Evaluation of different biological waste treatment strategies

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Abstract

Biological treatment of organic waste by aerobic composting and anaerobic digestion (biogas production) was compared with respect to a number of environmental effects and sustainability criteria including energy balance, nutrient recycling, global warming mitigation potential, emission of xenobiotic compounds, and economy. The parameters were assessed based on case studies in the literature as well as our own research. Assessment of energy balance, nutrient recycling, and global warming came out in favour of biogas production, but especially the results regarding estimation of global warming mitigation differ from the assumptions made. Our calculations show that a fugitive loss of approx. 14% of the biogas produced by anaerobic digestion will turn the scale in favour of composting regarding global warming mitigation. In Europe actual biogas losses from 3.5 to 8.4% are reported, but this may be exceeded in developing countries. Regarding emission of xenobiotic compounds composting is much in favour, as recent experiments show that a number of organic micro-pollutants are rapidly degraded during composting as opposite to anaerobic treatment. In most cases composting is more cost-effective compared to biogas production, but estimations of actual costs differ considerably. Published results of Life Cycle Assessment of organic waste management using the ORWARE model showed biogas production to have less environmental impact in general than composting, but it was demonstrated that changes in e.g. system boundaries or functional units may result in substantial differences on the conclusions as well. In conclusion, the optimum waste planning strategy may be the implementation of an integrated waste treatment system operating with different scales of composting and anaerobic treatment, depending on local conditions.

Keywords: Composting, biogas, anaerobic digestion, environmental effects, global warming, xenobiotics, energy, system analysis.

Introduction

Biological treatment of organic waste is an age-old practice that in relation to municipal solid waste has had a strong revival during the last decade. This is due to increased efforts to improve recycling of nutrients and organic matter to soil and in particular to minimise landfilling of biodegradable waste to reduce emission of greenhouse gases. In addition, special attention is given to the possibility of utilising the energy liberated during microbial decomposition of organic matter. Thus, the ultimate objective of biological waste treatment is to optimise the resource and energy use and simultaneously minimise the environmental impacts at the lowest possible investment and operational costs. The ideology behind this is supported at the highest political levels, e.g., the European Commission has recently proposed a directive with the intent of making biological waste treatment obligatory within the next few years.

Biological waste treatment can be carried out in two principally different ways: by anaerobic digestion, i.e. biogas production, or by composting. In industrialised countries biogas is traditionally produced in high-tech plants with a capacity of processing many thousands tons of waste per year. This is not always the case in developing countries where small-scale low-tech biogas plants may dominate. Composting is a more or less controlled aerobic microbial decomposition process that, in industrialised countries as well, is organised at very different scales and technological levels, from a simple heap or bin in the backyard to high tech in-vessel systems of very large capacities.

A generic assessment of functional differences between biological waste treatment systems is a difficult but important task as foundation for political decision making. Political reflections are most commonly made on a few, simple scenarios, if any at all. A more comprehensive background for implementing new waste systems can be generated by system analysis. Systems analysis including modelling to compare different biological treatment strategies has been practised in Sweden for some years. The ORWARE model (e.g. Dalemo, 1999, Sonesson, 1998) has been developed to evaluate environmental effects and energy turnovers for different biological waste treatment systems aiming at recycling as many nutrients as possible to arable land. Systems analysis, though, is vulnerable to lack of relevant data. Thus, data might origin from malfunctioning treatment plants or they may be totally lacking, so that assumptions have to be made. Other factors of great importance are the definition of system boundaries, functional units, and supplementary production.

The aim of the present study is to evaluate and compare different biological waste treatment strategies with respect to various parameters including energy balance, nutrient recycling, environmental impacts, and economy. This is done based on a literature review of individual case studies supplemented with data from our own studies on degradation of xenobiotic compounds during composting. In addition, some of the published results of the ORWARE model are discussed.

Evaluation of strategies based on case studies

Energy balance

At the technical level of today it is not possible in practice to utilise the energy generated during the composting process in other ways than to accelerate the microbial process itself and to sanitise the waste during the process. Biogas production should therefore - isolated seen - result in a better energy balance than composting independent of how the energy is utilised.

Another aspect of the energy balance is related to transportation. Urban ecologists, environmental grass roots, and others often point to the energy consumption and the emissions related to the transport work. Nevertheless, the energy consumption from waste collection and transportation of endproducts is in general of minor importance compared to other effects of the waste system including the energy production from biogas plants (or incinerators) (Sonesson, 1998). For example, within a distance from sources to plant of up to 50 km, energy used for transport constitutes only 12-16% of the energy produced (Börjesson, 1997). Also the environmental impacts from transportation are of minor importance in relation to the impact of the whole waste treatment system. Minimising transport seems more important for lowering costs, accidental risks, and noise effects (Sonesson, 1998).

