Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes and of agricultural wastes

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Abstract In order to get more detailed information for better decision making in future biogenic waste treatment, different processes to treat biogenic wastes in plants with a treating capacity of 10'000 tons of organic household wastes per year as well as agricultural codigestion plants were compared by life cycle assessments (LCA). With the tool EcoIndicator, anaerobic digestion shows to be advantageous as compared to composting, incineration or combination of digestion and composting, mainly because of a better energy balance. AD of OFMSW shows an excellent LCA performance. The management of the liquid manure in agricultural digestion causes increased Ammonia emissions, which have negative effects on the LCA, however. It is recommended to cover the slurry pit and to use an improved manure management in order to compensate for the additional gaseous emissions. The quality of the digester output could only be taken into account to a small extent; the reasons are discussed.

Keywords anaerobic digestion, composting, incineration, organic fraction of municipal solid wastes, biogenic wastes, environmental impact study, methane emission, life cycle assessment, codigestion, agriculture

Introduction

AD produces precious products, such as renewable energy as well as a compost rich in nutrients and organic soil conditioners. But each technical process produces also undesired by-products while building, running and breaking down the plant, such as gaseous emissions or consumption of resources. This paper condenses the results of two large life cycle assessment studies: one comparing six different treatment technologies to treat the organic fraction of municipal solid wastes (OFMSW) including composting and incineration *(Edelmann, Schleiss, 2000)* and another one, dealing with the co-digestion of OFMSW in agricultural biogas plants *(Edelmann et al., 2001)*. Additionally, data are given on the quality of the remaining compost.

Method of LCA and of gaseous emission measurement

For the comparisons, the method "ecoindicator99" *(Pre consultants, 2003)* was applied. In both studies, data were derived from existing plants. Their treating capacities and the local conditions (such as soil properties, transport distances etc.) were standardized to identical sizes. For the energy need and for an eventual surplus, it was calculated with the mean electricity mixture of the European Communities (fossil, nuclear, hydro etc.) (*Frischknecht, 1996*).

A life cycle assessment (LCA) includes the steps as shown in figure 1: A description of each process includes the evaluation of the infrastructure needed, such as buildings, asphalt surfaces, machines, infrastructure for pre- and posttreatment etc. (investment of materials and energy). The materials needed to provide the treating infrastructure were divided by the span of their life time in order to obtain the yearly amounts of cement, metals, asphalt etc. necessary to treat a defined amount of waste (assumptions: life span for mobile machines: 5a, stationary engines: 10a, buildings: 25a). All processes, such as raw material extraction, distribution and manufacturing were included up to the moment of building, running and breaking down the plants. The ecological running costs of the plant included energetic and material parameters such as energy fluxes, parts replaced because of attrition, transports, commodities etc. as well as the emissions into air and into water caused by the process itself.

