Considerations on LCA approaches for the evaluation of final urban waste sludge disposal options, including energy and materials recovery

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ABSTRACT

Thermal processing of sludge remains a convenient and efficient approach for the disposal of waste urban sludge without causing excess secondary pollution, which is used as much as possible in many countries The paper presents different LCA approaches to the evaluation of urban waste sludge disposal options that include resources and materials recovery. Main current options (incineration, pyrolysis, etc.) under different technologies (co-incineration, conventional pyrolysis, microwave pyrolysis, etc.) have been previously investigated and compared. Life-cycle assessment (LCA, also known as life-cycle analysis, ecobalance, and cradle-to-grave analysis) is a well-known methodology to assess environmental impacts associated with all the stages of a product's or technological process' life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. LCA application to the evaluation of urban sludge disposal options can objectively highlight which are the best "performing" technologies in respect to their impact on the environment. Results from several LCA application are compared, and show that one of the best processes to achieve energy and material recovery from urban waste sludge is the pyrolytic process, due to the advantages achieved when using microwave radiation as process-driving energetic input. This scenario also shows that, from a CO_2-savings point-of-view, the maximum advantage occurs when producing bio-oil and using sludge-derived biochar as agricultural soil ammendant.

INTRODUCTION

Notwithstanding the recent suggestion and occasional adoption of new paradigms in wastewater management and processing (Capodaglio et al., 2016a; Capodaglio et al., 2017) that could result in reduction of excess sewage sludge production, huge quantities of sludge are still produced worldwide from wastewater treatment plants nowadays: the average annual outputs of sewage sludge in Germany are over 2 x10^6 t/y Italy and France generate about 10^6 t/y each, Spain about 0.9 million, England 0.8 and the US 6.5 x 10^6 t/y, respectively. It is estimated that in China, more than 2 x10^7 t/y of sewage sludge are generated annually (Xu et al., 2014). Sewage sludge management poses not only financial, but also planning challenges, in order to achieve that objective efficiently and without environmental harm. Wastewater may contain large amounts of pathogenic organisms, heavy metals, micropollutants and Contaminants of Emerging Concern (CECs) which are difficult to detect (Capodaglio et al., 2016b) and could be harmful to both human health and the environment, and may not be completely removed from the treated effluents with the current process technologies (Trojanowicz et al., 2017). Most of these pollutants, un-degraded or only partially degraded end up adsorbed onto the activated sludge solids and, eventually, in the excess sludge withdrawn periodically from the system (Capodaglio, 2018). Hence, until effective methods to remove these pollutants are established and generally adopted, care must be taken not to reintroduce them in the environment with the residuals of the treatment process.

Based on two European directives (CEC, 1991; CEC, 1986), excess sewage sludge is defined as residual product, whether treated or untreated. Despite article 14 of directive 91/271/EEC, specifying that *sludge shall be re-used whenever appropriate* and *disposal routes shall minimize any adverse effect on the environment*, sludges are still classified as "waste". Despite this, sludge is a huge source of renewable resources and organic matter that should be considered for sustainable recovery, such as nutrient or energy, leading to sludge-based added value products.

The ongoing paradigmatic shift leading from “waste” sludge to “product” sludge implies that sludge production should be more controlled and oriented to reach one or more final marketable product(s), possibly with predictable characteristics in line with future reuse(s). Lately, research on innovative sludge disposal methods (i.e. pyrolysis) has postulated the possibility of adapting sludge process process conditions in the latter phases of the treatment in order to create “engineered” secondary products (biochar) in order to fulfill specific industrial applications (Wang et al., 2018). Unfortunately, both the way sludge is classified (alternatively as “waste” or “waste-to-product”) and the characteristics and specific uses of the final products impact any sludge-related LCA modelling, and affect considerably its results, making them hardly comparable if different approaches are used.

Currently, the most common sludge management approach is the ‘‘sludge-to-energy’’ (STE) approach, which carries substantial benefits, similar to those pertaining to any renewable energy source: decreasing energy dependency of WWTPs, and their greenhouse gas emissions. Sludge-to-energy is technically feasible if the recovered energy is directly used for WWTP operation, resulting in reduction of conventional energy (mostly electricity) requirements (Manara and Zabaniotou, 2012). Unfortunately, in order to convert produced biogas into the final energy used in a treatment plant one must come to terms with reduced process and conversion efficiencies, so that the potential chemical energy contained in the original wastewater can be recovered only in a small fraction (usually, between 1/3 and 1/4th of the total). Also final incineration (or co-incineration in cement kilns) can be considered ‘‘sludge-to-energy’’ approaches, as the energy (electrical in the former, heat in the latter) is generated and used directly at the production site.

Another approach of more recent implementation, called ‘‘sludge-to-fuel’’ (STF), involves conversion of the chemical energy from the sludge organic matter into combustible fractions (oils, gases and solids) using chemical (based on solvents, at T=200–300 ^{o}C , or at high temperatures, high pressure (≈10 MPa)) or thermal processes (gasification, pyrolysis). Produced oils are usually characterised by a high heating value (lower than that of common diesel, but similar to other renewable biooils) and can be used as motor fuel after refining or for other uses. The other fractions (syngas and biochar) can equally be used as fuels, however biochar has an almost unending list of alternative uses as secondary material (Callegari et al, 2018).

