AN ENVIRONMENTAL LCA OF ALTERNATIVE SCENARIOS OF URBAN SEWAGE SLUDGE TREATMENT AND DISPOSAL

by

Mario TARANTINI, Patrizia BUTTOL, and Lorenzo MAIORINO

Original scientific paper
UDC: 628.3:631.879.4
BIBLID: 0354-9836, *11*, (2007), 3, 153-164

The majority of pollutants that affect wastewater are concentrated by treatment processes in sludge; it is therefore critical to have a suitable evaluation methodology of sludge management options to analyse if pollution is redirected from water to other media, such as air and soil. Life cycle assessment is one of the most widely known and internationally accepted methodologies to compare environmental impacts of processes and systems and to evaluate their sustainability in the entire life cycle. In this study the methodology was applied to assess and compare three scenarios of urban sewage sludge treatment and disposal: sludge anaerobic digestion followed by dedicated incineration, sludge incineration without previous digestion, and sludge anaerobic digestion followed by composting. The potential benefits of spreading the compost to soil were not included in the system boundaries even if, due to its nutrients contents and soil improving features, compost could partially replace the use of commercial products. The study was aimed at finding out the environmental critical points of the treatment alternatives selected and at providing a technical and scientific contribution for further debates with national and local authorities on the environmental optimisation of sewage sludge management. Life cycle assessment results confirmed the major contribution of electricity and methane consumption on several environmental impact categories. Incineration contributes more than sludge composting to almost all categories, although the heavy metals content of urban wastewater sludge raises substantial concerns when composted sludge is spread to soil. In this paper the models adopted, the hypotheses assumed and the main findings of the study are presented and discussed.

Key words: *life cycle assessment, sewage sludge, waste management, compost*

Introduction

The world-wide diffusion of wastewater treatment (WWT) plants in recent years has led to pay particular attention to the management of the sludge generated, because of its huge mass and its potential environmental burdens. In Europe the implementation of the Urban Waste Water Treatment Directive 91/271/EEC has led the annual production from roughly 5.5 million tonnes of dry matter in 1992 to nearly 9 million tonnes (estimated, [1]) by the end of 2005. The majority of pollutants that affect water entering the treatment process are concentrated in sludge, so only an efficient and environmentally friendly management can avoid redirecting pollution from water to other media, such as air and soil. This could happen if the technologies adopted and the disposal strategies are inappropriate to or unsuitable for local conditions. A typical example of such a potential problem is the spreading of sludge, composted or not, to soil: if not adequately managed, it could lead to concentrate heavy metals and organic pollutants from water into soil. EU member states are bound by a 1986 directive that sets limits for metals and some nutrients in sewage sludge. The European Commission is currently working to revise such limits, a process that will probably lead to further limits on contaminants content.

Alternative methods for handling the sewage wastewater sludge must be assessed from technical, economic, and environmental points of view in observance of the legal boundaries. Life cycle assessment (LCA) is one of the most widely known and internationally accepted methodologies to compare environmental impacts of processes and systems and to evaluate their sustainability in the entire life cycle. Several authors adopted this methodology to evaluate the environmental burdens of alternative sludge management scenarios [2-5] or treatment technologies [6-7]. The LCA study here presented gives a contribution to the analysis of the potential environmental burdens of different sludge management scenarios. The study was funded by the Italian Ministry of Environment in the framework of a project concerning the water quality improvement in Regi Lagni, a wide and densely populated area near Naples and Caserta. The project was aimed at collecting environmental data and developing scientific models to support the planning of reclamation and environmental protection activities and was completed in 2002. The three sludge management solutions analysed in this study were identified in cooperation with local authorities as the most suitable for their public acceptance in this area.

Systems description

Figures 1 and 2 show a schematic flowchart of the three solutions analysed by means of the LCA methodology (Systems A, B, C) [8].