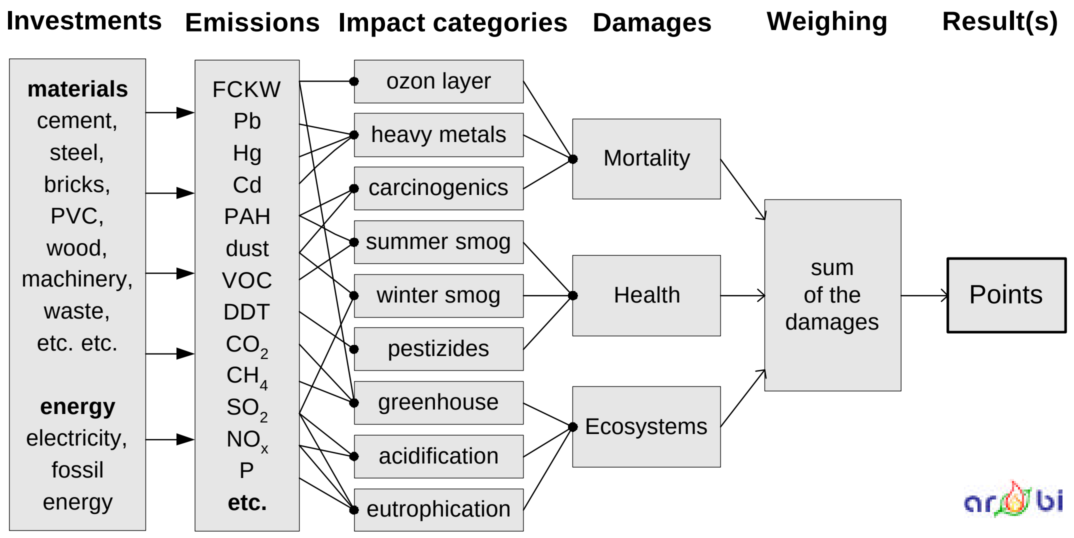


Fig. 1: Proceeding of a LCA (method Ecoindicator)

Materials and energy cause environmental impacts: The emissions to produce materials and energy for constructing, running and breaking down the plants (i.e. far over 100 impact factors) were quantified by taking data from ECOINVENT, a data base tool developed by Swiss Federal Institute of Technology, ETH (*Zimmermann, 1996*). These impact factors show effects on the impact categories (such as greenhouse effect, ozone layer depletion, acidification etc.) All impacts caused by the different activities of a waste treating process are first sorted and attributed to the relevant categories. For each damage category, a reference substance has been defined. The impacts are brought to a comparable size by multiplying with a factor corresponding to their relative damage potential (e.g. in greenhouse effect methane is weighted - depending on observation period - 21 times stronger than carbon dioxide, which is reference). Like this, effect scores can be normalized for each impact category.

The damages caused by the reference substances of each impact category are weighted for causing mortality, damage to health and ecosystem impairment. For damage weighting factors, subjective weighing is possible; in order to visualize the different scores depending on personal preferences, in EcoIndicator99 three typical profiles of persons with different preferences are defined. Here, the values for the so called „Hierachist“, who’s position is somewhat between an ecologist and an egocentric egoist, have been applied.

Only few data on methane emissions of composting sites are available. In order to get appropriate values, the gaseous emissions were measured three times over the year by the closed chamber method. Because the amount of degraded carbon is known (defined elementary composition and degree of dagradation), the moles of emitted carbon containing gas molecules could be calculated. Because CO_2 and CH_4 both contain just one carbon atom and have a similar volume requirement, it was possible to determine their total emissions, as soon as their relative ratio was known. For a more detailed description of the methods of LCA and of emission measurement see *Edelmann (2003).*

Comparison of OFMSW treatment plants

The first study compared six different technologies to treat 10'000 tons of biogenic wastes per year: **O**pen windrow **c**omposting (OC) as well as fully automated, **e**nclosed tunnel **c**omposting (EC), anaerobic **d**igestion with aerobic **p**ost-treatment (DP), combinations of **d**igestion with **o**pen (DO) and **e**nclosed composting (DE) as well as incineration in an **i**ncineration plant including exhaust gas **s**crubbing (IS; incinerating 10'000 tons of biogenic wastes together with a corresponding amount of “gray” waste in a plant with a treating capacity of 100'000 t/a). All basic data on biotechnological plants were derived from measurements on Swiss full size waste treatment plants (Sites of the plants: see annexe!). For incineration, it was calculated with the planning data of the most recent design of the plant of Thun. All data (emissions caused by infrastructure and plant running as well as ecological benefits) referred to treatment of 10'000 tons of fresh substance of biogenic waste per year (= "functional unit").

