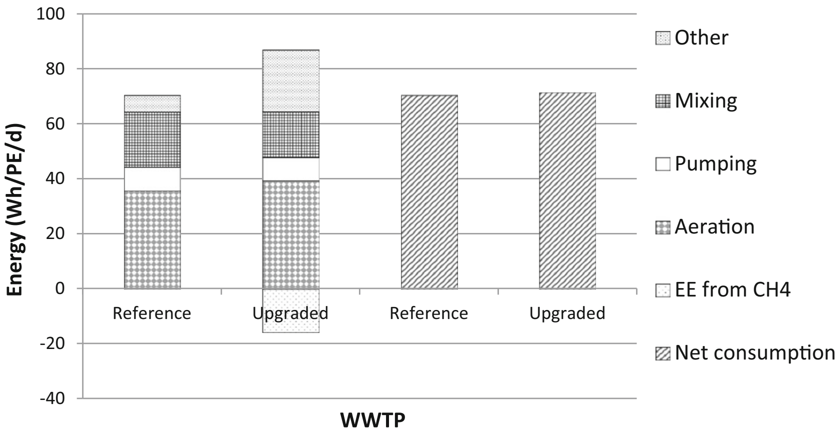


Table 2 Final results of the technical evaluation

Aspect	Colour code	Comment
Reliability of technology	GREEN	
Complexity and integration with existing facilities	BLUE	Blue colour because of personnel and safety standards requirements and the significant plant modification
Flexibility/Modularity	GREEN	
Residues & recovered materials	GREEN	
Consumption of raw materials and reagents	BLUE	Blue colour because the additional consumption of reagents (methane, oxygen, coagulant etcetera) is greater than 20%
Electric energy consumption	YELLOW	Yellow colour because the additional power consumption (WO unit, in particular) is greater than 20% (but lower than 100%)
Thermal energy consumption	BLUE	Blue colour because the additional methane consumption (WO unit) is greater than 20%
Energy available for external recovery	BLUE	Blue colour to underline that additional work is required for managing the energy recovery procedures and devices
Social & authorization aspects	YELLOW	Yellow colour mainly because of the complexity of the authorization process (gaseous emissions, external heating recovery, CHP, etcetera)

Colours indicate the technical operation situation for the upgraded plant as compared to the reference plant (no significant impact (green); moderate impact (yellow); impact is significant and should be more thoroughly considered (blue))

Economic assessment

In Table 3, the data collected and used for the economic calculations are reported: ranges of variation were used in the sensitivity analysis.

Under the aforementioned conditions, calculated operating costs for the reference WWTP (including sludge handling and disposal) range between 15 and 20 €/(PE year), in agreement with values reported by Kroiss (2004). In the upgraded solution, the global treatment cost (depreciation included) of WO accounts for 225–450 €/t_{DS} of treated sludge, which, again, is comparable with 425 €/t_{DS} reported by Debellefontaine and Foussard (2000).

Capital cost for upgrading can vary markedly in real situations depending on many constraints (local taxes, permits, fees or duties, etc.) and factors. In addition, as reported in literature (Bhargava et al. 2006; Stüber et al. 2005; Debellefontaine and Foussard 2000; Luck 1999; Hurwitz and Dundas 1960), the operative conditions, such as reaction temperature, characteristics of submitted waste (e.g. Cl ion concentration and solid concentration), kind of oxidiser and operative pressure, affect markedly the investment cost. If only sewage sludge is treated, no severe operative conditions must be applied and low Cl ion concentrations could permit reactors to be manufactured in AISI 316 with no increased wall thickness, because no corrosion problems are expected. Capital costs can be saved, consequently. Moreover, the use of pure oxygen (as assumed in this case) rather than air leads to lower costs (Bhargava et al. 2006).

