Environmental Impacts of Post-Consumer Material Managements: recycling, biological treatments, incineration

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ABSTRACT: The environmental impacts of recycling, mechanical biological treatments (MBT) and waste-to-energy incineration, the main management strategies to respond to the increasing production of post-consumer materials, are reviewed and compared. Several studies carried out according to life cycle assessment (LCA) confirm that the lowest environmental impact, on a global scale, is obtained by recycling and by biological treatments (composting and anaerobic fermentations) if compost is used in agriculture. The available air emission factors suggest that, on a local scale, mechanical biological treatments with energy recovery of biogas, may be intrinsically safer than waste-to-energy incinerators. Several studies confirm the capability of biological treatments to degrade many toxic xenobiotic contaminating urban wastes such as dioxins and polycyclic aromatic hydrocarbons, an important property to improve, for safe agricultural use of compost. Further LCA studies to compare the environmental impact of MBTs and of waste-to-energy incinerators are recommended.

Keywords: Municipal solid waste; Recycling; Incineration; Mechanical biological treatment; Air emission; LCA; biological detoxification.

1. INTRODUCTION

Modern post-consumer materials (PCM) management suggests the use of different strategies whose gerarchic sequence is to reduce, reuse, recycle, recover energy and finally dispose. Each of these activities has effects on environmental quality and on the health of exposed populations and it is important to evaluate and compare these effects in order to define the correct priorities.

Methods for the management of PCM may be classified into four main categories: recycling, biological treatments, thermal treatments, landfilling.

Controlled biological treatments such as composting, aerobic oxidation, anaerobic fermentations and mechanical biological treatments (MBT) usually occur at a temperature <70 °C; uncontrolled biological transformations, within this temperature range, occur during landfilling.

Incineration, gasification and pyrolyses are thermal waste treatments during which chemical oxidation and molecular degradation occur at temperatures >400 °C. Taking into account the final industrial transformation of recovered materials (glass, metals, paper, plastic) recycling may also be classified as a thermal treatments

Combustion, occurring in all thermal treatments, included energy use of biogas, produces toxic compounds, as fumes (NO_x, CO, fine and ultra fine particles, volatile and semivolatile organic compounds) and as toxic metals and persistent organic pollutants (POP) in solid residues: bottom and fly ashes (Valerio, 2008).

Many of these toxic compounds are absent or at lower concentrations in gaseous emissions of biological treatments and of landfill, characterised by specific pollutants of relatively low toxicity as ammonia, methane (Amlinger et al., 2008) and terpenes (Pierucci et al., 2005); POPs (Brandli et al., 2005) and inorganic pollutants (metals, nitrate) may contaminate end products (compost, digestate) and liquid emissions of biological treatments (Greenway and Song, 2002).

Several different environmental effects, on both the local and the global scale, are expected by these PCM managements and life cycle assessments (LCA) have been proposed and used to give a correct answer to public administrators asking for environmentally friendly disposal methods that are possibly inexpensive and energy saving (Bjorklund et al., 2007; den Boer et al., 2007).

The objective of this paper is to review existing LCA studies on PCM management methods, particularly recycling, biological treatments and waste -to-energy incineration, in order to compare their effects on a global scale and to collect information about air emission factors of the mechanical biological treatments and of the waste to energy incinerators, to compare local effects on air quality around these plants.

A specific chapter will be devoted to studies about the detoxification capability of MBTs, a property useful to improve agricultural use of compost and to decrease POP concentration in gaseous MBT emissions.

2. To incinerate or to recycle?

Life-cicle assessment (LCA) studies the environmental aspects and potential impacts throughout a product's life, from raw material acquisition through production, use and disposal: a global impact evaluation.

Due to the complexity of this olistic approach that try to evaluate the global impact , "code of practise" has been publisched and a ISO standard is developed. In LCA it is important to define correctly boundaries of studied systems and geographic variables.

In several different countries LCAs were carried out to compare environmental impact of applied waste managements.

2.1 Life cycle analyses of post-consumer material management in USA and Europe

One of the first studies aimed to compare life cycle studies on recycling, incineration and landfilling was carried out by R.A Denison (Denison, 1996). Each of the four studies he reviewed (Franklin Associates, 1994; Morris et al., 1992; Tellus Institute, 1994; US Department of Energy,

1992) used a life cycle perspective in order to account for the full cycle of production of potentially recyclable materials and their management after use. The common conclusion of these studies, across all the parameters examined, was that systems based on recycled production and PCM recycling offer “life cycle” environmental advantages over systems based on virgin production plus either incineration or landfilling. The advantages are related to solid waste output, energy use and the release of pollutants into the air and water. These conclusions, obviously, were related to the USA context and a limitation to their general extension was that only the cogeneration of electricity by incineration was evaluated and the emission factors applied in these analyses were related to relatively old technologies.