Figure 2 shows as an example the results of CO_2 and CH_4 emissions caused by composting and by the aerobic post-treatment while digesting, respectively. In digestion plants there is a considerable potential of methane emission during the "aerobic" post-treatment, even if just a small percentage of the organic breakdown takes place outside the digester. (The methane produced within the digester will be burnt to CO_2; CH_4 refers only to the amount generated after digestion). High methane emissions are caused by the intensive inoculation of the dewatered solid output with anaerobic bacteria. On the other hand, there exist also significant methane emissions even in pure composts, which are reversed very often (OC; reversed daily during intensive composting period, windrow height only 1.2 m !). The incineration plant emits no methane, but the double amount of gas in the form of CO_2 corresponding to the total oxidation of 100% of the carbon.

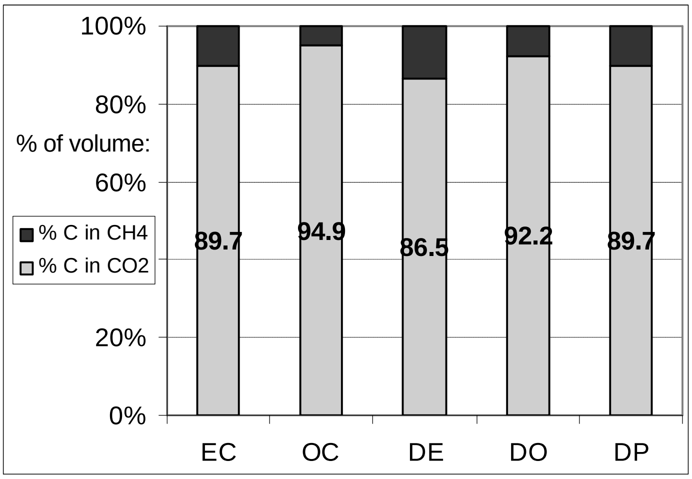
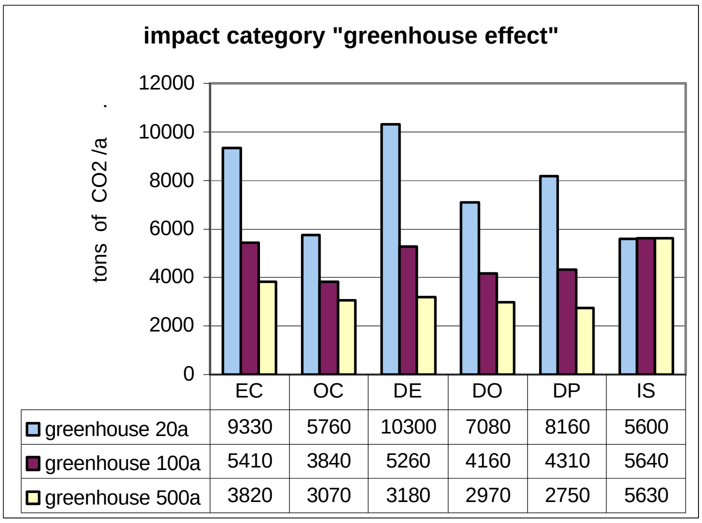


Fig 2: Ratio of CO_2 to CH_4 emissions of the composting (% of volume, weighted mean values of 3 campaigns). The graph shows the ratio of the total of the emissions, i.e. it was taken account of the fact that different percentages of the substrate were composted and/or digested depending on the technology applied. The methane generated by anaerobic digestion is counted as CO_2, because it will be oxidised while being burnt in the cogenerator.
(EC: 100% Enclosed automated Composting, OC: 100% Open windrow Composting, DE: combination 40% Digestion with 60% Enclosed composting, DO: combination 60% Digestion with 40% Open composting, DP: 100% Digestion with aerobic Post treatment)

The effects of all greenhouse gas emissions during construction, plant running, demolition and ash dumping (IS) are shown in Figure 3 (EI-points of impact category greenhouse gas). At the first sight it is surprising, that all biotechnological treatments show at short time (after 20 years) higher impacts than incineration, which sets free more CO_2 because of total oxidation of the waste. This is mainly due to methane emissions of the compost and/or the "aerobic" post treatment of digested matter. Because of slow photo-oxidation and biological degradation of methane within the atmosphere, the negative effect on global warming decreases only after 100 (default value) and 500 years respectively to values significantly better than incineration.