In system A (fig. 1) the mixture of primary and secondary sludge produced during the urban WWT processes is collected and gravity thickened to reduce the water content. The sludge undergoes anaerobic digestion with production of biogas, which is burnt in a boiler to generate heat and in gas engines to produce electricity. If more gas is produced than can be burnt, the excess gas is flared in torch. The digested sludge is thickened and dewatered in a filter press after chemical conditioning. The dewatered sludge is then incinerated in a multiple hearth incinerator with the use of methane as an auxiliary fuel. The combustion heat is recovered and used to pre-heat the input sludge. Bottom ashes are sent to a landfill, a scrubber removes fly ashes. The supernatant separated during the dewatering processes and the discharged water from cooling and washing of ashes go back to the inlet of the WWT plant. The output flows of the system are solid waste, air and water emissions, electricity.

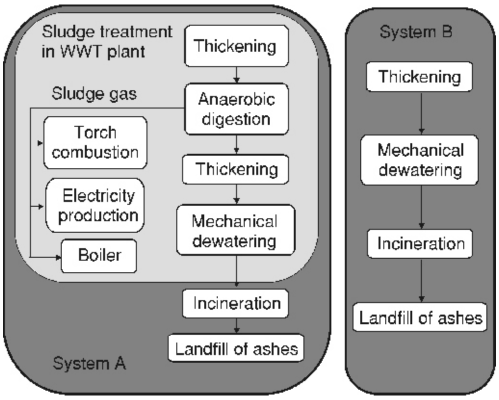

Figure 1. Schematic flowcharts of systems A (anaerobic digestion of sludge + incineration) and B (incineration of not digested sludge)

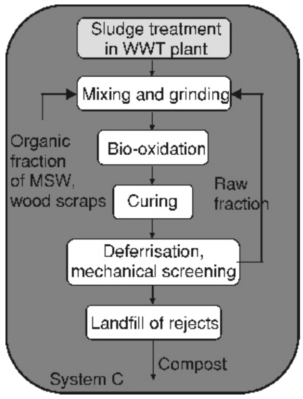

Figure 2. Schematic flowchart of system C (anaerobic digestion of sludge + composting)

In system B (fig. 1) the wastewater sludge mixture, gravity thickened and mechanically dewatered in a centrifuge after chemical conditioning, is sent directly to the incineration.

In system C (fig. 2) the wastewater sludge mixture is thickened, digested and dewatered as in system A and is sent to the composting plant. To optimize organic carbon content and humidity of the compostable mixture, the sludge is generally mixed with other highly fermentable organic waste with lower water content. In this system the sludge is carried to the composting plant where organic fraction of municipal solid waste (MSW) and wood scraps are mixed and grinded together. The compostable mixture is sent to a static pile with forced aeration for the bio-oxidation. A curing period completes the compost stabilization. The product is safe from microbiological hazards for land application and, before marketing, it undergoes a deferrisation process and a mechanical screening. The raw fraction is recycled at the inlet of the plant. The rejects of the composting process (10% of the input material) are sent to landfill. The leachate produced during the composting process is treated in a WWT plant.

LCA methodology

LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle [9, 10].

The LCA study was carried out according to ISO 14040 standards [11-14]. The goals were the evaluation of the environmental burdens for three alternative scenarios of treatment and disposal of urban sewage sludge and the identification of the most critical points.

The analysis of the functions of the systems that have been studied suggested the adoption of the following functional unit (FU) – the disposal, in compliance with the law, of 20000 kg of urban sewage sludge with the following characteristics: 1000 kg of dry matter (DM, 5% of total weight), and 700 kg of volatile solids (VS, 70% of DM).

Figure 3 shows the system boundaries adopted. The system included all the processes for treatment and incineration/composting of sludge, the transport and disposal in landfill of ashes/rejects, the production processes of chemicals, electricity, and fuels used for the sludge treatment processes.

