Environmental impact of NPK-fertiliser versus anaerobic digestion residue or compost - A systems analysis

Impact environnemental de l'utilisation d'engrais chimiques N-P-K comparativement aux résidus issus de digestion anaérobie ou de compostage : un système d'analyse

M. I. Dalemo
Swedish Institute of Agricultural Engineering, P.O.Box 7033, S-750 07 Uppsala, Sweden
E-mail : magnus.dalemo@jti.slu.se
Anna E. Björklund
Dept. of Chemical Engineering and Technology/Industrial Ecology, Royal Institute of Technology, S-100 44 Stockholm, Sweden
Ulf G. Sonesson
Dept. of Agricultural Engineering, Swedish University of Agricultural Sciences, P.O.Box 7033, S-750 07 Uppsala, Sweden

Abstract

A systems analysis approach was used to evaluate the environmental impact of four different fertilising alternatives in agriculture. Three scenarios with emphasis on recycling of nutrients from waste were evaluated against the most common situation when mineral fertiliser is used. The study was carried out for a large Swedish city. Activities studied were production of mineral fertiliser, waste treatment, production of electricity and heat, transportation and utilisation of nutrients in soil. Waste fractions included in the study were biodegradable household and industrial waste, slurry manure from cows and pigs, and sewage sludge.

Keywords: *Systems analysis, Environmental impact, Organic fertiliser*

Résumé

Une approche par système d'analyse a été utilisée pour évaluer l'impact environnemental de quatre fertilisants potentiels utilisés en agriculture. Trois scénarios insistant sur le recyclage des éléments nutritifs des résidus ont été comparés à celui plus conventionnel utilisant des engrais chimiques. L'étude a été réalisée pour une grande agglomération suédoise. Les activités étudiées concernaient la production de fertilisants minéraux, le traitement des déchets, la production d'électricité et de chaleur, le transport et l'utilisation des éléments par le sol. Les fractions de déchets associés à cette étude étaient des résidus ménagers biodégradables, des déchets industriels, des déjections animales bovines et porcines et des boues de stations d'épuration.

Mots-clés : systèmes d'analyses, impact environnemental, fertilisant organique.

1. Introduction

The most commonly used systems for disposal of solid organic waste are collection of the waste mixed with other fractions and treating it by incineration or landfilling. Landfilling of organic wastes decreases in Europe, and will probably not be permitted in the future. However, source separating of the organic waste fractions and treatment in a composting or anaerobic digestion plant is becoming more widespread. The intention is to decrease the environmental impact and to facilitate return of nitrogen and phosphorus to farmland. The return of nutrients implies transportation and spreading of treatment residues. However, due to the complexity of the waste handling system there is an obvious risk of introducing systems that reduce the environmental impact from one part of the system, while increasing the impact from other parts. Therefore, the aim of this study was to compare production and use of organic fertiliser with use of mineral fertiliser and traditional waste management from a systems perspective.

The biodegradable waste from an entire municipality with 190 000 inhabitants, is included in the study together with slurry manure produced in the surroundings. A more detailed description of the study can be found in Dalemo et al. (1998).

2. Method

A simulation model ORWARE is used for calculation of material flows, emissions and energy turnover. Life-cycle assessment (LCA) techniques are adopted to choose system boundaries, functional units and for evaluation (Lindfors et al., 1995).

Simulation model

The impacts of waste management are calculated using a computer model called ORWARE (ORganic WAste REsearch model. Dalemo et al., 1997). The model calculates energy flows, plant nutrient flows and emissions to air, water and soil in detail. It is a mathematical (non-linear) static model, implemented in MATLAB/Simulink (Maths Works Inc., 1997). All process sub-models are based on the same structure. Consumption of energy and resources, production of energy, emissions to air and water, and residual effluent are related to the quantity and composition of the material flow to the process (Figure 1).