More recent (1996–2004), relevant studies, in a European context, about the environmental performance of incineration with energy recovery, in comparison with other options, were analysed by PROFU, a Swedish independent consulting firm. The study was conducted under the commission of the Confederation of European Waste-to-Energy Plants (CEWEP) (PROFU, 2004).

Thirty-one case studies were examined and twelve of them were selected to compare the following environmental impacts: global warming potential (GWP), rain acidification, water eutrophication, production of photo-oxidants and toxicity of emissions. One of the criteria used to select the case studied was the absence of conflicts of interests: the studies were prevalently financed by a “neutral” player such as the EU, governments and national environmental agencies; if not, only peer-reviewed studies were included.

The majority of the studies concentrated on separate fractions of the waste (food waste, paper, plastic, metals); some studies included treatments of mixed waste.

The main conclusions of PROFU’s analyses were that in almost all the studies landfilling is the worst option. For well source-separated and clean fraction material, recycling led to lower environmental impacts than incineration. When incineration with energy recovery was compared with recycling, the LCA results were sensitive to the assumption of replaced electricity. If the electricity recovered through the incineration of waste was assumed to replace an average mix of electricity produced in the EU, the recycling option was preferred in the impact category GWP; if replaced electricity is only produced by coal power plants, incineration performs better than recycling.

According to PROFU's study, for organic waste, the choice between incineration, composting and anaerobic digestion was not obvious. Composting and digestion is the better choice when there is a demand, by the farmer, to use the produced compost and thus recycle the nutrients in cultivated soils, leading to the replacement of synthetic fertiliser production. Digestion residues and compost are credited with their content of phosphorous, nitrogen and potassium and, in this case, the emissions for the industrial production of the same amount of these fertilisers must be deducted from the overall emissions in favour of biological treatments.

Therefore, both for recyclable materials and for organic waste, the quality of the residue is the key factor of choice to minimise the environmental impact and make recycling, composting and anaerobic digestion the best choice.

2.3 LCA of waste management in the Italian context

Recently, some LCA studies on waste management, dealing with specific Italian situations were published. One case study regards the Bologna district (Buttol et al., 2007). The integrated waste management system of the Bologna district includes waste collection and transportation, sorting, recycling, composting, incineration and landfilling. Three scenarios, referring to 2006, with different types of collection and different waste treatments were compared, using the WISARD software (Waste Integrated System for Assessment of Recycling) (Wisard, 2010). The first scenario is the existing situation in Bologna (2003): an annual increase of 1.5% of the total waste produced, with a separate collection of 28% of the total waste and unsorted waste sent to incineration (30%) and landfill (48%). The second scenario increases to 50% the fraction sent to incineration with energy recovery and increases to 31% the separate collection. The third scenario foresees 31% of a separate collection and incineration of 37% of unsorted waste.

In all scenarios incineration was carried out in the waste-to-energy incinerator operating in Bologna and its exhaust gases are cleaned according to the best available technology to respect EU emission limits.

The conclusions of this LCA were: in all the scenarios, recycling is confirmed to save more energy (3–5 times) in comparison with incineration and landfill, and in all the scenarios, recycling guarantees the lowest emissions of volatile organic compounds; in the third scenario (31% separate collection and 37% incineration), the avoided impact of toxic compounds, expressed as 1–4 dichlorobenzene equivalent (1,4 DCB eq), by recycling was - 2.1 10^{9} g 1,4 DCB eq, about 5 times lower than the unsorted waste incineration avoided impact (- 1.1 10^{10} g 1,4 DCB eq).

According to these results, the authors recommended analyses of an additional scenario with a larger increase in separated collection and recycling, in accordance with new recycling targets suggested by the EU and accepted by Italian law (Decree no. 152, 3 April 2006): at least 35% of separate collection within 2006, 45% by 2008 and 65% by 2012. It is noteworthy that according to the previous Italian legislation (Decree 22/97), 35% of separate collection must be reached by 2003, a totally unattained target (Italy: 25%; Bologna: 28%).

An LCA was carried out for the Campania region, to support the decisions of the National Committee for Waste Emergency in Campania and Naples (Arena et al., 2003). In this Italian region the separate collection was 1.1% in 1999 and 12.8% in 2003, notwithstanding the urban waste emergency that had been declared in Campania since 1994. This LCA ignores any possible role of separate collection and examines three scenarios for rest-waste: landfilling, refuse-derived fuel (RDF) production and its combustion, mass burn combustion. The principal indicators of environmental impact were: the consumption of natural resources, air and water pollution and the quantities of solid waste generated. The obvious conclusions were the poor performance of the landfilling option and the validation of the waste management scheme proposed for the Campania region: sorting and RDF production by MBT and incineration with electricity production.

