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Quantification of environmental effects from anaerobic treatment of source-sorted organic household waste

Hansen, Trine Lund; Christensen, Thomas Højlund

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Trine Lund Hansen

Institute of Environment & Resources

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Trine Lund Hansen

Ph.D Thesis

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Preface

The work reported in this PhD thesis, “Quantification of environmental effects of anaerobic treatment of source-sorted municipal organic waste”, was conducted at the Institute of Environment & Resources at the Technical University of Denmark from January 2002 to July 2005. Professor Thomas Højlund Christensen supervised the project accompanied by Associated Professor Rena Irini Angelidaki.

The PhD thesis contains 10 papers, presenting the main results of my PhD work, prepared for scientific journals. My PhD project included much cooperation with both internal and external partners concerning fieldwork, experimental work, programming, model simulation and statistical evaluation of the results. The papers therefore represent the work of many people, my work being an important contribution.

The papers discuss different parts of the biological treatment system for municipal organic waste, defined as kitchen waste, in some cases including house plants with soil, cat litter and diapers, but no garden waste. Hansen et al **(I)** assess the composition of source-sorted municipal organic waste from different collection systems based on comprehensive sampling from full-scale systems in Denmark. In Hansen et al **(II)** the effects of three pre-treatment technologies on the composition and biogas potential of the pre-treated organic waste are investigated. Hansen et al **(III)** present a method for determination of the methane potential of organic waste, while Hansen et al **(IV)** present a simple model for quantification of methane production in storage tanks for digested organic waste. Hansen et al **(V)** contains a review of how agricultural application of digested organic waste has been included in existing models for environmental assessment of waste systems, while Hansen et al **(VI)** is a presentation of the land application module in EASEWASTE including a case study. Hansen et al **(VII)** (incomplete draft) present the biological treatment module in EASEWASTE. Jansen et al **(VIII)** is a description and statistical evaluation of methods developed for the sampling of pre-treated source-sorted municipal organic waste. Kirkeby et al **(IX)** present a case study assessing different treatment options for municipal organic waste in the municipality of Århus, while Davidsson et al **(X)** assess the methane yields of municipal organic waste based on pilot-scale reactor tests.

The papers are not included in this www-version but can be obtained from the library of Institute of Environment & Ressources, Technical University of Denmark, Bygningstorvet, Building 115, DK-2800 Lyndby, Denmark (library@er.dtu.dk).

July 2005

Trine Lund Hansen

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Summary

The Danish national waste strategy for 1998-2004 recommended increased biological treatment of municipal organic waste to improve the environmental profile of the Danish waste system (The Danish Government, 1999). However, data for a thorough environmental assessment of Danish systems for biological treatment of this waste fraction were not available. The results presented in this PhD thesis are based on a range of activities partly founded by the Danish Environmental Protection Agency in 2001-2003 to increase the knowledge within this field. The activities included a comprehensive field-sampling program including a range of existing large- and full-scale Danish systems for source-sorting and biological treatment of municipal organic waste, laboratory tests and analyses, literature studies, model simulations and construction of case studies. Municipal organic waste was defined as kitchen waste, in some cases including house plants with soil, cat litter and diapers, but no garden waste.

Based on analyses of waste samples, the typical chemical composition of collected organic waste could be determined. The composition of the waste varied between cities due to differences in sorting instructions and choice of collection bag material (paper or plastic). The main differences were seen for degradability of the waste, and content of ash and plastic. Minor, but nevertheless significant differences were seen between "identical" waste samples from different seasons. The dwelling type (single- or multi-family houses) did not influence the composition of the waste. On average 80% of the dry matter in the waste samples was easily degradable (determined as enzyme degradable organic matter, EDOM), while 12% was inorganic (ash). The dry matter contained on average 2.5% nitrogen, 0.4% phosphorus and 0.9% potassium. The calorific value was 20 MJ/kg dry matter, while the plastic content depended on the choice of collection bag material (0-8% of dry matter).

The methane potential for each waste sample was determined by laboratory batch tests (2-liter reactors). The average potential was 459 STPm^3 CH_4/t VS. Only minor variations with respect to city, pre-treatment technology, season and dwelling type were seen (428-489 STPm^3 CH_4/t VS). Pilot-scale digestion (35-liter reactors) of the same waste samples showed that 75-80% of the methane potential determined in the batch tests could be expected as methane yield on a larger scale (360 STPm^3 CH_4/t VS). The three investigated pre-treatment technologies, screw press, disc screen and shredder + magnet, routed on average 59, 66 and 98% (wet weight) of the collected organic waste to anaerobic digestion. Since 80-98% of the rejected material consisted of organic matter, the choice of pre-treatment technology was important for the methane potential per ton of collected municipal organic waste, ranging from 48 to 107 STPm^3 CH_4/t collected waste for the investigated systems.

Methane emissions from storage of treated organic waste were investigated through a combination of sampling from full-scale storage tanks and laboratory work. Assuming average Danish conditions with respect to temperature and operational pattern of the tanks, the produced methane may decrease the global warming savings from anaerobic treatment of municipal organic waste by 3%. Higher temperatures or changed practice could increase the methane production significantly.

The environmental effects of agricultural application of the treated organic waste are affected by many specific parameters and are thus difficult to generalize. Simulation of a range of typical Danish scenarios in the agro-ecosystem model Daisy showed wide intervals for the resulting nitrogen losses depending on the scenario: ammonia emissions, typically 15% of the applied ammonia; nitrous oxide emissions, typically 1.4-1.6% of the applied nitrogen; nitrate loss to surface waters, 0-30% of the applied nitrogen and nitrate loss to groundwater, 3-87% of the applied nitrogen. Carbon retention in the soil was estimated to 63-84, 17-37 and 2-16% of the applied carbon after 10, 50 and 100 years, respectively. Whether this effect contributes to the environmental assessment is a methodology question. The content of heavy metals and organic pollutants in the treated organic waste contributed to the environmental assessment through the toxicity impact categories. Substitution of commercial N, P and K fertilizers was based on nutrient content in the treated organic waste and the plant availability of organic waste compared to plant availability of commercial fertilizers, the mineral fertilizer equivalent (MFE) value. The MFE values were assessed to be maximally 0.3 for organic nitrogen, 0.8 for mineral nitrogen and 1 for phosphorus and potassium. Legal regulations and agricultural practice should be included in the MFE value in each specific scenario.

Based on the aforementioned data and literature studies, modules concerning biological treatment were constructed for the life cycle assessment-based pc-tool for environmental assessment of solid waste systems and technologies, EASEWASTE, developed at the Technical University of Denmark. The tool was used for environmental assessment of the system for source-sorting and anaerobic digestion of municipal organic waste in the Municipality of Århus, Denmark. The environmental effects of the anaerobic treatment system were strongly influenced by energy-related parameters, such as energy efficiency at the biogas and incineration plant, energy consumption in the system, efficiency of the pre-treatment plant, biogas potential and waste composition. The choice of the energy source substituted by the produced energy also influenced the results significantly. The potential toxicity effects from heavy metals in the treated organic waste applied to agricultural land had a large affect on the environmental assessment. These effects are, however, relatively uncertain due to methodology issues and varying heavy metal content in municipal organic waste. In most of the environmental impact categories assessed, the differences were only marginal between anaerobic digestion and incineration of the municipal organic waste fraction. Therefore, none of these treatment methods can be appointed as preferable to the other based on potential environmental impacts.

The work presented has increased the knowledge about environmental effects from anaerobic digestion systems in general through thorough investigation of existing Danish systems and evaluation of previously performed work within the area. The developed LCA-based tool may support future decisions at different political levels regarding biological treatment of municipal organic waste by allowing comparison of environmental effects with e.g. economics and service in the waste management system.

Dansk sammenfatning

Den nationale danske affaldsstrategi for 1998-2004 anbefalede øget biologisk behandling af organisk dagrenovation for at mindske miljøbelastningen fra det danske affaldssystem (The Danish Government, 1999). Pga. datamangel var det ikke muligt at gennemføre grundige miljøvurderinger af danske systemer for biologisk affaldsbehandling. Resultaterne præsenteret i denne afhandling bygger på en række aktiviteter gennemført i perioden 2001-2003 for at højne videns- og datagrundlaget indenfor området. Disse aktiviteter indbefattede omfattende prøvetagning fra en række stor- og fuld-skala systemer for kildesortering og biologisk behandling af organisk dagrenovation i Danmark, laboratorie forsøg, litteraturstudier, simuleringer og opstilling af aktuelle cases. Aktiviteterne var delvist finansieret af den danske Miljøstyrelse og blev gennemført i samarbejde med en række partnere. Organisk dagrenovation er i dette projekt defineret som køkkenaffald, i nogen tilfælde inklusiv kattegrus, bleer og potteplanter med jord, men ikke haveaffald.

De gennemførte affaldsanalyser dannede grundlag for bestemmelse af en typisk kemisk sammensætning af organisk dagrenovation. Denne sammensætning varierede mellem de forskellige byer i undersøgelsen pga. forskelle i sorteringsvejledninger og indsamlingsposer (plastik eller papir). De største forskelle blev fundet for indhold af aske og plastik samt nedbrydelighed af affaldet. Små, men dog signifikante forskelle blev fundet mellem ”identiske” affaldsprøver taget på forskellige årstider. Boligtype (etage ejendom eller villa) påvirkede ikke sammensætningen af affaldet. Gennemsnitligt 80% af tørstoffet i det analyserede affald var let nedbrydeligt (defineret ud fra andelen af enzym nedbrydeligt organisk stof, EFOS), mens 12% udgjordes af aske. Tørstoffet indeholdt i gennemsnit 2,5% kvælstof, 0,4% fosfor og 0,9% kalium. Den gennemsnitlige brændværdi var 20MJ/kg tørstof, mens indholdet af plastic i høj grad afhang af valget af indsamlingsposer (0-8% af tørstof).

Metan potentialet for hver affaldsprøve blev bestemt ved batch forsøg (2 liter reaktorer). Det gennemsnitlige potentiale var 459 Nm^3 CH_4/t VS og der blev kun fundet mindre variationer mht. by, forbehandlingsteknologi, årstid og boligtype (428-489 Nm^3 CH_4/t VS). Pilot-skala forsøg (35 liter reaktorer) med de samme affaldsprøver viste, at 75-80% af metan potentialet opnået i batch forsøg var opnåeligt i større skala (360 Nm^3 CH_4/t VS). De tre undersøgte forbehandlingsteknologier, skruepresse, rullesigte og shredder + magnet, ledte i gennemsnit 59, 66 og 98% (vådvægt) af det indsamlede affald til bioforgasning. Siden 80-98% af rejekt fraktionen bestod af organisk materiale, influerede valget af forbehandlingsteknologi kraftigt på metan potentialet per ton indsamlet affald. Dette potentiale varierede mellem 48 og 107 Nm^3 CH_4/ton indsamlet affald for de systemer der indgik i undersøgelsen.

Metan emissioner fra lagring af bioforgasset organisk dagrenovation blev undersøgt ved en kombination af målinger i fuld-skala lagertanke og batch tests i laboratoriet. Under typiske danske forhold mht. temperatur og drift af lagertanke har denne metan produktion potentiale til at mindske besparelserne på drivhuseffekten fra bioforgasning af organisk dagrenovation med omkring 3%. Højere temperaturer eller ændret drift af lagertankene kan øge produktionen af metan under lagring betydeligt.

Miljøeffekter fra anvendelse af behandlet organisk dagrenovation på landbrugsjord påvirkes af mange specifikke parametre og er derfor svære at generalisere. Simuleringer af en række typiske danske scenarier i jordbrugs modellen Daisy viste store udsving i tab af kvælstof afhængigt af det aktuelle scenarium: ammoniak emissioner, typisk 15% af det tilførte ammonium; lattergas emissioner, typisk 1,4-1,6% af det tilførte kvælstof; nitrat tab til overfladevand, 0-30% af det tilførte kvælstof og nitratudvaskning til grundvand, 3-87% af det tilførte kvælstof. Tilbageholdelse af kulstof i jorden blev estimeret til henholdsvis 63-84, 17-37 and 2-16% af det tilførte kulstof efter 10, 50 og 100 år. Om denne effekt bidrager til miljøvurderingen er et spørgsmål om metodevalg. Tungmetaller i den behandlede organiske dagrenovation bidrager til miljøvurderingen gennem de forskellige påvirkningskategorier for toksicitet (Wenzel et al., 1997). Substitution af kunstgødning (N, P og K) er baseret på næringsstofindholdet i det behandlede affald og plantetilgængeligheden af næringsstoffer i det organiske affald sammenlignet med plantetilgængelighed af kunstgødning. Dette forhold skønnes rent fysisk at være maximalt 0,3 for organisk kvælstof, 0,8 for mineralsk kvælstof og 1 for fosfor og kalium. Lovgivning og landbrugsmæssig praksis skal inddrages i vurderingen af den reelle substitution af kunstgødning i hvert enkelt tilfælde.

Baseret på ovenstående data og litteraturstudier konstrueredes moduler til miljøvurdering af biologisk behandling af organisk dagrenovation i den LCA-baserede computer model, EASEWASTE (environmental assessment of solid waste systems and technologies), der er under udvikling på Danmarks Tekniske Universitet. Modellen blev anvendt til miljøvurdering af Århus Kommunes system for kildesortering og bioforgasning af organisk dagrenovation. Miljøeffekterne fra systemet var kraftigt påvirkede af energi-relaterede parametre, såsom energi effektivitet på biogas- og forbrændingsanlæg, energiforbrug i systemet, effektivitet af forbehandlingsteknologi samt affaldets biogaspotentiale og sammensætning. Hvilken energikilde der substitueres af den producerede energi påvirkede også resultaterne betydeligt. De potentielle toksiske effekter af tungmetaller i behandlet organisk dagrenovation anvendt på landbrugsjord havde stor indflydelse på miljøvurderingen. Disse effekter må dog betragtes med visse forbehold pga. metodemæssige usikkerheder og relativt store variationer i tungmetalindholdet i organisk dagrenovation. I de fleste påvirkningskategorier i miljøvurderingen ses kun marginale forskelle mellem bioforgasning og forbrænding af organisk dagrenovation. Derfor kan ingen af de to behandlingsmetoder anbefales frem for den anden ud fra en ren miljømæssig begrundelse.

Arbejdet præsenteret i denne afhandling har bidraget til et generelt øget vidensgrundlag omkring miljøeffekter fra systemer til bioforgasning af organisk dagrenovation gennem grundige undersøgelser af en række eksisterende danske systemer samt evaluering af tidligere udført arbejde indenfor området. Den udviklede LCA-baserede model kan blive et vigtigt beslutningsstøtteværktøj for fremtidige beslutninger på forskellige politiske niveauer omkring biologisk behandling af organisk dagrenovation ved at muliggøre sammenligning af miljøeffekter med andre væsentlige parametre, såsom økonomi og service.

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Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. T.L. Hansen, J.l.C. Jansen, Å. Davidsson and T.H. Christensen. 2005. Accepted by Waste Management.

Method for determination of methane potentials of solid organic waste. T.L. Hansen, J.E. Schmidt, I. Angelidaki, E. Marca, J.l.C. Jansen, H. Mosbæk and T.H. Christensen. 2004. Waste Management. 24: 393-400

Methane production during storage of anaerobically digested municipal organic waste. T.L. Hansen, S.G. Sommer, S. Gabriel and T.H. Christensen. 2005. Accepted by Journal of Environmental Quality.

Environmental modelling of use of treated organic waste on agricultural land: A comparison of existing model for life-cycle-assessment of waste systems. T.L.Hansen, S. Schmidt and T.H. Christensen. 2005. Accepted by Waste Management & Research.

