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A study based on examples and cases from Denmark and Thailand

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SUSTAINABLE PIGGERY WASTE MANAGEMENT: A STUDY BASED ON EXAMPLES AND CASES FROM DENMARK AND THAILAND

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Preface and acknowledgements

This dissertation with nine supporting papers is submitted as one of the requirements for the Doctor of Philosophy (Ph.D.) degree. This work has been carried out at the Department of Biotechnology, Chemistry and Environmental Engineering and the Department of Planning and Development, Aalborg University since January 2006, and partly at the Faculty of Agricultural Science, Aarhus University from Fall 2006 to Spring 2007. The study has been financially supported by the Royal Thai Government including expenses of my stay in Denmark and many visits for meeting, interviews and conference participations and is gratefully acknowledged

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Special thanks go to my best friends, Dr. Barbara Marktl and Dr. Phenwisa Niyamakom. Their help for proof-readings of this dissertation is so appreciated and they always make me smile from good companions and relaxed conversations. Finally, thanks with all my heart to my family – their supports, advice and love always make me enjoy studying here in the far away city and give me motivations to bring success home.

Aalborg, January 2010
Trakarn Prapaspongsa

English summary

Pig manure may contribute to negative environmental impacts such as eutrophication, and greenhouse gas and odour emissions due to the large amounts generated globally in intensive pig production systems. However, pig manure could also be a source for nutrients and energy recovery. This study aimed to investigate new possibilities to handle pig manure with sustainable directions by effectively utilising existing technologies and available assessment techniques. Environment and resource protection were chosen as important sustainability criteria, and the entire chain of pig manure management was studied, including animal feeding and excretion, housing, treatment, transportation, and land application. Effective utilisation of energy and nutrients and control of losses from every handling stage were goals of the study.

The influences of diet compositions on the direct excretions from pigs were assessed. By using the dataset of 285 diets of digestibility experiments assayed at the Faculty of Agricultural Science, Aarhus University, sets of equations predicting the dry matter, nitrogen and carbon excretions from growing pigs were developed based on various dietary variables (e.g. dietary fibre content, dry matter intake, dietary nitrogen/protein intake, etc.). In addition, a simple input-output model – the Danish manure normative system was selected to estimate nitrogen and phosphorus excretions from pigs. The developed and chosen tools showed that the nitrogen, phosphorus and carbon excretions are predictable and controllable by the amounts of DM intake and dietary fibre content (for carbon), nitrogen/protein intake (for nitrogen) and P intake (for phosphorus).

Emissions in terms of greenhouse gases, ammonia, nitrate and nitrogen oxides at the housing, the storage and the land application stages for common and advanced systems were estimated based on Danish/European studies and reports from IPCC (Intergovernmental Panel on Climate Change). Slatted floor housing systems, storage tanks with a cover (e.g. natural crust), and deep injection systems have the lower losses when compared with other systems (e.g. deep litter, anaerobic lagoon, broadcast spreading, etc.) and thereby the higher potentials for energy and nutrient recovery.

Efficient use of pig manure as a resource of energy and nutrients demands different combinations of available and applicable treatment technology systems (anaerobic digestion,

incineration, thermal gasification in combination with thermal pre-treatment, separation, and drying). Such systems were assessed and compared. The data were taken from existing treatment plants in Denmark and Thailand supplemented with literature data. The accounted energy recovery comprised net electricity and heat production and energy equivalent of replaced fertiliser production. In the Danish cases, the integrated treatment systems based on anaerobic digestion, incineration or thermal gasification processes, the energy recovery efficiencies ranged from 30% to 50% of total potential energy content in the pig manure. Incineration based on dried manure yielded the highest net energy recovery, because both electricity and heat were produced and utilised, while the anaerobic digestion maximised the electricity production. In the Thai cases, energy recovery was low and similar for different systems due to low efficiencies of incineration and biogas plants. To improve the Thai systems, utilisation of the heat produced (e.g. for thermophilic digestion) and increase of the DM contents of the pig manure are suggested. Nutrients were recovered in all cases, but the systems with incineration and thermal gasification processes reduced the N recovery (loss to the atmosphere) and the availability of P.

To achieve sustainable directions in pig manure management, this study aimed to reduce overall environmental impacts on ecosystems, human health and resources by incorporating the obtained knowledge on energy extraction, nutrient recovery, emissions from various treatment, storage and land application systems into one comprehensive model. Life cycle assessment was selected as the modelling tool because it aims to assess overall impacts on the environment including all emissions, and usages and substitutions of resources from cradle to grave. A screening assessment showed that the more significant impact categories from pig manure management were global warming, respiratory effects on human health from inorganic substances (respiratory inorganics), and terrestrial and aquatic eutrophication. To reduce the negative and increase the positive environmental impacts, the further assessment revealed that the best option is the pig manure management system which yields the highest recovery of energy and nutrients combined with the lowest emission of greenhouse gases, ammonia, nitrate, and nitrous oxides.

All in all, this dissertation illustrates that knowledge, technologies and assessment tools are available for selecting pig manure management systems aiming at recovery of energy and nutrients, control of N and C emissions, and effective protection of natural resources, aquatic and terrestrial ecosystems, as well as human health. These results enable farmers and decision-makers to handle pig manure in a more sustainable direction.

While the potential benefits are documented, further studies are still necessary to optimise pig manure management systems at a regional and local scale, for example

- Specific adaptation of technology and management systems to available local human and material resources

- Analysis of social. Economic and technical drivers and barriers for pig manure management systems

Danish summary

Gylle fra svin kan få en række uønskede effekter i miljøet, herunder eutrofiering af vandige recipienter, udleding af drivhusgasser og lugtgener. Imidlertid udgør svinegylle også en ressource i form af potentiel udnyttelse af næringsstoffer og udvinding af energi. Denne afhandling analyserer nye og alternative strategier for bæredygtig håndtering af svinegylle ved brug af allerede eksisterende teknologi og værktøjer. Alle faser af gødningsproduktionen blev analyseret, herunder stalddesign, fodersammensætning, efterbehandling af gødning, samt dettes transport og slutanvendelse. Analysen fokuserede på optimering af energiudvinding og udnyttelse af næringsstoffer samt effektiv kontrol af tab.

En forudsætning for effektiv styring af gyllehåndtering er en grundlæggende viden om gyllens egenskaber samt om de faktorer, der påvirker selve produktionen. Således blev der foretaget en vurdering af betydningen af foderets sammensætning for potentialet for udvinding af energi og næringsstoffer. 285 forskellige fodersammensætninger blev benyttet, alle undersøgt på Jordbrugsvidenskabeligt Fakultet på Århus Universitet. På denne baggrund blev der opstillet empiriske sammenhænge mellem foderets indhold af fibre, tørstof og kvælstof/protein og den efterfølgende gylles indhold af tørstof, kvælstof of kulstof. Derudover blev en simpel input-output model anvendt til bestemmelse af den forventede udskilning af kvælstof og fosfor. Resultaterne viste, at det er muligt at både forudsige og kontrollere gyllens indhold af kvælstof, fosfor og kulstof ud fra foderets sammensætning.

Efterfølgende undersøgtes emissionen af drivhusgasser, ammoniak, nitrat og kvælstofoxider under produktion, opbevaring og landanvendelse, alt beregnet på basis af dansk-europæiske erfaringer og FN Klimapanelets rapporter. Herudfra blev det konkluderet, at stalde med tremmegulv, overdækkede opbevaringstanke og systemer med direkte gyllenedfældning havde et mindre tab end de øvrige undersøgte systemer (f.eks. dybstrøelse, åbne lagertanke, spredning med prelplade).