Nutrient recycling

Compost is generally more stabilised than the anaerobic residues. Therefore, it is also more attractive (both in relation to appearance and odour) and easier to apply to the soil, at least for laymen. The water-soluble nitrogen concentration is higher in the anaerobic digestate, but loss of ammonia during spreading and immobilisation of nitrogen in the soil afterwards result in a smaller difference in fertiliser effect than reflected by the product declarations. Furthermore, some of the organically bound nitrogen in compost is mineralised after applying the compost to the soil (Thomsen and Olesen, 2000).

Environmental impacts

Global warming potential from greenhouse gas emission

Mitigation of greenhouse gas emission is one of the main reasons for diverging organic waste from landfills to biological treatment facilities. The following calculations are, therefore, carried out in some detail.

In theory, anaerobic digestion as well as composting reduces greenhouse gas emission by 100% compared to landfilling of organic waste. Another aspect of greenhouse gas mitigation is the replacement of fossil fuel by the produced biogas: The net energy gain from biogas production can be estimated to 2000 MJ t^{-1} waste (Anon., 2000). Using a conversion factor of 77 kg of CO_2 released per GJ of energy produced from oil (IPCC, 1996), the substitution of fossil fuel thus corresponds to 154 kg CO_2 equivalents t^{-1} of waste. To achieve this, CH_4 must be totally converted to CO_2 during energy production, but it has been estimated (Danish EPA, 1997) that an average of 3.5% of the produced fuel is lost to the atmosphere as fugitive emissions due to incomplete combustion or leaks in biogas engines. This is in contrast to Dalemo (1999) who, based on older data, estimates the fugitive emission from biogas engines to 0.10 g CH_4 MJ^{-1} corresponding to 4.2 kg CO_2 equivalents t^{-1} of waste. Assuming an average biogas production from organic waste of 120 Nm^3 t^{-1} with a CH_4 content of 65% (Anon., 2000) a 3.5% loss will constitute approx. 2 kg CH_4 t^{-1} of waste. This corresponds to 42 kg CO_2 equivalents t^{-1} if the 100 year conversion factor of 21 for CH_4 (Ayalon et al., 2000) is used. As a consequence, the total greenhouse gas mitigation effect of biogas production – assuming a 3.5% loss - constitutes 154-42 = 112 kg CO_2 equivalents t^{-1} of waste.

The above mentioned gas loss of 3.5% from biogas combustion is calculated for state-of-the-art combustion engines, but this type of equipment may not always be at hand, especially in developing countries. As an example, the Indian state Himachal Pradesh has installed more than 35,000 biogas-plants at small farmers from 1982 to 1995 (Singh et al., 1997). In 1995 less than 50% of the plants were working due to incorrect handling, lack of maintenance and spare parts, etc. Presumably, the gas loss from this type of plants and the corresponding biogas engines vastly exceeds 3.5% and will, therefore, constitute a significant contribution to the total green house gas emission from India.

Cumby et al. (2000) measured fugitive biogas loss from digesters on farms in the UK and found losses from 3.4 to 8.4% of the produced CH_4. Thus, the above mentioned fugitive loss of 3.5% from biogas engines may be an underestimation of the actual loss, at least in farm-based systems.

Data on methane emission from composting of MSW are scarce, but Hellmann et al. (1997) measured CH_4 emission rates between 0 and 1,400 mg CH_4-C hour^{-1} t^{-1} (dry weight) of waste during windrow composting of MSW mixed with yard clippings. Using an average emission rate of 700 mg CH_4-C hour^{-1} t^{-1} of waste for a duration of 25 days (the period where CH_4 emission was detected) this corresponds to a total emission of 0.56 kg CH_4 t^{-1} of waste. Converted to fresh weight basis CH_4 emission from composting of MSW can thus be estimated to 0.22 kg CH_4 t^{-1} of waste corresponding to 4.6 kg CO_2 equivalents t^{-1}of waste.

It has to be stressed that another greenhouse gas, N_2O, can be emitted during composting, but according to Hellman et al. (1997) the emission rate of this gas was much lower than the emission rate of CH_4. Performing the same calculation as for CH_4 we estimate the emission of N_2O in this particular case to 0.025 kg N_2O t^{-1} of waste. The global warming potential of N_2O is 310 times that of CO_2, thus the greenhouse effect of N_2O emission from composting was 7.8 kg CO_2 equivalents t^{-1}of waste. The combined greenhouse effect of MSW composting from CH_4 and N_2O emission thus corresponded to approx. 12 kg CO_2 equivalents t^{-1}of waste.