Life cycle modeling of environmental impacts from application of processed organic municipal solid waste on agricultural land (EASEWASTE). T.L. Hansen, S. Bruun, G.S. Bhander, L. Stoumann-Jensen and T.H. Christensen. 2005. Accepted by Waste Management & Research.

Modeling of environmental impacts from biological treatment of municipal organic waste (EASEWASTE). T.L. Hansen, J.T. Kirkeby and T.H. Christensen. 2005. Incomplete Draft.

Assessment of sampling and chemical analysis of source-separated organic household waste. J.l.C. Jansen, H. Spliid, T.L. Hansen, Å. Svärd and T.H. Christensen. 2004. Waste Management. 24: 541-549

Evaluation of environmental impacts from municipal solid waste management in the Municipality of Århus. J.T. Kirkeby, G.S. Bhander, H. Birgisdottir, T.L. Hansen, M. Hauschild and T.H. Christensen. 2005. Accepted by Waste Management & Research.

Methane yield in the source-sorted organic fraction of municipal solid waste Å. Davidsson, C. Gruvberger, T.H. Christensen, T.L. Hansen and J.l.C. Jansen. 2005. Accepted by Waste Management.

Background

Biological treatment of municipal organic waste

The history of centralized biological treatment of municipal organic waste in Denmark goes back to the 1930s, where the first drums for composting of separately collected municipal organic waste were introduced. In the years after World War II, 19 plants were implemented throughout the country; however, during the following 20 years they were all closed again. The late 1970s saw the reintroduction of central composting of municipal organic waste, and in the mid-1980s biogas plants for anaerobic digestion of animal manure started accepting municipal organic waste as supplementing substrate (Reeh, 2000).

In Denmark, approximately 1.7 millions tons of household waste is produced annually (Danish EPA, 2004). Municipal organic waste constitutes 35-50% of this waste, corresponding to 6-850 000 tons/year or 3.7-5.0 kg/household per week for multi- or single-family housing, respectively (Petersen & Domela, 2003). The municipal organic waste is either collected separately for biological treatment or together with the remaining household waste for incineration. Field investigations have indicated that 40-90% of the municipal organic waste can be source-sorted and collected separately, depending on local conditions such as dwelling type and information effort from the municipality (Jørgensen & Jansen, 2003, Toudal, 2003).

In 2001 a total of 37 000 tons source-sorted municipal organic waste, corresponding to 6% of the potential, was biologically treated at nine composting plants and seven anaerobic digestion plants (Petersen & Hansen, 2003). In addition, 23-25000 tons municipal organic waste was assessed to be treated by home composting (Petersen & Kielland, 2003). The main part of the remaining municipal organic waste was incinerated, since only 1-2% of the Danish household waste is landfilled (Danish EPA, 2004). Since 2001, several Danish systems for source-sorting municipal organic waste have been closed due to financial, political or operational problems. The amount of municipal organic waste currently being biologically treated is therefore probably lower than in 2001.

Compared to other organic waste streams in the Danish society, the amount of municipal organic waste constitutes around half of the amount of sewage sludge produced (1 370 000 tons/year, wet weight) or five times as much as the organic waste from the industry and service sector (100 000 + 33 100 tons/year (Danish EPA, 2004)). Compared to the production of manure from pig and cattle, municipal organic waste constitutes 2% (34 000 000 tons/year, wet weight) (Eilersen et al., 1998). The dry matter content and composition, including nutrients, differ considerably between these organic materials.

Danish waste policy

The waste hierarchy

In industrialized countries the steadily growing amounts of waste increase the challenge of balancing environmental issues, economy and service within waste management. The waste hierarchy has been the guideline for environmental waste management in EU for many years, advocating the following prioritization: (1) cleaner technology and waste minimization, (2) waste recycling, (3) incineration with energy recovery and (4) landfilling.

The national Danish strategy for waste treatment 1998-2004 (The Danish Government, 1999) was based on the waste hierarchy with the overall aim of waste minimization and moving the remaining waste fractions up in the hierarchy. The goal for 2004 was 64% recycling, 24% incineration and 12% disposal in landfills. Thus, the main focus was on waste amounts and recycling percentages.

One way to increase the recycling percentage for household waste was to facilitate implementation of composting or anaerobic digestion of source-sorted municipal organic waste. However, the knowledge within this field was inadequate to support nationwide implementation of separate collection and treatment systems. Therefore, a range of large- or full-scale systems with source-sorting and biological treatment of municipal organic waste in Danish cities was investigated. Based on the results, an environmental assessment of different treatment options for municipal organic waste was performed. This showed only marginal differences in the environmental benefits obtained by anaerobic digestion and incineration respectively (Christensen et al., 2003).

Waste indicators

In 2003 a new waste strategy for 2004-2008 was presented by the Danish government (The Danish Government, 2003). The basic principles from the waste hierarchy were supplemented with three Life Cycle Assessment (LCA)-based “waste indicators” developed to increase environmental quality in the waste treatment; these waste indicators were: resource consumption, primary energy consumption and landfill requirement. Resource consumption reflects the loss (or gain) of resources caused by the chosen waste system. Primary energy consumption represents environmental impacts such as global warming and acidification, mainly related to energy production. The landfill requirement indicator reflects the waste hierarchy prioritization and measures the landfill space required for final disposal of products from the waste treatment system. The indicators may be used for comparison of whole waste systems, identification of the main environmental impacts from one system or for single waste fractions to compare different treatment options. The indicators chosen should reflect the most important environmental impacts from waste treatment (Dall et al., 2002). In the waste strategy, one official goal is to develop more waste indicators to further environmentally qualify decisions for development of the waste sector and thus qualify the prioritization of the monetary resources available to the sector.

The overall goals in the waste strategy are to separate economic growth and waste generation and to introduce more quality and efficiency in the waste sector. For each waste fraction it should be assessed whether recycling or incineration is the most desirable solution concerning the environment (waste indicators) and economics.

Disposal in landfills should be avoided if possible (The Danish Government, 2003). For comparison, the Swedish government advocates recycling of phosphorus to agriculture and production of high quality energy (biogas) in the treatment of municipal organic waste (Gruvberger et al., 2003).

Local authorities should assess whether the municipal organic waste should be recycled (biologically treated) or incinerated, since local conditions may have a significant influence on the environmental and economic effects of the treatment. A decision support tool for assessment of environmental and economic effects of a given treatment system for organic waste should be developed to support local authorities (The Danish Government, 2003).

EU regulation

The EU regulation constructs the overall frames and principles for the waste policy, while the national authorities are responsible for organization and implementation of the legislation (The Danish Government, 2003). The EU commission is currently working on the Biodirective, which concerns biological treatment of organic waste. The outcome of this directive may have a great influence on the Danish policy within the area, e.g. mandatory source-sorting of municipal organic waste in all countries has been suggested. However, the directive has been postponed several times and it is currently unclear what it will specify regarding municipal organic waste.

LCA and waste

Life Cycle Assessment (LCA) is an ISO-standardized method (ISO 14040) originally developed for environmental assessment of products (Wenzel et al., 1997). The mass flow through the well-defined system is modeled and all emissions, resource consumptions as well as up- and down-stream effects must be quantified. Up-stream effects originate from production of materials or energy used in the system. Products generated by the system may substitute other products and thereby avoid environmental effects from production of the original products (down-stream effects). Each emission or consumption contributes to a number of defined categories for environmental impacts. The results of the assessment can be given on different levels:

1. *Life cycle inventory (LCI)*: List of all emissions and resource consumptions for the defined system.
2. *Characterized impact potentials:* All emissions and resource consumptions recalculated into common units for every impact assessment category (e.g. kg CO_2-equivalents for global warming)
3. *Normalized impact potentials:* The contributions to each environmental impact category are compared to an average person's contribution to this category. The normalization references may be local, regional or global depending on the assessed impact. The unit for normalized impact potentials or resource consumption is Person Equivalent (PE) or Person Reserve (PR), respectively.
4. *Weighted impact potentials:* The normalized impact potentials are compared across the different impact categories. This requires a political decision about whether global warming is more or less important than e.g. acidification or human toxicity.

Through these four levels interpretation of the results and comparisons between different alternatives is simplified. However, in the aggregation process a substantial amount of information is lost and the resulting picture may be too simple. For a detailed assessment of a system, all four levels of results should be used to see both the overall picture and the details.

Even though the LCA method has been developed for environmental assessment of products, the same principles can be applied for environmental assessment of waste management systems. At the Technical University of Denmark a pc-tool based on LCA principles for environmental assessment of solid waste systems and technologies (EASEWASTE) is currently being developed. EASEWASTE includes the whole waste system from waste generation, through collection and treatment to final disposal or utilization. Modeling a whole waste system requires a substantial amount of specific data as well as detailed knowledge of the technologies chosen and the local area in which the system is to be implemented. EASEWASTE contains default data set (examples of waste composition and technologies), which may be used if no specific data are available. This enables the user to perform environmental screening of the systems to identify the main impact potentials without detailed knowledge of all parts of the system. A further description of the tool can be found in Kirkeby et al. (2005).

Data collection and generation

Environmental assessment of the biological treatment of municipal organic waste requires a substantial amount of data regarding the environmental effects of waste collection, pre-treatment, biological treatment, post-treatment and final disposal of the waste. The Danish national waste strategy (The Danish Government, 2003) as well as researchers within the area (e.g. Reeh (2000)) have requested detailed tools for LCA-based environmental assessment of different treatment systems for municipal organic waste.

At the start of this project (2001), the available data within this area were sparse and scattered. Some literature was available, but often describing treatment of different waste types (mixed waste, industrial organic waste, sewage sludge or manure) or systems very different to those of Denmark. Furthermore, this type of data often strongly depends on the systems chosen or the local conditions. Implementation of these technologies in EASEWASTE was therefore not possible without generation of more data. In the following years, the Danish EPA founded several investigations and experiments regarding biological treatment of organic waste. The activities were performed by a range of different partners and included comprehensive field sampling from large and full-scale systems, laboratory analyses and literature studies. Some of the issues investigated were waste composition and seasonal variation, effects of different dwelling types and collection systems, pre-treatment technologies, anaerobic digestion and storage of the treated organic waste. The overall result was substantially increased knowledge regarding treatment of municipal organic waste, including suitable data for environmental assessment of different treatment systems for this waste fraction (Jansen & Christensen, 2003).

As landfilling of organic waste is not permitted in Denmark, the main alternative to biological treatment is incineration with energy recovery (electricity and heat), often substituting fossil fuels. Biological treatment covers composting and anaerobic digestion. This thesis mainly focused on anaerobic digestion, since this technology seems environmentally preferable to composting due to the energy production from biogas. Both anaerobically digested and composted organic waste can substitute commercial fertilizers and/or peat; however, the saved effects from this substitution are not of the same magnitude as the effects from substituted energy production. Environmental advantages from composting will therefore often be smaller than those from waste treatment technologies with energy recovery (Kirkeby et al, **IX),** (Vogt et al., 2002) and (Poulsen & Hansen, 2003)).

Content of the PhD thesis

The main purpose of this PhD thesis was to develop a concept for consistent environmental assessment of biological treatment of municipal organic waste for implementation in EASEWASTE and provide data for this assessment for a range of Danish systems.

The general concept of the model structure for the biological treatment module in EASEWASTE was mainly obtained through thoroughly reviewing the literature about similar models, specific technology types and experimental work within the field. Accordingly, the governing parameters regarding environmental impacts were determined and the structure could be decided. Data for the model were obtained through investigation of large- or full-scale systems supplemented with laboratory tests, model simulation and literature studies.

The thesis describes the environmental effects from each step in the waste management systems for municipal organic waste: collection system and waste composition, pre-treatment, biological treatment, storage and utilization of the treated organic waste.

Resource consumption and economic effects of the waste system have not been included in this thesis, since the main focus was on environmental effects. EASEWASTE, however, includes resource consumption and economic effects.

The application of the model is illustrated by a case study performed for the Municipality of Århus. The environmental effects of their system for source-sorting and anaerobic digestion of municipal organic waste were estimated and discussed.

Presentation of papers

The PhD thesis contains 10 papers prepared for scientific journals. Together, these papers present the main results of the study. Below, the papers are briefly presented and my contribution to each paper is specified.

Hansen et al, I

Composition of source-sorted municipal organic waste collected in Danish cities. T.L. Hansen, H. Spliid, J.l.C. Jansen, Å. Davidsson and T.H. Christensen. 2005. Accepted by Waste Management.

This paper is based on results from a large sampling program investigating a range of Danish full-scale source-sorting systems for municipal organic waste performed for the Danish EPA in 2001-02. I contributed considerably to the planning, the conceptual outline of the sampling program, the statistical analyses performed as well as evaluation and interpretation of the results. In addition, I was responsible for sampling and laboratory work and I wrote up the main part of the paper.

Hansen et al, II

Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. T.L. Hansen, J.l.C. Jansen, Å. Davidsson and T.H. Christensen. 2005. Accepted by Waste Management.

This paper is based on waste analyses from the program described in Hansen et al (**I**). In addition to planning, sampling and processing of the samples, I performed the methane potential batch tests and contributed considerably to the statistical analyses performed as well as evaluation and interpretation of the results. I wrote up the main part of this paper.

Hansen et al, III

Method for determination of methane potentials of solid organic waste. T.L. Hansen, J.E. Schmidt, I. Angelidaki, E. Marca, J.l.C. Jansen, H. Mosbæk and T.H. Christensen. 2004. Waste Management. 24: 393-400

The method was developed for determination of the methane potential of waste from the sampling program described in Hansen et al (**I**). I performed the methane potential batch tests of the waste samples and contributed to development and improvement of the method. I also contributed to interpretation of the obtained data to evaluate and standardize the method. I wrote up a considerable part of this paper.

Hansen et al, IV

Methane production during storage of anaerobically digested municipal organic waste. T.L. Hansen, S.G. Sommer, S. Gabriel and T.H. Christensen. 2005. Accepted by Journal of Environmental Quality.

This paper is based on results from measurements at full-scale storage tanks and associated laboratory work. I contributed to the planning and conceptual outline of the project, performed the methane potential batch tests on digested organic waste, developed the suggested model and contributed considerably to evaluation and interpretation of the data. I wrote up the main part of this paper.

Hansen et al, V

Environmental modelling of use of treated organic waste on agricultural land: A comparison of existing model for life-cycle-assessment of waste systems. T.L. Hansen, S. Schmidt and T.H. Christensen. 2005. Accepted by Management & Research.

This paper is based on literature studies mainly performed by me. I wrote up the main part of the paper.

Hansen et al, VI

Life cycle modeling of environmental impacts from application of processed organic municipal solid waste on agricultural land (EASEWASTE). T.L. Hansen, S. Bruun, G.S. Bhander, L. Stoumann-Jensen and T.H. Christensen. 2005. Accepted by Waste Management & Research.

This paper presents the land application module in EASEWASTE. The structure of the module is a result of Hansen et al (**V**), thorough literature studies and evaluation of results from Danish scenarios modeled in the agro-ecosystem model Daisy. I performed the evaluation in cooperation with the co-authors and wrote up the main part of the paper.

Hansen et al, VII

Modeling of environmental impacts from biological treatment of municipal organic waste (EASEWASTE). T.L. Hansen, J.T. Kirkeby and T.H. Christensen. 2005. Incomplete Draft.

This paper presents the biological treatment module in EASEWASTE. I have been the main person responsible for the conceptual outline of the module and have written up the main part of this paper.

Jansen et al, VIII

Assessment of sampling and chemical analysis of source-separated organic household waste. J.l.C. Jansen, H. Spliid, T.L. Hansen, Å. Svärd and T.H. Christensen. 2004. Waste Management. 24: 541-549

This paper is based on results from the sampling program described in Hansen et al (**I**) and additional samples for the statistical analyses. In addition to sampling and laboratory work, I contributed to the planning, statistical analysis, evaluation and interpretation of the results.