Med det formål at udnytte gyllen effektivt blev forskellige kombinationer af behandlingssystemer (forgæring, forbrænding, termisk forgasning kombineret med termisk forbehandling, og tørring) vurderet og sammenlignet. Data blev indsamlet fra gyllebehandlingsanlæg i Danmark og Thailand, og suppleret med litteraturdata. Energiudvindingen blev bestemt som netto-produktionen af energi og varme samt energi

svarende til fortrængt produktion af handelsgødning. På danske anlæg gav behandling med forgæring, forbrænding og termisk forgasning 30-50 % øget energiudbytte sammenlignet med anlæg uden nogen behandling af svinegyllen. Forbrænding kombineret med effektiv tørring gav det højeste energiudbytte og næsten fuldstændig udnyttelse af gyllens kulstof, mens forgæring gav den største produktion af elektricitet. For thailandske anlæg gav alle typer behandlingsanlæg sammenlignelige resultater, herunder forbrænding, forgæring og ingen behandling. Dette hænger sammen med en lav effektivitet af de thailandske forbrændings- og biogasanlæg. Bedre resultater af disse anlæg ville sandsynligvis opnås ved bedre udnyttelse af varmeproduktionen (for eksempel til termofil i stedet for mesofil udrådning) samt øgning af svinegyllens tørstofindhold (for eksempel ved afvanding). Alle systemer viste samme effektivitet mht. genindvinding af kvælstof og fosfor - bortset fra systemer, der involverede forbrænding og forgasning, hvor N tabes til atmosfæren og P tilgængeligheden bliver lavere.

Dette arbejde fokuserede på reduktion af de overordnede miljø- og sundhedspåvirkninger ved produktion af svinegylle samt på optimering af energi- og næringsstofudnyttelse ved behandling og anvendelse af gyllen. En livscyklusanalyse blev udført med det formål at vurdere de overordnede konsekvenser ved forskellige behandlingsstrategier 'fra vugge til grav'. En indledende analyse viste, at global opvarmning, luftkvalitet, og eutrofiering af terrestriske og akvatiske recipienter er de centrale og mest betydningsfulde parametre. På dette grundlag viste analysen videre, at optimal håndtering af gyllen kan give et højt energi- og næringsstofudbytte med minimal afgivning af drivhusgasser, ammoniak, nitrat og kvælstofoxider. Disse erfaringer kan potentielt muliggøre en langt mere bæredygtig håndtering af svinegylle end den man ser i dag.

Videre studier bør omfatte:

- Tilpasning af teknologier og systemer til lokale forudsætninger, vidensmæssigt og teknologisk samt med hensyn tiol for eksempel klima og økonomi

- Undersøgelse af administrative (lovgivning og regulering) muligheder og forhindringer for bæredygtig håndtering af svinegylle

List of supporting papers

1 1A (journal): Vu, T.K.V., Prapaspongsa, T., Poulsen, H.D. & Jørgensen, H. (2009) Prediction of manure nitrogen and carbon output from growing-finishing pigs. Animal Feed Science and Technology 151, 97-110.

1B (journal): Prapaspongsa, T., Vu, T.K.V., Jørgensen, H. & Poulsen, H.D. (2010) Comparison of methods for quantification of excretions of dry matter, nitrogen, phosphorus and carbon in growing pigs fed regional diets. Submitted to Journal of Animal and Feed Sciences 26 January, 2010.

1C (conference): Prapaspongsa, T., Vu, T.K.V., Poulsen, H.D. & Hansen, J.A. (2008) Nitrogen, phosphorus, and carbon utilization and excretion in growing pig fed Danish and simulated Asian diets. Proceedings of International Conference on Agriculture Engineering and Industrial Exhibition, 23 – 25 June 2008, Crete, Greece.

2 2A (journal): Prapaspongsa, T., Poulsen, T.G., Hansen, J.A. & Christensen, P. (2009) Energy production, nutrient recovery and greenhouse gas emission potentials from integrated pig manure management systems. Waste Management and Research, DOI 10.1177/0734242X09338728.

2B (conference): Prapaspongsa, T., Pholchan, P., Hansen, J.A., Poulsen, T.G. & Christensen, P. (2009) Improved energy recovery efficiencies from piggery waste biogas plants in Thailand using Danish experiences. Proceeding of World Renewable Energy Congress 2009 – Asia, The 3rd International Conference on “Sustainable Energy and Environment (SEE 2009)”, 18-23 May 2009, Bangkok, Thailand.

2C (conference): Poulsen, T.G., Prapaspongsa, T. & Hansen, J.A. (2008) Energy and greenhouse gas balances for pig manure using alternative treatment options. Proceeding of ISWA/WMRAS World Congress 2008. East meets Waste, 3 – 6 November 2008, Singapore.

2D (conference): Poulsen, T.G., Prapaspongsa, T. & Hansen, J.A. (2008) Energy and greenhouse gas balances for organic household waste using alternative treatment options. Proceeding of ISWA/WMRAS World Congress 2008. East meets Waste, 3 – 6 November 2008, Singapore.

3 3A (journal): Prapaspongsa, T., Christensen, P., Schmidt, J.H. & Thrane, M. (2009) LCA of comprehensive pig manure management incorporating integrated technology systems. Submitted to Journal of Cleaner Production 11 November, 2009 and subjected to be significantly revised.

3B (conference): Prapaspongsa, T., Hansen, J.A. & Christensen, P. (2009) Greenhouse gas emission reduction by integrated technology systems applied to piggery waste. Published summary in the Proceedings of Waste and Climate Conference 2009, 3-4 December 2009, Copenhagen, Denmark. The published summary and poster presentation will be available at www.wasteandclimate.org.

1. Introduction

Over the last decades, rapidly increased world population has resulted in substantial rises in food consumption and energy requirement. Global population has increased from 2.3 billion in 1950 to 6.7 billion in 2008 (Population Reference Bureau, 2008). In the meanwhile, estimated world meat and energy demands grew by 2.4% and 1.6% per year on average, respectively (IEA, 2008; Rosegrant et al., 2001). Pig meat has represented the substantial percentages of the global meat products – 37% in 2007 (FAOSTAT, 2009), and 31% in 2020 according to estimations by Rosegrant *et al.* (2001). During pig production, pig manure was determined as the most significant contributor raising negative impacts on the environment in terms of global warming, eutrophication and acidification (Dalgaard, 2007). Accordingly, results from many studies reported that livestock manure has substantially contributed to eutrophication impacts, from ammonia emission and surpluses of nitrogen (N) and phosphorus (P) from field applied manure (Jongbloed et al. 1999); and also potentially causes global warming impacts, from emissions of greenhouse gases (GHG; CO_2, CH_4 and N_2O) (Gac et al., 2007). Furthermore, the global environmental concerns in the present include the anthropogenic climate change and the nitrogen cycle disturbed by humans because they are already beyond the acceptable thresholds, resulting in damages to the environment (Rockström *et al.*, 2009). Many evidences (e.g. the temperature rising; glacier melting; the high annual N conversion rate turning 120 million tonnes of N_2 from the atmosphere into the reactive forms such as N_2O, NH_3, NO_3^- and NO_x; Rockström *et al.*, 2009) declare the urgent needs to reduce the impacts arising from all human activities including the management of piggery waste.