System boundaries

The model calculates emissions and flows of energy and nutrients from solid and liquid organic waste. The comparisons of treatment methods are valid for plants with a high technical standard regarding environmental impact prevention. Only direct emissions from the handling of organic waste are included. For example, emissions produced when constructing infrastructure and buildings are not included.

Activities dealt with in the model include the collection and transport of waste fractions, treatment of waste and the recirculation or final disposal of residues. The recirculation of organic fertilisers includes transport, spreading operations on farmland, and increased nutrient emissions when using organic fertilisers on farmland in comparison with mineral fertilisers. Environmental impacts from landfilling of material are divided into time frames representing surveyable time (within ca 100 years) and a long-term perspective, corresponding to complete spreading of landfilled material. The long-term emissions are potential worst case emissions and presented separately.

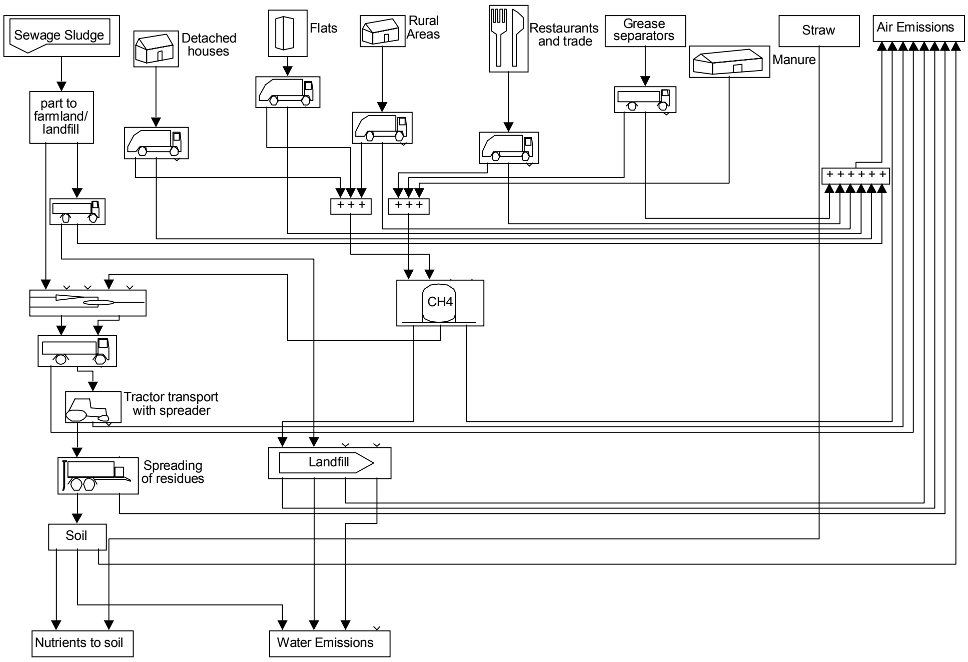

Figure 1.
The anaerobic digestion scenario, an example of the model picture in the Matlab/Simulink program

Waste fractions

The total quantity of biodegradable waste included in the study is about 63 000 tonnes generated during one year. Approximately 25 % is from sewage sludge, 30 % from other municipal waste sources and 40 % from slurry manure. The remaining 5 % consists of straw needed in the windrow composting scenario (table 1).

	Sludge	Block of flats	Single houses	Rural houses	Trade	Restau-rants	Grease water	Cow manure	Pig manure	Straw
Dry matter	3 900	2 161	1 593	801	150	550	108	1 512	288	2 550
Wet weight	16 250	6 175	4 550	2 288	500	2 200	3 000	21 600	3 200	3 000
Total N	152	43.2	31.9	16.0	2.3	12.1	0.1	84.7	17.0	12.8
Total P	137	8.2	6.1	3.0	0.8	0.6	0.1	18.1	4.6	1.8

Table 1.
Waste quantities included in the study of a large city region, and their contents of nitrogen and phosphorus (metric tonnes per year

Scenarios

Four scenarios are compared in this study. In all scenarios half of the sewage sludge is used as organic fertiliser on farmland and half is landfilled. Of special focus in the study is the influence of nitrogen emissions. A simplified model is used. Increased emissions of N_2O are related to the losses of nitrogen (1.25 % of the losses), the NO_3 and N_2 to the content of organic-bound nitrogen (35 % respectively), and the NH_3 to the ammonium content (15 %) in the organic fertilisers. A brief description of the calculation conditions in the scenarios is made below.