The above calculations are based on one specific case of windrow composting of MSW reported in the literature. Another approach to estimate greenhouse gas emission from composting is to use general conversion factors related to the amounts of C and N initially present in the waste. Beck-Friis (2001) supplies general information on greenhouse gas emission from the composting process and cites estimates of CH_4 and N_2O emission levels of 1 and 0.5% of the C and N initially present. Using typical values of C and N content of source separated MSW (Smårs et al., 2001) this corresponds to a greenhouse gas emission of CH_4 and N_2O of 34 and 17 kg CO_2 equivalents t^{-1}, respectively, which adds up to 51 kg CO_2 equivalents t^{-1} of waste. This is more than four times the emission calculated from the results presented by Hellmann et al. (1997) underlining the uncertainty associated with estimation of greenhouse gas emission from composting.

In conclusion, biogas production has a larger mitigation effect on greenhouse gas emission than composting largely due to fossil fuel substitution, but loss of CH_4 during the utilisation of biogas may alter this. Compared with composting, the break-even point is reached at an emission of approx. 154 (fossil fuel substitution from biogas)+12 (low estimate of net greenhouse gas emission from composting) = 166 kg CO_2 equivalents t^{-1} of waste from biogas production equalling approx. 14% loss of the produced biogas to the atmosphere. This can probably be avoided in industrialised countries, but the more low-tech solutions that are being promoted in developing countries can diminish the global mitigation effects.

Xenobiotic compounds

A prerequisite for utilising the endproducts from biological treatments is the absence of xenobiotic compounds in concentrations that will make the product unsafe for man and the environment. Regulation in Denmark prevents use of waste products in agriculture if one of the following four types of organic micro-pollutants are present in concentrations exceeding the stipulated limits: the plasticiser DEHP, the detergents LAS and NPE, and the sum of nine PAHs (Danish EPA, 2000). It is worth noticing, that the regulation is based on the concentration of pollutants in the raw waste, but this issue is presently being debated and some exemptions based on the concentration in the endproduct have been given by the authorities.

A number of reports have focused on biological degradation of xenobiotic compounds during composting as well as on production of biogas. Under anaerobic conditions - biogas production – complex organic molecules are generally recalcitrant. Examples are the incomplete anaerobic degradation of NPE leaving the aromatic ring structure of the ultimate degradation product intact (Ejlertsson et al., 1999) and the persistence of DEHP in anaerobic sewage sludge (Battersby and Wilson, 1989). In contrast, composting increases degradation of organic micro-pollutants. Thus DEHP and LAS were degraded to safe levels in less than two weeks by composting of MSW and sewage sludge, respectively (Møller et al., in press, Møller and Reeh, submitted). NPE and PAH were also degraded, but at slower rates than the former compounds. Composting thus has a clear advantage over biogas production with respect to degradation of xenobiotic compounds.

Recently, a Swedish investigation has documented the presence of another group of organic micro-pollutants in waste products: a number of pesticides, the use of which is not allowed in Sweden, were found in compost and anaerobic sludge made from the same waste (Nilsson, 2000). Ongoing investigations focus on the possibility of optimising the composting process to promote degradation of these types of compounds.

Economy

Table 1 shows examples of calculations of financial costs of waste treatment by composting and biogas production, respectively. In three of the four references biogas production comes out as the more expensive treatment, but there is no agreement on the actual costs or on the relative differences between the cost of composting and biogas production. Eriksson et al. (in press) have used the ORWARE model to calculate the financial cost of organic waste treatment in the community of Älvdalen. Here composting proved to be marginally more expensive than biogas production. Consequently, there is no overall agreement of financial cost, but in most cases composting is estimated to be the more cost-effective strategy.

Table 1 Examples of financial costs associated with treatment of organic waste by composting and biogas production

Cost of treatment of 1 ton of waste		
Composting	**Biogas production**	**References**
800 DKK (Windrows)	1,740 DKK (High solid anaerobic digestion process). Gas sold for energy production)	Anon., 2000
1,956 SEK (Windrows)	1,887 SEK[2] (Gas used in busses)	Eriksson et al., (in press)
339 DKK (Aerated windrows)	348 DKK (Gas sold for energy production)	Danish EPA, 1997
0.58 USD[1] per ton CO_2 equivalents mitigated. (Windrows)	2.59 USD per ton CO_2 equivalents mitigated (Gas flared)	Ayalon et al., 2001

1 One USD=8 DKK.
2 One SEK=0.80 DKK

Need for end-use area

True recycling of organic waste will always demand enough acreage so that the amount of nutrients in the processed waste can be utilised in an environmentally sound manner, i.e., minimising leaching and emission and maximising plant uptake. Therefore, the most successful Danish biogas plants today are run in close co-operation between municipalities and groups of farmers in the vicinity of the plant. The farmers then guarantee to take the end-product and spread it on their farmland in accordance with the national legislative guidelines, i.e. a maximum application rate of 170 kg N ha^{-1}, 30 kg P ha^{-1} or 7 ton dry matter ha^{-1}. Similarly, multifamily dwellings must have enough amenity areas to spread locally produced compost. According to the same guidelines, there should be at least 10 m^2 of green area available per dweller to recycle the composted vegetable fraction of the household waste, an area that can be reduced proportionally according to the achievable collecting efficiency (Reeh, 2001).