Twelve different PCM management scenarios were chosen for another LCA study aiming to choose the best system to solve the same waste emergency occurring in Avellino Province, in the Campania region (De Feo et al., 2009). More correctly, these scenarios were obtained considering different separated collection percentages, as well as two different treatments for the final unsorted PCM: incineration and the disposal of stabilised waste. In all the scenarios, unsorted materials were submitted to MBT and putrescible fractions, source collected and sorted by mechanical treatments, were composted for agricultural use. LCA WISARD software (Wisard, 2010) was used for this analysis.

The conclusions were that the scenario with 80% separate collection, no RDF incineration and dry residue sorting was the most environmentally sound option for six impact categories of the eleven chosen: renewable energy use, total energy use, water, suspended solids and oxydable matter index, eutrophication and hazardous waste.

The second-best scenario with three impacts of environmentally sound categories (non-renewable energy use, greenhouse gases and acidification) is 80% separate collection, RDF production and incineration.

For eight impact categories (renewable, non-renewable, total energy use, water, suspended solids and oxydable matter index, acidification, eutrophication, hazardous waste), all the PCM management scenarios produced a negative impact and the highest percentage of separate collection corresponded to the highest avoided impact.

Therefore, this study also confirmed the priority of separate collection and recycling to save energy and to reduce the environmental impact of PCM management.

An Italian industrial area with prevalent textile activities (Prato, Tuscany) was submitted to an LCA (Tarantini et al., 2009). The aims of this study were the identification of environmental critical points of the adopted waste management and the evaluation of opportunities and problems in applying the same methodology to other industrial areas. The industrial area of Prato produces annually 10,200 tons of waste; 7,760 tons (76%), predominantly paper, cardboard, plastics and wood, are sorted by door-to-door collection and recycled. Unsorted waste is sent to a selection plant, whose outputs are: RDF, organic fraction, metals and mixed waste. In total 1,835 tons of RDF are incinerated to produce electricity, the organic fraction (80 tons) is composted, 20 tons of metals are recycled and mixed waste are landfilled and 49% of the biogas produced is recovered and burnt in a cogeneration system to produce electricity and heat for district heating. The GaBi 4 software (PE International, 2010) was used to model the system and evaluate its environmental impact. The study tested 5 environmental indicators: non-renewable primary energy, GWP, eutrophication potential, photochemical ozone potential and environmental and human toxicity potential. The best performances, in terms of avoided impact for all these indicators, were obtained by polyethylene and paper recovery. Emissions of heavy metals from leachates treatment and electricity production were the main contributors to freshwater aquatic toxicity.

Therefore, according to these results, a specific recommendation has been made to the Managing Consortium of the industrial area of Prato to improve further the collection rate of polyethylene, paper, cardboard and wood. The analyses pointed out a general Italian problem: the spread over the national territory of PCM treatment plants, mainly incinerators and composting plants, placed a long distance from the production area: 791 km is the distance from Prato to the Massafra (TA) incinerator and 719 km the distance from the Modugno (BA) composting plant, the final destination of waste produced in Prato.

To find the optimum level of separate collection in an integrated PCM management system is the specific aim of a study carried out by the Milan Polytechnic Institute (Rigamonti et al., 2009).

The Simapro 7 software (PRè Consultants, 2010) was used for the evaluation of the energetic and environmental impact of three PCM integrated management systems, differing from each other in the quantity sent to material recovery and energy recovery: scenario 35%, scenario 50% and scenario 60%. The first 2 scenarios are compatible with the actual situation in several Italian provinces; a source separation of 60% is considered by the authors as a reasonable target level that can be reached within few years in the north and centre of Italy. In all the scenarios, steel, aluminium, glass, paper, wood and plastic are source separated and recycled. Source-separated green and food waste are composted to substitute peat and mineral fertilisers. All the residual is incinerated in three sub-scenarios: in a large plant that produces only electricity, in a large plant cogenerating heat and power (CHP) and in a small CHP plant. The electricity produced from WTE plants displaces the same amount of energy produced by the thermoelectric Italian mix and heat displaces the heat generated by household boilers fed with natural gas. Steel and aluminium separated from bottom ashes are recycled.