Mineral fertiliser scenario. All urban waste is incinerated except the grease water which is landfilled together with ashes from the incineration process. The incineration plant mirrors the waste incineration facility in Uppsala, with a capacity of 250 000 tonnes/year. It is equipped with flue gas condensation and cleaning. This includes dust removal, NO_x-reduction and dry removal of acid gases. Heat is recovered for district heating. The leachate from landfill is treated for removal of phosphorus and nitrogen. 50 % of the landfill gas is collected and burned in a gas engine, generating heat and electricity. Slurry manure is transported from farms and spread on arable land without any treatment. Half of the sewage sludge is used as organic fertiliser on farmland and the other half is landfilled. Straw is left on farmland. Production and use of nitrogen and phosphorus mineral fertiliser is included

Anaerobic digestion residue scenario. Urban and agricultural wastes are treated in an anaerobic digestion plant. The manure is transported with the same truck as the residue transport. The anaerobic digestion plant includes hygienisation (70°C) of the waste. The digester is a continuous, single stage, mixed tank reactor (C.S.T.R.) operating under mesophilic temperature. Heat exchanger is included, reducing heat consumption for hygienisation. The gas is used for production of electricity and heat in a stationary engine. Half of the sewage sludge is used as organic fertiliser on farmland and half is landfilled. Straw is left on farmland.

Reactor compost scenario. Urban waste is composted in a reactor composting plant. The reactor compost facility is a rotating drum, followed by maturing in the open air with controlled aeration. The exhausted gas equipment consists first of a condensation step and thereafter a biofilter. Slurry manure is transported from farms and spread on arable land without any treatment. Half of the sewage sludge is used as organic fertiliser on farmland and half is landfilled. Some production and use of nitrogen fertiliser is included.

Windrow compost scenario. Urban waste is composted in a reactor composting plant, except the grease water which is landfilled due to the low dry matter content. The straw is used as amendment in the composting process. Slurry manure is transported from farms and spread on arable land without any treatment. Half of the sewage sludge is used as organic fertiliser on farmland and half is landfilled. The windrow compost facility is an open-air compost with forced aeration but without equipment for exhaust gas purification. Some production and use of nitrogen fertiliser is included.

Functional units

System boundaries and functional units are chosen to make all scenarios comparable with respect to nutrients supplied to growing crops, the amount of waste treated, and the provision of district heating and electricity. The anaerobic digestion scenario results in the largest quantity of nutrients from organic fertilisers (170 tonnes N and 111 tonnes P), as anaerobic digestion residue and sewage sludge. In the other scenarios production of mineral fertiliser is included in a quantity so that these scenarios result in the same amount of nitrogen and phosphorus available to crops. With the same principle, heat production from wood chips and electricity production from oil are included in the scenarios in quantities so that all scenarios produce the same net amount of heat and electricity. The largest production of heat from waste is found in the mineral fertiliser scenario (77 TJ), and the largest production of electricity is found in the anaerobic digestion scenario (17 TJ).

Evaluation

The emissions are aggregated in environmental impact categories (Table 2). The impact categories presented are global warming potential, acidification and eutrophication. One reason for choosing only these categories is that the weighting factors for these categories are relatively well-defined. Weighting factors for human health and ecotoxicity are more uncertain, and there is a wide range of methods for aggregating these categories. However, results from these impact categories can be found in Dalemo et al. (1998). Furthermore, the use of resources in the scenarios are not presented in this paper.