Normally, purchasers of biogas residues are taking big bulks of material using large vehicles, often on a regular basis. On the contrary, more than half of the Danish compost production is disposed of using passenger cars or small vans by private garden owners. These aspects are important for the amount of transport labour associated with composting and biogas production, but the quantitative consequences are difficult to estimate.

Control of incoming waste and quality of endproducts

Quality control of incoming waste seems increasingly needed the bigger and more technically advanced the plant becomes, irrespective of whether the processing method is aerobic or anaerobic. In some ways, pre-control of incoming waste is easier to organise, but when it comes to identification of contaminating sources and prevention the difficulties arise. In this respect, local and especially home composting is in favour. Most home composting households will be very motivated to sort their biodegradable waste correctly since they are going to use the resulting compost themselves. In case of any wrong sorting the persons responsible can easily be identified and corrected. Thus compost produced at, or near the source, has in general a lower content of visible inerts and heavy metals than compost form centralised plants (Reeh, 2001).

Educational potential

Since composting is more easily downscaled compared to biogas production, composting systems can be placed close and visible to the public and therefore demonstration of the process and engaging people in recycling of organic waste can be accomplished. Moreover, due to the aerobic nature of the composting process, visitors to composting plants are able to experience the process at closer quarters than at biogas plants where the material have to be enclosed to maintain anaerobic conditions. Home composting, in particular, offers the possibility to convey a "hands-on" experience to children as well as adults regarding recycling of organic waste.

Evaluation of strategies based on system analyses: the ORWARE model

The ORWARE model uses a Life Cycle Assessment methodology and categorises some consequences of emissions in impact categories: Global warming, eutrophication, acidification, photochemical oxidants, and human health (not including working environment).

As expected, the ORWARE model in every case turns out with a better energy balance for biogas than composting, while the results regarding nutrient balance and especially the environmental impacts are more ambiguous.

Sonesson (1998) explains how in a first approach (in-vessel) composting came out with the least total environmental effects of the modelled treatment scenarios. Biogas production resulted in equal or nearly as low effects only with respect to global warming and eutrophication potential. With respect to nutrient recycling, the biogas- and composting scenario showed equal effects on phosphorus while biogas production turned out slightly better regarding nitrogen. As described elsewhere it is very important to include the spreading procedure and the soil-plant system when evaluating the degree of recycling of nutrients.

In a later study, also presented by Sonesson (1998), the boundaries/functions of the model were widened to include co-digestion of animal manure from an area in the surroundings of the city in question as well as fuelling busses with methane. The optimal treatment method then moved in favour of anaerobic digestion compared to composting. Thus global warming potential, acidification, and the recycling ratio of both nitrogen and phosphorus were in favour of biogas production. Still composting resulted in lower emissions of photochemical oxidants while the eutrophication effects were of similar size.

Conclusion

Functional differences between organic waste treatment systems based on composting compared to anaerobic digestion seems to be small in many aspects. In fact, differences between systems with the same kind of waste treatment principle might be bigger. The differences may reflect specific local conditions, such as the degree of public participation in source separation schemes, the actual design of the plant in question, the access to farm yard manure, and the access to district heating systems.

Using system analysis, preference of one treatment method to another can actually change with changes in system boundaries, including functional units and supplementary means of production. Still a detailed systems analysis seems to be an excellent tool to understand the consequences of implementing different waste management strategies and improve the overall functioning in an order of priority. To do this the model should – as the ORWARE model - be able to combine different treatment options and thereby reflect the complex reality that might lead to the optimal result from a broad sustainability perspective.

It is still an open question whether the technical development can equalise, or even turn, the principal differences in environmental impact and sustainability that we find today in clear favour of one process or the other, but at least the following points can be made:

- With existing technology, biogas production is favourable to composting regarding energy production
- Biogas production has a mitigation effect on greenhouse gas emission due to fossil fuel substitution, but this effect may be diminished by fugitive CH_4 loss from biogas engines and storage facilities.
- In most cases, composting is more cost-effective, but the actual economy is very much dependent on the technological level and transport distances.
- In Denmark, at least, it is a prerequisite for recycling of organic waste to agriculture that the concentrations of organic micropollutants are below certain limits. In respect to this, composting is very much in favour because of the high potential for degradation of this type of compounds.

These point, and especially the last one, may in fact lead to the implementation of integrated solutions in the future where composting and biogas production are combined in order to minimise environmental impacts and increase sustainability of biological waste treatment.

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