Figure 6 shows the detailed results of the economic assessment. It can be seen that the total cost gap varies between a negative and a positive value, depending on how different inputs are varied. This means that economic sustainability may either be satisfied or not, depending on the local conditions. The sensitivity analysis showed the two items which have the greatest impact on the final economic outcome. When assessing the applicability of this solution in real cases, these two items should be evaluated and quantified with particular accuracy. The first one is the cost of residue disposal: for the upgraded plant, it ranges between 0.117 and 0.584 €/(PE year), while the sludge disposal cost calculated for the reference scenario is in the range 1.67–8.35 €/(PE year), which is consistent with values reported by Kroiss (2004): 3–4 €/(PE year). The second relevant cost item is related to material and reagent consumption (methane and pure oxygen in particular). Despite this, it has to be underlined that, as shown by Bhargava et al. (2006), oxygen-based WO system are more profitable than air-based systems, primarily because of the lower oxidant flow and lower energy losses.

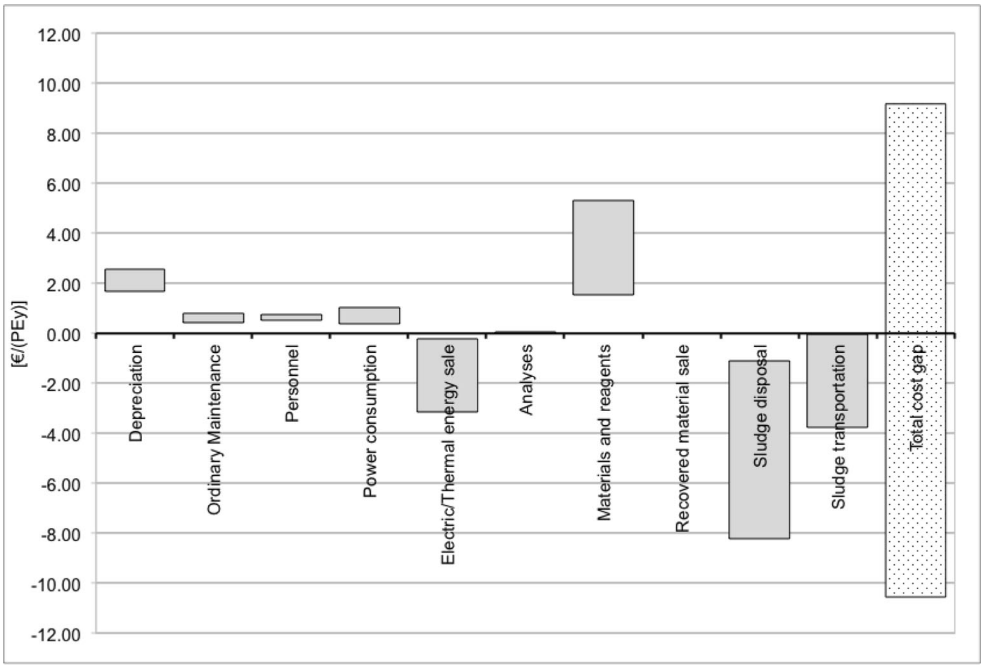
Both capital and operation costs were calculated based on the average loading conditions, which have been considered as correspondent to actual (design) loading conditions. In case they are expected to change appreciably over the year, an extra cost has to be considered for equipment and device oversizing and for taking into account performance loss due to working periods under suboptimal conditions.

The economic evaluation was not carried out for a real plant. Some uncertainties in the cost estimation must therefore be underlined, in particular concerning the possible recovery of the WO residue. In fact, a recent industrial experimental activity performed in the 3V Green Eagle Environmental Center (Slavik et al. 2013) was aimed at drying the WO solid residue to produce a material that was subjected to the environmental and mechanical assessment procedures in order to evaluate the possibility to be used as filler for bituminous materials and similar, according to UNI EN 13043

Table 3 Numerical values of economic items collected and used in the economic evaluation