Combustion is the most commonly used thermal treatment method for STE energetic valorisation. The amounts of sludge incinerated in Europe tend to about 1/4th of the total production (especially in Northern Europe), while the USA burn about 25% of their production, and Japan around 55% (Lundin et al., 2004). Sludge combustion of excess sludge (dry sewage sludge has a calorific value of 12–20 MJ/kg, similar to that of lignite or low-quality coal) remains an attractive disposal method for sludge in Europe, given the strict limitations concerning both sludge landfilling and its agricultural reuses, even though preliminary partial (85% d.m.) or total (>85% d.m.) dehydration is often required for process efficiency. Co-combustion as alternative fuel in existing cement production facilities, with the incorporation of ashes into the final product, seems an even more promising outlet, compared to stand-alone incinerators, and is considered a zero-waste technology, as ashes are incorporated in the final product, but is limited by industrial demand (excessive P content in the sludge can worsen the resulting product properties). The drawbacks of incineration, in fact, lie in public concern about possible harmful atmospheric emissions, and in the fact that, rather than achieving complete disposal, about 30 wt% of the original dry solids (a potential hazardous waste due to their heavy metals content) are left as ash residual after processing.

Pyrolysis, the thermal decomposition of material in inert, oxygen-free atmosphere, is being proposed as an alternative process to combustion. Compared to the latter, highly exothermic, pyrolysis is endothermic (about 100 kJ kg^{-1}), thereby producing energy-rich vapors (uncondensable gases – syngas), liquids and solid products (char, or bio-char, depending on the feedstock organic content) by thermal cracking and condensation reactions. Pyrolysis is less polluting than incineration, due to lower operational temperatures, and absence of oxygen, which are conductive to the generation of pollutants such as furans and dioxins.

Pyrolysis can be achieved by thermal means (burning a fossil or renewable fuel to generate process heat, or by other energy carriers, such as microwaves. Microwave assisted pyrolysis (MAP) has recently been advocated as a more efficient, more controllable sludge pyrolysis technology (Lam and Chase, 2012). The low operating temperature of pyrolysis in general (lower for MAP) is also responsible for the absence of heavy metals in pyrolysis gases, the former remaining trapped in the solid fraction with strong adsorption bounds. Nevertheless, its relative technological complexity makes the process economically viable only when relying on the effective contribution of the added value of its final products. Even though pyrolysis of sewage sludge for by-products recovery is raising much interest, full-scale implementation of this technology has been quite limited.

Gasification is a thermal process during which the organic content of sewage sludge is converted to combustible gas and ash, in the presence of a reactive atmosphere, air or steam. While sometimes erroneously addresses as pyrolysis, gasification transforms organic materials to a combustible syngas, using 20-40% of the oxygen required for full combustion, whereas thermal pyrolysis is carried out at elevated temperatures (500–1000 ^{o}C) and in inert atmosphere. Syngas from sewage sludge, a mixture of CO (6-10% vol.), H_2 (8-11% vol.), CH_4 (1-2% vol.) and other gases, has heating value around 4 MJ/m^3. While the process can avoid problems commonly faced in incineration, like emissions of SO_x's and NO_x's, heavy metals, fly ash, and potentially of chlorinated dibenzo-dioxins and dibenzo-furans, it works best if the sludge is dried at > 90% dry solids content, requiring additional energy expenditure.

Purpose of this paper is to compare available examples, and evaluate the applicability of LCA methods to the selection of the most promising sewage STE or STF approach(es) meeting current sustainability goals, followed by a discussion.

SWOT ANALYSIS OF SLUDGE-TO-ENERGY METHODS

As a preliminary step to the analysis of the more complex LCA applications to waste sludge processing technologies, simpler SWOT analysis could also be evaluated. SWOT is a strategic planning technique used in preliminary decision-making stages to identify Strengths, Weaknesses, Opportunities, and Threats of a planned event or process, intended to identify internal and external factors that are favourable/un-favourable to a certain objective, in which technologies and methods are compared on the basis of economic, environmental and social metrics.

Samolada and Zabaniotou (2014) conducted a SWOT analysis for the preliminary selection of the most promising sludge-to-energy method meeting the goals for ‘‘sustainable development’’. Aim of their study was a comparative assessment of three common energy recovery options (incineration, pyrolysis, gasification) for municipal sewage sludge, taking into account technologies’ development status. SWOT analysis of sludge disposal technologies was conducted by listing all factors, internal and external, contributing to strengths, weaknesses, opportunities and threats of each considered technology according to 4 criteria: its potential to finally and efficiently solve a problem (sludge disposal), its potential to reduce GHG emissions, technology maturity (i.e. robustness and reliability of application) and legislation (adequate and established supporting framework legislation for application of the technology). Each criterion was rated from “very poor/low/inadequate” (1 point) to “excellent/advanced/high” (4 points). Technologies were rated by summing up partial scores.