The main conclusions of this study of recycled materials are:

- For all the analysed materials, recycling is the most efficient choice, compared with incineration.
- The highest energy saving is related to aluminium (165,951 MJ eq per tonne collected).
- The second most energy-saving process is plastic recycling (42,637 Mj eq per tonne).
- In relative terms, paper recycling allows the highest energy saving: the production of pulp from recycled paper requires only 1% of the energy necessary for pulp production from wood.
- For all the materials, recycling is environmentally advantageous; aluminium recycling has the highest avoided human toxicity impact (- 47.001 kg 1,4 dichlorobenzene (DCB) eq), followed by plastic and steel recycling (- 248 and - 247 kg 1,4 DCB eq).
- The avoided human toxicity increases according to the recycling percentages: -71 kg 1,4 DCB eq. t_{MSW}^{-1} in scenario 35%; -183 kg 1,4 DCB eq. t_{MSW}^{-1} in scenario 60%.
- In scenarios 50% and 60%, the avoided human toxicity produced by recycling is increasingly higher than that produced by waste-to-energy incineration.
- Composting appears neutral from an environmental point of view.

The conclusions of the LCA carried out by the Milan Polytechnic Institute for the waste-to-energy plants are:

- Incineration with energy recovery is environmentally convenient when the replaced electricity is produced from coal; it is not convenient when the displaced electricity is produced from natural gas in a combined cycle plant.

- The avoided human toxicity, obtained from recycling aluminium and steel from bottom ashes, is very low, compared with the same parameter from aluminium and steel recycled by source sorting.

The general conclusion of this study is that the PCM management system that is more convenient for cumulative energy demand and environmental impact indicators is the one with a source-separated collection of 60%.

2.3 LCA for paper and cardboard management

Paper and cardboard are important fractions of PCM and their high calorific content may justify their incineration with energy recovery. Specific LCAs were devoted to post consumer paper and cardboard, to compare environmental impact of incineration and recycling. The Danish Institute of Environmental Assessment claimed, in several reports, that it was not cost-effective to recycle both paper and plastic packaging and the report authors argued that these waste fractions, produced both by industries and by households, should be kept together and incinerated (Petersen et al., 2002).

These cost–benefit analyses were criticised by other authors, especially with regard to the limited number of environmental problems investigated and omission of important issues as impacts on forestry and generation of energy from wood residues. In a report from the European Topic Centre on Waste and Material Flow, nine LCA studies in regard to post-consumer paper, selected on the basis of a set of quality criteria, were critically investigated (Villanueva and Wenzel, 2007; Villanueva et al., 2007). The conclusion of this report was that the overall results of the nine LCA studies indicate that recycling of waste paper has a lower environmental impact than landfilling and incineration.

The different conclusions of previous studies were due to differences in the LCA methodology applied and especially the definition of the system boundaries; the outcome of the individual investigated LCA studies largely depended on the choices made in preliminary assumptions, particularly the ones concerning energy use and generation and forestry: energy and material marginal for wood, alternative uses of wood and forest land.

These criticisms were taken into account by a new LCA study about the Danish consumption of paper (Schmidt et al., 2007) and conclusion confirmed that recycling paper is better than incineration. The advantage of paper recycling is related to the saved wood resources for energy production and wooden manufacturing.

3. MECHANICAL BIOLOGICAL TREATMENTS

Mechanical biological treatments (MBT) of sorted (humid fraction) or unsorted PCM are relatively new pre-treatment processes (Velis et al., 2009) which, since the 1970s, have spread widely in Germany, Austria, Italy (Adani et al., 2004; Gioannis et al., 2009) and the UK (Hall et al., 2006).

Biological procedures may be both aerobic and anaerobic (Fricke et al., 2005) or a combination of these two procedures and their main objectives are:

- Minimisation of landfilled masses and volume
- Inactivation of biological and biochemical processes to avoid or reduce biogas and leachates emissions during landifilling of treated waste
- Safer separation of recyclable fractions
- Drying of high calorific fractions to use as fuel
- Collection of the produced biogas (in anaerobic treatments) to produce heat and electricity.

Notwithstanding the increasing number of MBT plants, their environmental impacts lack systematic studies that are statistically representative. We found only one dedicated study about the

LCA of an MBT plant operating in Pudong, China (Hong et al., 2006); this study was used for comparing the environmental impact potential of five different alternative waste treatment strategies: direct landfill and incineration, MBT and compost production, MBT and incineration of bio-dried fraction and MBT and landfill of stabilised residue. The results of this LCA show that incineration has the highest acidification potential, while landfill presents both the highest GWP and the highest eutrophication potential. The lowest total environmental impact potential was for the MBT–compost scenario, followed by MBT–incineration and MBT–landfilling. A general conclusion of this study was that the pre-treatment by MBT reduces the impact of waste management.

These conclusions are similar to those obtained by De Feo and Mangano (2009), already discussed, the only other LCA study we found that included MBT treatments as possible choice.