Economic items	Min	Max	Data source
Distance covered for disposal per trip [km]	20	200	Real cases
Graduated technician [€/year per worker]	50,000	80,000	Real cases
Specialised worker [€/year per worker]	35,000	50,000	
Worker [€/year per worker]	25,000	35,000	
Unitary cost of electric energy [€/kWh_e]	0.06326	0.16953	Europe's Energy Portal
Unitary income for electricity sale [€/kWh_e]	0.038	0.224	
Unitary income for thermal energy sale [€/kWh_t]	0	0.05	
Unitary cost of polyelectrolyte for water or sludge line [€/kg]	2	4	Real cases
Unitary cost of coagulants for water or sludge line ($FeCl_3$) [€/kg]	0.1	0.3	Real cases
Unitary cost of pure oxygen for water or sludge line [€/kg]	0.04	0.10	Real cases
Unitary cost of methane [€/Nm^3]	0.2276	0.839	Europe's Energy Portal
Unitary cost for solid/slurry disposal [€/t]	20	100	Real cases (European countries)
Unitary cost for transportation of solid/slurry residues [€/km]	2.2	6.8	Real cases
Interest rate	2.5	7.5	Market conditions

Fig. 6 Result of the economic assessment, including the sensitivity analysis: each bar represents the range of variability of cost gap for a given item. The upgraded plant is cheaper if the gap is negative



"Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas". The leaching tests on the samples simulating the whole life of the bituminous mixture containing the filler from WO residue indicate no variations with respect to the use of a traditional filler. These results allowed the filler from WO residue to receive the CE mark for bituminous materials and similar. Therefore, a recovery of the WO solid residue using WO surplus heat may be possible, avoiding landfill disposal, according to the classification of the filler and to the national standard requirements.

Environmental assessment

Results from the LCA are shown for both systems in Fig. 7. Results are divided into contributions from different parts of the processes. Note that the replacement of heat from other sources by heat recovered during WO ("replaced heat") generates an environmental benefit to the WO system that appears as negative emissions in the LCA. Sludge end disposal is different in the two systems as sludge is incinerated in the reference plant, and WO residue is landfilled in the upgraded plant.