From the SWOT assessment, pyrolysis resulted to be as the most suitable sludge-to-energy method Table 1. The main reasons for this are:

- it is a zero waste technology.
- it can produce energy, fuel and materials with economic benefits.
- it has the lowest gas emissions.
- it can be applied in an integrated approach to solve wastewater treatment problems, since it does not produce further liquid or solid waste residuals.

Table 1. Comparative assessment of three thermal methods examined

Method/Criterion	Solution to the problem	GHG emissions	Technology maturity	Legislation	SCORE
Incineration	1	1	3	4	9
Gasification	4	2	2	2	10
Pyrolysis	4	4	2	4	14

Notwithstanding the approximation of this method, SWOT analysis gives a preliminary indication concerning applicability of the mentioned technologies to final excess sludge disposal.

LCA PROCESS FOR SEWAGE SLUDGE MANAGEMENT

Life-cycle assessment (LCA) is a procedure used to evaluate the environmental impacts associated with the whole life-cycle treatment of a product, process, or activity (ISO, 2006), and compare the relative environmental performance of competing processes. LCA is widely used for eco-labeling programs, strategic planning, and other purposes, with applications that include product/process design, product/process improvement, and consumer education. In a LCA application, environmental impacts, generated by processes within defined categories and boundaries, are analysed, and inclusion of each single process or product's stage in the life cycle is fundamental for the analysis. Analysis of the full life cycle of a process or product ("cradle to grave") is not always pertinent, and the analysis could often end at an intermediate stage ("cradle to gate"). LCA is therefore a suitable tool for assessing environmental impacts and as such has been applied to the most diverse industrial processes. LCA has in fact been used to assess potential environmental impacts of wastewater treatment, including sewage sludge management (Yoshida et al., 2013; Corominas et al., 2013).

Herein recent, available studies concerning final disposal of sewage sludge life cycle analysis were examined, in order to evaluate different adopted approaches and extract a generalized "consensus" based on specific results obtained.
Valderrama et al. (2013) conducted a LCA to evaluate the environmental impact of urban sewage sludge use in clinker production, a zero-waste disposal option as previously mentioned. Excess sewage sludge from wastewater treatment was pre-processed: a) by using low temperature drying in the case of fuel substitution, obtaining dried sludge with moisture content around 10% (w/w) and LHV around 16.7 MJ/kg as alternative fuel, and b) lime stabilization (22.5% w/w CaO addition) in the case of raw material substitution. The substitution ratios of fuel (coke) and raw material (limestone) by sludge were fixed between 5-15%, according to the limitations imposed by the cement production plant. The Life Cycle Impact Assessment (LCIA) impacts considered were: climate change (IPCC, 100 years) (IPCC, 2007), acidification, eutrophication, abiotic depletion, ozone layer depletion, fresh water aquatic ecotoxicity, photochemical oxidation and terrestrial ecotoxicity, and Cumulative Exergy Demand. CO_2 emissions related to sewage sludge combustion are assumed 100% biogenic, showing CO_2 savings varying between 3 and 7% compared to clinker production without fuel substitution. The differences calculated for material substitution, instead, were lower about 1%. Hence, fuel substitution represents a significant improvement compared to raw material substitution alone, and production without substitution. Results presented in the study were focused to the direct reduction of CO_2 emissions, however, indirect reduction could have been considered, since if not used, this waste would have likely been landfilled or incinerated increasing GHG's emissions. Damage assessment analysis (DAA) indicated that the fuel substitution scenario implied a reduction of 2.6, 4.4 and 8.1% for damage to human health, ecosystem and resources, respectively. Minimal differences in these areas were observed between the material substitution and clinker production without substitution scenarios.

Mills et al. (2014) conducted an environmental and economic LCA of sludge-to-energy technologies, considering: 1) conventional AD with CHP (combined heat and power); 2) Thermal Hydrolysis Process (THP) AD with CHP; 3) THP AD with bio-methane grid injection (GtG – Gas to Grid); 4) THP AD with CHP followed by digested sludge drying for solid fuel production; 5) THP AD with drying, pyrolysis of digested sludge and use of both biogas and syngas in a CHP. Thermal Hydrolysis Process (THP) is the most widespread technology used by the UK company Thames Water to enhance biogas yield in AD, as hydrolysis is typically the rate limiting step of the process. THP uses high temperature (165 ^{o}C) and pressure (7 bar) for 30 min to hydrolyse sludge before feeding it to a conventional digester, while inducing its homogenization to render it more digestible, resulting in increased methane production and smaller volumes of digestate. As THP requires input of heat and additional electrical energy, its introduction does not necessarily improve the overall energy balance of the process (Figure 1).