As commonly accepted in LCA the contribution to life cycle inventory (LCI) of equipments, buildings and capital goods required in the system was not included in the analysis.

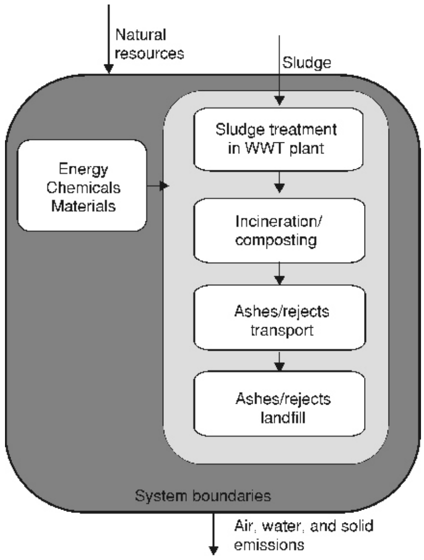

Figure 3. System boundaries of the three analysed plant solutions

The benefits of spreading the compost to soil were not taken into account. The compost nutrients content and its soil improving features could allow a partial replacement of the use of commercial products such as fertilizers or peat, but, taking account of the local agricultural practices, we assumed that its use does not replace any product but only improves the soil physical characteristics.

To model the systems and to evaluate their environmental impact the TEAM software, developed by Ecobilan, was used [15]. The software includes several internationally accepted methodologies to classify the input and output flows into environmental impact categories and characterize them. Table 1 shows the impact categories and the methods selected for the assessment of the scenarios analysed.

The following hypotheses were assumed to model the systems: the empirical formula for the volatile solids content of sludge was assumed to be $C_5H_7O_2N$; thickening and dewatering processes do not release dry matter in the separated liquid; the sludge anaerobic digestion reduces the volatile solids content by 50%. Moreover, for the evaluation of the landfill emissions, the time boundary was set equal to 100 years [16].

Sludge treatment and incineration processes were modelled on the basis of the experimental data from the WWT plant in Bologna, because this plant shows several similarities with the WWT plants located in the Regi Lagni area. Calculations of energy and mass balance were carried out to obtain specific data for the defined FU and to extrapolate the parameters for incineration in system B. In fact, FU being the same, the amount of sludge incinerated in systems A and B and the sludge parameters are different. The operating conditions assumed for sludge incineration and the sludge parameters are summarised in tab. 2.

Table 1. Environmental impact categories and assessment methods

Impact category	Units	Assessment methods
Air acidification	g eq. H^+	CML 1992
Eutrophication	g eq. PO_4^3	CML 1992
Greenhouse effect	g eq. CO_2	IPCC 1998 (100 years)
Aquatic ecotoxicity	g eq. 1-4-dichlorobenzene	USES 2.0 1998
Human toxicity	g eq. 1-4-dichlorobenzene	USES 2.0 1998
Terrestrial ecotoxicity	g eq. 1-4-dichlorobenzene	USES 2.0 1998
Sediment ecotoxicity	g eq. 1-4-dichlorobenzene	USES 2.0 1998
Photo-oxidant formation	g eq. ethylene	WMO (high level)
Depletion of non renewable resources	Fraction of reserve	CML 1992

Table 2. Operating conditions assumed for sludge incineration

	Units	System A	System B
Oxygen content in combustion gas(1)	%	11	11
Combustion air temperature	°C	700	700
Sludge to incinerator/FU(2)	kg	2170	3330
Sludge parameters			
Low calorific value/Volatile matter	kJ/kg	21000(3)	23000(3)
Dry matter	%	30	30
Volatile matter	%	54	70

1 – measured after post-combustion chamber, 2 – FU = 20 t, 3 – literature data [17, 18]

Operating conditions of the composting plant were based on a plant design, developed in collaboration with ENTSORGA Italia. Specific data were obtained on the basis of energy and mass balances. The mixing ratio of sludge, organic fraction of MSW, and wood scraps has been assumed to be respectively equal to 1:0.5:1.5. Because the composting process is a waste treatment for all the fractions of the mixture, the related impacts have been allocated to sludge on a mass basis.