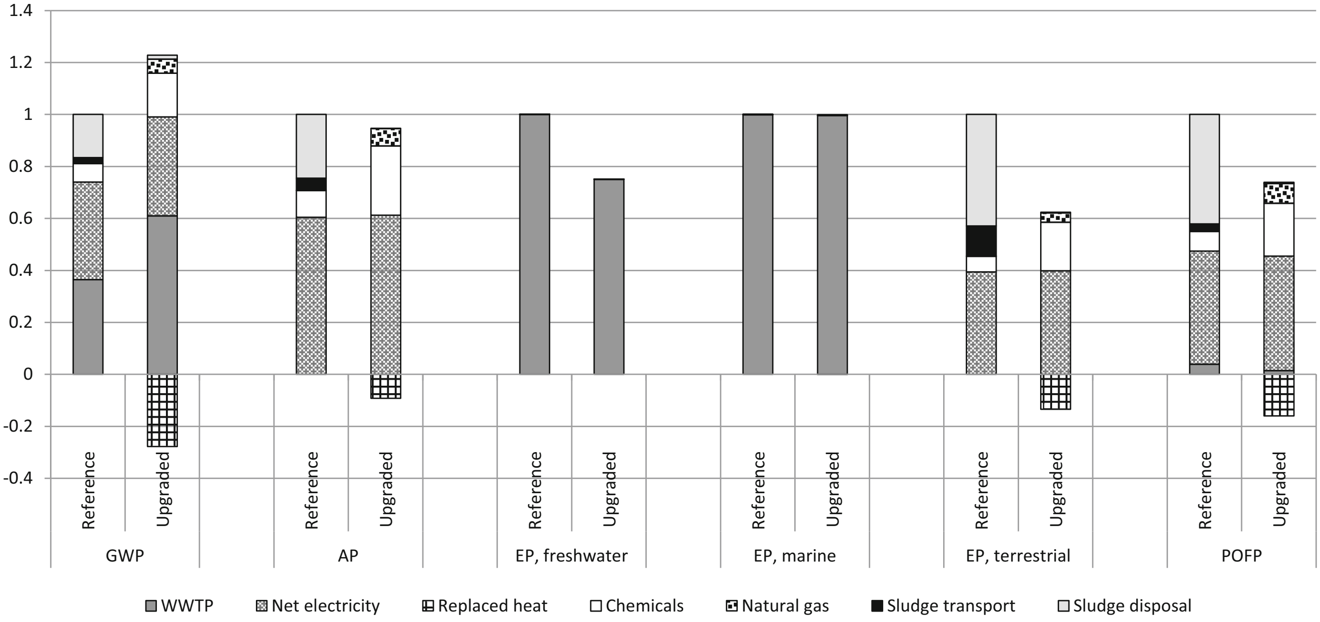


Fig. 7 Results for the environmental LCA of the reference system and for the WO system for different environmental impact categories

It can be seen in Fig. 7 that the WO process results in more greenhouse gas emissions to air from the WWTP but in less phosphorus emissions in the effluent. The impact from use of chemicals and natural gas in the WO process provides a disadvantage to this process; however, impacts related to sludge transports are decreased. A considerable improvement results from that incineration of sludge is avoided in the WO system. In summary, however, the two systems perform almost equally. The WO system performs better than the reference system mainly for freshwater and terrestrial eutrophication, whereas other impacts are very similar. The overall result for the innovative system is thus dependent on how impact categories are prioritised.

It can also be discussed whether or not the assessment captures the most important aspects or if there are important gaps that should be filled before any final conclusions can be drawn. For environmental evaluations of wastewater and sludge management, impacts related to the content of chemicals, pathogens and even carbon and organic material in effluent and in sludge are sometimes discussed, especially when sludge is to be applied on land. These aspects are, however, seen as less important in this case as sludge or remaining solids are incinerated or landfilled. However, since some heavy metals may escape to air from incineration of sludge (e.g. 38 % of the mercury but much less of other heavy metals according to Larsen et al. 2010), human and ecosystem toxicity may be impact categories that could provide additional information.

Integrated assessment and discussion

As expected, the upgrade of a WWTP with WO as considered in this study has both advantages and drawbacks, and the way in which different aspects are prioritised will determine the outcome. In fact, if the WO process may not be the most favourable solution in many cases, there are specific situations in which WO is a well-balanced solution for solving issues in sludge treatment and management. This study was performed to provide a holistic understanding of all important impacts in terms of technical, economic and environmental aspects of the upgrade of the reference plant with WO technology and to highlight areas that need a more detailed evaluation for the specific case in which this upgrade is to be applied. Once more exact numbers have been derived for a specific plant, each of the evaluated aspect could receive its own weighting factor, possibly determined in a multicriteria decision analysis (MCDA) process, in light of the specific situation in which the technology is to be applied and with stakeholders relevant for the specific case.

Results from the present study are valid for a plant that is characterised in terms of process configuration, size, wastewater and sludge characteristics, effluent standards to be complied with. They cannot be extended to other case studies: specific circumstances and constraints can be very different for different sites and can modify the role of considered parameters, leading to different final results. Moreover, the applied assessment procedure requires many calculations (biological process design, mass balance, energy balance, cost estimation, etc.). A certain degree of uncertainty is therefore inherent in the procedure. This has to be taken into account when comparing the reference and the innovative solutions: slight differences are not relevant. Looking at the different results in light of these limitations, the upgrade seems reasonable from economic and environmental viewpoints, with some technical criticisms that should be evaluated case-by-case, according to the specific plant sludge management options. Table 4 summarises the important findings.

It is important to recognise that there seems to be some conflicting results where trade-offs might have to be considered in a more detailed assessment, e.g. when changes lead to technical issues but to a reduction of costs or reduced environmental impacts. For this reason, some of these areas are highlighted and discussed here. WO allows for heat recovery and electricity recovery. The installation of a CHP unit (accounted for, in this analysis, as a technical issue) leads to a net environmental impact related to electric energy

Table 4 Summary of important findings from the techno-economic-environmental assessment