Figure 4 shows the final result for the different treatment methods: Sensitivities were calculated to quantify the influences of gaseous emissions into air, of the benefit by inorganic nutrient savings while recycling compost and of washing out heavy metals from compost into surface water. The dark sensitivity (left) is the default value.

From an ecological point of view, anaerobic digestion with an aerobic post-treatment shows by far the very best performance with all sensitivities of Ecoindicator, followed by digestion combined with enclosed composting and digestion combined with open composting. Pure open composting shows environmental impacts similar to incineration. Highest impacts with most of the sensitivities are caused by fully enclosed tunnel composting.



	EC	OC	DE	DO	DP	IS
▨ greenhouse 20a	9330	5760	10300	7080	8160	5600
■ greenhouse 100a	5410	3840	5260	4160	4310	5640
□ greenhouse 500a	3820	3070	3180	2970	2750	5630

Fig. 3: Scores of total greenhouse gas emissions per 10'000 t of waste/a (converted corresponding to the damage potential into CO_2) after 20, 100 and 500 years, respectively.

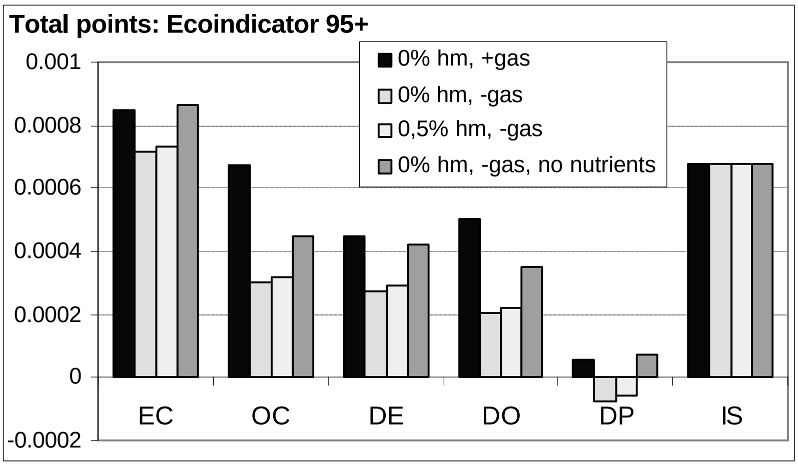


Fig 4: Total sums of ECOINDICATOR 95+ points for different sensitivities: +/- gas: influence of emission of NH_3, N_2O and H_2S into air; no nutrients: no benefit for fertilizer substitution; 0/0,5% hm: influence of heavy metal export from soil by water.
For incineration, no sensitivities were calculated, because not the same sensitivities are relevant as for biotechnological processes. For more details on incineration, see Hellweg (1999).

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Energy plays a predominant role while comparing the technologies: Taking into account the primary energy for construction and running of the plants, i.e. including all loses from the moment of extracting crude oil or Uranium, as well as the substitution of nuclear and fossil energy by renewable biogas, there is a energy difference as huge as 700 kWh/ton comparing anaerobic digestion (DP) with fully enclosed tunnel composting (EC). Compost contains nutrients such as N, P and K. If no compost is produced (IS), the energy demand for producing an equal amount of mineral fertilizer equals nearly 90 kWh/t. The non-renewable energy causes large environmental impacts in most of the impact categories, especially for treating technologies which show a high energy demand for plant running (and construction). Mainly for this reason, fully enclosed composting shows highest environmental impacts. Open technologies cause high gaseous emissions into the air, such as ammonia escaping from the windrows. Emissions of ammonia may be drastically reduced in enclosed technologies equipped with biofilters. Thus, open technologies are not suited for waste containing kitchen refuse, because of bad odours and ammonia emissions.