The treatment of the water separated from the sludge during the thickening processes and the treatment of the leachate were modelled on the basis of data of the urban WWT plant in Bologna [19].

Inventory data were completed with the information gathered from the chemicals manufacturers and from the AQUASAVE project [19]. Where specific data were not available, reference was made to TEAM 3.0 database or to relevant scientific literature.

Results

Figure 4 shows the contribution of systems A, B, and C to the environmental impact categories adopted for this study, except for the toxicity related ones, that will be discussed below. Results are presented as percentages of the maximum values (set equal to 100) of each category. As specified before, the avoided impacts of compost spreading to soil have not been included in system C analysis. The potential environmental impacts of the three systems are characterised by electricity consumption. Since the Italian electricity mix is mainly based on the use of fossil fuels, significant environmental impacts arise from the use of electricity. If systems A and B are compared, the potential impacts of system B are higher in all categories. For both systems the incineration section gives the highest contributions to the impacts, because of methane and electricity consumption. System A consumes less electricity than system B because the anaerobic digestion process reduces the amount of sludge to be incinerated, but methane consumption is higher because of the lower calorific value and volatile solids content of digested sludge. Moreover in system A the production of electricity by combustion of sludge gas cuts down the use of power supply and avoids the potential environmental impacts of its production.

System C is the major contributor to photo-oxidant formation category.

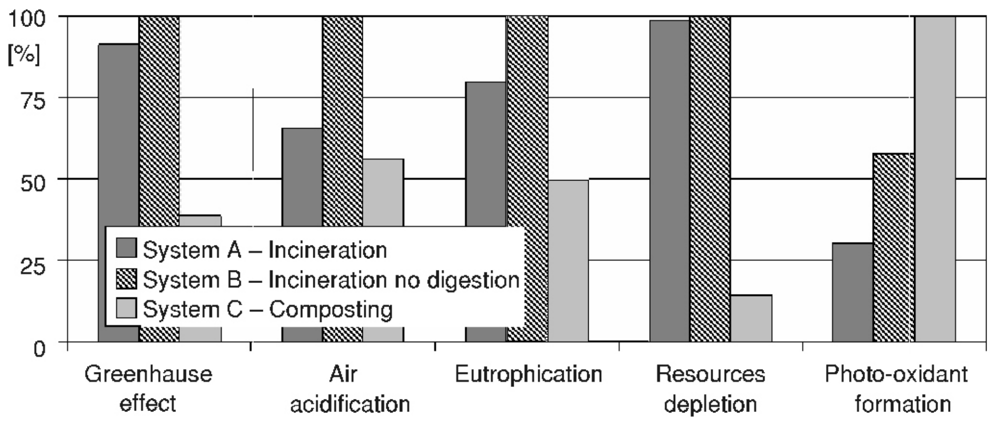

Figure 4. Environmental impact categories for systems A, B and C

In figs. 5-8 the environmental impacts of the main sections of systems A and C are compared. Since the sludge treatment processes in WWT plant are identical in the two systems, the results of this section present always the same values.

Figure 5 shows the contribution to the photo-oxidant formation impact category. The impacts are mainly due to hydrocarbons and methane emissions into the environment. Landfill gas, generated by residual decomposition activity of the compost rejects (which come not only from sludge but also from organic fraction of MSW and wood scraps) and not completely caught by the landfill gas control system, gives the highest contribution, despite fairly modest in absolute value. The incineration/composting section is characterised by the emissions related to methane extraction and production processes. Since local availability of compost treatment plants and local compost market were assumed, the impact of transport in system C is not significant.