Aspect	Conclusion
Overall impact	Some potentially critical technical items Economic sustainability dependent on local conditions (−52 % / +62 % of operation and maintenance costs of reference WWTP) Slightly lower global environmental impact
Impact on sludge production	Drastic reduction of sludge production (>96 % of VSS)
Resource recovery	Heat and power recovery Possible recovery of WO residue
Most influencing cost item(s)	Disposal of residues Material and reagent consumption
Uncertainties of cost estimation	Possible recovery of WO residue
Main improved environmental impact categories	Freshwater eutrophication, terrestrial eutrophication and photochemical oxidant formation
Main reasons behind environmental improvements	Less emissions from sludge disposal including transports Heat recovery
Main worsened environmental impact categories	None
Main reasons behind negative environmental consequences	Greenhouse gas emissions at WWTP Use of chemicals and natural gas at WWTP

consumption which is equivalent in both solutions, despite the greater power demand of the WO plant. Heat recovery, as considered to replace thermal heat produced from natural gas, contributes to lowering almost all environmental impact categories. In addition, an economic advantage arises. However, the resulting increasing plant complexity in terms of handling energy flows is seen as a technical disadvantage. It is clear that this point of view is limited and specific of the methodology adopted; in fact, further factors related to the plant technical manager viewpoint could be taken into account when evaluating the effectiveness of the WO solution described for a specific real case, such as the advantage of increasing sludge management options, that is a general troubling issue for the technical manager, but that is almost impossible to quantify.

The additional facilities to be installed and the increased reagent consumption, although introducing potentially critical technical items, eventually lead to a drastic sludge reduction with a remarkably positive effect on environmental impacts (transportation is drastically reduced as well) and sludge management within the WWTP. Environmental benefits will also play an important role in the authorisation process, allowing for smoother and possibly shorter approval process from regulatory agencies. Such benefit will allow plant manager to improve his relationship with the community and other stakeholders involved. On the other hand, sludge disposal and material/reagent costs represent the most important items to define in case-specific economic calculations. Since the specific priorities may vary between different cases, similar assessment results may thus lead to different preferences in terms of whether to upgrade a WWTP with WO or not.

Conclusions

A techno-economic and environmental evaluation was made for the specific case study of upgrading a WWTP with a WO unit for sludge reduction. The integrated assessment indicates that, depending on local conditions, the proposed upgrade can result in both environmental and economic advantages. However, the evaluation also evidenced some potential drawbacks in terms of technical management: the most important technical issues relate to additional facilities to be operated and chemicals consumption. Nevertheless, technical management at WWTP is improved by increasing sludge management options and therefore avoiding disposal site bottlenecks, and also by adopting an environmentally friendly technology which allows to improve acceptance to local regulatory agencies, communities and other stakeholders.

The adopted approach provides a guidance in terms of which aspects need a more thorough evaluation in relation to the specific case in which an upgrade with WO is considered. Although the results of this evaluation are valid under the assumed conditions of the case study, it can be generalised that economic sustainability of this solution depends mainly on both sludge disposal (and transportation) and reagent costs. The complexity of a WO facility is counterbalanced by overall reduced environmental impacts; here, the possibility of external heat recovery plays a relevant role.

Overall, the proposed WO technology can be a sustainable alternative to conventional sludge stabilisation and incineration, especially for large WWTP or for centralised sludge treatment plants.

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References

Abe N, Tang YQ, Iwamura M, Ohta H, Morimura S, Kida K (2011) Development of an efficient process for the treatment of residual sludge discharged from an anaerobic digester in a sewage treatment plant. Bioresource Technol 102:7641–7644

Baroutian S, Smit AM, Gapes DJ (2013) Relative influence of process variables during non-catalytic wet oxidation of municipal sludge. Bioresource Technol 148:605–610

Bertanza G, Canato M, Laera G, Tomei M C (2014a). Method for technical and economic assessment of advanced sludge processing routes. Accepted for publication in*Environmental Science and Pollution Research*

Bertanza G, Galessi R, Menoni L, Pedrazzani R, Salvetti R, Zanaboni S (2014c) Anaerobic treatability of liquid residue from wet oxidation of sewage sludge. Accepted for publication in*Environmental Science and Pollution Research*