Comparison of agricultural (co-)digestion plants

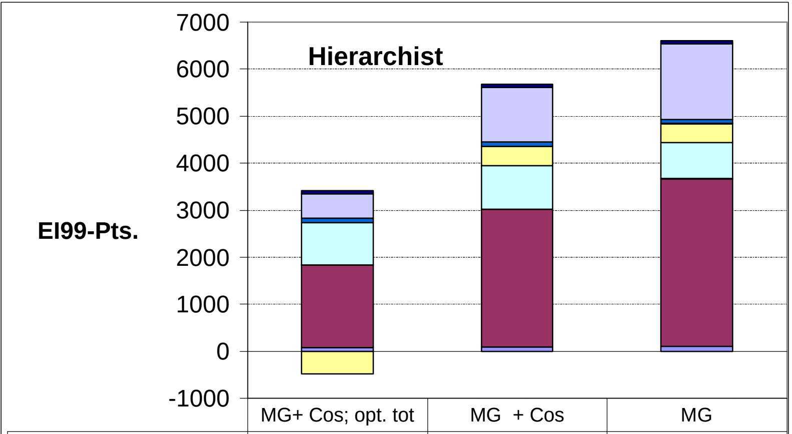
In the second study, different combinations of biogas production in agricultural plants including codigestion of OFMSW were calculated: Different digester construction materials (cement, steel or wood) were compared with different substrates (pig or dairy manure, respectively a mixture of both, eventually combined with the addition of co-substrates). The amounts of the emissions were varied by different technical assumptions (reduction of ammonia emissions by improved manure handling; capture of biogas generated in the storage tank by covering it with a plastic membrane in order to reduce CH_4 and N_2O-emissions; use of different motor technologies for electricity generation). The calculation of sensitivities allowed an accurate discussion of the parameters important in the context of this LCA. In this study, the functional unit was the generation of 1 TJ electricity by burning biogas in a cogenerator. Biogas production was compared to ordinary storing of undigested manure, i.e. only surplus emissions caused by anaerobic digestion were taken into account.

The amounts of CH_4, N_2O and NH_3-emissions may vary considerably depending on many factors. At the same time, these gaseous emissions show to have a very large influence on the LCA result: ammonia surplus emissions of the slurry while being stored and brought out to the fields count for over 50% of the environmental impact. The amounts of these emissions depend on factors such as: feeding diet of the animals, water use on the farm, kind of storage tank (covered/uncovered), type of soil, manure management etc.. Simultaneously, the bacteria producing undesired gases depend on a variety of abiotic factors such as soil conditions, climate, availability of oxygen and water, availability of organic matter etc.. Despite of these uncertainties, the following statements seem to be accurate:

- Modern agriculture, especially the storing and bringing out of animal manure, is very polluting and responsible for the main parts of global CH_4, N_2O and NH_3 emissions.
- While producing biogas, especially the emissions of ammonia are increased: anaerobic digestion increases the degree of organic matter degradation and hence the mineralisation of nitrogen. More ammonium-ions at simultaneously higher pH-levels (0.5 – 1 units) cause higher concentrations of free ammonia and thus higher emissions.
- CH_4 and N_2O-emissions are reduced considerably, if covering the storing tank by a plastic device, taking simultaneously profit of the biogas generated in the storage tank. This improvement compensates for a large part of the surplus emissions caused by biogas production.
- Ammonia emissions may be reduced considerably by applying manure with accurate methods at good meteorological conditions. If a farmer changes its manure management, the savings may be up to 2-3 times larger than the additional environmental impact caused by biogas production. The undesired ammonia emissions may be reduced specially, if the manure is applied directly to the soil by a trailhose or by a similar device.