A)

B)

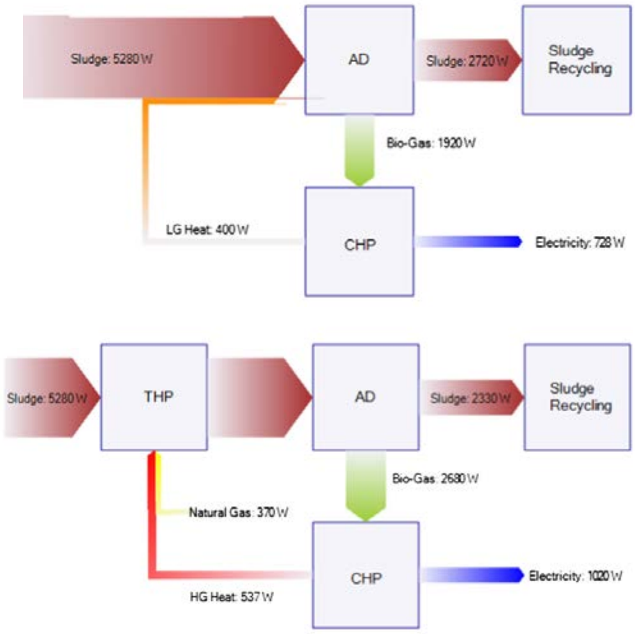

Figure 1. Energy flows for A) conventional AD with CHP and B) THP/AD and CHP. Overall CHP losses about 41% (heat & electric). The greater energy production in B) is negatively compensated by additional natural gas requirements for THP operation

Among impacts analysed in this study were:
1. GWP – Global Warming Potential (excluding biogenic) (kg CO_2eq)
2. POCP – Photo Ozone Creation Potential (kg Ethene$_{eq}$)
3. EP – Eutrophication Potential (kg Phosphate$_{eq}$)
4. FDP – Fossil Depletion Potential (MJ)

The largest determined impact from all the examined technologies, was on FDP that benefitted from displacement, at various degrees, of fossil fuel use. In this respect, conventional AD performed better in the analysis than THP (CHP & GtG) and pyrolysis due to the relatively low energy and chemical demands. The drying to fuel scenario was the best due to the direct displacement of hard coal, still used in the UK as a fossil fuel source, but banned in many other European countries, the second optimum to be the pyrolysis option.
The second largest impact, GWP, of the five scenarios described showed that moving from conventional AD with CHP to THP can be beneficial, despite the additional fuel requirements, as these consisted mainly of natural gas. The GtG option performed badly as beneficial impact of injecting bio-methane into the gas grid could not be as relevant as displacing electricity, and as the process could require a large energetic ‘top up’ to maintain the steam demand of the THP plant. Although producing bio-methane for grid injection may be financially attractive, it scored in this study at the worst environmental impact of all the scenarios, due to contemporary UK financial incentives policy. Finally, emissions of CH_4 and N_2O from recycled sludge applied on agricultural soil could be significant, and influenced negatively this options.
The pyrolysis option, on the other hand, improved significantly overall energy recovery, doubling electrical output, compared with conventional AD. The pyrolysis scenario could even increase its performance, by enhancing waste heat utilization from the pyrolysis CHP in the THP plant. Table 2 shows the scoring outcome where each scenario was ranked between 1 and 5 (5 being best) for the following performance indicators: a) net environmental impact, b) GWP, c) Internal Rate of Return (IRR) with incentives, representing commercial reality, d) IRR without incentives, to reflect possible elimination of present incentives.
Overall results show THP/AD had significant advantages over conventional AD, improving the latter financial and environmental performances. Post-AD drying options turned out to be both

environmentally and economically good solutions, while GtG turned out to be preferably avoidable due to its poor scoring performance. In actuality, upgrading biogas to bio-methane suitable as locally-distributed transport fuel might be an even better solution, displacing other carbon fuels that would be more environmentally challenging.

Table 2. Combined ranking of scenarios.

Scenario	Net impact	GWP	IRR with Incentives	IRR without Incentives	Combined total
Conv AD with CHP	2	2	1	2	7
THP AD with CHP	3	3	2	3	11
THP AD with GtG	1	1	5	1	8
THP AD, CHP & drying	5	5	3	5	18
THP AD, CHP, drying & pyrolysis with CHP	4	4	4	4	16

It should be noted that the results of this study were strongly affected by the presence in the UK of an electricity grid heavily dependent on coal. It could be stated, *a posteriori*, that UK policy on biomethane was not, at the time, driving the best environmental practice. Possibly this could, in the future, reversed to conditions where production of biomethane for grid injection could be environmentally favourable (as it is currently, for example, in Germany).

A similar study based in China (Liu et al, 2013) consisted in a life cycle inventory analysis to investigate GHG performance of six scenarios involving different sludge treatment technologies and disposal strategies: landfilling (1), mono-incineration (2), co-incineration (3), brick manufacturing (4), cement manufacturing (5), and urban green fertilizer (6). In terms of GHG emissions, Scenario 2 demonstrated the best performance, with large GHG offset from co-incineration energy recovery, followed by scenarios 4 and 6, whereas scenario 1 demonstrated the poorest performance, due to the large quantity of methane leaks it may cause. Scenarios rankings (Figure 2) are heavily affected, as shown, by assumptions related to GHG offset calculation.