Kirkeby et al, IX

Evaluation of environmental impacts from municipal solid waste management in the Municipality of Århus. J.T. Kirkeby, G.S. Bhander, H. Birgisdottir, T.L. Hansen, M. Hauschild and T.H. Christensen. 2005. Accepted by Waste Management & Research.

This paper is a case study using EASEWASTE for environmental assessment of municipal waste treatment systems in Århus. I contributed to sampling at the pre-treatment plant in Århus, data collection and construction of the modules for biological treatment (together with JTK) and land application in EASEWASTE.

Davidsson et al, X

Methane yield in the source-sorted organic fraction of municipal solid waste. Å. Davidsson, C. Gruvberger, T.H. Christensen, T.L. Hansen and J.l.C. Jansen. 2005. Accepted by Waste Management.

This paper describes the results of pilot-scale anaerobic digestion of waste samples collected in the sampling program described in Hansen et al (**I**). In addition to sampling at the full-scale pre-treatment plants and processing of the waste samples, I participated in discussion and evaluation of the results.

Anaerobic treatment systems

A full environmental assessment of anaerobic waste treatment includes the whole waste system: waste generation, collection, treatment (including any pre- and post-treatment) and final disposal or utilization (see Figure 1). Changes in one part of the system may cause significant changes in others and therefore estimation of environmental effects from the anaerobic treatment step only is inadequate to give the full environmental picture. This chapter presents the approach and results from field sampling, laboratory tests and literature studies regarding environmental effects for each step of the anaerobic treatment system.

Collection systems and waste composition

Source-sorting and separate collection of municipal organic waste has been introduced in several Danish cities, either as time-limited large-scale experiments or permanent full-scale systems. The collected organic waste is either anaerobically co-digested with organic industrial waste, manure and/or sewage sludge or composted mixed with garden waste.

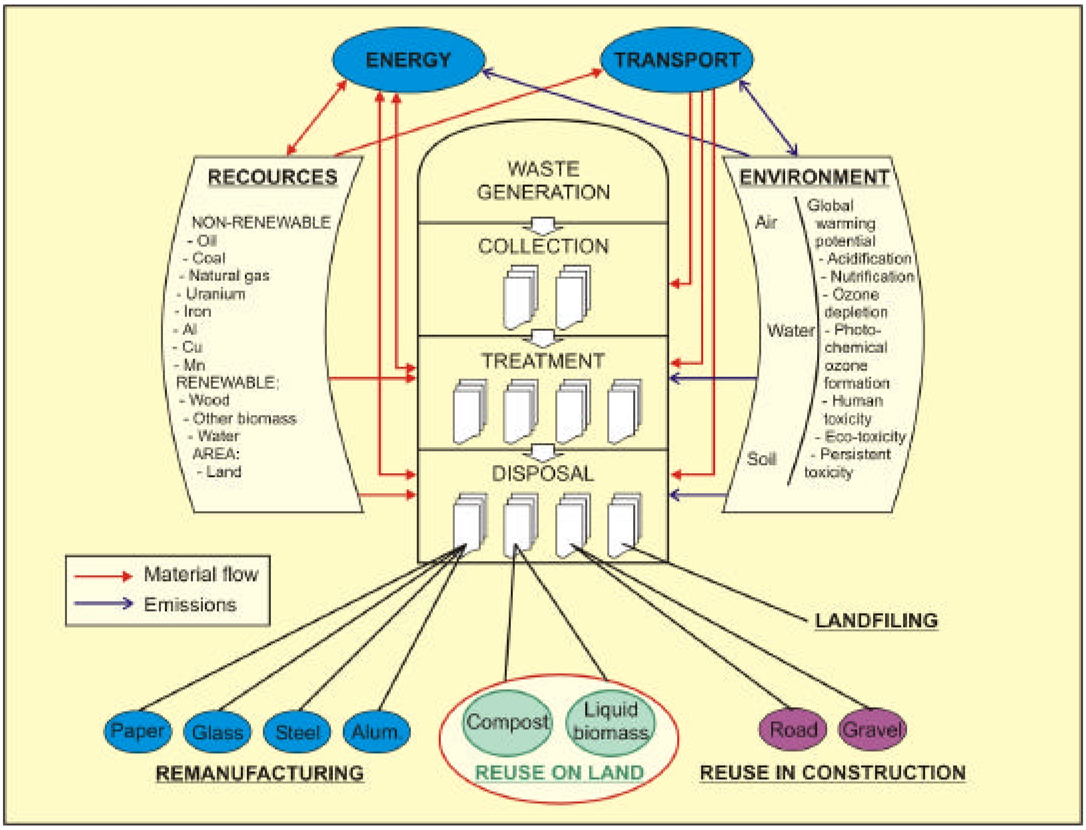


Figure 1: The waste system in EASEWASTE includes all steps from waste generation to final disposal or utilization (Kirkeby et al., 2005). All up- and down-stream effects as well as emissions from any part of the system are included. The tool can be used for estimating the effects from one waste fraction (e.g. municipal organic waste) as well as a waste system containing several waste fractions.

Table 1: Description of the investigated collection systems (Hansen et al, I)

	Copenhagen	Aalborg	Vejle	Kolding	Grindsted
Collection system	Experimental	Experimental	Permanent	Experimental	Permanent
No of households, total	16366	2294	26339	2037	7250
Single-family	2433	647	12643	1623	6050
Multi-family	13933	1647	13696	414	1200
Bag type, in door	Paper	Plastic	Plastic	Plastic	Paper
Bag type, out door	Paper/container	Container	Container	Paper	Paper
Sorting instructions					
Food leftovers (raw or cooked)	x (solid)	x	x	x	x
Fruit and vegetables	x	x	x	x	x
Meat (without bones)	x	x	x	x	x
Animal bones		x	x	-	
Coffee and tea (incl. filters)	x	x	x	x	x
Kitchen paper/napkins (used)	x	x	x	x	x
Animal fodder		x			
Animal excrements	x		x		
Cat litter			x	x	
Flowers, cut		x	x	x	x
Flowers (incl. soil)		x	x	x	
Diapers			x	-	

The success and outcome of biological treatment depend, among other factors, on the composition of the incoming waste. To investigate how the collected municipal organic waste was influenced by collection system, dwelling type and season, a comprehensive sampling program was established by the Danish EPA in 2001-2002 (Jansen & Christensen, 2003). Municipal organic waste collected in five different cities (Copenhagen, Aalborg, Vejle, Kolding and Grindsted) from different dwelling types (single- and multi-family housing) was sampled several times over one year. The systems investigated are described in Table 1. The sampling yielded a total of 40 waste samples characterized with respect to 15 chemical components. All sampling was performed after pre-treatment to obtain more homogeneous and representative samples. Sampling of both pre-treated organic waste and the rejected fraction allowed calculation of the composition of the collected municipal organic waste before pre-treatment (including collection bags). Details regarding the sampling program, chemical analyses, statistical analyses and the results are further described in Hansen et al (**I**).

Several chemical components were significantly influenced by the collection system. One of the main tendencies was that the choice of collection bag material (plastic or paper) affected the composition of the collected waste. Naturally, the largest plastic content was found in collection systems using plastic bags, while the content of crude fibers was the highest for collection systems using paper bags. Variations in ash content, degradability and calorific value of the collected waste from the different collection systems could be explained by differences in the sorting instructions. If soil and cat litter are permitted in the organic fraction, the ash content increases and the degradability and calorific value decreases. A few components (ash, S and Cl) were influenced by the season of the sampling, while no significant differences could be identified between single- and multi-family housing (dwelling type). The waste

Table 2: Composition of the collected waste (dry matter, least square means). All values except plastic and "other" are based on the organic fraction (o.f.) of the waste (not including the plastic and "other"). The overall average is determined as the intercept from the analysis of variance.

	Copenhagen	Aalborg	Vejle	Kolding	Grindsted	Multi	Single	Spring	Fall	Winter	Average
Number of samples	12	7	8	8	5	17	23	17	14	9	
Ash [% o.f. dm]	8.4	13.3	13.0	13.9	10.5	12.0	11.6	12.9	11.6	10.8	11.8
Fatt [% o.f. dm]	14.0	14.7	12.9	13.7	14.4	14.3	13.6	14.1	13.5	14.3	13.9
Protein [%o.f. dm]	15.1	15.5	14.6	14.9	14.4	14.9	14.8	15.4	14.6	14.7	14.9
Fibres [% o.f. dm]	19.7	15.2	17.8	17.8	22.3	18.8	18.4	17.9	20.3	17.5	18.6
EDOM* [% o.f. dm]	83.3	78.0	75.4	75.3	81.8	78.3	79.2	78.6	77.6	80.1	78.8
K [% o.f. dm]	1.0	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
P [% o.f. dm]	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4
N [% o.f. dm]	2.5	2.6	2.4	2.5	2.4	2.5	2.5	2.6	2.4	2.4	2.5
C [% o.f. dm]	49.2	48.1	47.3	47.2	48.1	47.7	48.3	47.9	48.1	48.0	48.0
H [% o.f. dm]	7.3	7.1	7.0	7.0	7.1	7.1	7.1	7.1	7.0	7.2	7.1
S [% o.f. dm]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Cl [% o.f. dm]	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.4	0.7	0.6
Calorific value [MJ/kg o.f. dm]	20.8	20.1	19.7	19.7	20.3	20.1	20.1	20.1	20.1	20.1	20.1
Plastic [% dm]	1.9	6.9	8.1	7.2	.	6.1	5.9	5.0	5.6	7.5	6.0
"Other" [% dm]	0.2	0.7	0.7	0.9	.	0.7	0.5	0.5	0.7	0.7	0.6

*)Enzyme Degradable Organic Matter

composition for each of the investigated systems (cities), dwelling types and seasons as well as mean values across all categories, are shown in Table 2.

Statistical test results (Kolmogorov-Smirnov test) indicated that the collection system and season affected the general overall composition of the collected waste. The strongest tendency was seen for collection system. Dwelling type did not seem to affect the general waste composition (further details in Hansen et al (**I**)).

Despite being significant, many variations in the chemical waste components were too small to be important in a waste management context (see Table 2). However, some issues should be considered. The collection system, especially choice of collection bag material, is important when introducing a new system. Use of plastic bags necessitates a thorough pre-treatment, since plastic may cause serious operational problems in the treatment step or limit the usability of the end product. The variations in ash content and degradability may affect the biogas production. However, since these components only vary a few percent, the effect in a full-scale system will be minor. A sampling program for municipal organic waste should cover different seasons to ensure representative sampling. Sampling from different dwelling types will be less important in Denmark, since the composition of the waste was not affected by this factor.

Pre-treatment

Pre-treatment of source-sorted municipal organic waste is crucial for most anaerobic treatment systems to avoid operational problems in the treatment step and to ensure a high quality end product. The main purposes of the pre-treatment process are removal of foreign objects (mainly plastic and metal), mixing and size reduction.

The choice of pre-treatment technology should fit the rest of the system: All materials allowed in the organic fraction of the municipal waste (decided by the sorting instructions) should either be acceptable in the anaerobic treatment plant or removed by the pre-treatment step. If plastic is introduced as collection bag material, a pre-treatment technology capable of removing plastic must be chosen if required by the following steps. The sensitivity of anaerobic treatment technologies towards impurities differs considerably, affecting the requirements for the collection system and the pre-treatment step. Furthermore, utilization of the treated waste in e.g. agriculture demands a much higher quality end product than other applications such as landfill covering.

Investigated systems

In the Danish full-scale sampling program, three pre-treatment technologies were represented: screw press, disc screen and shredder + magnet (see Figure 2). More details

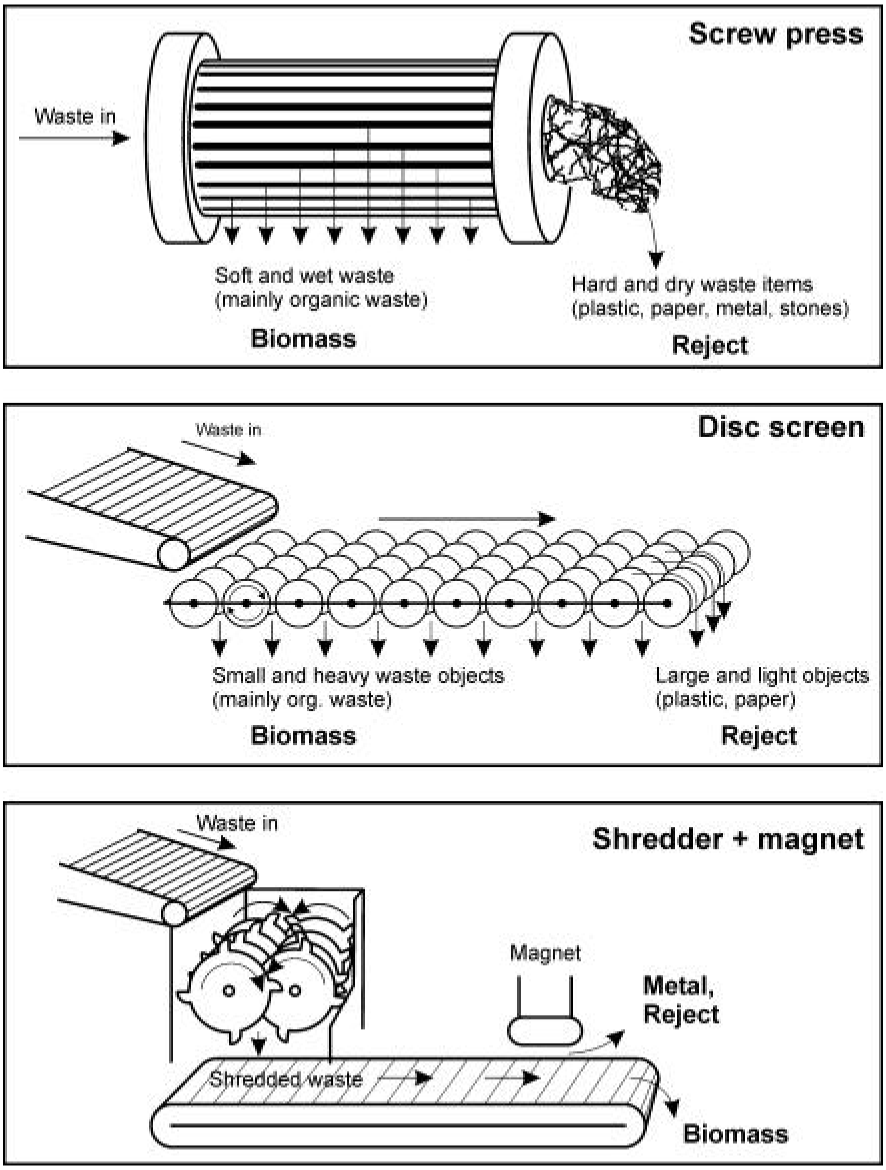


Figure 2: Sketch of the investigated pre-treatment technologies (Hansen et al, II)

are available in Hansen et al (**II**). These pre-treatment technologies were applied for source-sorted municipal organic waste prior to anaerobic co-digestion with either manure or sewage sludge in Aalborg, Herning and Grindsted, respectively.

The source-sorted municipal organic waste from each city in the Danish sampling program was treated by the three different pre-treatment technologies to investigate the origin of any variations found. However, since pre-treatment with shredder + magnet cannot deal with plastic in the waste, only waste collected in paper bags (waste from Grindsted and Copenhagen) was pre-treated with this technology. The pre-treated waste as well as the reject was sampled at least twice within one year for the different combinations of waste from a specific city and pre-treatment technology. The effects of the three pre-treatment technologies are described in detail in Hansen et al (**II**).