Global warming potential [CO_2-equivalents]		Eutrophication [O_2-equivalents		Acidification [kmol H^+]	
CO_2-f	1	NO_x	6	SO_2	0.031
CH_4	24.5	NH_3	16	HCl	0.027
N_20	320	NH_4	15	NOx	0.022
		NO_3	4.4	NH_3	0.059
		P	140		
		COD	1		

Table 2.
Weighting factors used for evaluation of environmental impact (Lindfors et al.,1995

The three categories studied cover many of the important environmental impacts from waste management. Global warming reflects the consumption of non-renewable energy sources. CH_4 emissions from organic waste and N_2O emissions from farmland are also important sources for global warming impact. Reducing eutrophication is an important reason for introducing new waste management systems and also for introducing anaerobic digestion of manure. Acidification reflects the emissions of NO_x and SO_2 from transport and energy utilisation, and also the increased emissions of NH_3 when using organic fertilisers instead of mineral fertiliser.

Economic considerations are also necessary to find systems capable of reducing the environmental impact at reasonable cost. It is also often possible to reduce a specific substance with purification technology but this will also influence the costs.

3. Results

The results indicate that the anaerobic digestion residue scenario is preferable regarding global warming and eutrophication, while the mineral fertiliser is preferable when studying the acidification effect. Urban/agricultural waste treatment has a large impact in all categories (Table 3). The substances and processes contributing to the different categories vary between scenarios. This is discussed separately below. Electricity production has a large impact, primarily on the global warming category, since the energy source is oil and therefore results in emissions of CO_2 from fossil origin. Environmental impacts from heat production from wood chips are emissions of NO_x and SO_2, contributing to acidification. Phosphorus production has only a minor impact in all categories. Natural gas is the source for production of nitrogen fertiliser, which therefore results in CO_2 emissions contributing to global warming. The long-term emissions influence the global warming with emissions of CH_4 and eutrophication with emissions of P to water. Including these uncertain future emissions makes the mineral fertiliser scenario worse depending on the landfilling of ashes from incineration

	Urban/ agricultural waste management	Electricity production	Heat production	Phosphorus production	Nitrogen production	Long-term emissions from landfilling	Total
Global warming potential (tonnes of CO_2- equivalents)							
Mineral fertiliser	2435	1847	0	39	693	1633	6647
Anaerobic d.residue	1852	0	0	0	0	351	2203
Reactor compost	2373	1570	0	0	416	355	4714
Windrow compost	4038	1475	0	0	560	397	6471
Eutrophication (tonnes of O_2- equivalents)							
Mineral fertiliser	2141	11	0	1	11	11436	13600
Anaerobic d.residue	1983	0	20	0	0	9414	11417
Reactor compost	2233	10	35	0	7	9416	11700
Windrow compost	2497	9	34	0	9	9355	11904
Acidification (kmol H+)							
Mineral fertiliser	1095	78	0	15	40	3	1232
Anaerobic d.residue	2982	0	128	0	0	3	3112
Reactor compost	1205	66	216	0	24	3	1515
Windrow compost	2844	62	213	0	33	3	3154

Table 3.
Total contribution to global warming, eutrophication and acidification from the four scenarios

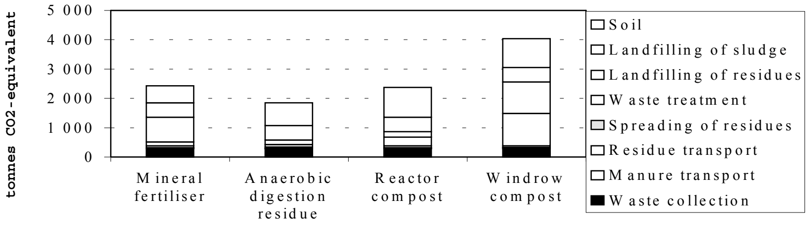

Figure 2.
Global warming potential from urban/agricultural waste management.