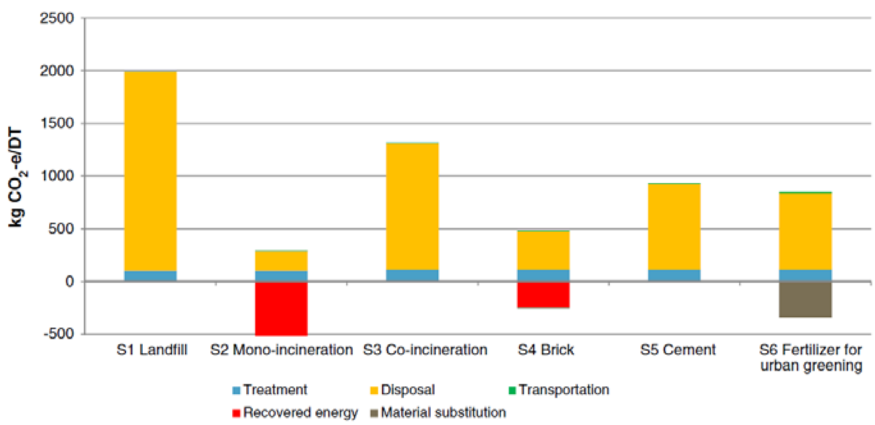

Figure 2. GWP of treatment, disposal, and transportation phases of various sludge disposal options, as well as the offsets caused by energy recovery and material substitution (Liu et al., 2013)

Carbon sequestration is an important topic in GWP as well. In the reported study by Liu et al (2013), scenarios 1 and 6 could possibly be accompanied by carbon sequestration, decreasing their GWPs by 15% and 45%, respectively. Including carbon sequestration considerations could significantly improve GHG performance of scenario 5, which may nearly become the second best scenario in the study. The relatively good GHG performance of scenario 4 in the study could actually be attributed to the efficient use of heat to dehydrate sludge before incineration, preventing 48% of GHG emissions as compared with scenario 5.

Buonocore et al. (2016) applied LCA to compare the environmental performance of different scenarios for sludge disposal at a WWT plant located in Southern Italy. Three scenarios were considered: in the first, dewatered sludge was taken by truck to a landfill for final disposal (business as usual - BAU); in the second, AD of sludge generated biogas, used for electricity and heat cogeneration, integrated by additional external energy from previously recovered waste cooking oil (WCO), recovered energy was fed back to the WWTP (including sludge drying processes), with final disposal of dried sludge to landfill; the third scenario suggested an improved circular pattern with dried sludge gasification to further support heat and electricity production (with little residue directed to landfill). Results showed that scenarios 2 and 3 contributions to the chosen impact categories, compared to BAU, decreased significantly. Scenarios 2 and 3 reduced contribution to the GWP impact by 9% and 35%, respectively, about the same level shown for the Fossil Depletion Potential (FDP), at 9% and 36%.

Recently Abusoglu et al. (2017) presented a comparative LCA of (digested) sewage sludge combustion for heat and power production, based on use of sewage sludge incineration and cement kiln co-combustion as two different scenarios. The results obtained showed that the sewage sludge incineration scenario carried a better environmental performance in most impact categories, including: GWP, aquatic and terrestrial ecotoxicity, terrestrial acidification/nutrition, aquatic acidification, land occupation, and mineral extraction. Notwithstanding that energy recovery of cement kiln co-combustion compensated the avoided use of other nonrenewable energy sources, the high operational temperature (≈1400^{o}C) of the cement-making process lead to the generation of NOx emissions, a main harmful contributor for several impact categories. In the human health category, however, the cement kiln scenario actually preceded the incineration scenario, as residual materials in the former are immobilized with the product, whereas in incineration they are landfilled.

Discussion

As exemplified from the previous brief review, LCA of waste management focuses on the “end of life” of a waste, and therefore only takes into account the processes involved to manage it. The functional unit of waste management systems is defined in terms of system input, such as the quantity of waste initially generated (McDouglas et al., 2001). By definition, the main function of such a system is to treat and dispose the waste, but additional functions should be considered if energy is produced from the waste processing (heat and electricity from waste incineration, for example) or if the waste is used as a product, such as fertilizer on agricultural soils, or as a transformation material.

Given the possible multiplicity of products (and the further diversity of their specific characteristics) that could be obtained as secondary products from sludge, it is quite difficult to conduct a general LCA according to a specific functional unit output that may have quite different final applications (for example, biochar from pyrolysis could be burned, or applied on agricultural land, or again used as activated carbon substitute in pollution reclamation activities, or all of the above). Applying the best “value-added” use in the analysis could be misleading, as perhaps that use could be unneeded or un-applicable in that specific context.

In a review of LCAs applied to sludge processing technologies, Pradel et al. (2016) showed that all authors who had conducted LCAs of sewage sludge treatment technologies considered that sewage sludge had added value potential through nutrient and energy recovery, therefore assigning to it a “waste-to-product” status. All authors considered that sludge entering a specific treatment technology (i.e. STE, like an anaerobic digestion treatment systems) leading to the production of valuable products (biogas, electricity) also originated, according to the adopted technology, a valuable byproduct (i.e. digestate), regardless of its actual final utilization. In all these studies, the system was simplified by excluding the water line, alone or combined with part of the sludge treatment line, as they would be identical regardless of the studied scenarios. The way sludge is considered by the specific LCA extender (“waste” or “waste-to-product”) impacts heavily LCA application and on its results. This leads to a great variability in the way systems can be modelled and it is therefore not possible to compare “waste” sludge LCA results and “waste-to-product” LCA results, or to quantify exactly the variability obtained between them.