The amount of pre-treated waste resulting from the three pre-treatment technologies investigated varied significantly: 59% (wet weight) from screw press, 66% from disc screen and 98% from shredder + magnet. Since the rejected material from disc screen and screw press consisted of 80-98% organic matter, a substantial fraction of the collected organic waste was not routed to anaerobic digestion. Plastic collection bags significantly increased the risk of plastic in the pre-treated organic waste and resulted in up to 10% plastic (wet weight) in the reject fraction (Hansen et al, **II**).

Table 3: Composition of the biomass (average values) for the different cities and pre-treatment technologies (Hansen et al, II).
dm = dry matter, SP = screw press, DS = disc screen and S+M = shredder and magnet

	Copenhagen			Aalborg		Vejle		Kolding		Grindsted
	SP	DS	S+M	SP	DS	SP	DS	SP	DS	S+M
Number of samples	4	12	4	11	3	4	4	4	4	5
Biomass, [% w/w]	55.5	70.0	<100	63.7	66.8	56.1	67.2	61.9	58.2	<100
Dry matter, dm, [% w/w]	27.3	29.2	29.5	23.4	29.4	26.7	33.1	28.0	31.7	32.3
Organic matter ,VS,[% dm]	92.3	88.8	93.3	88.8	85.6	85.2	83.5	84.3	83.4	90.0
Ash, [% dm]	7.7	11.2	6.7	11.2	14.4	14.8	16.5	15.7	16.6	10.0
Fat, [% dm]	16.6	13.8	14.9	18.1	14.1	15.0	12.2	16.8	15.0	13.9
Protein, [% dm]	17.0	15.5	14.3	17.0	15.0	15.6	14.0	16.4	16.0	14.2
Starch, [% dm]	22.5	14.5	15.1	17.1	16.1	15.7	13.2	16.6	12.8	13.5
Sugar, [% dm]	8.1	9.5	9.5	5.2	8.6	4.3	5.6	4.6	4.9	8.2
Crude fibres, [% dm]	12.2	17.4	21.3	10.1	14.8	11.5	19.6	10.2	16.0	22.8
EDOM*, [% VS]	93.0	89.9	91.0	93.9	90.0	93.0	88.5	93.3	88.0	91.4
K, [% dm]	1.0	1.0	0.9	1.1	1.0	1.0	0.9	1.1	1.0	0.9
P, [% dm]	0.3	0.5	0.4	0.3	0.5	0.2	0.5	0.3	0.5	0.4
N, [% dm]	2.8	2.6	2.4	2.8	2.4	2.7	2.5	2.8	2.6	2.3
C, [% dm]	50.5	48.3	51.3	49.3	46.7	48.5	47.0	47.6	47.5	48.4
H, [% dm]	7.7	7.1	7.5	7.4	6.8	7.2	6.9	7.2	7.0	7.0
S, [% dm]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Cl, [% dm]	0.7	0.5	0.4	0.9	0.5	0.8	0.4	0.7	0.7	0.5
Calorific value (upper) [MJ/kg dm]	21.5	20.3	21.1	20.8	19.6	19.7	19.4	19.7	19.3	20.3

*) Enzyme Degradable Organic Matter

The screw press was more selective than the disc screen. Table 3 shows that the dry matter content was 2-7% higher for waste pre-treated by disc screen than screw press, while the fraction of enzyme degradable organic matter (EDOM, representing easily degradable matter) was a minimum of 3% lower, and the content of crude fibers (slowly degradable organic matter) 4-8% higher. Hansen et al (**II**) also showed that the plastic content in the pre-treated organic waste was significantly higher for the disc screen solution than for screw press. Thus, the screw press routed more water and easily degradable organic matter and less slowly degradable matter and collection bag material (plastic or paper) to the pre-treated organic waste fraction than the disc screen. The magnitude of these differences may not be important in a waste management context assessing a whole waste system. However, the dry matter content of the reject is important for the energy yield from incineration, while the degradability of the organics directed to anaerobic digestion may affect the biogas production.

Sampling

Representative sampling was essential for characterization of the collected municipal organic waste. The waste was very heterogeneous and still in collection bags (plastic or paper) when delivered to the pre-treatment plants. One truckload of 2-5 tons was represented by a sample of 30 kg. This sample was further processed in the laboratory (mixing, size reduction and drying) and analyzed for several parameters; some of the analyses required only a few grams.

All the investigated pre-treatment technologies performed both size reduction and mixing and therefore all sampling was performed after the pre-treatment unit. For each pre-treatment technology a specific method of sampling was developed to ensure representative samples. A statistical test program (based on a revised Staggert diagram) was made to investigate whether any step in the sampling methods introduced significant uncertainties. This was found not to be the case and the sampling methods were therefore acceptable (Jansen et al, **VIII**).

Technology examples

The three investigated pre-treatment technologies are examples of technology solutions in an area under development. Several other options for pre-treatment of municipal organic waste exist.

In 2001, the city of Århus introduced a full-scale source-sorting system based on optical sorting before anaerobic digestion: the organic waste was collected in green plastic bags, while the remaining waste was collected in black plastic bags. The waste was collected by the same truck and sorted at a central plant. The organic fraction (green bags) was treated by a bag opener and a screw press before anaerobic digestion, while the remaining fraction (black bags) went directly to incineration. Optical sorting is also used in Vejle for pre-treatment of source-sorted municipal organic waste prior to composting.

Another opportunity for separate collection of municipal organic waste is a food waste disposer as introduced in some areas in the Swedish city Malmö (Gruvberger et al., 2003). The organic waste is ground by a grinder installed in the kitchen sink and led to a storage tank through a separate pipe. In the tank, the organic waste separates, the supernatant is then led to the sewage system and the settled material is collected by truck and transported to a biogas plant. No further pre-treatment is required for this fraction; however, the dry matter content of the settled fraction was considerably lower than expected and further dewatering may be necessary (Jansen et al., 2004).

In the same area in Malmö, the vacuum system has also been introduced (Gruvberger et al., 2003). The source-sorted organic waste is delivered in special collection bags (paper) at a collection point close to the dwellings. The organic waste is sucked through a vacuum pipe into a central storage tank, where a truck regularly collects the waste. The collected waste must be pre-treated (e.g. by a piston press) before anaerobic digestion (Jansen et al., 2004).

Some biological treatment technologies are not sensitive to impurities in the waste. If the treatment technology also includes post-treatment (removal of plastic and other impurities) to ensure a high-quality end product, pre-treatment is not always necessary. This is often the case for composting or combined processes (anaerobic digestion and composting).

An alternative to source-sorting and separate collection is central sorting of mixed household waste. A pilot plant tested in Odense in 2003 could separate mixed municipal waste into several useable fractions: organics for anaerobic digestion, plastic for incineration in a power plant, metal for recycling and reject for incineration. The plant sorted 6-12 tons of municipal waste per day for three months. In general, the resulting organic fraction was found suitable for anaerobic digestion with agricultural application of the end products (Rosen et al., 2004).

Status for the described pre-treatment systems

During the last years, many of the investigated Danish systems have been closed. The system in Aalborg was closed in 2002 due to a political decision weighting the extra monetary costs of separate collection against the environmental benefits estimated in Christensen et al. (2003) and Damgaard & Strandmark (2003). The system for disc screen sorting and anaerobic digestion of municipal organic waste in Herning was closed after considerable problems with impurities (plastic) in the biogas reactor. However, the decision was also influenced by the results in Christensen et al. (2003) estimating only minor differences in the environmental advantages between anaerobic digestion and incineration. In Grindsted, the system is still in operation and no problems have been reported. The optical sorting system in Århus was closed in 2004 after an intense political debate of costs and benefits of the plant partly based on Kirkeby & Christensen (2004). The plant had been modified several times due to operational problems, which increased the costs considerably. In Vejle the optical sorting system prior to composting is still running, as are the two systems introduced in Malmö. The plant for central sorting in Odense was a test plant only and the test period has now expired.

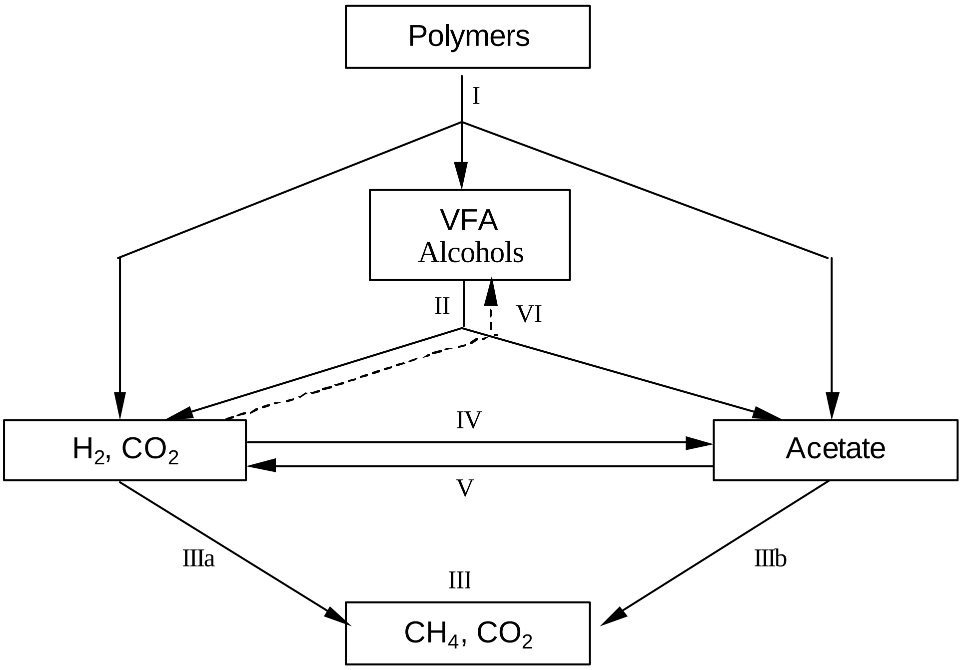


Figure 3: Basic principles of anaerobic digestion (Angelidaki, 2002)

Anaerobic digestion

The process

Anaerobic digestion is degradation of organic matter under anaerobic conditions creating methane, carbon dioxide and water. Figure 3 shows the basic steps in anaerobic digestion. The first step is the hydrolysis, where complex organic compounds are broken down into smaller organic molecules (sugars, amino acids and long-chain fatty acids). These are further degraded yielding acetate or hydrogen and carbon dioxide before the final step, where these intermediates are transformed into methane and carbon dioxide. The different steps are performed by different groups of bacteria as shown in the figure.

Technologies

A range of different technologies for anaerobic digestion of organic waste exists. The technologies can be divided into wet, semi-dry and dry processes containing typically <10, 10-20 and 20-40% dry matter, respectively. Wet and semi-dry processes normally require stirred reactors and often treat a mixture of municipal organic waste, industrial organic waste and manure or sewage sludge. In dry anaerobic digestion, the municipal organic waste is often mixed with drier waste, e.g. garden waste, to obtain a good structure. The dry process may be batchwise or continuous (plug flow). The anaerobic digestion may be performed in one or two steps. In the two-step process, hydrolysis is often performed in a smaller tank before leading the waste to the main biogas reactor. The anaerobic digestion may be performed at thermophilic (typically 50-55°C) or mesophilic temperatures (typically 35-37°C).

In Denmark, the most common technology for anaerobic digestion of municipal organic waste is wet one-step co-digestion with manure or sewage sludge as the main component (thermophilic or mesophilic). One reason for this choice of technology in Denmark is the already existing centralized biogas plants for digestion of animal manure, where municipal organic waste can be an important contribution to the energy production (Hartmann et al., 2004). In Sweden, co-digestion is also the preferred technology for anaerobic digestion of municipal organic waste (Svärd, 2003). However, separate digestion of municipal organic waste may be increasingly favorable in Sweden due to a ban on agricultural application of residues from treated sewage sludge and other waste types with a high content of unspecified industrial contributions (Jansen et al., 2004). In Europe, the distribution between wet and dry anaerobic digestion capacity for solid organic waste (not including sewage sludge and manure) was 40:60 in the year 2000. Mesophilic process temperatures were slightly more common than thermophilic (62% of the capacity), while one-step processes clearly dominated over two-step processes (90% of the capacity) (De Baere, 2000).

The biological treatment module in EASEWASTE is capable of environmental assessment of all the aforementioned anaerobic technology types as well as composting and combined anaerobic and aerobic technologies, assuming that the necessary data are available. Hansen et al (**VII**) contains a detailed description of the biological treatment module.

Methane potential of municipal organic waste

Knowledge of the methane potential of the organic waste is essential to assess the energy yield and thereby the value of the waste for the biogas plant. The theoretical methane potential by full degradation of the organic waste can be determined by the Buswell formula (Symons & Buswell, 1933), if the chemical composition of the waste is known:

Equation 1

$$C_nH_aO_bN_c + (n-\frac{a}{4}-\frac{b}{2}+\frac{3c}{4})H_2O \rightarrow (\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-\frac{3c}{8})CH_4 + (\frac{n}{2}-\frac{a}{8}+\frac{b}{4}+\frac{3c}{8})CO_2 + c\cdot NH_3$$

$$B_{O,th} = \frac{22.4\cdot(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-\frac{3c}{8})}{12n+a+16b+14c} \quad \frac{STPl\ CH_4}{g\ VS}$$

However, the organic waste contains a variety of organic components with varying degradability. A part of the waste may therefore not be degraded and the maximal obtainable methane potential is lower than the theoretical potential calculated by the Buswell formula. The degradability of the organic waste was assessed by the enzyme degradable organic matter (EDOM) value; a test originally developed to assess the degradability of animal fodder. The method is further described in Hansen et al (**I**) and determines the enzyme degradable fraction of the organic matter (VS).

Direct measurements of methane yields from anaerobic digestion of municipal organic waste were not possible at any Danish full-scale biogas plant, due to co-digestion with a much larger fraction of manure or sewage sludge. Therefore, the methane production of municipal organic waste in Danish biogas plants must be estimated based on waste composition and/or laboratory tests.

A method for assessing the methane potential of municipal organic waste in laboratory batch tests was developed. The tests were performed in 2-liter glass bottles under thermophilic conditions with inoculum from a full-scale biogas plant. The accumulated methane production was measured over 50 days to ensure that slowly degradable organic matter was also degraded (Hansen et al, **III**).

The batch tests for methane potential of waste samples based on the VS content showed only minor variations with respect to city, pre-treatment technology, dwelling type and season. The overall average for all performed tests of pre-treated municipal organic waste was 459 STPm^3 CH_4/t VS (Hansen et al, **II**). The governing factor for the methane potential per ton collected waste is therefore the weight-based efficiency of the chosen pre-treatment technology (the distribution of the incoming waste between pre-treated organic waste and reject) rather than the quality of the pre-treated waste. Pre-treatment with shredder + magnet showed the highest expected methane yield per ton collected waste: 107 STPm^3 CH_4/ton waste collected as opposed to 48 - 60 STPm^3 CH_4/t waste collected for screw press and disc screen, respectively (see Table 4). Further details can be found in Hansen et al (**II**).

The retention time in the biogas reactor at full-scale biogas plants is limited (often around two weeks), possibly decreasing the methane yield compared to the obtainable methane potential. A range of pilot-scale tests was performed in 35-liter thermophilic reactors, which were fed daily with municipal organic waste diluted to 5% dry matter. On average, 75-80% of the methane potential (batch tests) could be realized in pilot-scale reactors (Davidsson et al, **X**).