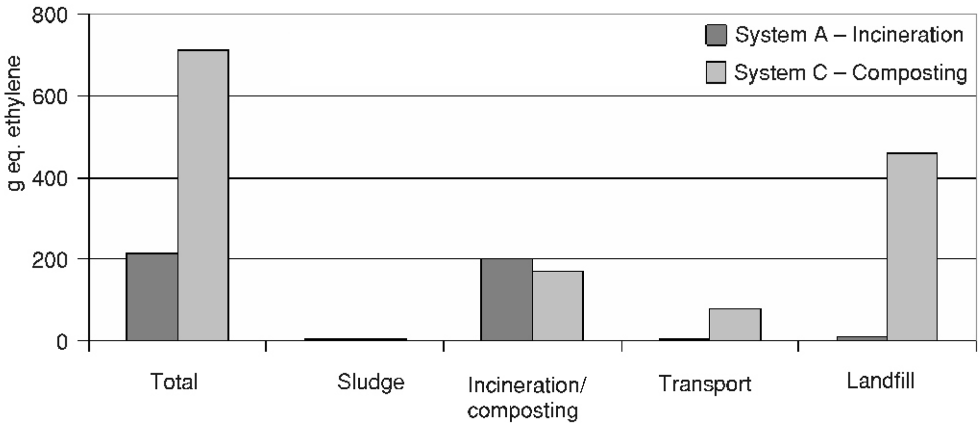

Figure 5. Photo-oxidant formation for systems A and C

Figure 6 shows non renewable resources consumption, as a fraction of estimated reserves, for the main sections of systems A and C. Extraction of natural gas dominates the impact of system A with 89% contribution to the total of the category. Oil needed for electricity production accounts for 7%. The impact of system C, mainly due to electricity consumption in composting system, is far lower if compared to system A.

Figure 7 shows total primary energy consumption for systems A and C. Primary energy is the energy embodied in natural resources (*e. g.* coal, crude-oil, natural gas, uranium) that has not undergone any anthropogenic conversion or transformation. It is an indicator of the efficiency of the use of energy natural resources in the overall system. Electricity and methane used in incineration and electricity used in composting are the main contributors to the total of the category. The environmental impact categories related to energy use (greenhouse effect and acidification) show a similar trend.