Due to the relevant differences of technology applied to MBTs concerning waste input, anaerobic and aerobic treatments, different output materials and their use, these conclusions, even if interesting and worthy of attention, are too limited to be generalised.

3.1 Exhaust emissions from MBTs

To stabilise 1 ton of mixed waste in an MBT plant, 6,000–10,000 m^3 of air are necessary for an aerobic procedure, while an optimised anaerobic/aerobic procedure requires 2,000–6,000 m^3 of air (Fricke et al., 2005).

In raw exhaust emissions from an MBT plant several organics are present (Fricke et al., 1997). Many gaseous pollutants are produced by biodegradation activity: ammonia, n-alcanes, terpenes, alcohols (ethanol), ketones (acetone, butanone), aldehydes (acetaldehyde) and aromatic hydrocarbons (benzene, toluene, xylenes).

Other gaseous pollutants that may be found in raw exhaust emitted by MBT are volatile or semi-volatile waste contaminants that are desorbed from waste by the high temperatures (50–75 °C) of the aerobic process and by the forced aeration. Important xenobiotics that may be found in MBT exhausts are tricholorethene, tetrachloroethene and PCDD/F (Rada et al., 2007).

It is important to observe that, according to studies carried out by Fricke (Fricke et al., 1997), toxicologically relevant compounds and pollutants such as dioxins, heavy metals, NO_x and dust present in raw gas from MBT plants are already far below those of purified air from incineration plants.

3.2 MBT exhausts emissions purification

Various exhaust purification procedures are available to remove pollutants and eliminate odour-intensive substances (Schlegelmilch et al., 2005) emitted during MBTs; the two main applied techniques are biological treatment by bio filters (Clemens and Cuhls, 2003) and thermal regenerative procedures (Chou et al., 2007; Dvorak et al., 2007). Bio filters can reach a total organic compound (TOC) reduction of 50–70%, but only thermal treatments such as thermal regenerative oxidation (TRO) reduce the TOC concentration below the limit of German legislation (20 mg/Nm^3).

Because of the high costs of thermal regenerative air treatments, this method is applied to treat highly contaminated exhaust air produced during the first decomposition stage, while slightly contaminated exhaust air flows are supplied to bio filters.

Another drawback of TRO is the production of secondary pollutants (ultra fine particles, NO_x, SO_2) (Chou et al., 2007); therefore, this technique must be preferred to decontaminate only toxic effluents.

3.3 PCDD/F emission factor of waste biodrying by MBT

An experimental study was carried out by the Mario Negri Institute to evaluate PCDD/F concentration along the air line of an MBT plant operating in Italy, in the Lombardy region, in Montanaso Lombardo (Benfenati et al., 2004).

The plant has a capacity of 60,000 ton/year of source-segregated residual from the Milan district, where there is 40% recycling. Shredded waste is moved by crane to the aerobic fermentation area in a closed environment, and air is drawn through the waste piled up to 6 m height. An exothermic biological reaction increases the pile temperature to 50–60 °C. The exhaust air is transferred to bio filters (a bed of woody materials 100 cm high). After 12–15 days of aerobic treatment, the material is stabilised, sanitised and practically odour free, dry and suitable for mechanical treatments to separate metals, glass, inert and compostable fines. The main output of this plant is 50% of RDF, used in a nearby fluidised bed boiler. Emissions produced by RDF combustion were not evaluated in this study.

In 2002–03 two sampling campaigns were carried out to measure PCDD/F concentrations in the ambient inlet air, before and after the bio filter and from the chimney where filtered air is conveyed from the mechanical treatments and CDR production. Table 1 summarises the results, which show significant reductions of dioxins concentrations, particularly after the passage through the bio filters and the air treatment to remove dust produced by the mechanical treatments.

According to these results, MBT, without energy recovery and thermal treatment of exhaust air, decontaminates inlet air (82–62%) from dioxins and furans. The authors explain these phenomena as an adsorption of volatile PCDD/F by organic matter in the bio filter and by filtered dust.

Supposing for this MBT plant the highest specific air flow for aerobic procedures (10,000 Nm^3/ton) (Fricke et al., 2005), a factor emission of 0.33–0.36 ng I-TEQ of PCDD/F per ton of PCM may be estimated for the aerobic oxidation.

This is the lowest factor emission available from European MBT plants (Rada et al., 2006), whose highest factor emission was 70 ng I-TEQ/ton and the average values of 5 different studies ranged from 0.9 to 22.0 ng I-TEQ/ton. This high variability may have several explanations: the amount of dioxins in treated PCM (sorted or unsorted), different treatment temperatures, different dioxin mobility from the waste and the humic fraction produced during the biological treatment, different air exhaust treatments and different contamination of inlet air.