Based on the results, it can be assumed that the methane potential for pre-treated municipal organic waste (with a similar composition as the waste in Table 3) will be in the magnitude of 460 STPm^3 CH_4/t VS. The efficiency of a well functioning biogas

Table 4: Typical methane quantities (potentials and yields) for biomass from different pre-treatment technologies (Hansen et al, II). STPm^3 is one m^3 gas under standard conditions: 0ºC, one atmosphere

Typical methane potentials, CH_4	SP	DS	S+M
Theoretical methane potential (components), STPm^3 CH_4/ton VS	530	530	530
Methane potential, batch experiments, STPm^3 CH_4/ton VS	461	428	487
Methane yield, pilot scale, STPm^3 CH_4/ton VS	369	342	390
Methane yield, pilot-scale, STPm^3 CH_4/ton TS	313	291	351
Methane yield, pilot-scale, STPm^3 CH_4/ton wet biomass	81	90	109
Methane yield, pilot-scale, STPm^3 CH_4/ton collected waste*	48	60	107

*Collected wet municipal organic waste

plant can be assessed to be 75-80%, the resulting methane yield thus being around 360 STPm^3 CH_4/t VS. The methane yield per ton collected waste depends on the efficiency of the chosen pre-treatment technology.

The described methane potentials were all determined for samples of relatively easily degradable municipal organic waste with EDOM values of 88-93% of VS (Hansen et al, **II**). For waste types with a large content of slowly or non-degradable VS (e.g. wood or plastic), the EDOM value may be useful for estimation of the degradability and thus the obtainable fraction of the average methane potential (460 STPm^3 CH_4/t VS), the methane yield.

Storage of anaerobically digested waste

In Denmark, anaerobically digested organic waste is often applied to agricultural land in spring to ensure the most efficient uptake of the nutrients and minimal loss to the environment. Storage of the treated organic waste for up to one year may therefore be necessary.

Due to limited retention time in the biogas reactor, degradable organic matter is present in the digested waste and is a possible source of methane. If the produced methane is collected, it may contribute to the energy production of the biogas plant, while if emitted to the atmosphere it contributes to global warming. Most Danish biogas plants have a storage tank directly connected to the biogas reactor for storage of digested material for one to two months. These tanks are normally covered and have gas collection. Storage tanks for anaerobically digested organic waste may also be separate tanks situated on farms, receiving digested material from the biogas plant by truck. These storage tanks often have no gas collection and may be covered by a floating surface layer of e.g. straw to limit odor and air emissions.

Since co-digestion with either manure or sewage sludge is the most common anaerobic treatment technology for municipal organic waste in Denmark, the methane emissions from the digested municipal organic waste could not be measured directly. Alternatively, it was chosen to measure methane production of digested municipal organic waste in laboratory batch tests at a range of temperatures (5-55°C) and to measure temperature and filling degree in full-scale storage tanks over one year. Based on these data, model estimates were obtained of methane production from storage of anaerobically digested municipal organic waste. Details about the measurements and the suggested model for quantifying methane production in Danish storage tanks are further described in Hansen et al (**IV**).

For a separate storage tank placed on farms under typical Danish conditions, the suggested model estimated the methane production as 0.08 STPm^3 CH_4/t digested waste or 0.4% of the methane potential of the waste delivered to the biogas plant (VS basis). Compared to the global warming savings from the whole anaerobic treatment system, these emissions constituted 3% measured as CO_2 equivalents. The fact that only little digested material is stored during the summer months limits the methane production in the typical storage tanks, since the methane production increases exponentially with increasing temperature. Emptying the storage tanks in September instead of April resulted in a doubling of the methane production during storage, while a warm winter meant 10% increased methane production compared to average temperatures. Whether the produced methane is emitted to the atmosphere depends on the physical features of the storage tank, e.g. cover and gas collection (Hansen et al, **IV**).

Emissions of nitrous oxide and ammonia from the storage tanks were not quantified, since methane was assumed to be the most significant emission.

Agricultural application

Anaerobically digested organic waste may be suitable for application on agricultural land, possibly substituting production and use of commercial fertilizers. The treated organic waste differs from commercial fertilizers with respect to nutrient availability and content of contaminants. This may affect the soil system with respect to e.g. nutrient losses to air and water as well as heavy metal contamination of soils. Governing factors are, among others, waste composition, climate, soil type and agricultural practice. Thus, environmental impacts of the land application of treated organic waste are the result of many complex and interacting processes strongly depending on local conditions.

Quantification of effects from land application in EASEWASTE

Figure 4 shows the effects included in the module for agricultural application in EASEWASTE. The choice of included effects is the result of a thorough study of existing models, available literature and reported field-experiments within the area. Based on these investigations, the most important and quantifiable effects were chosen (Hansen et al, **VI**).

The effects of one application of treated municipal organic waste extend beyond a single growing season and the environmental assessment must therefore consider the accumulated effects in the year of application *and* the following years. All emissions to air and water are quantified as emission coefficients, defined as extra loss (kg) of the substance per kg applied with the treated organic waste compared to a standard scenario

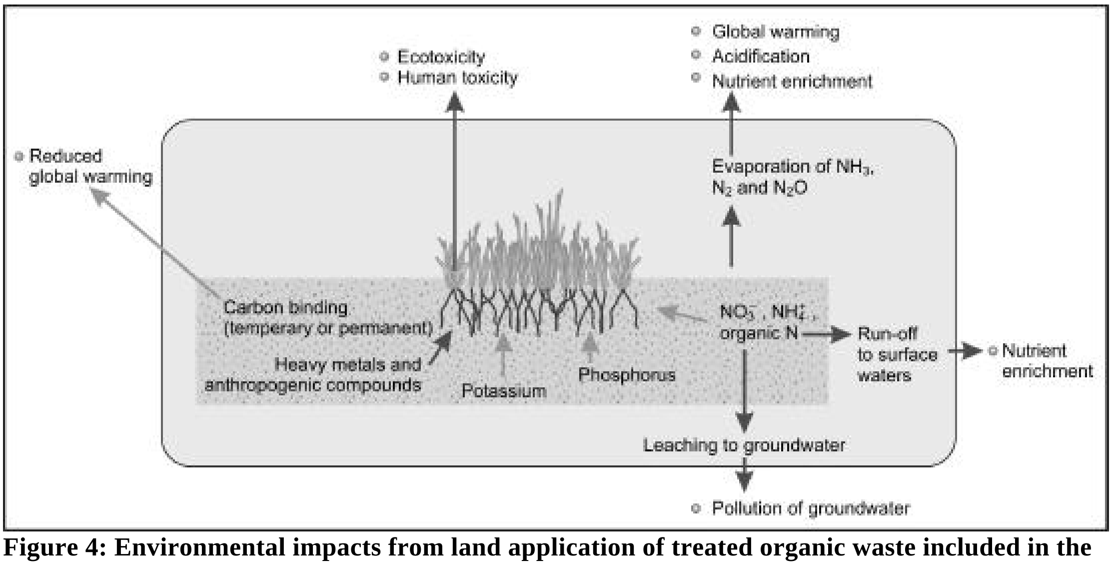


Figure 4: Environmental impacts from land application of treated organic waste included in the land application sub-model in EASEWASTE (Hansen et al, VI)

using commercial fertilizers (further details in Hansen et al (**VI**)). Thus, the emission coefficient quantifies the extra emission originating from the use of treated organic waste substituting commercial fertilizers.

Quantification of the emission coefficients is beyond the scope and capability of waste management models. Therefore, the agro-ecosystem model Daisy was used to estimate emission coefficients for the land application of treated organic waste in a range of typical Danish scenarios (Bruun et al., 2005). Similar agro-ecosystem models may be used to estimate emission coefficients for different conditions.
Table 5 shows examples of emission coefficients based on Daisy simulations for four Danish scenarios: application of anaerobically digested or composted organic waste to agricultural land in western Denmark on either sandy or loamy soil. The resulting emissions depended on different parameters (Hansen et al, **VI**):

- Ammonia loss mainly depended on the fraction of nitrogen present as ammonia. Typically 15% of the applied ammonia was emitted to air.

Table 5: Input data for the land application model in EASEWASTE for the four presented scenarios: Anaerobic digestion residue and compost applied on loamy and sandy soil on a plant farm in western Denmark. The emission coefficients are based on simulations of the actual scenarios in Daisy. The utilization ratios for nitrogen are set according to the Danish law.

		Anaerobic digestion residue		**Compost**	
	Units	Loam	Sand	Loam	Sand
Ammonia evaporation	Fraction of ammonia N	0.15	0.15	0.15	0.15
Nitrous oxide (N_2O-N) evaporation	Fraction of nitrogen applied with the treated org. waste	0.014	0.016	0.014	0.015
Nitrate run off (NO_3^--N) to surface water	Fraction of nitrogen applied with the treated org. waste	0.19	0	0.08	0
Nitrate leaching (NO_3^--N) to groundwater	Fraction of nitrogen applied with the treated org. waste	0.18	0.60	0.07	0.53
MFE* value N	Fraction of applied nutrient substituting commercial fertilizer	0.4	0.4	0.2	0.2
MFE* value P	Fraction of applied nutrient substituting commercial fertilizer	1	1	1	1
MFE* value K	Fraction of applied nutrient substituting commercial fertilizer	1	1	1	1
C binding Infinite/100 years	Fraction of C applied with the treated org. waste	0 / 0.14	0 / 0.10	0 / 0.14	0 / 0.09

*) MFE = Mineral Fertilizer Equivalent value (compares the utilization of the organic fertilizer with that of commercial fertilizer)

- The level of nitrous oxide emissions was relatively stable for the four investigated scenarios (1.4-1.6% of the nitrogen), partly due to the fact that a simplified method was used for quantification, since exact quantification was very complicated, even for the agro-ecosystem model.
- No direct run-off of nitrate to surface water was found. Nitrate emissions to surface water via drains were found only for loamy soils, since sandy soils are normally not drained. Emissions of nitrate through drains were larger for anaerobically digested waste (19% of the nitrogen) than for compost (8% of the nitrogen), due to the large fraction of nitrogen in compost bound in organic matter.
- Nitrate leaching to the groundwater was largest for sandy soils (53-60% of the nitrogen compared to 7-18% for loamy soils), since more nutrients were washed out. For the same soil type the emissions were largest for anaerobically digested waste.

The substitution of commercial fertilizer is determined from the nutrient content in the treated organic waste and their mineral fertilizer equivalent (MFE) value (plant-availability of organic waste compared to plant availability of commercial fertilizers). The determination of the MFE values are based on field experiments, which showed MFE of 0.8 and 0.3 for mineral and organic nitrogen respectively, while phosphorus and potassium proved to be as effective as commercial fertilizers (MFE = 1) (Bundgaard et al., 1993, Nielsen, 1994). However, for each specific case the actual substitutional effect must be assessed for each nutrient including the effect of legal regulation and agricultural practice. In Denmark, the legal regulations define the MFE values for nitrogen in anaerobically digested or composted organic waste to 0.4 and 0.2 respectively, meaning that the farmer has only to reduce the amount of applied commercial fertilizer by 40 or 20% of the nitrogen inherent in the treated organic waste.

Degradation of organic matter results in release of carbon dioxide, which is a global warming gas. However, carbon dioxide from degraded fresh organic matter is considered neutral with respect to global warming, since the plants have recently removed an equal amount of carbon dioxide from the atmosphere during growth. Non-degraded organic matter stored in the soil thus represents a “saved” emission of carbon dioxide (carbon sequestration). The Daisy simulations showed that the fraction of applied carbon remaining in the soil after 10, 50 and 100 years constituted 0.63-0.84, 0.17-0.37 and 0.02-0.16, respectively, depending on the actual conditions in the scenarios. In EASEWASTE it is possible to include carbon sequestration as a percentage of the applied carbon permanently bound in the soil.

The heavy metal content in the municipal organic waste is assumed unchanged through the treatment and storage step and therefore all heavy metals present in the waste will be emitted to the agricultural soil. The heavy metal content of the substituted commercial fertilizers is included as “saved” emissions.

Effects such as increased soil quality or increased crop resistance towards certain diseases cannot be quantified with respect to the impact categories in EASEWASTE and are therefore not included in the land application module.

Table 6: Data for environmental assessment of substitution of peat with treated municipal organic waste (Vogt et al, 2002).

Substitution	1 kg peat (dm)/kg VS in digested waste
CO_2 saving	2 kg CO_2/kg waste VS
Dry matter (dm)	40% of wet weight
Volatile solids (VS)	94-99% of dm
Density, fresh	850-900 kg/m^3
Density	350 kg/m^3
Density, dry	120-250 kg/m^3
Processing	0.86 l diesel/t dm (peat) 0.53 kWh/t dm (peat)

Separation of the treated organic waste

The treated organic waste may be separated in different output streams. In Grindsted (Denmark), where municipal organic waste is co-digested with sewage sludge, the digested material is separated into a dry fraction (24% dm), which is composted and utilized in agriculture, and a wet fraction (2% dm) directed back into the wastewater treatment plant. Another solution is agricultural utilization of the wet fraction and disposal (landfill cover) or incineration of the dry fraction. The Danish legislation does not allow incineration of anaerobic digestion residue mainly consisting of manure (relevant for co-digestion of municipal organic waste and manure). However, this is currently being discussed and may be changed (FVM, 2005). In the combined biological treatment plant described in Hansen et al (**VII**) the treated organic waste is separated into several fractions. The liquid residue from the biogas reactor is re-circulated to the anaerobic phase of the treatment. The solid fraction of the treated waste is separated in a residue fraction (plastic, paper and similar items) for incineration and an organic fraction for utilization in agriculture or greenhouses (Kjellberg et al., 2005).

Peat substitution

The treated organic waste may be used in private gardens, plant production or green houses substituting a mixture of peat and commercial fertilizers. Peat consists of old, partly degraded organic material and is therefore considered a fossil reserve. When the peat is utilized, the organic matter is degraded and the carbon dioxide released to the atmosphere contributes to global warming (contrary to carbon dioxide from organic waste). Substitution of peat with treated organic waste therefore saves this limited fossil reserve and reduces the effect on global warming.

Data for environmental assessment of peat substitution based on Vogt et al. (2002) can be seen in Table 6. Transportation distances are not included, since they depend on the origin of the peat production. Different end utilizations of the peat products require different levels of fertilizer addition. Being too specific, substitution of commercial fertilizers yielded by the substitution of peat products is not included in Table 6.

Comparison of models

Hansen et al (**V**) investigated the land application module in the following five models for environmental assessment of waste systems: DST (Decision Support Tool, USA), IWM (Integrated Waste Management, UK), THE IFEU PROJECT (D), ORWARE (ORganic WAste REsearch, SE) and EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies, DK).

The DST and IWM models were developed for overall assessment of whole waste systems and deal with use of treated organic waste in agriculture in a rather simple way with few scenario-specific results. THE IFEU PROJECT, ORWARE and EASEWASTE, were all developed with special focus on organic waste: ORWARE was originally developed for environmental assessment of organic waste, the land application module in THE IFEU PROJECT was developed specifically for assessing different treatment technologies for organic waste and the development of EASEWASTE was influenced by a strong debate in Denmark concerning treatment of organic waste. Therefore, these models have included considerably more details in their land application modules.

A case study estimating the environmental impacts from land application of one ton of composted source-sorted municipal organic waste was performed to compare the results from the different models. The contributions from the DST and IWM models were limited and not dependent on waste composition or local agricultural conditions. The LCA models, THE IFEU PROJECT, ORWARE and EASEWASTE, used the same overall approach for quantifying the impacts of the system. The results of the case study for these models were divided into impacts from direct land application (LA), avoided production of commercial fertilizers (FP) and avoided energy production from fertilizer production (EP), see Figure 5.

The impact on global warming directly from land application differed by a factor two between the three models. This impact mainly originated from formation of nitrous oxide, which depends on the soil conditions. ORWARE showed a significantly higher contribution to nutrient enrichment from land application than the two other models due to long-term leaching of nitrate (nitrogen not lost within the first year enters a nitrogen pool in the soil, which is eventually lost to the environment if not taken up by plants). Contributions to acidification were one magnitude larger for THE IFEU PROJECT than for the two other models due to the assumption that ammonia evaporation occurs from both organic nitrogen and ammonia in the compost. EASEWASTE and ORWARE assume ammonia evaporation only from the content of ammonia-nitrogen. Since the ammonia content in compost is low compared to the content of organic nitrogen, ammonia formation from organic nitrogen strongly influences the ammonia evaporation (thus acidification) even though the percentage of organic nitrogen lost as ammonia is low (4%).