Notwithstanding the concerned significant environmental consequences, pig manure can be a valuable source for energy and nutrients. The recovered energy and nutrients from pig manure can partially shift the associated environmental deterioration to substitution of the increased energy and resource demands. To reduce the environmental impacts from the pig manure management, many efforts have focused on various strategies aiming at energy and nutrient recoveries, effective nutrient controls and reductions in greenhouse gas and ammonia emissions (Maraseni & Maroulis, 2008; Monteny et al., 2006; Møller et al., 2004; Petersen et al., 2007; Sommer & Hutchings, 2001). Nutrient losses from livestock manures in some regions of the world have been estimated by various models, e.g. MITERRA-EUROPE (Oenema et al, 2007). Biogas potentials from anaerobically digested pig manure have been studied extensively (Maraseni & Maroulis, 2008; Møller et al., 2004). Various housing, storage and spreading systems have also been investigated and suggested to reduce the large amount of ammonia emissions (Oenema et al, 2007; Petersen et al., 2007; Sommer and Hutchings, 2001).

Despite advanced research and ongoing developments a complete linkage between the comprehensive management systems applying various existing technologies is still missing. Most studies have focused on different but narrow perspectives. For examples, the focus is either on a single treatment technology (e.g. anaerobic digestion and composting), on the ammonia emission reductions, or on greenhouse gas emission reductions (Mareseni & Maroulis, 2008; Monteny *et al.*, 2006; Summer & Hutchings, 2001). Furthermore, the consideration of pig manure characteristics influenced by diets and production systems for the overall management systems is also scarce. To develop more effective management strategies for decreasing environmental pollutions from pig manure a more holistic view of factors including new available data has to be considered. According to this holistic perspective, nutrient and energy flows of piggery waste from cradle to grave must be known and controlled in order to produce more usable energy and nutrients but less environmental burdens.

With respect to these circumstances, the overall aim of this dissertation is to find new perspectives on how piggery waste could be properly managed to contribute to a more sustainable direction in effective utilisation of existing technologies and available assessment techniques. According to the World Commission Report “Our Common Future” (WCED, 1987), sustainable development should meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Although sustainability includes economic development, social acceptance and environmental protection, some environmental problems such as global warming and loss of biodiversity are determined as the major threats to sustainable development (COM, 2001). In this study, the improvements of environmental conditions in terms of the impacts on ecosystems, human health and resources are of highest priority in the sustainability. Subsequently, pig manure management systems in Denmark and in Thailand were modelled and evaluated in order to improve the environmental outcomes from the existing conditions. Denmark was selected as the representative for industrialised countries whereas Thailand was determined as the representative for developing countries. The following problems have been investigated so as to answer the stated overall aim of the research.

- How can different diet compositions influence the pig manure characteristics?

- How can varied housing and storage systems minimise the N and carbon (C) losses from pig manure management?

- How can various treatment technology combinations improve the system performance in terms of energy production and nutrient recovery from pig manure management?

- What are significant environmental impacts on ecosystems, human health and resources arising from pig manure management?

- How can different integrated systems reduce the more significant environmental impacts towards sustainable pig manure management?

This dissertation is organised, according to the above research problems and based on the supporting publications in the former list, as follows. The overall framework of the dissertation is illustrated in Figure 1. First, in chapter 2 (based on Paper 1A to 1C) the influences of diet compositions on the excretions from the pigs are identified. Afterwards, the potential losses of nitrogen and carbon at housing and storage stages are investigated. In chapter 3 (based on Paper 2A to 2D) energy and nutrient flows and balances of integrated treatment technology systems for pig manure management are estimated and compared. In chapter 4 (based on Paper 3A and 3B) the more significant environmental impacts of integrated manure management systems are identified and assessed from a holistic perspective with the purpose for reducing the negative impacts and increasing the positive impacts. Finally, the conclusions and perspectives for future research are presented in chapter 5 and 6, respectively.

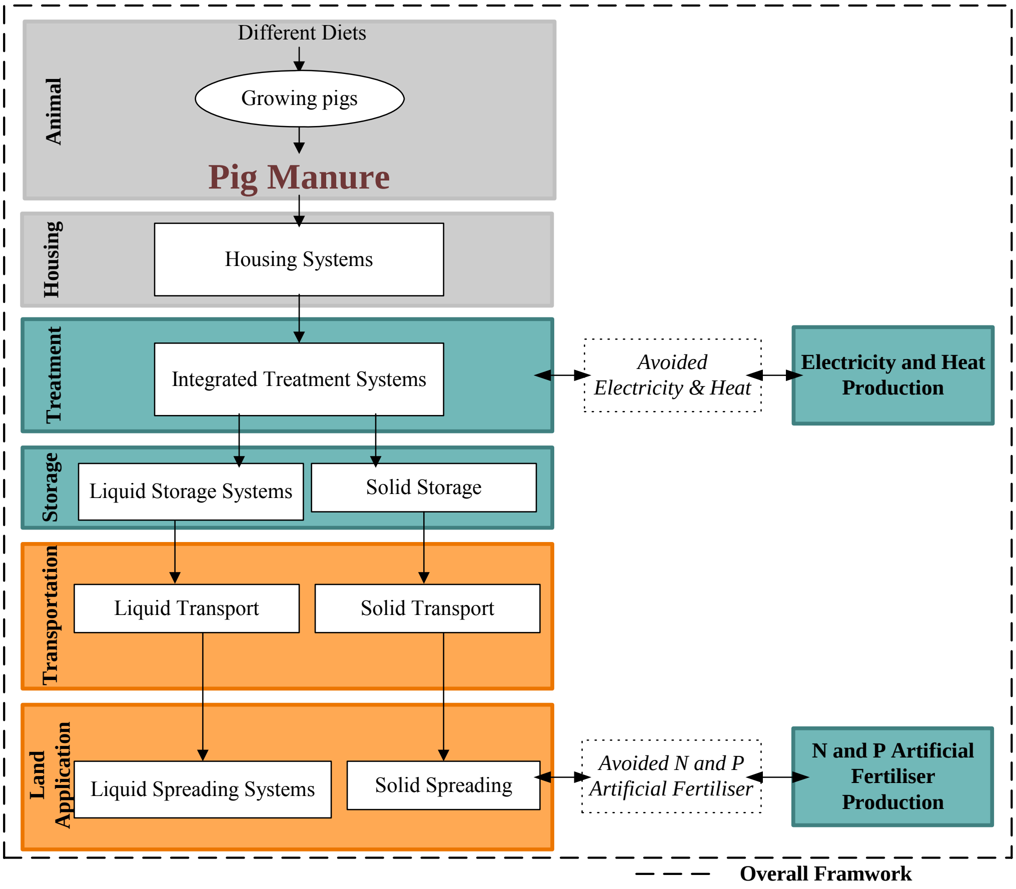


Fig. 1.1 Overall framework of this PhD dissertation. The gray, blue and brown boxes represent considered pig manure management stages (animal, housing, treatment, storage, transportation, and land application) and production systems of the avoided products. The handling stages encounter losses in terms of carbon, nitrogen and phosphorus. The dotted boxes with italic characters illustrate the avoided products. Research presented in chapter 1 focuses on topics marked in the gray boxes and in the storage stage. The blue boxes mark research topics discussed in chapter 2. Research topics presented in chapter 3 are marked in both blue and brown boxes. The details of different systems and stages are given in chapter 2 to 4.