Soil contributes to global warming by emissions of N_2O. The emissions of N_2O are related to the total dosage of nitrogen. The composting scenarios with largest amount of organic bound nitrogen have the largest nitrogen losses and therefore largest emissions of N_2O (Figure 2). In all scenarios half of the sludge quantity is landfilled and contributes with CH_4 emissions. In both the mineral fertiliser scenario and windrow composting scenario, grease water is landfilled, thus resulting in CH_4 emissions. Emissions from main treatment processes are low except for the windrow compost emitting N_2O and CH_4. Transport and spreading result in CO_2 emissions in all scenarios.

The major eutrophication effects of waste management are from emissions of NH_3 and NO_3^- from soil. Emission of NO_3^- from organic-bound nitrogen is the dominating part and represents 80 % of the eutrophication effect from soil in the mineral fertiliser scenario, 68 % in the anaerobic digestion scenario and 88 % in the compost scenarios. The emissions from waste treatment in the mineral fertiliser scenario are P to water from water used in the incinerator's gas purification process. The treatment in windrow compost causes eutrophication through emissions of NH_3. Other activities have low impact on the eutrophication effect.

Gases contributing to the acidification effect from waste management originate primarily from soil and treatment processes. The acidificating emission from soil is NH_3. The anaerobic digestion scenario has the largest NH_3 emissions due to a high proportion of NH_4^+ in digestion residue. The mineral fertiliser and anaerobic digestion residue scenarios emit mainly NOx and SO_2. Acidificating emissions from the composting treatment processes primarily consist of NH_3.

The economic calculations consider the overall costs of the four waste management strategies. This includes costs for collection and treatment as well as costs for mineral fertiliser and revenue from energy. The total costs are almost similar, but in the mineral fertiliser and anaerobic digestion scenarios the revenue from energy results in a lower net cost for these scenarios (Figure 5). The markets for heat from incineration and heat and electricity from anaerobic digestion are therefore important issues in these scenarios. The transportation of waste has a much larger influence on the economic calculations than on the environmental impact. The costs for mineral fertiliser are low in relation to other costs also in the mineral fertiliser scenario.

4. Conclusions

4.1. None of the scenarios are best in all of the environmental impact categories studied. The anaerobic digestion residue scenario has the lowest emissions of global warming, while the mineral fertiliser scenario and reactor composting scenario have the lowest for acidification.

4.2. The largest contribution to the global warming effect in this study comes from electricity production (CO_2), landfilling (CH_4) and soil (N_2O).

4.3. The eutrophication effect is dominated by long-term emissions of phosphorus from landfilling. The largest immediate emissions are NO_3^- and NH_3 from soil.

4.4. Important sources for acidification are NH_3 from soil, NH_3 from the composting process in the windrow composting scenario, and NO_x and SO_2 from burning the gas in the anaerobic digestion residue scenario.

4.5. Emissions from soil have a large impact on the results for all categories. Parameters influencing these emissions have to be studied further.

4.6. From both environmental and economic views, the emissions and costs arising from production of mineral fertilisers have a minor influence on the results of the studied system.

5. Acknowledgements

We wish to thank Hydro Agri Europe for financially supporting this study.

6. References

Dalemo M., Sonesson U., Björklund A., Mingarini K., Frostell B., Jönsson H., Nybrant T., Sundqvist J-O. & Thyselius L., (1997) ORWARE - A simulation model for Organic Waste Handling Systems, Part 1: Model Description, *Resources, Conservation and Recycling vol. 21 pp. 17-37.*

Lindfors L-G., Christiansen K., Hoffman L., Virtanen Y., Juntilla V., Hanssen O-J., Ronning A., Ekvall T. & Finnveden G. 1995. Nordic Guidelines on Life-Cycle Assessment. Nordic Council of Ministers. Nord 1995:20. Copenhagen, Denmark.

Dalemo M., Björklund A., Oostra H. & Sonesson U. 1998. Systems Analysis of Nutrients Recycling from Organic Waste. Swedish Institute of Agricultural Engineering. JTI report, Kretslopp & avfall nr. 15. Uppsala, Sweden.

Maths Works Inc. Simulink User's Guide. Natick, Massachusetts. 1997.