In particular, the “zero-burden assumption” should be considered valid only when the sludge has a “waste” status, meaning it is not a valuable output of the system, whatever the system boundaries. If sludge is considered as a possible renewable resource, with a “waste-to-product” status, or if treatment is oriented to give added-value to the sludge, leading to a "product" sludge, then the former assumption is questionable. One school of approach maintains that if sludge possesses the same characteristics of valuable raw materials it could replace, then it should be charged with an environmental burden due to its production, otherwise, it will always appear more interesting to use sludge instead of traditional raw materials. On the other hand, current wastewater treatment technology does not really allow to dispose of sludge production altogether, otherwise this option (with the high costs of sludge disposal) would have already been taken. In other LCAs, sludge was considered as "waste-to-product", that is, all the benefits are affected to the main function as avoided burden, and not to sludge production. This can also be an acceptable way of LCA approach as sludge treatment leads to the creation of cofunctions to the waste management system (treat sludge and recover nutrient or energy from it), or the WWTP (treat the wastewater and provide energy or nutrient from it via sludge recovery). Such multi-functionality due to the appearance of these cofunctions is solved by expanding the LCA boundaries.

Oldfield and Holden (2014) stated that the environmental impact of waste itself carries large part of the overall system generating it, hence, in order to show impact reduction when waste reduction occurs, they proposed to include the environmental burden due to its generation. This implies that once a waste gains value, or is seen as a "product", part of the environmental burdens of the system should be allocated to it. As an example, if sludge is considered as "waste" with no added value, only a single function, the production of good quality water, is assessed as well as a single output, the treated water that was generated. The sludge, having no added value, leaves the system as a waste. The waste has no environmental impact as all the impacts are allocated to the single product (treated water). It follows that its production is not charged with an environmental impact, and it cannot be reused in another system.

As new technologies are developed to create "additional added-value" to sludge, the question is to properly define which technologies could create enough added-value to get a "product-defined" sludge. Another challenge is how to assess allocation of an environmental burden to the sludge produced, since both treated water and "product" sludge (or "waste-to-product" sludge) are valuable outputs of the WWTP, and an environmental burden must be applied to each of them. The sludge production process is dependent, but indivisible from the treated water process, hence allocating an environmental burden to the sludge needs to define allocation factors between sludge production and the treated wastewater for each step of the treatment process that generates sludge, in greater or smaller quantity. This constitutes an important research issue, as the traditional allocation factors can no longer be used.

COMPREHENSIVE ASSESSMENT OF SCENARIOS

Notwithstanding the previously drawn considerations, the selection of appropriate sludge management methods requires more extensive investigations than simple comparison of GHG emissions scenarios: cost effectiveness is also a crucial aspect in sludge management. Apart from cost, then, other factors affect decision making on sludge management, including environmental risks, feasibility and applicability in specific areas, energy saving potential and other socio-economic barriers (Capodaglio et al, 2016c).

Landfilling was commonly used until recently, however, apart from showing high GWP, it is also commonly associated with infiltration and leaching that may affect soil and groundwater quality. In addition, land available for landfills has become increasingly limited, and the public opinion, once indifferent or mildly contrary to landfilling (usually, in a manner inversely proportional to its distance), is now mostly openly hostile to this practice.

Incineration is in general preferred by local environmental protection departments as it minimizes negative environmental effects of end-products, however, it is sometimes strongly opposed by public opinion, fearing unlikely episodes of highly toxic emission (dioxins, furans). Co-incineration in power plants (e.g. with Municipal Solid Waste, MSW) is generally better accepted, even with some local opposition. Co-combustion in cement kilns is ecologically safer than the previous considering that higher furnace temperature helps reduce dioxin discharge, and that it has great potential for conserving

energy and reducing costs through technological innovation of sludge drying systems, including re-use of waste flue gases, and materials recovery.
Among all the scenarios considered in the literature, fertilizer uses, whether in urban green or agriculture, were found to exhibit fair GHG performance and some potential for carbon sequestration, although recent studies showed that waste sludge, as is, has a much weaker C sequestration potential than, for example, char from sludge pyrolysis that could sequester this element for over 1000 years even when distributed into soil. Even though fertilizer use of the sludge as is could help increase organic content of soils, reduce use of chemical fertilizers, and regenerate infertile/poor soils at low cost, studies have shown that that such uses could be harmful due to sludge contents (heavy metals, polycyclic aromatic hydrocarbons, emerging micropollutants) that could be reintroduced into an environmental compartment through this disposal pathway. Furthermore, using sludge in urban greening/agriculture may not be welcomed by local stakeholders due to both the mentioned contamination issues and nuisance (odour, pests, etc.) that such uses may cause.
Most results of LCA sensitivity analyses indicate that, independently of the scenario, reducing sludge water content significantly reduces GHG emissions from transport or other activities. In reality, however, different disposal technologies require significantly different sludge water contents; furthermore, the costs of drying could be extremely high (approximately 400 Euro/dry t). For general disposal practices, it commonly accepted that sludge with 60% water content could meet the demands of several post-treatment technologies at reasonable cost, while significantly reducing the influence of transport costs compared to sludge at 80% water content.
The accurate assessment of a specific scenario must consider exact specifications for the final products of that scenario, even though economic and applicability considerations may suggest interim changes during its development. In general, however, a sludge disposal technology that is able to obtain multiple final products just by changing operating parameters should be preferable to a technology that can provide only one type of output.