2. Pig manure characteristics influenced by diet compositions, and the potential losses of nitrogen and carbon at the housing and storage stages

Piggery waste (pig manure/pig slurry) is not only “a waste” but also a valuable resource in terms of nutrients for crops and energy. Nonetheless, improper management of pig manure can harm the environment via different kind of emissions (e.g. ammonia, greenhouse gases, nitrate, etc). Hence, it is crucial to control pig manure at the beginning or at source. Pig manure at the animal stage (at source) includes the direct excretions from pigs, the bedding materials and water used in the system. The main compartment of pig manure, which can be transformed to resources as nutrients (N and P) and energy (C), are the direct excretions from the pigs. In order to know the magnitude of this resource, the knowledge how the excretions in terms of N, P and C are generated is needed. Thus, the first objective of this chapter is the determination of how the various diet compositions can influence the direct excretions (Dry matter [DM], N, P, and C) from growing pigs. As a result, models to predict the excretions by using dietary data and growing conditions were developed and selected. In addition, the model applications using regional based diets are demonstrated via the experiments. Afterwards, the losses of N and C at the housing and storage stages are identified in order to reduce the potential emissions by applying various systems such as slatted floor barn, deep litter, anaerobic lagoon and covered storage tank. The better understanding of the manure characteristics and losses allows farmers and researchers to precisely predict and control the amounts of nutrients and energy for further processing and improvements.

2.1 Estimation of nitrogen, phosphorus and carbon excretions from growing pigs based on diet compositions

2.1.1 Developed model to estimate nitrogen and carbon excretions based on diet compositions.

The assessments using the datasets of 285 diets, which have been assayed in digestibility experiments at the Faculty of Agricultural Science, Aarhus University, indicated that various dietary parameters (e.g. dietary fibre content, DM intake, dietary N/protein intake, etc.) were highly correlated to the nitrogen and carbon excretions from growing pigs. As a result, the sets of predicting equations using the correlated dietary variables were proposed and validated using an independent dataset (cross validation) as shown in Paper 1A. In this dissertation, the main influential parameters on the DM, N and C excretions were selected from Paper 1A based on easily obtainable criteria and presented in the linear and multiple prediction equations as shown in Table 2.1.

Table 2.1 The selected equations from the developed predicting models (Paper 1A).

No.	Equations
1	Faeces DM (kg/day) = -0.105 + 0.118*DMintake (kg/day) +0.00110*DF (g/kg DM)
2	Faeces N (g/day) = 0.685 + 0.0260*DF (g/kg DM) + 0.0855*Nintake (g/day)
3	Faeces C (g/day) = -98.82 + 68.95*DMintake (kg/day) + 0.541*DF (g/kg DM)
4 [a]	Urine N (g/day) = –28.50 + 0.143*Crude protein (g/kg DM) + 13.23*DMintake (kg/day)

DM = dry matter content, DF = dietary fibre content, Faeces DM/N/C = DM/N/C content in faeces, Urine N = N content in urine.

[a] From the subset of protein content from 15 to 26 % of DM and protein retention between 70 to 160 g/day.

As can be seen from the chosen equations (no.1 and 3; Table 2.1), the daily amounts of DM and C in faeces can be estimated and controlled by the DM intake and dietary fibre content. Due to the fact that most of DM and C are excreted via faeces, the total DM and C excretion can subsequently be controlled via the DM intake and dietary fibre content. The N content excreted via faeces and urine can be calculated by using the N intake or dietary crude protein content in combination with the dietary fibre and DM intake (equation no.2 and 3; Table 2.1). This infers that the N losses via excretion can be directly reduced through the limited N intake or dietary crude protein content in the case that dietary fibre and DM intake are fixed. Likewise, many studies have also shown that a reduction of the N excretion was successfully performed by reduced N intakes to an amount that still maintains the sufficient contents of N and essential amino acids required for the pigs (Jongbloed & Lenis, 1992; Portejoie *et al.*, 2004). The models developed in this study reveal the potentials for N and C estimation and control of the pig excretions by the diet compositions and amount.

2.1.2 The Danish manure normative system (DMNS)

Alternatively, the DMNS was selected as a simple input-output model to estimate the N and P excretions from pigs. The DMNS has estimated the nutrient flows (N, P and potassium (K)) in term of excretions and losses at different handling stages from the Danish standard pigs and systems (Fernández *et al.*, 1999; Poulsen *et al.*, 2006). However, the estimation in this section focuses only on the excretion at the animal stage (or ex animal in Poulsen & Kristensen, 1998). The N and P excretions are calculated by considering the difference between the dietary intake and the amount of nutrients retained in the pig body. The related equations are listed in Table 2.2.

Table 2.2 The equations for estimating N and P contents in excretions from pigs by the DMNS

No.	Equations [a]
1	N or P, $_{\text{in excretion}}$ (g/day) = N or P, $_{\text{in feed}}$ (g/day) – N or P, $_{\text{in retention}}$ (g/day)
2	Faeces N or P (g/day) = N or P, $_{\text{in feed}}$ (g/day)*(100-N or P, $_{\text{digestibility}}$)/100
3	Urine N or P (g/day) = N or P, $_{\text{in excretion}}$ (g/day) – Faeces N or P (g/day)

Faeces N/P = N/P content in faeces, Urine N/P = N/P content in urine.

[a] Digestibility: protein (or N) 81%; phosphorus 50%. Retention per kg gain: 29.6 g N; 5.5 g P.

The direct relationship between dietary compositions and total excretions in term of N and P contents can be easily drawn from these equations. If the retentions of N and P for the diets are alike, the excretions will depend only on the intake amount and digestibility. Generally, the oversupplied nutrients in feeds with respect to the pig's physiological requirement are excreted in urine. In the meanwhile, the nutrients that cannot be digested are excreted in faeces. For the total excretion, the higher N and P contents in the feeds are, the higher N and P outputs in the total excretion occur. In accordance with the reduction of N intake as discussed before, the P intakes (in term of feed phosphate) can be reduced to limit the loss via excretion with respect to the requirement of the pigs and the supplementation of phytase (Johansen & Poulsen, 2003; Knowton *et al.*, 2004). Nevertheless, the specific knowledge on the relations between the phytase supplementation and P digestibility of the diets and the local pigs is needed for an application.

2.1.3 Comparison of different approaches using Danish and simulated Asian diets

In order to demonstrate the potentials of the developed and selected approaches (Paper 1A and the DMNS, respectively) to estimate the excretion from growing pigs and the dietary effects on the nutrient excretion, experiments with Danish and simulated Asian diets and growing pigs were carried out. Subsequently, the comparison between the experimentally obtained and the calculated results are illustrated.

The experiments are demonstrated in Figure 2.1. Nine sibling female pigs (with 40 to 45 and 55 to 60 kg body weight) were allocated separately in metabolism cages. The diets were formulated according to the practical diets used in Denmark, Thailand, and Vietnem, in combination with the available feedstuffs purchased in Denmark. The faeces and urine were daily collected for seven days after the five days of adaptation. The urine was taken through indwelling Foley catheters as illustrated in Figure 2.1. The experimental procedure was further described in Paper 1B.