Bertanza G, Galessi R, Menoni L, Salvetti R, Slavik E, Zanaboni S (2014b). Wet oxidation of sewage sludge: process modeling and full scale experience, Accepted for publication in*Environmental Science and Pollution Research*

Bhargava SK, Tardio J, Prasad J, Föger K, Akolekar DB, Grocott SC (2006) Wet oxidation and catalytic wet oxidation. Ind Eng Chem Res 45:1221–1258

Collado S, Laca A, Diaz M (2012) Decision criteria for the selection of wetoxidation and conventional biological treatment. J Environ Manage 102:65–70

Corominas L, Foley J, Guest JS, Hospido A, Larsen HF, Morera S, Shaw A (2013) Life cycle assessment applied to wastewater treatment: state of the art. Water Res 47(15):5480–5492

Debellefontaine H, Chakchouk M, Foussard JN, Tisso D, Striolo P (1996) Treatment of organic aqueous wastes, wet air oxidation and wet peroxide oxidation. Environ Pollut 92(2):155–164

Debellefontaine H, Crispel S, Reilhac P, Perie F, Foussard JN (1999) Wet air oxidation (WAO) for treatment of industrial wastewater and domestic sludge. Design of bubble column reactors Chem Eng Sci 54:4953–4959

Debellefontaine H, Foussard JN (2000) Wet air oxidation for the treatment of industrial wastes. Chemical aspects, reactor design and industrial applications in Europe. Waste Manage 20:15–25

Devlin HR, Harris IJ (1984) Mechanism of the oxidation of aqueous phenol with dissolved oxygen. Ind Eng Chem Fundam 23:387–392

Duprez D, Delanoe F, Barbier J Jr, Isnard P, Blanchard G (1996) Catalytic oxidation of organic compounds in aqueous media. Catal Today 29: 317–322

Europe's energy portal: http://www.energy.eu/. Accessed 03rd March 2014

European Commission Joint Research Centre (2010) ILCD Handbook—International Reference Life Cycle Data System. First edn. European Union. doi:10.2788/38479

Foladori P, Andreottola G, Ziglio G (2010) Sludge reduction technologies in wastewater treatment plants. IWA Publishing, London

Foussard JN, Debellefontaine H, Besombes VJ (1989) Effective elimination of organic liquid wastes: wet air oxidation. Environ Eng 115: 367

Gielen G, Love S, Lei R, Gapes D, Strong J, McGrouther K, Stuthridge T (2011) Wet oxidation technology—a potential biosolids management alternative, IPENZ Transactions 2011/2

Hii K, Baroutian S, Parthasarathy R, Gapes D, Eshtiaghi N (2014) A review of wet air oxidation and thermal hydrolysis technologies in sludge treatment. Bioresource Technol 155:289–299

Hurwitz E, Dundas WM (1960) Wet oxidation of sewage sludge. Water Pollut Control 32(9):918–929

Jaroslaw M, Roman Z (2008) Analysis of wet oxidation process after initial thermohydrolysis of excess sewage sludge. Water Res 42: 3025–3032

Joglekar HS, Samant SD, Joshi JB (1991) Kinetics of wet oxidation of phenol and substituted phenols. Water Res 25(2):135–145

Khan Y, Anderson GK, Elliott DJ (1999) Wet oxidation of activated sludge. Water Res 33(7):1681–1687

Kroiss H (2004) What is the potential for utilizing the resources in sludge? Water Sci Technol 49:1–10

Larsen HF, Hansen PA, Boyer-Souchet F (2010) NEPTUNE—New sustainable concepts and processes for optimization and upgrading municipal wastewater and sludge treatment, Work Package 4—assessment of environmental sustainability and best practice. Deliverable 4.3 - Decision support guideline based on LCA and cost/efficiency assessment. pp. 163

Liu Y, Tay JH (2001) Strategy for minimization of excess sludge production from the activated sludge process. Biotechnol Adv 19:97–107

Luck F (1999) Wet air oxidation, past, present and future. Catal Today 53: 81–91

Mahmood T, Elliott A (2006) A review of secondary sludge reduction technlogies for the pulp and paper industry. Water Res 40:2093–2112