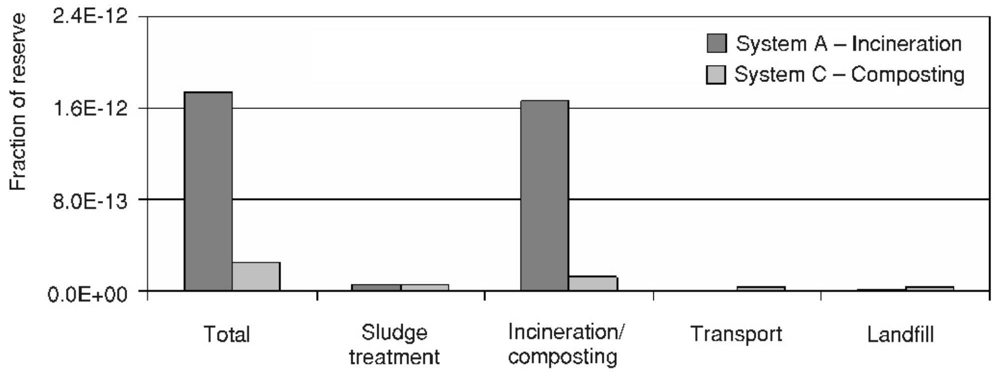

Figure 6. CML-Depletion of non renewable resources of systems A and C

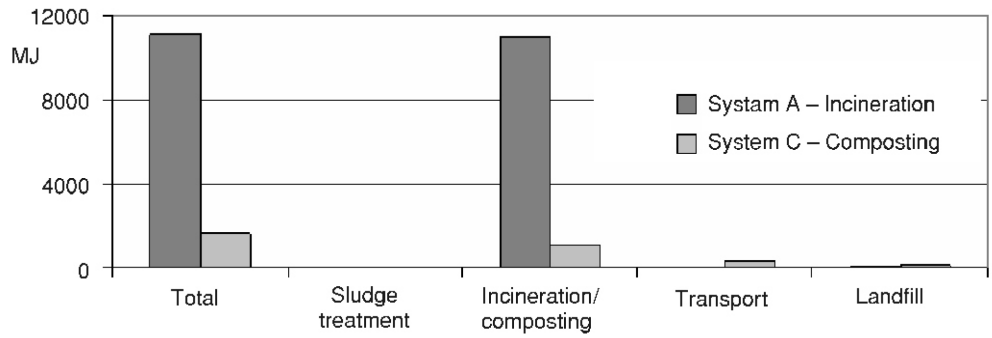

Figure 7. Total primary energy consumption for systems A and C

Figure 8 shows the potential contribution to eutrophication of the main sections of the systems. The release into the environment of the phosphorus contained in the wastewater originated from the incineration process and from the sludge treatment sections dominates the contribution of the entire system A, even if the water is treated in WWT plant; composting section of system C shows a much lower contribution because of the smaller wastewater volume.

Figure 9 shows the systems contribution to human toxicity and aquatic, sediment and terrestrial ecotoxicities. Emissions originated from electricity production are the main contributors to the potential impacts of human toxicity and water and sediment ecotoxicity; heavy metals in composted sludge spread to soil (tab. 3) dominate the impact of terrestrial ecotoxicity for system C.

The results of this category are significant enough to anticipate potential problems for composted sludge spreading, though organic micropollutants and PCBs were