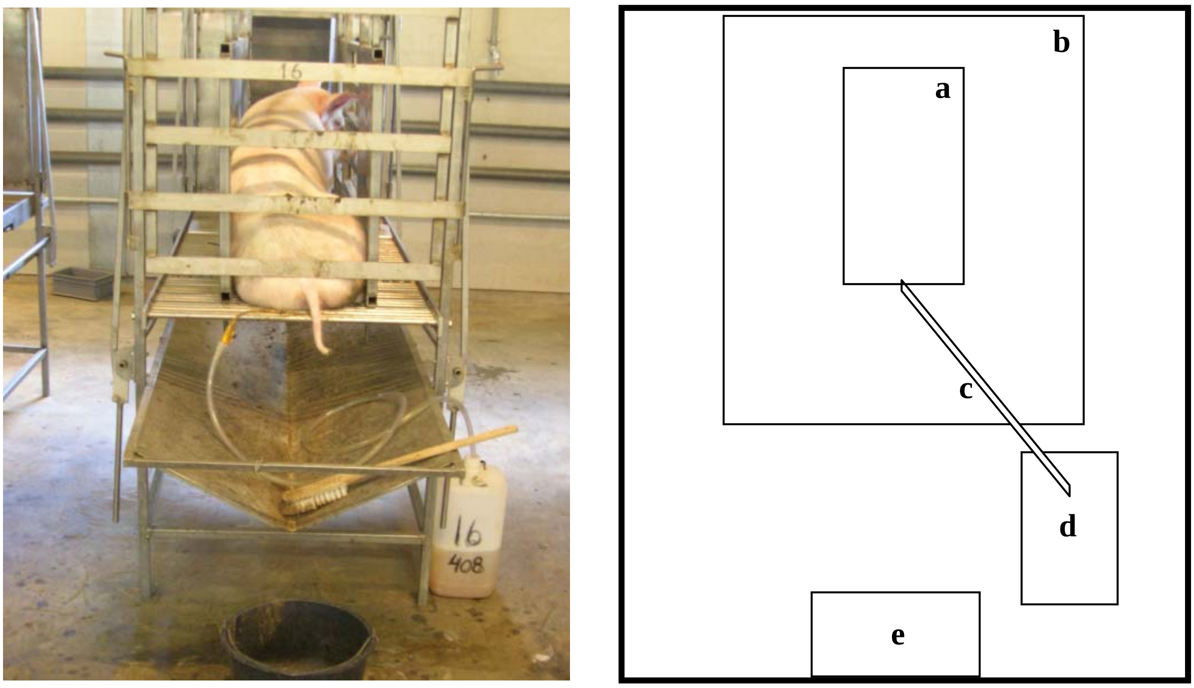


Fig. 2.1 The experiment with a growing pig in a metabolic cage with urine and faeces collection (left). The right figure indicates the system for faeces and urine collection. a) The growing pig. b) The metabolic cage. c) The catheter to collect urine. d) Urine collection. e) Faeces collection.

The experimental diets, collected faeces and urine were analysed with the methods explained in Paper 1B. Afterwards, the chemically analysed results were used to obtain values of the digestibility, the retentions, the utilisations and the excretions of N, P and C (based on the methods in Sørensen & Fernández, 2003). The experimental results and the calculated values using the two selected and developed models are shown in Figure 4.3.

In general, all calculated excretions from both models in Paper 1A and in DMNS are in the ranges of the standard deviation of the experimental values (Fig. 2.2). Therefore, it was possible to apply the two approaches for an estimation of nutrient excretions. The comparison is further carried out by considering the biases derived from the following equation.

$$\text{Bias (\%)} = (\text{Calculated value} - \text{Experimental value}) / \text{Experimental value} * 100$$

Based on the equations in Paper 1A, the estimated values for the N, C and DM contents in faeces are closed to the experimental values to some extent (with 10%, 12% and 16% of the average biases in Fig. 2.2a, d and h, respectively). In contrast, the calculated N contents in urine based on the equations (Paper 1A) are overestimated with 31% of the average bias (Fig. 2.2b). This could be explained by the varied availability of the N content in the experimental diets in this study and in Paper 1A. According to Just *et al.* (1983), the protein (or N) content in various feedstuffs did not have the same availability for pigs. As a result, the biases of total N excretion calculated from Paper 1A can be observed (12% to 21%; Fig. 2.2c) mainly because of the biases from the calculated N content in urine.

In DMNS, the quantified total N and P excretion went quite precisely within the biases of ± 3% for N and within 7% for P except for the Vietnamese (VN) diet (Fig. 2.2c and g, respectively). In contrast, the DMNS is not able to predict the precise content of N and P in faeces and in urine on average since it depends upon the nutrient digestibility in the feedstuffs. The digestibility of N and P is fixed at 81% and 50%, respectively according to the commonly used feed ingredients in Denmark. However, the original aim of the DMNS for application was to estimate the total excretion rather than the specific content in faeces and in urine.

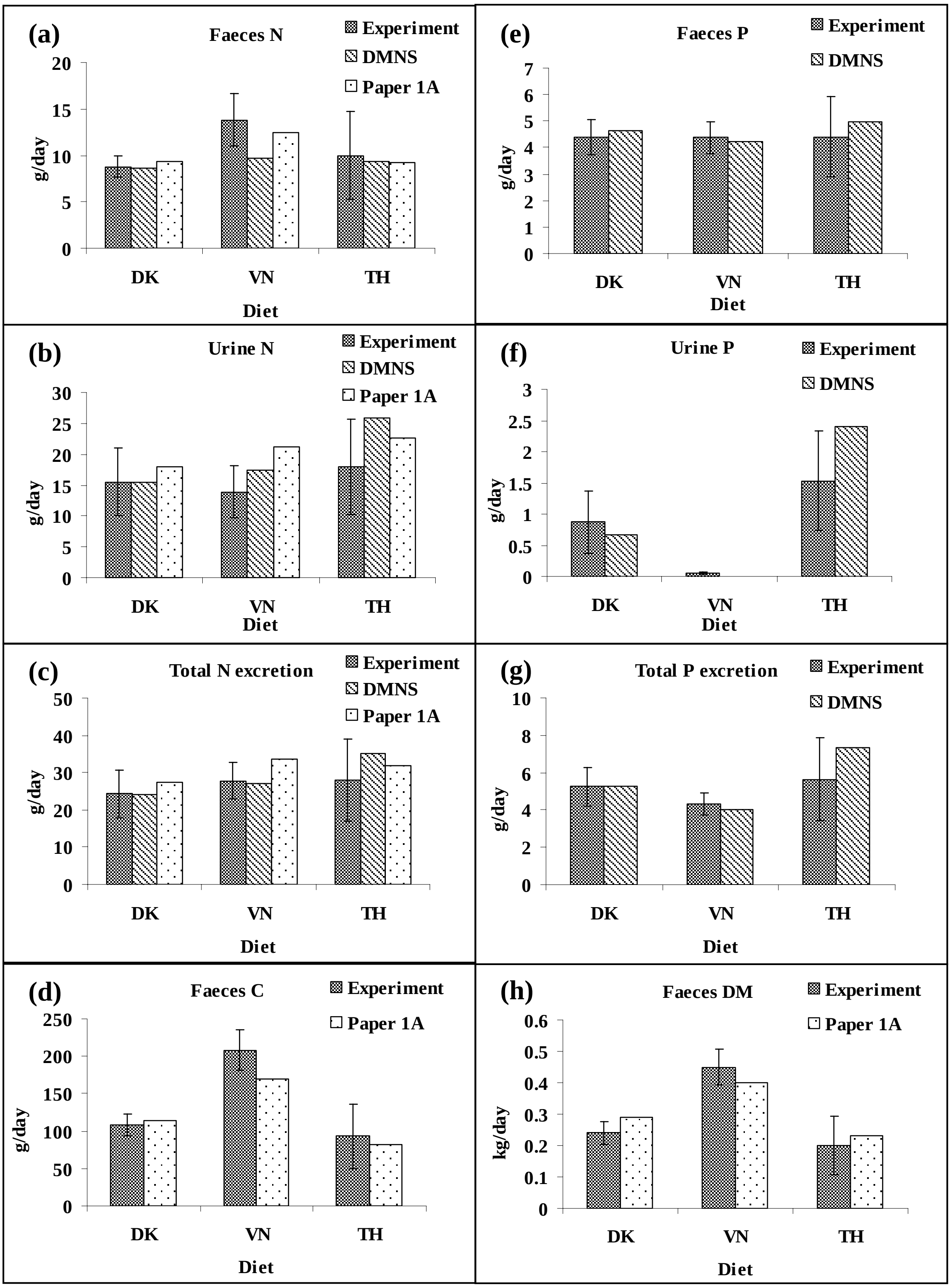


Fig. 2.2 The experimental and calculated values of the daily excretions from growing pigs fed the three common diets in Denmark (DK), in Vietnem (VN) and in Thailand (TH). The prediction models are the Danish manure normative system (DMNS) and the model chosen from Paper 1A. a) Daily N content in faeces, b) Daily N content in urine, c) Total N excretion, d) Daily C content in faeces, e) Daily P content in faeces, f) Daily P content in urine, g) Total P excretion, h) Daily DM content in faeces. The ranges represent the standard deviation in the experiments.