Therefore, from an environmental point of view, it has to be recommended to cover the storage tank in order to reduce CH_4 and N_2O-emissions and to bring out the digested manure as carefully as possible. No significant difference between the construction materials steel and cement was found. Wooden digester walls *(Egger, 1992)* will save nearly 98% of the impacts in comparison to walls out of cement or steel; the savings by using wood are about 20% of total infrastructure costs. (However, the impacts caused by infrastructure are significantly smaller than those by plant running).

No large difference was observed comparing pig and cow manure; the impacts per amount of electricity generated are comparable (swine manure sets free more ammonia, but also more electricity). There was hope that codigestion shows a positive effect on environmental impacts because of better infrastructure utilisation (digester, devices for gas use etc.). In the standard variant, 12,5 m^2/d of a manure mixture were digested in a fermenter of 300 m^3. The effect of adding 2 m^3/d of biogenic solid wastes was calculated. However, as shown in Figure 5, electricity generation by codigestion turned out to be just around 15% less polluting than digesting a mixture of swine and cow manure alone. This is due to the facts that there is additional nitrogen import into the digester as well as additional pollution because of longer transport distances.



	MG+ Cos; opt. tot	MG + Cos	MG
■ Land Use	76	79	64
■ Acidifi- & Eutrophication	513	1150	1620
■ Ecotoxicity	98	101	85
■ Ozone Depletion	1	1	1
■ Greenhouse Effect	-471	405	407
■ Res. Surplus Energy	889	923	755
■ Ionising Radiation	7	7	9
■ Respiratory	1750	2930	3560
■ Carcinogenics	84	88	106

Fig. 5: Impacts in different categories of generation of 1 TJ electricity by digestion of i) a mixture of cow and pig manure + 2 m^2 cosubstrate/d with optimisation of manure handling (MG + Cos; opt. tot.), ii) Mixture + cosubstrate and iii) mixture alone.

Comparing codigestion including optimisation (Fig. 5, left) to that without (centre), the advantages of optimised manure management appear to be evident: By covering the storage tank with a gas tight device in order to recover the methane and N_2O-emissions, the greenhouse effect turns to a negative value; i.e. more greenhouse gas emission is avoided by substituting for fossil fuels than is generated by building and running the plant as well as by methane emissions from manure handling. Acidification and eutrophication of the environment as well as impacts on the respiratory tract are significantly reduced by using a trailhose instead of sprinkling the manure out to the field. By covering the storage tank and handling the digested output in a gentle manner, the total impacts are reduced by nearly 50% (2947 vs. 5684 EI-pts.)! (For more detailed information – e.g. on performance of different types of cogenerators – see *Edelmann et al., 2001*).

Quality of digested organic matter

Today, general criteria for definition as well as methods for determination of the different compost qualities are still missing on an international level, as already stated in *IEA (1997)*. However, the solid and liquid outputs of anaerobic digestion are considered to show different advantages in comparison to untreated manures and wastes (*Klingler 2000; Ortenblad 2000*). Digested slurries may be used directly in agriculture. However, for solid matter an aerobic post-treatment is recommended in order to improve further the quality of the digester output.

Compost and manure qualities could not be taken into account adequately – except fertilizer savings by recycling macro-nutrients - because precise, quantifiable data on additional advantages of digested matter are missing. Digested organic material shows advantages in different categories, such as increased availability of nitrogen for plant growth (if applied properly), significant reduction of bad odours because of volatile carbon compound degradation, avoidance of plant burning by high acid concentrations, increase of diversity of soil biocenoses and hence of fodder quality, hygenisation and killing of weed germs. suppression of phytopathogens (by antibiotics released by microorganisms during aerobic treatment), increase of water and nutrient retaining capacity of the soil, improved manure fluidity and handling because of homogenisation, increased degradation of toxic organic compounds such as pesticides etc.. Compost and digested manure are not only sources of macro- and micronutrients, but also important soil conditioners supplying the soil with recalcitrant carbon compounds, which are important for humus formation and for compensation of humus losses of modern agriculture. If taken into account in a LCA, all these factors would favour for a still significantly better ranking of biotechnological solid waste treatment.