Mishra VS, Mahajani VV, Joshi JB (1995) Wet air oxidation. Ind Eng Chem Res 34:2–48

Padoley KV, Tembhekar PD, Saratchandra T, Pandit AB, Pandey RA, Mudliar SN (2012) Wet air oxidation as a pretreatment option for selective biodegradability enhancement and biogas generation potential from complex effluent. Bioresource Technol 120: 157–164

PE International (2013) Gabi Professional database 6

Pérez-Elvira SI, Nieto Diez P, Fdz Polanco F (2006) Sludge minimisation technologies. Rev Environ Sci Biotechnol 5:375–398

Ploos van Amstel JJA, Rietema K (1973) Wet-air oxidation of sewage sludge part II: the oxidation of real sludges. Chem Ing Tech 45: 1205–1211

Ploos van Amstel JJAP (1971) The oxidation of sewage sludge in the liquid water phase at elevated temperatures and pressures (wet-air oxidation). PhD thesis, Eindhoven University of Technology, Netherlands

ROUTES - Novel processing routes for effective sewage sludge management: http://eurotes.org/index.php?option=com_content&view=article&id=50&Itemid=28. Accessed 03rd March 2014.

Schmidt AS, Thomsen AB (1998) Optimization of wet oxidation pretreatment of wheat straw. Bioresource Technol 64(2):139–151

Seiler GS (1987) Twenty five years of sludge management by wet oxidation. Sludge Manage Ser 17:100–105

Slavik E, Galessi R, Salvetti R, Bertanza G (2013) Experiences of sludge treatment by wet oxidation. In: Effective sewage sludge management—minimization, recycling of materials, enhanced stabilization, disposal after recovery, CNR Quaderni de "La Ricerca Scientifica" n. 120 – ISBN: 978-88-8080-113-9, p 111–130

Strehlenert RW (1911) Swedish Patent 34, 941

Strong PJ, Gapes DJ (2012) Thermal and thermo-chemical pre-treatment of four waste residues and the effect on acetic acid production and methane synthesis. Waste Manage 32:1669–1677

Strong PJ, McDonald B, Gapes DJ (2011) Combined thermochemical and fermentative destruction of municipal biosolids: a comparison between thermal hydrolysis and wet oxidative pre-treatment. Bioresource Technol 102(9):5520–5527

Stüber F, Font J, Fortuny A, Bengoa C, Eftaxias A, Fabregat A (2005) Carbon materials and catalytic wet air oxidation of organic pollutants in wastewater. Top Catal 33(1–4):3–50

Svanström M, Bertanza G, Bolzonella D, Canato M, Collivignarelli C, Heimersson S, Laera G, Mininni G, Peters G, Tomei MC (2014) Method for technical, economic and environmental assessment of advanced processing routes, accepted for publication (feb 7th, 2014) in Water Sci Technol

Tomei MC, Carucci A, Ramadori R, Rossetti S (1994) Validation of "ASCAM" model for biological nitrogen removal. In: Horan Nutrient NJ (ed) Removal from wastewaters. Technomic Publishing Company Inc., USA, pp 143–149

Tomei MC, Di Pinto AC and Ramadori R (1990) ASCAM: A simplified model for biological nitrogen removal. Proceedings of the IAWPRC 15th Biennial International Conference, Kyoto, 26th July–3rd August, 449–452

Wei Y, Van Houten RT, Borger AR, Eikelboom DH, Fan Y (2003) Minimization of excess sludge production for biological. Water Res 37:4453–4467

Yang X, Wang X, Wang L (2010) Transferring of components and energy output in industrial sewage sludge disposal by thermal pretreatment and two-phase anaerobic process. Bioresource Technol 101:2580–2584

Zerva C, Peschos Z, Poulopoulos SG, Philippopoulos CJ (2003) Treatment of industrial oily wastewaters by wet oxidation. J Hazard Mater 97:257–265

Zimmermann FJ (1958) New waste disposal process. Chem Eng 25:117–120