2.2 Losses of nitrogen and carbon at the housing and storage stages

Different housing and storage systems lead to varied magnitudes of emissions and impacts on the environment. The N and C losses in terms of NH_3, N_2O, NO_3^-, N_2 and CH_4 from the selected housing and storage systems in Denmark and Thailand are presented in Table 2.5. In Denmark, the housing systems as slatted floor and deep litter and storage systems in a tank or deep litter were commonly used (based on Hutchings *et al.*, 2001). In Thailand, the solid floor housing system with manual separation of solid manure by scraping was widely applied. Subsequently, the solid fraction of manure were dried and used as fertiliser and the liquid fraction was stored in anaerobic lagoon without a cover or liner (Gerber & Menzi, 2006; Sommer, 2000). The N-related emissions were primarily based on Danish/European studies (EMEP-CORINAIR, 2001; Poulsen & Kristensen, 1998; Poulsen *et al.*, 2001; Velthof *et al.*, 2007) as there is no available data for the Thai conditions. The GHG emissions were derived from the IPCC report (Dong *et al.*, 2006).

Table 2.5 Emission factors at the housing and storage stages in Denmark (DK) and Thailand (TH)

Systems	**Emission factors (EF)**					
	NH_3-EF (kg NH_3-N/kg of remaining N)	**Uncertainties** (kg NH_3-N/kg of remaining N)	**N_2O-EF** (kg N_2O-N /kg of remaining N)	**NO_3-EF** (kg NO_3-N /kg of remaining N)	**N_2-EF** (kg N_2-N /kg of remaining N)	**CH_4-EF** (%)
1. At the housing stage ^{a}						
Slatted floor, DK	0.15 [1]	-	-	-	-	-
Deep litter, DK	0.15 [1]	-	-	-	-	-
Solid floor, TH	0.18 [1]	-	-	-	-	-
2. At the storage stage						
Uncovered anaerobic lagoon , DK	0.09 [2]^{b}	0.04-0.13 [2]	0 [3]	0.2 [4]	0 [5]	74 [3]^{d}
Storage tank with a cover /natural crust, DK	0.02 [2]^{c}	0.01-0.03 [2]	0.005 [3]	0 [4]	0.015 [5]	17 [3]^{d}
Deep litter, DK	0.25 [1]	-	0.01 [3]	0.05 [4]	-	27 [3]^{d}
Solid fraction manure, TH	0.30 [1]	-	0.005 [3]	0.1 [4]	-	5 [3]^{d}
Uncovered anaerobic lagoon , TH	0.09 [2]^{b}	-	0 [3]	0.2 [4]	-	80 [3]^{d}

[1] Poulsen & Kristensen (1998), [2] Poulsen *et al.* (2001), [3] Dong *et al.* (2006), [4] Velthof *et al.* (2007), [5] EMEP-CORINAIR (2001); The values are derived from the calculation method as 3xN_2O-N.

[a] Methane emissions at the housing and storage stages are not separated in Dong *et al.* (2006) and the total emissions are thus only presented at the storage stage, [b] Determined the storage system as slurry without surface cover, [c] Determined the storage system as slurry with surface cover, [d] CH_4-EF for digested/ incinerated/ gasified slurry = 0%; Based on CH_4-EF/MCF values at 15˚C for DK and at 27˚C for TH; Applied on the modified equation - $EF = VS*B_0*0.67 kg/m^3*MCF$; EF = Total methane emission (kg CH_4); VS = VS in the fraction (kg); B_0 = Methane yield (m^3 CH_4/kg of VS).

The emissions from pig manure handled with the commonly used systems were calculated from Danish and Thai cases as presented in Paper 1C. The results showed that the Danish system using slatted floor and storage with a cover yielded the lowest N and C emissions (17% and 10% of total excretion, respectively) compared with the other typical Danish and Thai systems (deep litter for the Danish system; solid floor and uncover anaerobic lagoon with solid fraction manure in the Thai system). Similarly, other studies revealed that slatted-floor housing systems and storage systems with a cover and concrete floors can reduce GHG, ammonia and nitrate emissions considerably (Hansen *et al.*, 2006; Rotz, 2004). Despite the fact that the Danish systems in Paper 1C considered methane emission factors at the temperature lower than 10°C - the annual mean temperature in Denmark (Rasmussen & Jørgensen, 2005) - this does not influence the conclusions when applying the factors at 15°C in Table 2.5.

Not only do the N and C losses result in negative impacts on the environment, but the potentials in energy and nutrient recovery from pig manure are also decreased. The potential energy and nutrient recoveries from pig manure handling systems will be investigated and illustrated in next chapter. Furthermore, the environmental impacts of the emissions in terms of CH_4, N_2O, NH_3, and NO_3^- will be included in the assessment of chapter 4.

2.4 Highlights

With respect to the purposes for determining the influences of diet compositions on pig manure characteristics and the potential N and C losses from different housing and storage systems, the highlights are.

- Diet compositions highly influence the manure characteristics. With respect to the developed and selected prediction models for the manure excretion using dietary variables, the predictions and control of excretions can be done via the known and restricted amounts of the DM intake and dietary fibre content (for the C content), N/protein intake (for the N content) and P intake (for the P content). The controls depend on the requirements regarding pig healthiness and good pork quality. Therefore specific knowledge on the relations between the reductions of the N and P intakes and the supplementation of essential amino acids and phytase is needed. Although the potentials for these improvements have been studied, they have not been fully applied worldwide due to the constraints from the availability of specific feed ingredients and economy.

- The two approaches to estimate the characteristics of the excretions in term of N, P, and C are further applied to three common diet compositions in Denmark, in Thailand and in Vietnam. The comparison between the experimental and calculated results show that the very simple input-output model like the Danish manure normative system is very useful to estimate the total N and P excretion. In the same time, the newly developed equations using diet variables are beneficial for prediction of the DM, N and C content in faeces and in urine. However, the biases from the model, especially the N excretion via urine, were observed. Hence, the model modifications in relation to the local pig production systems and the availability of nutrient in local feed ingredients are required in order to quantify the excretion more precisely.

- The losses of CH_4, N_2O, NH_3 and NO_3 from pig manure management at the housing and storage stages can be decreased by applying proper systems. In this study, the slatted floor and the storage tank with a cover can limit the N and C emissions better than the other considered systems (e.g. deep litter and anaerobic lagoon) commonly applied in Denmark and in Thailand.

3. Integrated treatment technology systems for pig manure management

To facilitate the effective utilisation of energy and nutrients from pig manure, it is essential to consider the available and applicable treatment technologies with up-to-date information. Most of the existing plants treating pig manure with energy recovery are based on anaerobic digestion technology despite other existing available systems (e.g. incineration and thermal gasification). In addition, the most common system worldwide is either the handling system without energy recovery or direct land application. Thus, the aim of this chapter is to identify the potentials to recover energy and nutrients from pig manure management by applying various integrated treatment technology systems aiming at energy extraction with the utilisation of the existing knowledge. The results can support the farmers to improve their traditional systems due to possible better economy while still protecting the resources and the environment. For the evaluations, the system efficiencies were selected from treatment facilities in Denmark and in Thailand supplemented with available literature. The Danish efficiencies are considered as the state-of-the-art systems and the representative for industrialised countries whereas the Thai efficiencies are determined as the representative for developing countries.