Another possible explanation, not yet studied very much but realistic, and discussed in the following s, may be the different biodegradation activity of the microbial community developed inside the plant and in the bio filters.

It is possible that the Montanaso Lombardo plant may be an example of the best available technology to reduce persistent organic pollutants (POP) emissions applied to MBT: inlet waste is selected by a high source segregation of domestic waste, POP stripping is limited by air flow sucked through a high PCM layer, the rapid humification of organic waste increases the absorption capability of oxidised organic material and the bio filters are efficient and well maintained.

These results, if confirmed, deny the conclusions of other authors who claimed MBT plants to be important sources of PCDD/F air contamination (Rada et al., 2007); on the contrary, it is possible that a well projected and managed MBT plant for sorted waste, may have a PCDD/F emission factor (0.33–0.36 ng I-TEQ of PCDD/F per ton of PCM) lower than that of the best PCM incinerators (44.4 ng I-TEQ /ton) (Joint Research Centre, 2005).

5. BIODEGRADATION OF TOXIC CONTAMINANTS IN PCM

POPs are ubiquitary toxic compounds that are normally also found in our food (Miraglia et al., 2009); therefore, their presence in PCM is not surprising and it is not surprising that their concentration may increase when food waste and other organic residuals are composted (Brändli et al., 2005; Lee et al., 2003), as the mass of solid organic waste decreases by about 50% at the end of the maturation step (de Araújo Morais et al., 2008). An extended review of POP in source-separated compost and its feedstock materials was published by Brandli et al. (Brändli et al., 2005).

Other xenobiotic compounds, with possible adverse health effects, are found in our foods, in urban waste and in compost and sludge from sewage treatments: phthalates (Kapanen et al., 2007; Staples et al., 2000), herbicides (Delgado-Moreno and Pena, 2009; Kamei and Kondo, 2006; Lemmon and Pylypiw, 1992) and pesticides (Lee et al., 2003; Nilsson, 2000; Taube et al., 2002).

Otherwise, as POP weather, their concentrations in soil, decrease both for physical reasons (photodegradation, translocation to other environmental compartments) and by biodegradation induced by bacteria and fungi that use these organic compounds as a carbon source (Singh and Ward, 2007).

5.1 BIODEGRADATION OF PCDD/F AND POLYCHLORINATED BYPHENILS

Several studies confirmed that PCDD/F compounds are subject to biodegradation in the environment by aerobic and anaerobic bacteria (Field and Sierra-Alvarez, 2008; Habe et al., 2002) and by specific white rot fungus (Kamei and Kondo, 2006; Mori and Kondo, 2002).

These results suggested the possibility that dioxin-polluted soil could be submitted to bio-remediation (Hiraishi et al., 2001) and further studies treated dioxin-contaminated soil in a bioreactor using an isolated dioxin-degrading fungus (*Pseudallescheria boydii*) (Ishii and Furuichi, 2007) with very interesting results: the removal of 92% of the dioxins.

Similar results were obtained using another fungus strain (*Phanerochaete sordida YK-624*). The degradation values of PCDDs and PCDFs were approximately 40% (tetra-chloro-) to 76% (hexachloro-) and 45% (tetrachloro-) to 70% (hexachloro-), respectively (Takada et al., 2003).

A microbial biocatalyst (a mixture of 4 bacterial and 5 fungal dioxin-degrading strains) was used as PCDD/F bioremediation of a contaminated municipal solid waste incinerator. After a treatment of 21 days, 68.7% of the total toxic PCDD/Fs was reduced (Nam et al., 2008).

In a laboratory scale digester, seeded with activated sludge, with a thermophilic and mesophilic anaerobic digestion, polychlorinated biphenyl (PCB) and adsorbed organic halogen compounds were degraded. The total PCB removal efficiency was in the range of 59.4–83.5% under thermophilic conditions and 33.0–58.0% under mesophilic conditions. The efficiency of the adsorbed halogen organic removal was lower (30–50%) (Benabdallah El-Hadj et al., 2007).

This result was not confirmed in the only field study we have found (Brandli et al., 2007). During composting by open windrow, concentrations of low-chlorinated PCBs increased (by about

30%) and a slight decrease occurred for higher chlorinated congeners (10%). No particular effect on PCB concentrations was observed during anaerobic digestion.

5.2 BIODEGRADATION OF PAH BY COMPOSTING

PAH bioremediation was obtained in a compost-assisted remediation of a manufactured-gas plant soil contaminated with PAHs. The degradation of individual PAHs was in the range of 20–60% at the end of 54 days of composting, followed by a further increase of PAH removal (37–80%) after another 100 days of maturation (Sasek et al., 2003).