The toxicity categories were not comparable between the models (and not included in ORWARE). They are therefore not included in Figure 5.

In the case study the same type of commercial fertilizers were substituted in all three models. The different potential impacts from avoided production of fertilizers originate from the use of different MFE values.

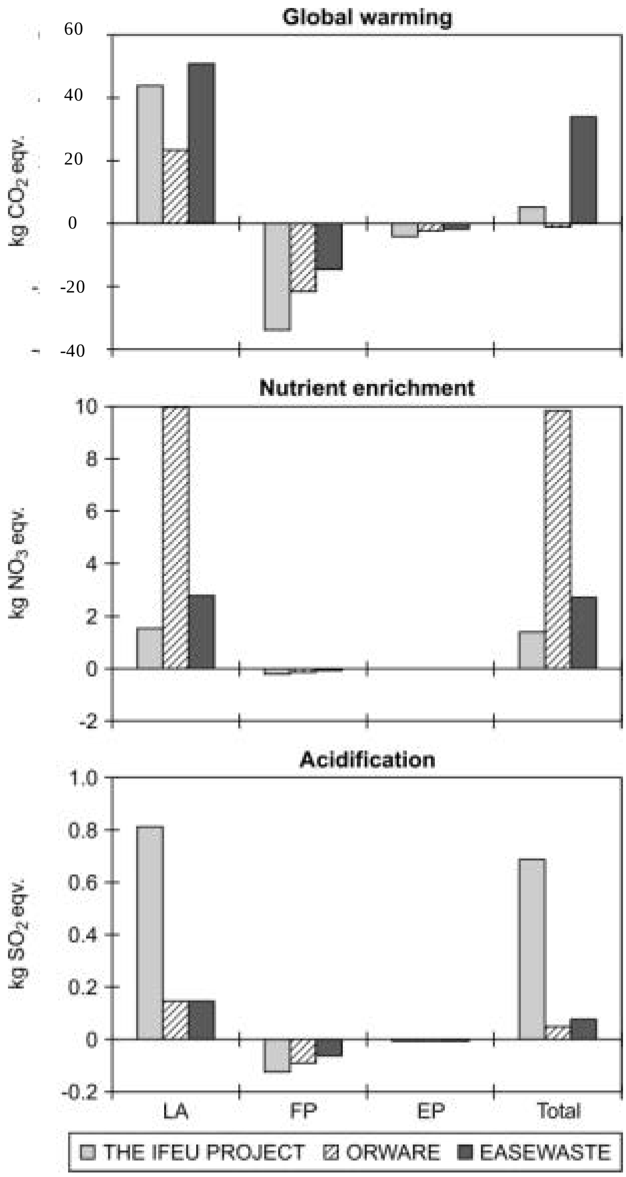


Figure 5: Impacts on global warming, nutrient enrichment and acidification from application of 1 ton of composted organic MSW in the three investigated LCA models (Hansen et al, V). LA= Land application (direct), FP=Fertilizer production, EP=Energy production

In the case study, “identical” scenarios were simulated and differences in the results were therefore caused by slightly different assumptions, quantification methods and environmental impact assessment in the three models. The differences were especially significant for nitrous oxide formation (global warming), nitrate loss (nutrient enrichment) and ammonia evaporation (mainly acidification).

Changes in local conditions (e.g. soil type, farm type, climate and legal regulation), waste composition or choice of external processes (e.g. fertilizer types or energy source) will further strongly affect the environmental assessment. Due to the many factors influencing the results, the interval for environmental impacts from land application of treated organic waste is very broad.

The anaerobic treatment system in Århus; a case study

To fully assess the environmental effects from anaerobic treatment of municipal organic waste and compare the contributions from each part of the treatment system, a case study of the waste treatment in the municipality of Århus was performed (Kirkeby et al, **IX**). The study builds on specific data for the system in Århus and the results obtained are therefore not necessarily representative of other systems.

System and scenarios

In the municipality of Århus, a source-sorting system for municipal organic waste was implemented in 2001. The system was based on optical sorting of green and black bags containing organic waste and the remaining waste, respectively. The bags were collected by the same trucks and sorted at the optical sorting plant separating the green bags from the black. The green bags were further treated by bag opener and screw press before anaerobic digestion in the local biogas plant. The black bags were incinerated together with the reject from pre-treatment of the green bags (Tønning, 2003).

The total amount of municipal waste constituted 81 582 ton/year including 17 000 tons organic waste, 1004 tons iron scrap, 18 706 tons paper and 4559 tons glass, all suitable for recycling. Thus, the 17 000 tons organic waste constituted around 20% of the total amount of municipal waste or 30% of the mixed municipal waste fraction (iron, paper and glass for recycling not included). Based on measurements at the optical sorting plant, it was assessed that the 17 000 tons municipal organic waste in green bags would yield around 6000 tons pre-treated organic waste for anaerobic digestion, meaning that 2/3 of the collected organic waste (wet weight) was incinerated. The source of electricity and heat (consumed and produced) was assumed to be the local power plant.

The environmental assessment in Kirkeby et al (**IX**) included the following four scenarios:

A Assessment of the whole waste system (municipal waste). Anaerobic digestion of the organic fraction, incineration of the remaining waste.

B Assessment of the whole waste system (municipal waste). Incineration of the organic fraction together with the remaining waste.

C Assessment of the source-sorted municipal organic waste fraction only. Anaerobic digestion (including incineration of the reject).

D Assessment of the source-sorted municipal organic waste fraction. Incineration.

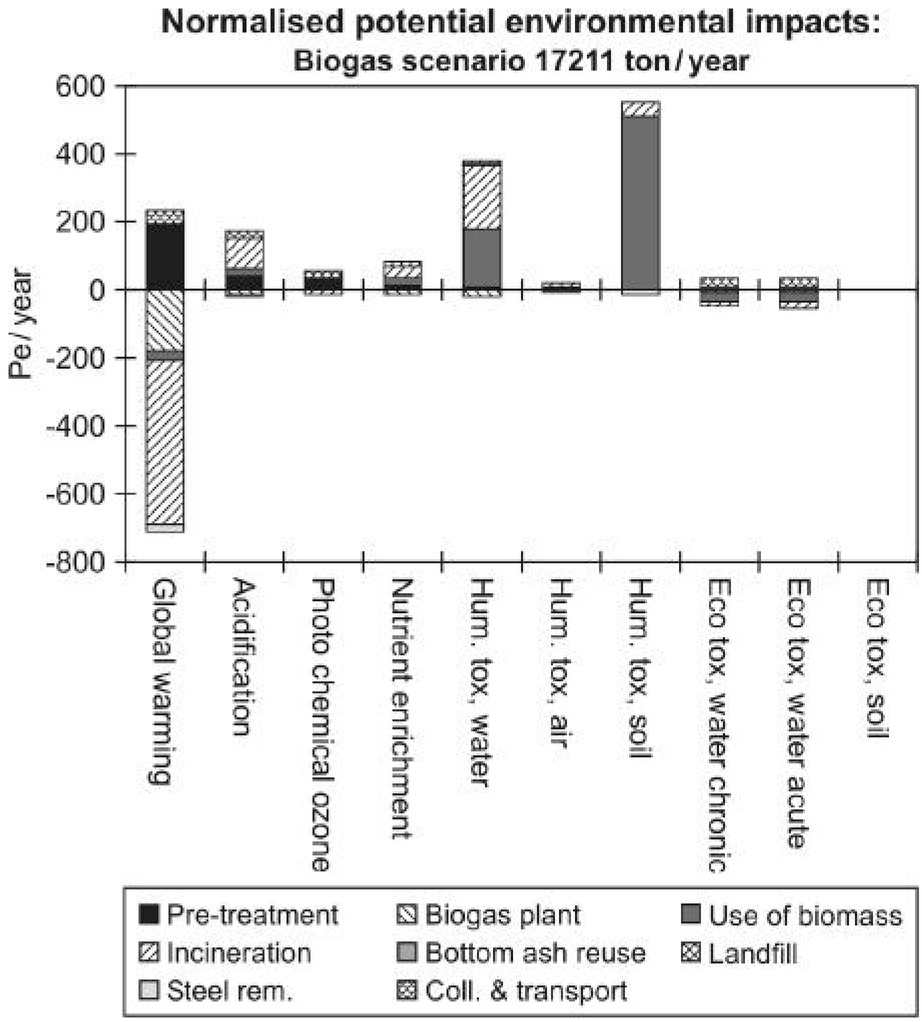


Figure 6: Environmental effects from Scenario C (anaerobic treatment of municipal organic waste) from each part of the waste treatment system.

Results

Scenario A and B showed that choice of treatment system for the organic fraction (incineration or anaerobic digestion) had only a minor influence on the environmental impacts of the waste system. One reason was that the organic waste treated by anaerobic digestion constituted only 20% of the total amount of waste.

Scenario C focused on the impacts from anaerobic digestion of the municipal organic waste fraction (including incineration of the residues). Figure 6 shows the normalized potential impacts from scenario C from each part of the waste system.

Global warming

The potential global warming savings in Scenario C were obtained by waste-based energy production from biogas and incineration substituting energy from fossil fuels. Since a large part of the source-sorted municipal organic waste was incinerated due to low efficiency of the pre-treatment plant, the savings obtained from incineration were larger than those from biogas. A sensitivity analysis was performed assuming a larger percentage of the collected organic waste going to anaerobic digestion (60% of the dry matter and 73% of the water). Since more organic matter was anaerobically digested and less was incinerated, the global warming savings increased for anaerobic digestion and decreased for incineration. However, the overall savings increased only marginally. No considerable changes were seen in other impact categories.

Collection, transport and pre-treatment are activities consuming fossil energy therefore contributing to global warming. The effects from pre-treatment included energy for production of extra-strong plastic bags for the system. The normal plastic bags broke in the collection trucks and during handling at the optical sorting plant, making sorting by recognition of bag color inefficient. In Kirkeby et al (**IX**), a sensitivity analysis showed that avoiding the extra plastic consumption, but assuming the same efficiency, increased the potential savings in global warming by 25%.

Increased energy efficiency at the biogas plant significantly increased the savings in global warming, while increased biogas potential of the waste (11% on VS basis) increased the global warming savings by 5%. Storage of the anaerobically digested organic waste was not included in Scenario C. However, Hansen et al (**IV**) showed that this contribution is marginal (may decrease the total global warming savings from anaerobic treatment of the organic waste by ~3%), assuming average Danish conditions. Carbon sequestration was not included in the standard scenario C. A sensitivity analysis assuming permanent binding of 15% of the applied carbon in the soil showed increased potential global warming savings of 8%.

Acidification

Acidification is mainly caused by emissions from the incineration plant (NO_X and SO_2) and to some extent by emissions from collection and transport. The contributions from the optical sorting plant originate from the energy consumption.

Photochemical ozone formation

The contributions to photochemical ozone formation were all related to energy consumption and/or production.

Nutrient enrichment

The contributions to nutrient enrichment were relatively small and originated from all parts of the system. The energy production at the biogas plant “saved” air emissions (mainly NO_X) due to substitution of fossil energy. The energy consumption in the optical sorting plant and incineration of the reject contributed with NO_X emissions to air. The contributions from land application were caused by nitrate emissions to surface waters and air emissions of ammonia.

Toxicity

The toxicity effects were mainly caused by heavy metal emissions to the soil through agricultural application of the treated organic waste. Therefore, the magnitude of the potential toxicity impacts is very sensitive to the heavy metal content in the treated organic waste, which is often determined with a relatively large uncertainty. A sensitivity analysis (see Kirkeby et al (**IX**)) decreasing the heavy metal content in the waste to half of that assumed in Scenario C decreased the corresponding toxicity effect by more than 50%.

Comparison of anaerobic digestion and incineration

Kirkeby et al (**IX**) compared the environmental effects from anaerobic digestion and incineration (Scenario C and D). Incineration was marginally better regarding global warming and human toxicity to water and significantly better considering human toxicity to soil. For the remaining environmental impact categories the differences were small. Except for human toxicity to soil, the differences between the two systems all corresponded to less than 100 people's annual impact (person equivalents, PE) for each impact category. Considering the waste system assessed handles the waste produced from nearly 300 000 inhabitants, these differences seem minor.

Conclusions

The main contributors to many of the environmental impact categories were energy related. Thus, the broad range of factors throughout the waste system contributing to energy production or consumption strongly affects the results. The choice of energy source consumed and/or substituted is also important for the assessment.

Apart from energy-related subjects, the effect of nitrate emitted to surface waters, ammonia evaporation and heavy metals added to agricultural soil strongly affected the environmental assessment of the system in the case study.

The anaerobic treatment of source-sorted municipal organic waste from nearly 300 000 people did not influence any of the assessed environmental impact categories by more than 600 PE (positive or negative); corresponding to maximum 600 persons' annual impact. The environmental impacts from the alternative treatment system, incineration, were in the same order of magnitude with marginal differences in the different environmental impact categories.

The case study illustrated the applicability of the constructed tool for quantification of environmental effects from anaerobic treatment of source-sorted municipal organic waste. The modules regarding biological treatment of organic waste in EASEWASTE are flexible regarding inclusion of specific data and the results depend to a large extent on waste composition, technology choice and site-specific parameters. EASEWASTE enables assessment of one single waste fraction (e.g. municipal organic waste) as well as a whole waste system including several waste fractions. It may be used for comparison of different waste treatment systems as well as identification of the largest environmental impact potentials within one treatment system.

Discussion and conclusions

This thesis and the projects related to it have resulted in development of a tool for environmental assessment of anaerobic treatment of municipal organic waste. The tool builds on literature studies and thorough investigation of a number of Danish source-sorting and pre-treatment systems. Thus, a range of data examples are now available, describing Danish systems with respect to collection system, waste composition, pre-treatment efficiency and biogas potential. The exact biogas yield from the biogas plants, emissions from storage and effects from agricultural application of the treated organic waste could not be measured directly. These effects were estimated based on a combination of field sampling, laboratory tests, simulations in other models and literature studies.

Systems for anaerobic treatment of municipal organic waste vary considerably with respect to collection system, pre- and post-treatment technologies, anaerobic digestion technology and utilization of the treated organic waste. These variations significantly influence the environmental impacts of the system. Furthermore, the environmental impacts are affected by site-specific conditions such as climate, soil type and agricultural practice as well as system-specific conditions, e.g. choice of the substituted energy source. The presented data examples are therefore only directly representative for similar systems under similar conditions. However, the examples indicate order of magnitude for the described effects and identify the most important parameters in the waste system influencing these effects.

Environmental effects: Magnitude and governing factors

The case study of the municipality of Århus is one example of quantification of environmental effects from anaerobic treatment of municipal organic waste including all parts of the waste system. Figure 7 shows the sensitivity analyses performed in Kirkeby et al (**IX**). Energy-related parameters had a large influence on the results, which was also found in other studies, e.g. Dalemo et al. (1998) and Pitschke et al. (2004). The quality of the data used in the case study was relatively high, due to many case-specific data. Generally, the quality of input data is important for the results of the environmental assessment, since anaerobic waste treatment systems can be very different and the environmental effects from the systems depend on a range of parameters.