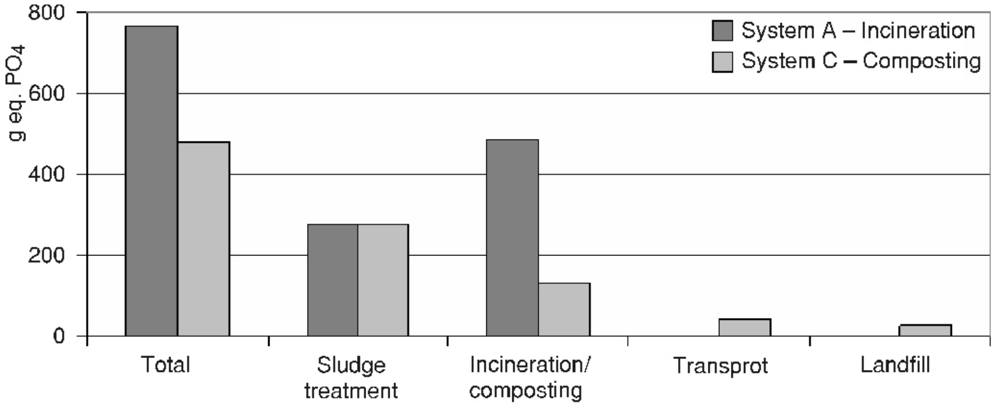

Figure 8. CML 1992 eutrophication for systems A and C

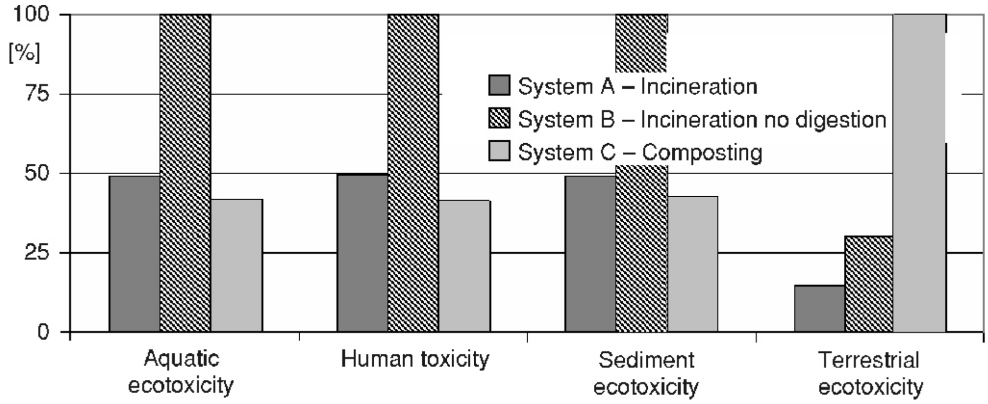

Figure 9. USES 2.0 toxicity categories for systems A and C

Table 3. Typical metals concentration in wastewater sludge of Regi Lagni area

	Al	Cd	Cr(III)	Fe	Mn	Hg	Ni	Pb	Cu	Zn
Metal/DM [mg/kg]	0.82	<0.1	2.8	678	<0.01	<0.1	0.81	49	14.8	550

not included in this analysis. Actually urban wastewaters, which are often mixed with urban runoff and small quantities of industrial wastewaters, contain non-negligible quantities of metals and other potentially harmful substances that concentrate mainly in sludge. Regulatory limits have been fixed at European level for heavy metals content in compost, but not yet for organic pollutants because their concentration has proved low so far.

An accurate analysis of the environmental burden of heavy metals in soil cannot be made without site specific assessments. It depends on several factors, among others, on the physical, chemical, and biological characteristics of soil, on the assimilation by plants and subsequent contamination of food chain. LCA environmental impact categories and USES 2.0 model in particular are not able to model all these aspects and should therefore be considered just a synthetic indicator of potential problems.

Conclusions

Different scenarios of urban sewage sludge treatment and disposal were assessed and compared by application of the LCA methodology to identify the environmental critical points of the alternatives selected. The assessment of the potential environmental impacts showed that system A scores systematically better than system B in all categories. The combustion of sludge gas for generating electricity proved to be an environmentally friendly option in Italy because it avoids burning fossil fuels.

System A contributes more than system C to almost all categories, because incineration, when compared to composting processes, needs higher electricity consumption and the use of methane as auxiliary fuel. The category photo-oxidant formation is more critical for system C, but with fairly low absolute values. The interpretation and discussion of the results of the terrestrial ecotoxicity category deserve particular attention. Even if the simplified models used in LCA cannot replace a complete risk assessment of the use of compost in agriculture, the results can be considered an aggregated indicator of potential problems. The heavy metals content of composted sludge is the main cause of the results of this category. The damages can be minimised by applying well known good practices such as: use of high quality sludge; use of compost in sectors where no risk exists of contaminating the animal or human food chain, *e. g*. floriculture; industrial quality control of compost production chain (from the control of wastewaters discharged into the sewer to the management of WWT plants and composting processes); establishment of good relations and communications among the actors of the product chain.

The results of this study confirm that for a sustainable wastewater sludge management it is necessary to take into account different technological options, depending on the characteristics of the sludge and of the specific area (soil typology, agricultural use, local availability of treatment plants, local market demands, *etc*.). This can be obtained if the optimisation is done at a significant geographic scale (districts, optimised territorial areas), where the plants can be sized properly and managed with industrial criteria and efficient water pollution prevention strategies can be introduced.

Acknowledgments

The authors would like to thank Mr. Bondesan of HERA spa and Mr. Bertossi of Entsorga Italia for their support in gathering LCI site specific data.