A combined mixture of fungal and bacterial co-culture significantly enhanced high molecular weight PAH degradation (Boonchan et al., 2000). After 49 days, 25% benzo(a)pyrene was mineralised. Inoculation of the fungal–bacterial co-cultures into PAH-contaminated soil improved degradation (53% of BaP was degraded in 100 days of incubation time).

This result suggests that, also for PAHs, a mixed culture of selected bacteria and fungus may increase biodegradation, which in all previous studies significantly (50–90% reduction) involved only light PAHs (Brandli et al., 2007).

In field studies, PAH removal from urban sludge was observed during thermophilic anaerobic treatments at higher temperatures (Trably et al., 2003) and during open windrow composting of contaminated sludge and straw, the results of which suggested both biodegradation and adsorption mechanisms (Amir et al., 2005).

Another field study (Hafidi et al., 2008) evaluated the fate of 16 PAHs during the composting of activated sewage sludge with green waste. The initial PAH concentration was 0.48 mg kg^{-1}, far below the accepted European Union limit for sludge to be considered safe for agricultural application: 6 mg kg^{-1}. After 90 days of composting treatment the concentration of the total PAH was 0.0173 mg kg^{-1}, a reduction of about 96.4% in comparison with the initial amount. The degradation rates were different according to the molecular weight and the number of benzene rings: naphthalene showed the lowest degradation (67.8%) and carcinogenic PAHs (benzo(a)anthracene, benzo(k)fluorantene and benzo(g,h,i)perylene) were not detected after composting. This result was explained by the presence of a wide range of microbial communities both in the activated wastewater plant and during composting.

5.3 BIODEGRADATION OF OTHER XENOBIOTICS BY COMPOSTING

During composting and digestion at full-scale plants, several currently used pesticides showed dissipation rates higher than 50% (Kupper et al., 2008). Several other studies have confirmed important biodegradation by the composting of pesticides such as diazinon, chlorpyrifos, isofenphos and pendimethalin (Lemmon and Pylypiw, 1992).

Composting was also effective in the degradation of triazine herbicides, whose half lives ranged form 5 to 15 days (Delgado-Moreno and Pena 2009).

Pentachlorophenol (PCP) contaminated soil was mixed with farm animal manure and composted under fully aerobic conditions. The disappearance and fate of PCP was monitored by gas chromatography and its mineralisation was confirmed in experiments with 14C-radiolabelled PCP. The disappearance of PCP was rapid and virtually complete within 6 days (Jaspers et al., 2002).

Relevant fates (range 69–91%) of ubiquitary hydrophobic xenobiotic pollutants such as linear alkyl benzene sulfonates (LAS), nonylphenol ethoxylates (NPEO) and di-ethyl-hexyl phthalate (DEHP) were observed during sewage sludge composting (Pakou et al., 2009).

Toxicological activities (estrogen receptor alpha, dioxin receptor and pregnan X) were measured in both wastewater biosolids and in the initial and final compost: oestrogenic activity increased whereas dioxin-like and pregnan X activities decreased (Patureau et al., 2008).

Bioremediation by composting may be enhanced by earthworm activity. Through a combination of direct and indirect earthworm effects such as the promotion of catabolically competent micro organisms and through earthworm biological, chemical and physical actions, earthworm-assisted bioremediation has been shown to be suited to a wide range of organic compounds.

A recent review presented and discussed a number of investigations that support earthworm-assisted bioremediation as a viable approach for the application to contaminants such as agrochemicals, crude oils, PAHs and PCBs (Hickman and Reid, 2008).

4. EMISSION FACTORS OF BIOLOGICAL AND THERMAL TREATMENTS WITH ENERGY RECOVERY

LCA does not take into account the local environmental impact of a specific industrial activity; in this case an environmental impact assessment is necessary and comparison of emission factors of different treatments may be useful.

A review of the environmental effects of waste managements and of their emission factors, was carried out by the Department for Environment, Food and Rural Affairs (DEFRA) of the UK (DEFRA, 2007). These data are useful to compare local impact of biological and thermal treatments, both with energy recovery. In this study, data on MBT and anaerobic digestion (AD) emissions are limited, notwithstanding the growing interest in these biological treatments and the many MBT plants built in Europe.

The best estimate of the DEFRA of emissions to air from MBT processes, shown in Table 2, are, from one German plant (Bassum) only, an AD (65,000 tonnes/yr) with the following treatments: separation of mixed unsorted wastes and digestion and aerobic stabilisation of the separated organic fraction. The produced biogas is used in a nearby energy utilisation plant to produce electricity. The flue gases from the biogas combustion are cleaned by selective catalitic reduction (SCR), activated coal filtration and thermal oxidation. After these treatments, the NO_x and CO concentrations are below 100 mg/Nm^3 and hydrocarbon concentrations below 50 mg/Nm^3. The emission factors from this MBT plant are shown in Table 1.