SUSTAINABLE SEWAGE SLUDGE MANAGEMENT

Approaches contemplating energy and materials recovery from sewage sludge offer many opportunities for sustainable management of this waste. Among the most promising applicable approaches for STE confirmed by many LCA application examples are incineration or co-incineration of the waste sludge. The former, however, is often poorly accepted due to perceived excessive environmental impact (atmospheric emissions and residual waste), the latter's application is limited by industrial demand (with possible heavy impact of transportation costs) and by similar resistance to its emissions into atmosphere. On the other hand, a promising sludge-to-energy-and-materials (STEM) conversion approach is given as anaerobic digestion (AD) of excess raw sludge with subsequent pyrolysis. AD is an anaerobic biological process capable of converting biodegradable organics to biogas, in the absence of molecular oxygen. It is currently one of the most widely applied excess sludge process technologies, mostly due to its relative simplicity of implementation and energetic benefits, consisting of biogas recovery with high calorific value suitable to a variety of beneficial uses (Capodaglio et al., 2016c; Raboni et al., 2015). These benefits were confirmed by various LCA applications, and increasing attention was recently given to the enhancement of biogas production and quality, involving:

- optimization of process conditions (Capodaglio et al., 2016d);
- application of multi-stage processes, to enhance sludge hydrolisys and methane generation;
- sludge pre-treatment to increase biodegradability;
- sludge post-treatment for quality enhancement (Callegari et al., 2013).

Application of these measures, though they might imply an increased output of biogas, generally requires additional energy (heat and electricity) inputs to increase process temperature or pre-treat the sludge, and should be carefully evaluated according to specific circumstances.
The process has also several limitations, the main one being that it cannot completely extract the chemical energy contained in the raw sludge. Digested sludge is still rich in energy after processing, since it contains considerable amounts of organic matter that, however, is poorly biodegradable. As

such, digested sludge is usually distributed to agriculture to recycle the contained carbon and nutrients into cultivated soils, however this practice is been lately limited by national regulations due to increasing environmental contamination risks and by new residual valorization technologies.

Sludge pyrolysis is an innovative, endothermic thermo-chemical process technology capable of converting raw or digested sludge into useful bioenergy (oil and gas) (Capodaglio and Dondi, 2016) and a solid residue (biochar, or char) (Callegari and Capodaglio, 2018) with several potential environmentally beneficial applications, regardless of the fact that the treated organic matter is biodegradable, or not. This process was initially introduced for bioenergy production from crops and biomass wastes, but was also proposed for application in sewage sludge management (Inguanzo et al., 2002). Recently, an innovative form of pyrolysis, microwave assisted pyrolysis (MAP) was proposed as it makes better process control feasible at lower temperatures (Motasemi and Afzal, 2013; Capodaglio et al. 2016e).

All of the process product fractions, either by conventional pyrolysis or MAP have the potential for heat and electricity generation, although recently better uses have been proposed as sustainable and more interesting alternatives (Callegari et al., 2018). It is the versatility of possible applications of all pyrolysis products that makes this process in general more sustainable and beneficial, compared to gasification and incineration.

The energy output of a pyrolysis process (energy contained in its final products) for a given feedstock does not automatically reflect the process' energy-effectiveness. Since pyrolysis is, as mentioned, an endothermic process, this implies that the energy content of its products is partly due to the reaction heat of the process, and is not just transferred (transformed) from the feedstock. If the final energy content of the process products exceeds the energy content of the feedstock, this might be dependent, to a degree, on the contribution of reaction heat. On the other hand, as shown by Capodaglio et al. (2016e), optimization of the process operating conditions may substantially improve the net energy yield of the process. Therefore, reaction heat and duration of pyrolysis should be carefully evaluated in process choice and optimization.

In several authors' experience, the ideal initial feedstock humidity to initiate a pyrolysis process is around 10% (Capodaglio et al., 2016e; Racek et al., 2017), therefore substantial energy inputs will be required prior to pyrolysation in order to achieve this target. However, if we exclude agricultural spreading of waste sludge, every other available final disposal option for this waste material will require substantial humidity reduction: thermal energy recovery and co-combustion efficiency will be diminished by excess water content (even if this evaporates during incineration, it would still require additional external fuel), and even landfilling will be penalized by excess water content.

As suggested by Cao and Pawłowski (2012) it could be possible to efficiently use either of the pathways schematized in Figure 3 for bioenergy production and material recovery while achieving final disposal of sewage sludge. The first is based on an AD process followed by pyrolysis processing, using digested sludge (ADS) as pyrolysis feedstock. The other is based on direct pyrolysis of this feedstock. Since raw sludge contains higher levels of organic matter than ADS, pathway 2 may provide a higher yield of pyrolysis products than the former. This, however, will produce an additional bioenergy product, biogas, and result in ADS at a lower water content, requiring lower energy expenditure during or prior to pyrolysis, for sludge drying. It should be noted that both pathways can be classified as zero-waste, as they do not produce any non-reusable product.