3.1 Integrated treatment technology systems

3.1.1 System description

The integrated treatment technology scenarios include the treatment and storage stages considering the recoveries of energy and nutrients (Fig. 1.1). The characteristics of pig manure and other chosen types of wastes were measured at a Danish farm supplemented with literature data as shown in Table 3.1. The overall mass and energy flow diagram of the considered integrated treatment scenarios are illustrated in Fig. 3.1.

The eight integrated scenarios are based on the combinations of various practically applicable treatment technologies – anaerobic digestion, thermal pre-treatment, liquid/solid separation, drying, incineration, and thermal gasification. The reference scenario is no treatment system (S1). In order to determine the potential for energy recovery for the integrated treatment scenarios, the system efficiencies of the technologies were collected as presented in Table 3.2.

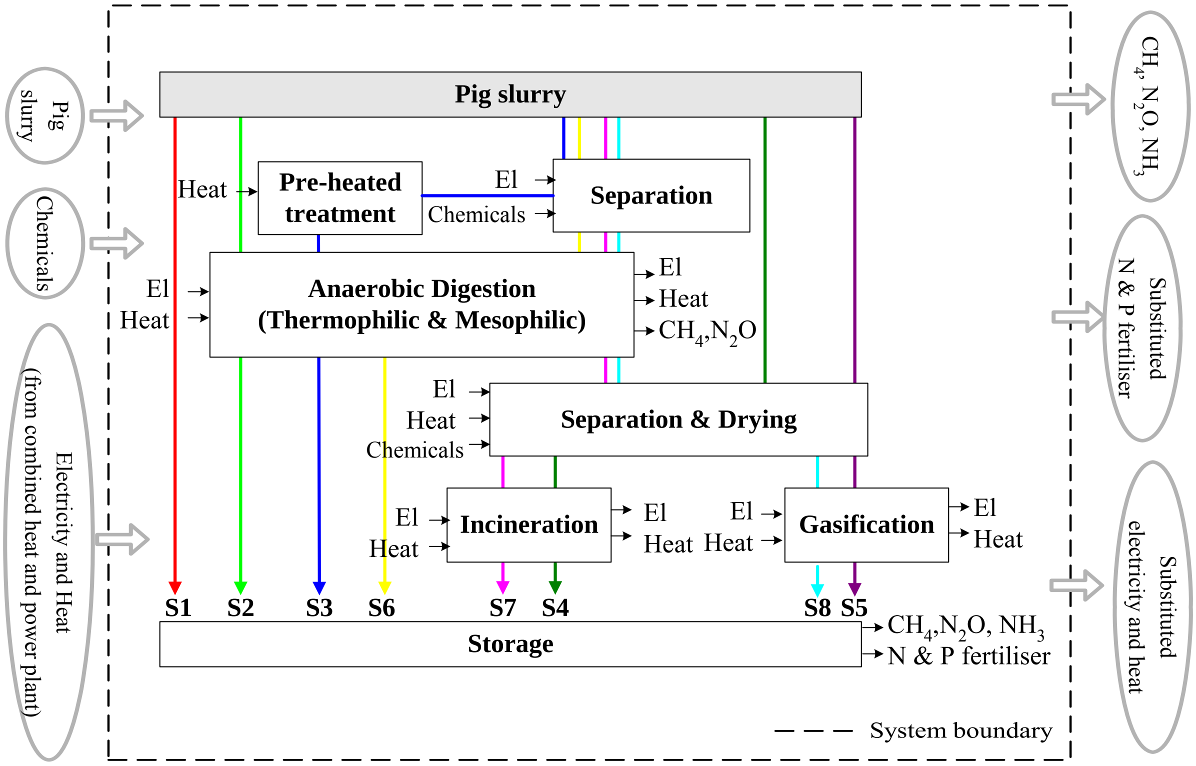


Fig. 3.1 Overall mass and energy flow diagram for pig manure management scenarios (S1-S8). The colour horizontal arrows indicate overall mass flow of each scenario. The vertical arrows inside the boundary indicate internal mass and energy flows in terms of electricity (El), heat, main gas emissions (CH_4, N_2O and NH_3) and N and P fertiliser. The gray arrows indicate mass and energy either entering or leaving the system.

Table 3.1 Characteristics of the waste fraction.

Characteristics	Pig manure	Glycerine	Grass silage	Solid manure	Mixed waste [d]
DM (%)	8.3 [1]	40 [1]	30.2 [1]	53.9 [c]	12.0
N (% of DM)	4.8 [1]	0 [1]	2.7 [1]	3.1 [c]	3.4
P (% of DM)	1.57 [1]	0 [1]	0.04 [1]	1.6 [c]	0.95
C (% of DM)	40 [2]	39.1 [1]	48.6 [1]	40.1 [c]	42
VS (% of DM)	73 [3]	78 [1]	86 [8]	73 [c]	77
Ash (% of DM)	-	0.2 [a]	5.46 [9]	5.94 [10]	5.6
Methane yield (m^3 kg^{-1} VS)	0.32 (pilot scale) [4], 0.36 (plant scale) [5]	0.75 [7]	0.36 [8]	0.29 [4]	0.42
Energy content (GJ $tonne^{-1}$ DM)	15.2 (raw), 12.2 (digested) [6]	32.9 [b]	17.3 [9]	15.2 (raw), 12.2 (digested) [6]	19.2 (raw), 15.4 (digested)

[1] Data from a Danish biogas plant (Grøngas), [2] Murto *et al.* (2004), [3] Azam (2007), [4] Møller *et al.* (2007b); applied in Paper 2A and this chapter, [5] Paper 2B; only applied in Paper 2B, 3A and 3B due to the data availability when carrying out the studies, [6] Poulsen & Kuligowski (2007), [7] Amon *et al.* (2006), [8] Azam (2007), [9] Ptasinski *et al.*, (2007); determined as grass/plant, [10] Miles *et al.* (2004). [a] Determined as fats, [b] Calculated from $C_3H_8O_3$, [c] Based on the pig manure characteristic in this Table and applied separation efficiency form Møller *et al.* (2007a) in Table 3.2, [d] Calculated from 85.8% of pig slurry, 6% of glycerine and 8.2% of grass silage by mass.

To compare the Danish and Thai cases, varied parameters are only the system efficiencies of the technologies at the treatment stage whereas other parameters are mainly based on Danish/European conditions.

In addition, the emissions of different scenarios are required to estimate the nutrient recovery and the environmental impacts afterwards. The losses from biogas combustion, incineration and thermal gasification processes at the treatment stage are presented in Table 3.3. The storage system applied in this part is the storage tank with natural crust cover and the N and C losses in terms of CH_4, N_2O and NH_3 from the system are listed in Table 2.5.

3.1.2 Calculation approach

The calculations are based on mass and energy balances. The functional unit was selected as 1 tonne of raw pig manure or other considered input wastes. For nutrient recovery, the nutrients (N and P) leaving the system boundary (storage stage; Fig. 3.1) are assumed to substitute equal amounts of nutrients in commercial fertiliser (based on Laboski & Lamp, 2003; Maraseni & Maroulis, 2008). Nonetheless, with respect to the holistic perspective, the system boundary will be broadened and include the land application stage in chapter 4. For energy recovery, it considers net direct energy production and equivalent energy avoided by the potential fertiliser values of recovered nutrients. The energy equivalent from fertiliser replacement is calculated as energy required for the N and P fertiliser production. The energy recovery efficiency is defined as the ratio of net energy production to total energy content of the input material.