Table 2 also presents the emission factors of an anaerobic digestion (AD) plant with energy recovery. In this case the AD plant treats residual organics from a source-separated collection.

Mechanical pre-treatment removes metals, paper and plastic and the residual waste is sent to the anaerobic digester. Also, in this case the emission factor due the biogas combustion is estimated, assuming that the emissions are similar to those measured at an utilisation plant burning landfill gas. No information is given about exhaust gas treatments.

Much more information exists on incinerator emissions and some examples of emission factors from European incinerators are shown in Table 2; they confirm the considerable variation that can be observed in these plants and the possibility that, comparing plants treating the same PCM amounts, toxic emissions from MBT plants with energy recovery by biogas combustion may be lower than emissions from waste-to-energy incinerators.

6. DISCUSSION AND CONCLUSIONS

All reviewed LCA that, in their scenarios, have taken into account the production of national electricity mix to evaluate avoided electricity generation, confirmed that recycling is the best option to save energy, reduce climate altering emissions and reduce toxic environmental impacts; this result was obtained by LCA carried out in different geographical contexts (USA, Europe, China) and this make more robust this conclusion.

Incineration with energy recovery performs better than recycling if replaced electricity is produced only by coal power plants (PROFU 2004; Rigamonti et al., 2009). This assumption seems too limited; electrical grids are national and international connected, therefore to carry out a LCA it is more correct to refer to the average mix of electricity sources used in the studied country.

Conclusions of LCA that evaluated biological treatments are less clear (PROFU 2004; Rigamonti et al., 2009); for biodegradable wastes, composting and anaerobic digestion may be preferred if their output is of good quality and suitable for agricultural use (PROFU 2004, Hong et Al. 2006). For this reason more attention must be devoted to improving the detoxification capability of biological treatments towards organic contaminants, occasionally present in urban waste, in order to permit, without limitations, the agricultural use of compost obtained by biological treatments of biodegradable wastes.

Only one reviewed LCA included in its scenarios a MBT and landfilling of all biostabilised dry residue (De Feo, Malvano 2009) without any energy recovery. The scenario with 80% separate collection, no incineration, dry residue sorting and recycling was the most environmental sound option. It is an interesting result that deserves to be confirmed by a new LCA, comparing scenarios with more realistic percentage of separate collection and use of different MBT technologies.

The production of liquid fuel by chemical recovery of cellulose (Tan et al., 2009; Uihlein et al., 2009) and plastic fractions (Zhang et al., 2007) that can be separated by MBT from unsorted wastes need proper attention and a specific LCA to verify if these new technologies may be a solutions to recovery energy from wastes with low environmental impact.

Comparison of available emission factors (Table 2) suggests that MBT and AD, with energy recovery from biogas, may have a local impact lower then modern waste-to-energy incinerators, in relation to several air pollutants: NO_x, CO, SO_2, HCl, PCDD/F. It is possible that the best results obtained by MBT and AD are due to the low emission of natural gas, whose combustion it is intrinsically cleaner than solid waste combustion.

Further studies are recommended to estimate correctly the environmental impacts, on a local scale, of biological treatments, in particular MBT, in their several variants, with and without energy recovery, and confirm their lower impact, in comparison with incineration.

Table 1. Emission factors (gr/ton of PCM) of air pollutants from thermal treatments of waste: MBT, Anaerobic Digestion (AD) and European incinerators (UK, Austria, Belgium, Italy).

	MBT [1]	***AD*** [1]	***Inc UK*** [1]	***Inc AU*** [2]	***Inc B*** [2]	***Inc I*** [3]
NO_x	72.3	188	1600	189	2.141	303
CO	72.3	nd	nd	102	126	61
SO_2	28	3.0	42	24.8	129	12.1
PM	nd	nd	38	7	165	12.1
VOC	36	nd	8	nd	19	18
HCl	1.2	<0.047	58	4	70	12.1
PCDD/F **ng I-TEQ ton^{-1}**	40	nd	400	44.4	250	61

References : [1] (DEFRA, 2007); [2] (Joint Research Centre, 2005); [3] (Rigamonti et al., 2009)
nd: no data

Table 2. PCDD/F concentrations (pg/ Nm^3) along the air line of MBT biodrier plant of Montanaso Lombardo

Sampling data	Human-TCDD Equivalent (pg/m^3)			
	Ambient air	Before biofilter	After biofilter	RDF chimney
20 -25/ 11/ 2002	0.181	0.129	0.033	0.015
4 – 6 / 03 / 2003	0.094	0.044	0.036	n.a

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