Syngas properties vary considerably according to feedstock and process conditions. Syngas produced under this scenario would contain mainly CO_2 and CO, with volumetric proportion of CO_2 around 40–60% (Kim & Parker, 2008). Hence, syngas should have a low energy content, with no or very limited potential for energy recovery. This could then be considered as unrecoverable energy andneglectedm with small energy loss, from the balance. The energy recovery efficiency of the two pathways under the scenario turns out to be substantially equivalent, although pathway 1 has a higher apparent energy efficiency (AEE) than pathway 2. On average, 78% of the excess sewage sludge (ESS) energy in pathway 1 is converted to target bioenergy (biogas plus bio-oil), approximately 14% more than in pathway 2 (bio-oil). However, a more careful analysis shows that no significant difference in gross energy efficiency (GEE, calculated on the basis of all energy products: biogas, bio-oil and biochar) could be observed between the two pathways. The energy efficiencies of the two pathways depend partly on bio-oil production: generally, this is intrinsically related to the properties of sludge feedstock, since conversion of feedstock with higher volatile content can gain higher yields. However, for a specific feedstock, differences in oil yields can be attributable to optimization of operating conditions (mostly temperature and hearth time), applied pretreatments, and application of catalysts. The energy contents of bio-oils from ESS were found to be quite similar in published studies, with values around 37 MJ/kg, however, it has been shown that energy content is not be dependent on properties of sludge feedstock alone, but also related to the type of pyrolysis process applied, and its operating conditions.

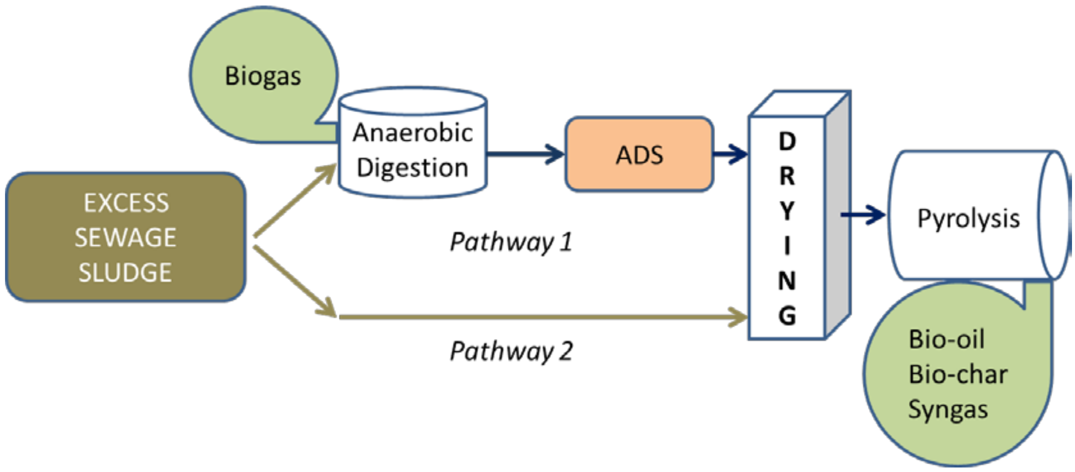

Figure 3. Possible sewage sludge-to-energy pathways for final disposal

DISCUSSION AND CONCLUSIONS

In applying LCAs, care ought to be taken: for example, the contribution associated to avoided impact is calculated by subtracting the environmental burden of the electricity generated by primary sources mix that would otherwise be used by the regional system. If the mix changes, due to Country current primary supply conditions or in time, the results of the assessment would change as well. Furthermore, such benefits can only be included if boundary scenarios are extended to a broad enough scale to account for fossil energy replacement. Furthermore, LCA results cannot be freely generalized out of context for technical issues: once a waste gains value, or is seen as a “product” in a management system, part of the environmental burdens of the system should be allocated to it. As new technologies are developed to create “additional added-value” to sludge and its by-products, there is an issue of properly defining which technologies create enough added-value to get a “product-defined” sludge. As the sludge production process is dependent, but indivisible from the wastewater treatment process, the allocation of an environmental burden to the sludge needs new definition of allocation factors for each step of the overall treatment chain. All this constitutes an important research topic, as traditional allocation factors can no longer be used.

Notwithstanding these caveats, as confirmed by all LCA examples herein presented, energy production from sewage sludge (i.e. biogas, syngas and/or bio-oil) represent an important renewable energy source, capable of improving significantly the environmental impact of a sludge management approach and, in perspective, of reducing considerably current dependence on fossil resources, mitigating current and future energy-related environmental burdens. To this end, most LCA examples examined concur in the conclusion that combined application of anaerobic digestion, dehydration and gasification (or pyrolysis) is accepted to be one of the most promising technological approaches in terms of both energy recovery and GWP. Pyrolysis, instead of gasification, would allow also recovery of solid secondary materials, with a greater overall added value.

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