Heavy metals are not problematic while digesting: In agricultural digestion, the quantity of heavy metals brought out to the fields is identical whether digesting or not. The heavy metal content of separately collected OFMSW is very low practically without exception. Own data of more than 1’000 (aerobic and anaerobic/aerobic) compost samples show in general values of (significantly) less than half of the (low) Swiss limits (mg/kg dry matter: Pb: 120, Cr: 100, Ni: 30, Zn: 400, Cu: 100, Hg: 1, Cd: 1; *Bundeskanzlei 1986*).

Even with so called dry anaerobic digestion processes, some surplus water is generated by the solid/liquid separation after digestion. The quantity of surplus water depends on the substrate properties, on the digestion technology applied and on the dewatering technology. Table 1 shows the composition of some liquids of dry digestion processes. The liquid is rich in nutrients and DM. The heavy metal contents (ppm) are higher than in the compost, but do not reach the low limits given by the law. The content of inorganic nutrients limits its agricultural application, because in several European countries the farmers are obliged to obey the maximal limits of nutrient import per surface. In Switzerland, such liquids are approved as soil conditioners and fertilizers for use in “Bio”-agriculture, where very strict limits for toxic substances are existing.

General parameters	**dry matter**	**org. matter**	**pH**	**C/N**	**NH_4-N**	**N-Min**
13 samples	% FM	% DM			kg/t DM	kg/t DM
Average	14.2	44.8	8.2	10.2	11.24	11.25
Standard deviation	2.9	4.4	0.2	1.1	4.81	4.81

Macro-Nutrients	**N-tot**	**P_2O_5 (tot.)**	**K_20 (tot.)**	**Ca (tot.)**	**Mg (tot.)**
13 samples	kg/t DM	kg/t DM	kg/t DM	kg/t DM	kg/t DM
Average	21.0	12.8	31.6	36.4	9.7
Standard deviation	3.6	1.6	6.5	7.8	0.8

Heavy metals	**Cd**	**Cu**	**Ni**	**Pb**	**Zn**	**Cr**	**Hg**
13 samples	g/t DM	g/t DM	g/t DM	g/t DM	g/t DM	g/t DM	g/t DM
Average	0.62	77.9	28.2	59.5	269.7	36.7	0.18
Standard deviation	0.10	6.3	6.7	21.9	29.0	8.2	0.06

Tab. 1: Typical composition of liquids after solid/liquid separation of source separated OFMSW treated by thermophilic digestion. FM: fresh matter, DM: dry matter

Conclusions

For selling Swiss “Naturemade-Star” eco-electricity (www.naturemade.ch), LCA’s are required. AD of OFMSW results to show the very best LCA of all renewable energies (wind, photovoltaic, water etc.) *(ESU-services, 2000)*. However, if the OFMSW is codigested in agricultural plants, covering of the manure storage tank and/or the use of a trailhose is required to fulfil the severe prerequisites of “Naturmade-Star” electricity.

Digestion plants are better from an ecological point of view, mainly because they don't need external fossil and electric energy. Aerobic breakdown takes place in nature only, if there are thin layers of organic matter, where both oxygen and water have easy access. That's why composting - such as done by man - is *not* a "natural" process: When organic matter is piled up to high heaps, the anaerobic digestion is the natural pathway. Therefore technical composting needs external, non renewable energy for turning the windrows and/or for artificial aeration, i.e. for forcing air to enter into the compost. However, the solar energy fixed in biomass escapes in the form of waste heat. Anaerobic digestion, on the other hand, sets the solar energy free for the needs of man.

The results strongly recommend to treat in future as much material as possible by the anaerobic way. It seems to be reasonable to adapt the national laws on waste management in favour of anaerobic digestion (as already happened in some Swiss states; *Kanton Zürich, 1983, 1994*). This will, on the one hand, allow an ecologically safe waste management and, on the other one, save money in a medium term, mainly by reducing incineration plant capacity and by reducing environmental costs as well as by generating a sustainable energy supply.