Collection, pre-treatment and anaerobic digestion

The collection system influenced the composition of the collected waste through sorting instructions and choice of collection bag material, affecting the degradability of the waste as well as the content of ash, plastic and fibers (Hansen et al, **I**). This affects the methane potential of the waste and thus possibly the biogas production, which is important for the energy balance of the system. The screw press exemplified a selective pre-treatment technology with respect to easily degradable organic matter and water (Hansen et al, **II**). The methane potentials (batch tests) of waste samples from the investigated systems were in the range of 428-489 STPm^3 CH_4/t VS (average 459 STPm^3 CH_4/t VS).

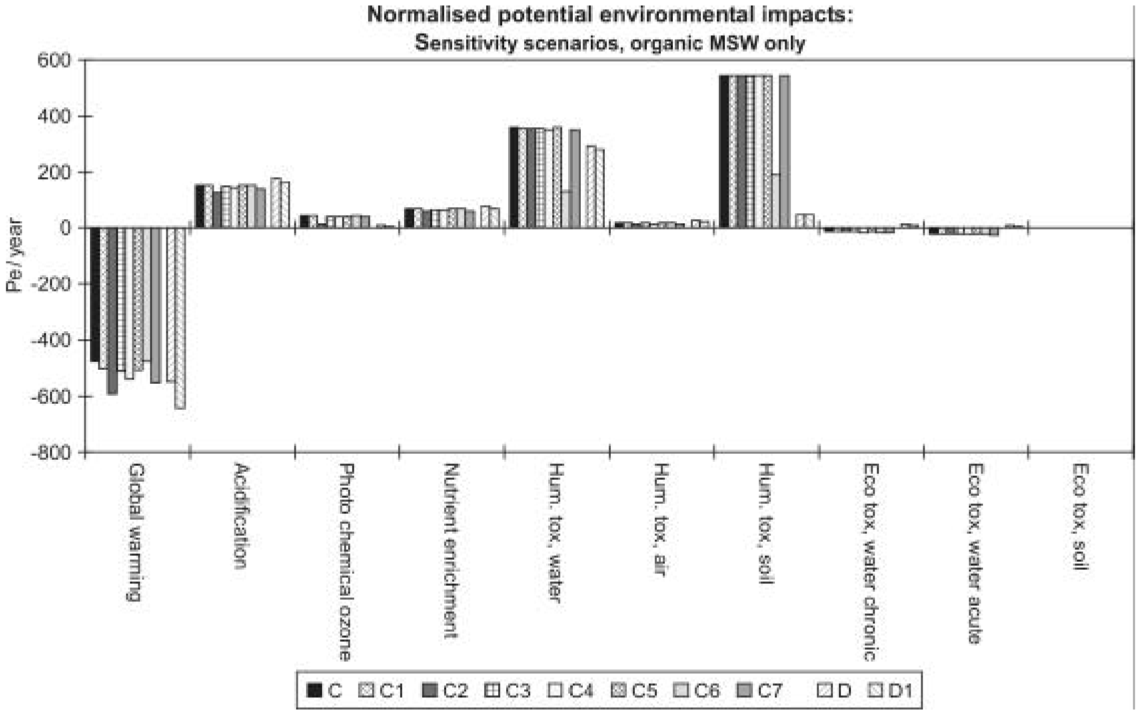


Figure 7: Normalized potential environmental impacts from sensitivity analysis of the case study of Århus.

C	**Scenario C: Anaerobic digestion of the municipal organic waste including incineration of residues.**
C1	**11% increase in the methane potential (VS based)**
C2	**Avoiding extra consumption of plastic for the waste collection bags**
C3	**50% decreased energy consumption for the pre-treatment**
C4	**Energy efficiency for the biogas plant increased from 70 to 88%.**
C5	**Unburned methane emissions from the biogas engine decreased from 3 to 1% of the produced methane.**
C6	**The content of heavy metals is half of that in Scenario C and Mn is zero.**
C7	**Electricity efficiency increased and the heat efficiency decreased in the incineration plant.**
D	**Scenario D: Incineration of the municipal organic waste fraction.**
D1	**Energy efficiencies at the incineration plant as in Scenario C7.**

The effect of increased methane potential (VS based) was investigated in Scenario C1 (Figure 9): 11% higher methane potential increased the global warming savings from the system by 5%.

The pre-treatment technology strongly affects the distribution of the collected waste between pre-treated waste and reject and thus the methane potential per ton collected waste. The investigated pre-treatment technologies routed 2-41% (ww) of the collected waste to the reject fraction (80-98% organic material). This distribution yielded methane potentials of 48-107 STPm^3 CH_4/t collected waste (Hansen et al, **II**). The further treatment of the reject fraction determines whether inefficiency of the pre-treatment plant causes negative effects on the energy balance of the system. If the reject is incinerated with high energy efficiency (as in the case study), the environmental advantages obtained by the system may not decrease despite inefficiency in the pre-treatment step. In this case a dry reject fraction and a correspondingly wet pre-treated waste fraction may be preferable (Ostrem et al., 2004). However, if incinerated with lower energy efficiency or disposed in landfill, the large reject fraction will have negative environmental consequences for the system.

The effect of the extra-strong plastic bags needed for the system in Århus (C2) illustrates the influence of additional energy consumption (25% of the global warming savings). Energy savings in the pre-treatment plant had a minor influence (C3), while increased energy efficiency at the biogas plant (C4) made the biogas solution comparable to incineration (Scenario D) with respect to global warming. Increased energy efficiency at the incineration plant (C7 and D1) strongly improved the results of the scenarios.

Decreased methane emissions from the biogas engine did not affect the overall scenario significantly (C5). If anaerobic digestion is followed by composting, air emissions from the composting process may be of importance. However, the interval for these emissions is large and depends on a range of factors (see Hansen et al (**VII**)).

Storage

Storage of the treated organic waste was not included in the case study. According to Hansen et al (**IV**), methane emissions from separate storage tanks can maximally decrease the global warming savings from the anaerobic treatment system by 3%, assuming typical Danish conditions. However, a warmer Danish climate (4°C increased temperature) increased the methane production in the storage tanks by 60% and even higher temperature will have dramatic effects, since the methane production is exponentially related to temperature. Change in the operational pattern of the storage tanks (filling and emptying during the year) can increase the methane production by 70%. The fraction of the produced methane emitted from the storage tanks, and thus contributing to the environmental effects, depends on whether the tanks are covered. If the storage tanks have gas collection, the produced gas may even contribute to the energy production of the biogas plant.

Therefore, assuming Danish conditions, the methane emissions from storage of anaerobically digested organic waste have only a minor influence on the overall results. However, changes in the operational procedure of the storage tanks or (especially) increased temperature may increase the methane emissions from storage to a level significantly influencing the results of the waste system, assuming that the tanks are not adequately covered.

Application to agricultural land

Nitrate loss to surface water and ammonia emission to air contributed significantly to the overall results of the system. Coefficients for nitrate loss to surface waters (run-off and loss through drains) were found in the interval of 0-30% of the applied nitrogen, mainly depending on soil type and precipitation. The ammonia emissions typically constituted 15% of the applied ammonia in the waste and thus were mainly controlled by the chemical form of the nitrogen in the waste.

The potential toxicity impacts of the system, especially human toxicity, were strongly affected by the heavy metal content of the organic waste due to application of the treated waste to agricultural land (C6). Several issues should be considered when evaluating the results of the potential toxicity categories. The calculation of potential ecotoxicity impacts includes the actual toxicity of each compound (determined in laboratory tests) and the distribution of the emitted compound between air, water, surface water, ground water and soil. The potential human toxicity impacts also include the human exposure routes directly through these compartments or through food (plants, meat, milk or fish). All this information is compiled in one factor for each compound: the toxicity factor (Wenzel et al., 1997). Due to the range of assumptions included in the toxicity factor, the actual obtained toxicity effect may be very far from the calculated potential effect. In principal, the toxicity factors should include as much local information as possible (similar to risk assessment). However, this would demand large data material for each location and could hardly be included in a general method such as LCA.

The potential toxicity impacts have often been omitted from LCA studies due to the aforementioned problems, e.g. in Poulsen & Hansen (2003). In Sundqvist et al. (2002) the potential toxicity impacts were not presented, but only discussed based on the heavy metal flow through the system. Vogt et al. (2002) operated with carcinogenic risk (human toxicity), PM10 risk (human toxicity) and the amount of emitted copper and zinc (ecotoxicity). Pitschke et al. (2004) chose to represent human toxicity by the amount of emitted cadmium and SO_2 and ecotoxicity by ammonia and NO_X. This variety of quantification methods for toxicity reveals shortcomings and uncertainty of the existing methods, which was also pointed out in Fridriksson et al. (2002).

Despite the problems, toxicity should be included in environmental assessment, since it represents important potential environmental impacts. However, when evaluating potential toxicity impacts, the aforementioned problems should be considered.

Variations in the heavy metal content of the municipal organic waste may be introduced by actual differences between the collection systems, uncertainty in the sampling procedure or by including different components in the sampling program. Thorough sampling and standardization of the included heavy metals is therefore a requirement before comparing the toxicity of different systems.

Dalemo et al. (1998) compared the heavy metal load per hectare agricultural land by a certain phosphorus dose from different organic fertilizer types. Generally, the heavy metal load from anaerobically digested municipal organic waste was two to three times higher than from manure. However, the load of copper and nickel from manure was higher than from the organic waste. Comparing per kg nitrogen, the content of copper, zinc, cadmium and chromium was higher in pig manure than in anaerobically digested municipal organic waste, while the content of nickel and lead was highest for the waste (RVF, 2005). If the treated organic waste substituted manure instead of commercial fertilizers, the potential toxicity impacts from agricultural application would therefore be considerably lower than in the performed case study. However, since manure *must* be applied as fertilizer due to Danish legislation, commercial fertilizers (with generally lower heavy metal content) are considered the marginally substituted fertilizer type under Danish conditions.

Carbon sequestration is often mentioned as an important effect of agricultural application of treated organic waste; however, quantification of this effect is difficult. Bruun et al. (2005) simulated the retention of carbon in soil for different Danish scenarios in the agro-ecosystem model Daisy. After 10, 50 and 100 years the fraction of applied carbon remaining in the soil constituted 0.63-0.84, 0.17-0.37 and 0.02-0.16, respectively, depending on the scenarios. Thus, the delay of carbon dioxide release is clear. However, how to include this effect in the environmental assessment is a methodology question. When quantifying nutrient losses from one application of organic waste the goal was to determine the total effect of the application, meaning that the yearly effects were accumulated until no more (simulated) effects could be related to the application. Applying the same principle to carbon sequestration, the effect of delayed carbon release will be zero, since each carbon atom will eventually be released (Audsley et al., 1997). In the impact assessment, release of one kg of CO_2 has a certain defined impact in the atmosphere during its lifetime (120 years in the EDIP method) not depending on the time of release. Therefore, temporary binding of carbon will not affect the global warming impact in the EDIP method. However, if the application is considered to contribute to a permanent increase of the carbon level in the soil due to changed agricultural practice, it will represent an actual decrease in CO_2 release thereby contributing (by a saving) to the global warming impact. More details can be found in Hansen et al (**VI**).

Canals (2003) suggested using the content of organic matter in the soil as a separate indicator for soil quality in LCA assessment, since the level of organic matter (carbon) is an indicator of a range of soil qualities, such as chemical, physical and biological soil fertility, infiltration rate and water retention capacity. However, assessment of the actual degradation of applied organic matter requires detailed simulations of soil processes and many site-specific data. In Dalemo et al, (1998) the addition of organic carbon to agricultural soil was included as a separate impact category to represent the potential for improved soil quality. However, the extent of degradation of the carbon was not assessed. In EASEWASTE increased soil quality and increased crop resistance toward diseases were not included, since they could not be quantified at a general level. Thus, despite a generally expressed need for developing methods to include these types of effects in environmental assessment (e.g. Poulsen & Hansen (2003) and Fridriksson et al. (2002)), they must at present be assessed separately and qualitatively along with the quantitative results of the existing environmental impact categories.

Energy substitution

All energy produced in the waste system is assumed to substitute another energy source. The choice of this energy source may be crucial for the outcome of the environmental assessment. In Denmark the substituted energy source will often be based on fossil fuels, which strongly affects a range of environmental impacts categories. In Kirkeby et al (**IX**) production of electricity and heat at the local power plant was used as energy source. Fridriksson et al. (2002) recommend using case-specific local energy sources as substituted energy when assessing specific cases and more general energy sources (national mix or marginal energy sources) for more general evaluations, e.g. comparisons of two waste technologies.

Often, either the national average energy mix or the marginal energy source is used. The choice of energy source for substitution is an ongoing discussion and should be a matter of attention when performing environmental assessments.

Anaerobic digestion contra other waste treatment technologies

Whether an environmental assessment would recommend anaerobic digestion as treatment technology for municipal organic waste depends on the alternative treatment options. In Kirkeby et al (**IX**) anaerobic digestion of the municipal organic waste from Århus was compared to incineration at a Danish incineration plant producing electricity and heat (energy efficiency 11 and 69%, respectively). The environmental impacts from the two systems were in the same order of magnitude with marginal differences in the different impact categories. The same results were found in Sundqvist et al. (2002), where neither incineration nor anaerobic digestion of municipal organic waste could be appointed as the preferable solution in all the environmental impact categories.

Less efficient incineration or more efficiency at the biogas plant would probably make the anaerobic digestion technology preferable to incineration. Since anaerobic digestion is a relatively new waste treatment technology (De Baere, 2000), further improvements in e.g. energy efficiency are likely.

In many countries, the main part of the municipal waste is disposed in landfills. In Mbuligwe & Kassenga (2004) feasibility studies and strategies for implementing anaerobic digestion in Dar es Salaam, Tanzania, were described. The implementation of the biogas plant was assessed to clearly improve the existing waste system through decreasing the amount of waste disposed in landfills and substituting energy from wood, which is a limited resource in the area. Generally, anaerobic digestion will be preferable to landfilling due to the energy production. Inadequately control of the landfills may further increase the environmental impacts through emissions to air and water.

Composting and anaerobic digestion of municipal organic waste have similar environmental effects regarding agricultural application of the residues. However, the lack of energy production from composting and the risk of emissions from the process (especially open windrow composting) generally make this technology less attractive than anaerobic digestion from an environmental point of view.

Application and perspectives

The developed EASEWASTE modules concerning biological treatment fully live up to the guidelines for LCA in the waste management sector developed for Nordic countries (Fridriksson et al., 2002). At some points the tool even exceeds the recommendations by including more details, e.g. nutrient losses and carbon sequestration in the agricultural application module. The main focus of the work in this PhD thesis was on anaerobic digestion of municipal organic waste; however, the biological treatment module in EASEWASTE also includes composting and with some modifications many of the findings of this thesis are applicable for other organic waste types, such as industrial organic waste and garden waste.

As requested in the national Danish waste strategy, EASEWASTE can include local conditions in the environmental assessment of biological treatment of municipal organic waste (The Danish Government, 2003). The tool represents an extension of the three LCA-based waste indicators presented in the waste strategy (resource consumption, primary energy consumption and landfill requirement), as a full LCA is performed. The results of the assessment include environmental impact potentials (global warming, acidification, nutrient enrichment, ozone depletion, photochemical ozone formation, toxicity), resource consumption (Al, Cu, Fe, coal, natural gas, water etc.) and economics (business economics and welfare economics). The assessment can be based on case-specific data, if available, or the EASEWASTE database. The inherent data may be appropriate for an environmental screening of a waste system without detailed knowledge of all processes. However, case specific data will yield more correct results.

The increased knowledge of anaerobic digestion of municipal organic waste and the developed LCA-tool can support decisions in waste management policy, since it allows comparison of estimated potential environmental effects with other important factors in waste management, such as economics, policy and service. The tool will be applicable for supporting general decisions of future developments in waste management (EU, governmental or EPA level) as well as concrete planning of waste systems in e.g. municipalities.