Abbreviations

CML – Centrum voor milieuwetenschappen Leiden
DM – dry matter
FU – functional unit
IPCC – Intergovernmental panel on climate change
LCA – life cycle assessment
LCI – life cycle inventory
MSW – municipal solid waste
USES – Uniform system for the evaluation of substances
WMO – World Meteorological Organisation
WWT – waste water treatment

References

[1] ***, Directorate-General Environment of European Commission, 2005 http://europa.eu.int/comm/environment/waste/sludge/index.htm
[2] Suh, Y., Rousseaux, P., An LCA of Alternative Wastewater Sludge Treatment Scenarios, *Resources, Conservation and Recycling, 35* (2002), 3, pp. 191-200
[3] Lundin, M., Olofsson, M., Pettersson, G.J., Zetterlund, H., Environmental and Economic Assessment of Sewage Sludge Handling Options, *Resources, Conservation and Recycling, 41* (2004), 4, pp. 255-278
[4] Houillon, G., Jolliet, O., Life Cycle Assessment of Processes for the Treatment of Wastewater Urban Sludge: Energy and Global Warming Analysis, *Journal of Cleaner Production, 13* (2005), 3, pp. 287-299
[5] Hospido, A., Moreira, M. T., Martin, M., Rigola, M., Feijoo, G., Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion Versus Thermal Processes, *Int. J. LCA, 10* (2005), 5, pp. 336-345
[6] Svanström, M., Fröling, M., Modell, M., Peters, W. A., Tester, J., Environmental Assessment of Supercritical Water Oxidation of Sewage Sludge, *Resources*, *Conservation and Recycling, 41* (2004), 4, pp. 321-338
[7] Peregrina, C. A., Lecomte, D., Arlabosse, P., Rudolph, V., Life Cycle Assessment (LCA) Applied to the Design of an Innovative Drying Process for Sewage Sludge, *Process Safety and Environmental Protection, 84* (2006), 4 B, pp. 270-279
[8] Maiorino, L., Buttol, P., Tarantini, M., Life Cycle Assessment of Sewage Sludge Management (in Italian), Report ENEA PROT-P577-001Rev 0, Bologna, Italy, 2002
[9] Curran, M. A., Environmental Life Cycle Assessment, McGraw-Hill, New York, USA, 1997
[10] ***, SETAC, Guidelines for Life Cycle Assessment: A Code of Practice, Society of Environmental Toxicology and Chemistry, Pensacola, Fla, USA, 1993
[11] ***, ISO 14040 Environmental Management, Life Cycle Assessment, Principles and Framework, 1997
[12] ***, ISO 14041 Environmental Management, Life Cycle Assessment, Goal and Scope Definition and Inventory Analysis, 1998
[13] ***, ISO 14042 Environmental Management, Life Cycle Assessment, Life Cycle Impact Assessment, 2000
[14] ***, ISO 14043 Environmental Management, Life Cycle Assessment, Life Cycle Interpretation, 2000
[15] ***, TEAM 3.0 Software Manual, Ecobilan Group, 1999
[16] Nielsen, P. H., Hauschild, M., Product Specific Emissions from Municipal Solid Waste Landfills, *Int. J. LCA, 3* (1998), 3, pp. 158-168

[17] Beccari, M., Di Pinto, A. C., Passino, R., Mininni, G., Santori, M., Sludge Treatment Schemes with Final Incineration (in Italian), *Ingegneria ambientale, 13* (1984), 7-8, pp. 391-397
[18] McLean, J. E., Behaviour of Metals in Soils, Report no. EPA/540/S-92/018, US Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Research and Development, Washington, DC, 1992
[19] Ferri, F., Tarantini, M., AQUASAVE Project – Life Cycle Assessment of Drinking Water and Wastewater Treatments of Bologna City (in Italian), Report ENEA OT-SCA-00024 Rev 2, 2001, Bologna, Italy

Authors' address:

M. Tarantini, P. Buttol, L. Maiorino
ENEA Italian National Agency for New Technologies,
Energy and the Environment
4, Via Martiri di Monte Sole
40129 Bologna, Italy

Corresponding author M. Tarantini
E-mail: mario.tarantini@bologna.enea.it

Paper submitted: January 31, 2007
Paper revised: April 7, 2007
Paper accepted: April 10, 2007