Literature

Bundeskanzlei(1986) *Verordnung über umweltgefährdende Stoffe, StoV*, EDMZ, CH-3003 Bern

Edelmann W., Schleiss K. (2000): *Ökologischer, energetischer und ökonomischer Vergleich von Vergärung, Kompostierung und Verbrennung fester biogener Abfallstoffe*, final report, BFE/BUWAL, BFE, CH-3003 Bern (118 pages)

Edelmann W., Schleiss K., Engeli H., Baier U. (2001): *Ökobilanz der Stromgewinnung aus landwirtschaftlichem Biogas*, final report, BFE Bern (95 pages)

Edelmann W. (2003): Products, impacts and economy of anaerobic digestion of OFMSW, in : J. Mata-Alvarez (ed.): *Biomethanization of the organic fraction of MSW*, IWA Publishing, ISBN 1 9002222 14 0, London, pp.265-302

Egger K. (1992): *Biogasanlage aus Holz*, Die Grüne, 22/92, pp.26-29

ESU-services (2000): *Globale Umweltkriterien für Ökostrom*, VUE, Zürich http://www.naturemade.org/common/texted_zertifizierung/Stromlabel_7.2000.PDF

Frischknecht R. (1996): *Ökoinventare von Energiesystemen*, ISBN 3-9520661-1-7, ENET, Postfach, Bern dritte, überarbeitete Auflage) (Data on CD-ROM)

Hellweg S. (1999): Life cycle assessment of thermal waste processes, in: *Proceedings of R99*, Feb. 1999, Geneva

IEA (1997): *Development of a protocol for assessing and comparing the quality of aerobic composts and anaerobic digestats*, Bioenergy AD activity, International Energy Agency

KANTON ZÜRICH (1983): *Energiegesetz*, Zürcher Gesetzessammlung, Loseblattsammlung (LS), Staatskanzlei Zürich, 19.6.83 (including changes, version 3.99)

KANTON ZÜRICH (1994): *Gesetz über die Abfallwirtschaft (Abfallgesetz),* Zürcher Gesetzessammlung, Loseblattsammlung (LS), Staatskanzlei Zürich, 25.9.1994 (including changes, version 3.99)

Klingler B. (2000): Environmental aspects of biogas technology, in: AD-Nett (ed): *AD: Making energy and solving modern waste problems,* Ortenblad H., Herning municipal utilities, Denmark, pp. 22-33

Ortenblad H. (2000): The use of digested slurry within agriculture, in: AD-Nett (ed): *AD: Making energy and solving modern waste problems,* Ortenblad H., Herning municipal utilities, Denmark, pp.53-65

Pre Consultants (2004): Internet www.pre.nl

Zimmermann P. (1996): *Ökoinventare von Entsorgungsprozessen: Grundlagen zur Integration der Entsorgung in Ökobilanzen*, ISBN 3-9520661-0-9, ENET, Postfach, Bern

Annexe:

In the LCA's, data were derived from the following full size plants:

DP: KOMPOGAS plant, Otelfingen, ZH, Switzerland www.kompogas.com
DE: Allmig plant, Baar, ZG, Switzerland http://www.alfred-mueller.ch/de/dienstleistungen/ka.asp
DO: RomOpur plant, Frauenfeld, TG, Switzerland http://www.rom.ch/anlagen_plan_d.html
EC: KEWU plant, Krauchtal, BE, Switzerland
OC: Gerber plant, Fehraltdorf, ZH, Switzerland
IS: Incineration plant of Thun, BE, Switzerland http://www.avag.ch/kva/

Agricultural plant metal: Lipp design http://www.lipp-system.de/
Agricultural plant cement: Böhni design http://www.euu.ch/
Agricultural plant wood: own design (Züger, Galgenen) http://www.arbi.ch/entwickl.htm