Further research

The case studies performed in this thesis and the connected papers all assumed Danish conditions and relatively similar treatment systems. The developed tool should be used to perform a range of case studies of different waste systems including anaerobic digestion to compare the results and identify the governing parameters under different conditions. Within the European Union, traditions for waste treatment, existing waste systems, energy production, climate and agricultural practice differ considerably. These parameters all affect the results of environmental assessment of anaerobic digestion of organic waste. A range of case studies performed for different EU countries would be a strong tool for EU politicians in the further development of a sustainable waste policy for Europe. The recommendations for treatment of municipal organic waste based on these environmental assessments may differ between regions depending on the local conditions. The largest environmental effects may therefore be obtainable through a differentiated waste policy. Looking outside Europe, another interesting case study could be the implementation of anaerobic digestion of municipal organic waste in Dar es Salam, Tanzania (Mbuligwe & Kassenga, 2004), where anaerobic digestion replaces disposal in landfills (controlled or uncontrolled) and the produced energy substitutes wood burning. In general, this waste treatment system is considerably different from the Danish (and European) systems. How these differences affect the results is unclear.

EASEWASTE should be expanded to include other organic waste types, such as industrial organic waste and garden waste. With minor modifications many of the presented principles could be applicable also for these waste types.

It may be possible to use the EDOM value as a measure for degradability of organic waste for anaerobic digestion, and thereby the obtainable fraction of the VS-based calculated methane potential. This measure is relevant especially for waste containing a large degree of non- or slowly degradable VS, such as plastic or lignin. However, the connection between the EDOM value and methane yield has not yet been proved.

The many assumptions and the complicated procedure, which the toxicity factors in e.g. the EDIP system (Wenzel et al., 1997) are based on, add uncertainty to the estimated potential toxicity impacts. This problem is general for the LCA methodology and not specific for assessment of waste systems. It would be interesting to investigate and compare different opportunities for quantification of toxicity from waste systems and consider further development of the methodology. One option could be to add a qualitative assessment to the EDIP toxicity results by including local conditions (e.g. sensitivity of the area and current pollution level) in some kind of risk assessment of the actual system. Application of local normalization references could also be considered.

Energy consumption and production are important for the results of environmental assessment of waste systems. However, the choice of energy source is often discussed: Should the average national energy mix or the marginal energy source be chosen? And how is the marginal energy source in a country defined (especially considering the liberalization of the energy market increasing import and export of energy)? Studies assessing the actual effects from marginal production of "green" energy would be valuable for environmental assessment of production of renewable energy in general, including anaerobic digestion of waste.

References

Angelidaki, I. 2002. Environmental Biotechnology. Environment & Resources, DTU, The Technical University of Denmark, Course No. 12133

Audsley, E., S. Alber, R. Clift, S. Cowell, P. Crettaz, G. Gaillard, J. Hausheer, O. Jolliet, R. Kleijn, B. Mortensen, D. Pearce, E. Roger, H. Teulon, B. Weidema and H.v. Zeijts. 1997. Harmonization of environmental life cycle assessment for agriculture. AIR3-CT94-2028, Community Research and Technological Development Programme in the field of "Agriculture and Agro-Industri, including Fisheries" AIR 3, European Commission DG VI Agriculture

Bruun, S., T.L. Hansen, T.H. Christensen, J. Magid and L. Stoumann-Jensen. 2005. Application of processed organic municipal waste on agricultural land. Environmental modeling and assessment. Accepted

Bundgaard, S., M. Carlsbæk, U. Juul and E. Jørgensen. 1993. Jordbrugsmæssig værdi af produkter fra organisk dagrenovation (Agricultural value of products form organic household waste). Arbejdsrapport nr. 64, The Danish Environmental Protection Agency, Copenhagen, Denmark

Canals, L.M.i. 2003. Contributions to LCA Methodology for Agricultural Systems. Site-dependency and soil degradation impact assessment. PhD Thesis, Universitat Autonoma de Barcelona, Barcelona, Spain

Christensen, T.H., J.l.C. Jansen, T.L. Hansen, J.T. Kirkeby, Å. Svärd, J.K. Toudal, T. Hulgaard and C. Gruvberger. 2003. Basisdokumentation for biogaspotentialet af organisk dagrenovation. Environmental project No. 802, The Danish Environmental Protection Agency, Copenhagen, Denmark

Dalemo, M., A. Björklund, H. Oostra and U. Sonesson. 1998. System analysis of nutrient recycling from organic waste. JTI Rapport, Kretslop & Avfall, Nr 15, Swedish Institute of Agricultural Engineering (JTI), Uppsala, Sweden

Dall, O., C. Lassen and E. Hansen. 2002. Affaldsindikatorer. Environmental Project No. 672, The Danish Environmental Protection Agency, Copenhagen, Denmark

Damgaard, C. and L. Strandmark. 2003. Skal husholdningernes madaffald brændes eller genanvendes? Samfundsøkonomisk analyse af øget genanvendelse af organisk dagrenovation. Environmental project No. 814, The Danish Environmental Protection Agency, Copenhagen, Denmark

Danish EPA. 2004. Affaldsstatistik 2003. Orientation from the EPA No. 14, The Danish Environmental Protection Agency, Copenhagen, Denmark

De Baere, L. 2000. Anaerobic digestion of solid waste: state-of-the-art. Water Science and Technology. 41: 283-290

Eilersen, A.M., J.C. Tjell and M. Henze. 1998. Muligheder for jordbrugsanvendelse af affald fra husholdninger. In Magid, J. (ed): Recirkulering fra by til land -Næringsstoffer på afveje: 11-40, Institut for Jordbrugsvidenskab, KVL, Copenhagen, Denmark

Fridriksson, G.B., T. Johnsen, H.J. Bjarnadottir and H. Sletnes. 2002. Guidelines for the use of LCA in the waste management sector. Nordtest Project Nr. 1537-01, Linuhönnun, Nordtest

FVM. 2005. En rapport fra arbejdsgruppen om afbrænding af fraktioner af husdyrgødning. Fødevareministeriet, Copenhagen, Denmark

Gruvberger, C., H. Aspegren, B. Andersson and J.l.C. Jansen. 2003. Sustainability concept for a newly built urban area in Malmö, Sweden. Water Science and Technology. 47: 33-39

Hartmann, H., H.B. Møller and B.K. Ahring. 2004. Efficiency of the anaerobic treatment of the organic fraction of municipal solid waste: collection and pretreatment. Waste Management & Research. 22: 35-41

Jansen, J.l.C. and T.H. Christensen. 2003. Samlerapport for projekter om bioforgasning af organisk dagrenovation gennemført i 2000-2002. Environmental Project No. 803, The Danish Environmental Protection Agency, Copenhagen, Denmark

Jansen, J.l.C., C. Gruvberger, N. Hanner, H. Aspegren and Å. Svärd. 2004. Digestion of sludge and organic waste in the sustainability concept for Malmö, Sweden. Water Science and Technology. 49: 163-169

Jørgensen, O. and J.l.C. Jansen. 2003. Sammenhæng mellem sortering, forbehandling og kvalitet af biomasse. Environmental Project No. 767, The Danish Environmental Protection Agency, Copenhagen, Denmark

Kirkeby, J.T. and T.H. Christensen. 2004. Miljøvurdering af affaldssystemet for dagrenovation i Århus Kommune. 2. Version, Environment & Resources, DTU, The Technical University of Denmark, Lyngby, Denmark

Kirkeby, J.T., T.L. Hansen, H. Birgisdottir, G.S. Bhander, M. Hauschild and T.H. Christensen. 2005. Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Management & Research. Accepted

Kjellberg, K., M. Carlsbæk, J. Lillelund and M. Brøgger. 2005. Kombineret bioforgasning og kompostering af kildesorteret organisk dagrenovation i batch-anlæg. Environmental project No. 1002, The Danish Environmental Protection Agency, Copenhagen, Denmark

Mbuligwe, S.E. and G.R. Kassenga. 2004. Feasibility and strategies for anaerobic digestion of solid waste for energy production in Dar es Salaam city, Tanzania. Resources, Conservation and Recycling. 42: 183-203

Nielsen, L.K. 1994. Dyrkningsforsøg med kompost 1989-1993. Miljøprojekt nr. 258, The Danish Environmental Protection Agency, Denmark

Ostrem, K.M., K. Millrath and N.J. Themelis. 2004. Combining Anaerobica Digestion and Waste-To-Energy. 12th North American Waste To Energy Conference (NAWTEC 12), Savannah, Georgia, USA

Petersen, C. and I. Domela. 2003. Sammensætning af dagrenovation of ordninger for hjemmekompostering. Environmental Project No. 868, The Danish Environmental Protection Agency, Copenhagen, Denmark

Petersen, C. and V.L. Hansen. 2003. Statistik for behandling af organisk affald fra husholdninger 2001. Environmental Project No. 856, The Danish Environmental Protection Agency, Copenhagen, Denmark

Petersen, C. and M. Kielland. 2003. Statistik for jordbrugsmæssig anvendelse af affaldsprodukter fra husholdninger og institutioner og virksomheder 2001. Environmental Project No. 858, The Danish Environmental Protection Agency, Copenhagen, Denmark

Pitschke, T., U. Roth, S. Hottenroth and W. Rommel. 2004. Ökoeffizienz von öffentlichen Entsorgungsstrukturen. BIfA-Text Nr. 30, ISSN: 0944-5935, Bayerisches Institut für Angewandte Umweltforschung und tecknik GmbH (BIfA), Germany

Poulsen, T.G. and J.A. Hansen. 2003. Strategic environmental assessment of alternative sewage sludge management scenarios. Waste Management & Research. 21: 19-28

Reeh, U. 2000. Recirkulering af organisk affald ved kompostering i lokale og større kredsløb. PhD thesis, Danish Forest and Landscape Research Institute, Hørsholm, Denmark

Rosen, M.P., T.L. Hansen and J. Brandt. 2004. Central sortering af dagrenovation. Environmental Project No. 932, The Danish Environmental Protection Agency, Copenhagen, Denmark

RVF. 2005. Använding av biogödsel. En rapport från BUS-projektet, RVF Utvekling 2005:10, Sweden

Sundqvist, J.-O., A. Baky, M. Carlsson, O. Eriksson and J. Granath. 2002. Hur skall hushållsavfallet tas om hand? Utvärdering av olika behandlingsmetoder. Project nr. P10544-2, IVL Svenska Miljöinstituttet AB, Sweden

Svärd, Å. 2003. Anaerobic digestion of urban organic waste -Evaluation of potentials. Licentiate Thesis, Lund University, Department of Water and Environmental Engineering, Lund, Sweden

Symons, G.E. and A.M. Buswell. 1933. The methane fermentation of carbohydrates. Journal of the American Chemical Society. 55: 2028-2036

The Danish Government. 1999. Affald 21, National Danish Waste Strategy 1998-2004.

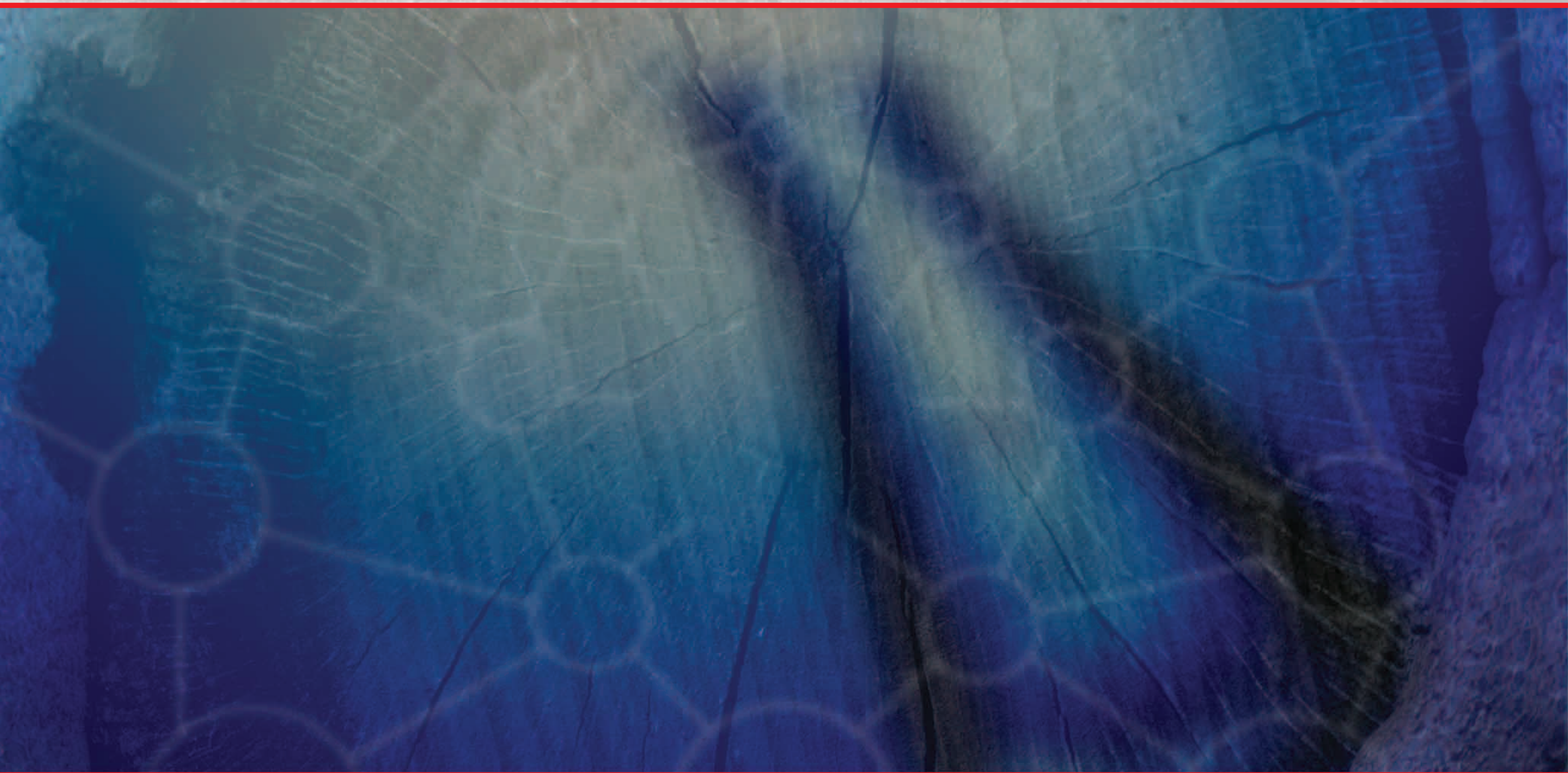
The Danish Government. 2003. Affaldsstrategi 2005-2008.

Tønning, K. 2003. Erfaringer med indsamling og behandling af bioaffald i Århus Kommune. Environmental Project No. 820, The Environmental Protection Agency, Copenhagen, Denmark

Toudal, J.K. 2003. Status for indsamlede mængder kildesorteret organisk dagrenovation. Appendix 1 in Environmental Project No. 802, The Danish Environmental Protection Agency, Copenhagen, Denmark

Vogt, R., F. Knappe, J. Giegrich and A. Detzel. 2002. Ökobilanz Bioabfallverwertung, Untersuchungen zur Umweltverträglichkeit von Systemen zur Verwertung von biologish-organischen Abfallen. Ifeu, Institut für Energie- und Umweltforschung, Heidelberg GmbH, Erich Schmidt Verlag, Berlin, Germany

Wenzel, H., M. Hauschild and L. Alting. 1997. Environmental assessment of products, volume 1. Chapman & Hall, London



Institute of Environment & Resources
Technical University of Denmark
Bygningstorvet, Building 115
DK-2800 Kgs. Lyngby

Phone: +45 4525 1600
Fax: +45 4593 2850
e-mail: reception@er.dtu.dk

Please visit our website www.er.dtu.dk

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