3.1.3 System efficiencies of the technologies in Denmark and in Thailand

Data used for the selected technologies were collected mainly from existing treatment facilities or pilot scale research facilities in Denmark and in Thailand and presented in Table 3.2.

Table 3.2 System efficiencies of the technologies in Denmark (DK) and in Thailand (TH).

Process/Parameter	Unit	Value	Reference
Anaerobic digestion (AD), DK			
Biogas energy content (65% of CH_4)	kWh m^{-3} biogas	6.5	Christensen (1998)
Electricity production efficiency for gas engine-generator	%	38	Poulsen & Kuligowski (2007)
Heat production efficiency for gas engine	%	40	Poulsen & Kuligowski (2007)
Biogas plant energy consumption, electricity	kWh tonne^{-1} biomass	6	DEA (2005)
Biogas plant energy consumption, heat	kWh m^{-3} raw material	34	DEA (2005)
CH_4 emission, biogas process	%	2	Poulsen & Hansen (2003)
AD, TH			
Methane yield, pig manure	M^3/ kg VS	0.11	**Paper 2B**
Biogas loss	%	5	**Paper 2B**
Unused and burnt biogas	%	15	**Paper 2B**
Electricity production	kWh/m^3 CH_4	2.15	**Paper 2B**
Heat production	kWh/m^3 CH_4	0	**Paper 2B**
Separation, DK			
Separation efficiency, mass (weight)	% in solid fraction	13.0	Møller *et al.* (2007a)
Separation efficiency, DM/VS [a]/C [a]	% in solid fraction	84.4	Møller *et al.* (2007a)
Separation efficiency, N	% in solid fraction	54.3	Møller *et al.* (2007a)
Separation efficiency, P	% in solid fraction	84.6	Møller *et al.* (2007a)
Energy consumption for separation	kWh tonne^{-1} input material	3	Møller *et al.* (2000)
Thermal pre-treatment, DK			
Thermal pre-treatment CH_4 potential improvement (127˚C)	%	51	Raju (2005)
Drying, DK			
Manure drying heat consumption	MJ tonne^{-1} water	2970	Simonsen (2008)
Manure drying power consumption	MJ tonne^{-1} input mass	314	Poulsen & Kuligowski (2007)
Manure drying relative heat recovery	%	72.5	Simonsen (2008)
Incineration, DK			
Electricity production efficiency	% of energy content in waste	25.9	Reno-Nord (2006)
Electricity production efficiency (without heat production)	% of energy content in waste	45	Poulsen & Kuligowski (2007)
Heat production efficiency	% of energy content in waste	71.5	Reno-Nord (2006)
Total energy consumption	% of energy production	3.99	Reno-Nord (2006) [b]
Incineration, TH			
Electricity production efficiency	% of energy content in input waste	21.14	Data from Phuket waste incineration plant, Nov07-Dec08
Electricity consumption	% of energy production	61.85	Data from Phuket waste incineration plant, Nov07-Dec08
Gasification, DK			
Thermal gasification chemical energy output	% of input energy	83	Poulsen & Kuligowski (2007)
Thermal gasification heat energy output	% of input energy	10	Poulsen & Kuligowski (2007)
Electricity consumption	% of energy production	10	Poulsen & Kuligowski (2007)
Electricity production efficiency for combustible gases	%	38	Assumed to be equal to AD
Heat production efficiency for combustible gases	%	40	Assumed to be equal to AD
Energy reference systems, DK			
CO_2 equivalent for natural gas power CHP plant – gas turbine combined cycle	Kg CO_2 equivalent MWh^{-1} electricity or heat	282.77	DEA *et al.* (2005)

DM = dry matter, VS = volatile solids, C = carbon, AD = anaerobic digestion.

[a] Assumed to be equal to separation efficiency of DM, [b] Based on electricity and diesel consumption of the incineration plant. Energy equivalent of diesel is 42.3 MJ kg^{-1} (Haşimoğlu *et al.* 2008).

Short description of the treatment technologies is explained as follows.

Anaerobic digestion (AD)

In the Danish case, the AD process is operated under thermophilic conditions (52°C) with post-digestion under mesophilic conditions (35°C) to extract the additional methane (20 – 26 days of hydraulic retention time, in total). In the Thai case, the AD process is based only on mesophilic conditions with hydraulic retention time of 7 days (or less).

Liquid/solid separation (SEP)

The SEP process is based on experiments with a commercial separator system from Kemira Water Denmark A/S applying a cationic polymer and a filter press separator (Møller *et al.* (2007a,b).

Thermal pre-treatment (TPT)

The TPT process, applied to separated solid manure fraction prior to the AD process, is operated under 127°C to improve biogas yield. Additional energy input is not required in the TPT-AD process (compared to the AD process) because the heat used in TPT is assumed to replace the heat required in the thermophilic AD digesters.

Drying (DRY)

In the Danish case, the DRY process evaporates water from the separated solid fraction of pig manure until achieving 95% of DM content. The system can recover utilised heat for evaporation by using heat exchangers up to 72.5%. In the Thai case the DRY process is based on air-drying by sunlight without energy input. However, it is assumed that the DM content of the air-dried pig manure is equal to the DM content of the composted input waste (56%) in the Thai incineration plant where data were taken.

Incineration (INC)

The INC process is based on excess air combustion converting the combustible materials to hot flue gases and bottom ashes with energy extraction via stream turbine and heat exchangers (McKendry, 2002a).

Thermal gasification (GAS)

The GAS process is based on partial combustion, with a limited oxygen condition, to produce syngases (e.g. CO, H_2, CH_4), which can be combusted and produce energy by using a gas engine (McKendry, 2002a, b).

3.1.4 Emissions at the treatment stage

The gas emissions from the combustion processes (biogas combustion, incineration and thermal gasification) are listed in Table 3.3. For incineration and thermal gasification, all N content of pig manure encompassed the processes are converted to N_2O, NO_x and N_2. The N_2 emission in this fraction does not contribute to the results and is subsequently excluded.

Table 3.3 Emission factors at the treatment stage in Denmark (Nielsen *et al.*, 2007) and Thailand (Liamsanguan & Gheewala, 2007)

	Emission factors (EF)					
	CH_4-EF	**N_2O-EF**	**NOx-EF**	**SO_2-EF**	**CO-EF**	**NMVOCs-EF**
Danish Systems\Units (g/GJ waste)						
Anaerobic digestion, DK	323 [a]	0.5	540	19.2	273	14
Incineration and Thermal gasification, DK [b]	0.59	1.2	124	23.9	7.4	0.98
Thai Systems\Units (kg/ net MWh produced)						
Incineration, TH	0.201	0.001	46.662[c]	8.472	11.336	N/A

[a] This is only from biogas combustion. Total CH_4-EF is also included 2% of biogas losses during biogas process (see Table 3.1), [b] Assumed to be identical to emissions from incineration of municipal waste, [c] Determined as NO_2

3.2 Energy and nutrient recovery efficiencies of the integrated treatment technology systems

The energy production and nutrient recovery of selected integrated treatment scenarios are presented in Fig. 3.2.

3.2.1 The Danish cases

Eight scenarios representing the Danish cases were compared with respect to the net energy production, the energy recovery efficiencies and the substituted fertiliser potentials (S1 to S8; Fig. 3.2).

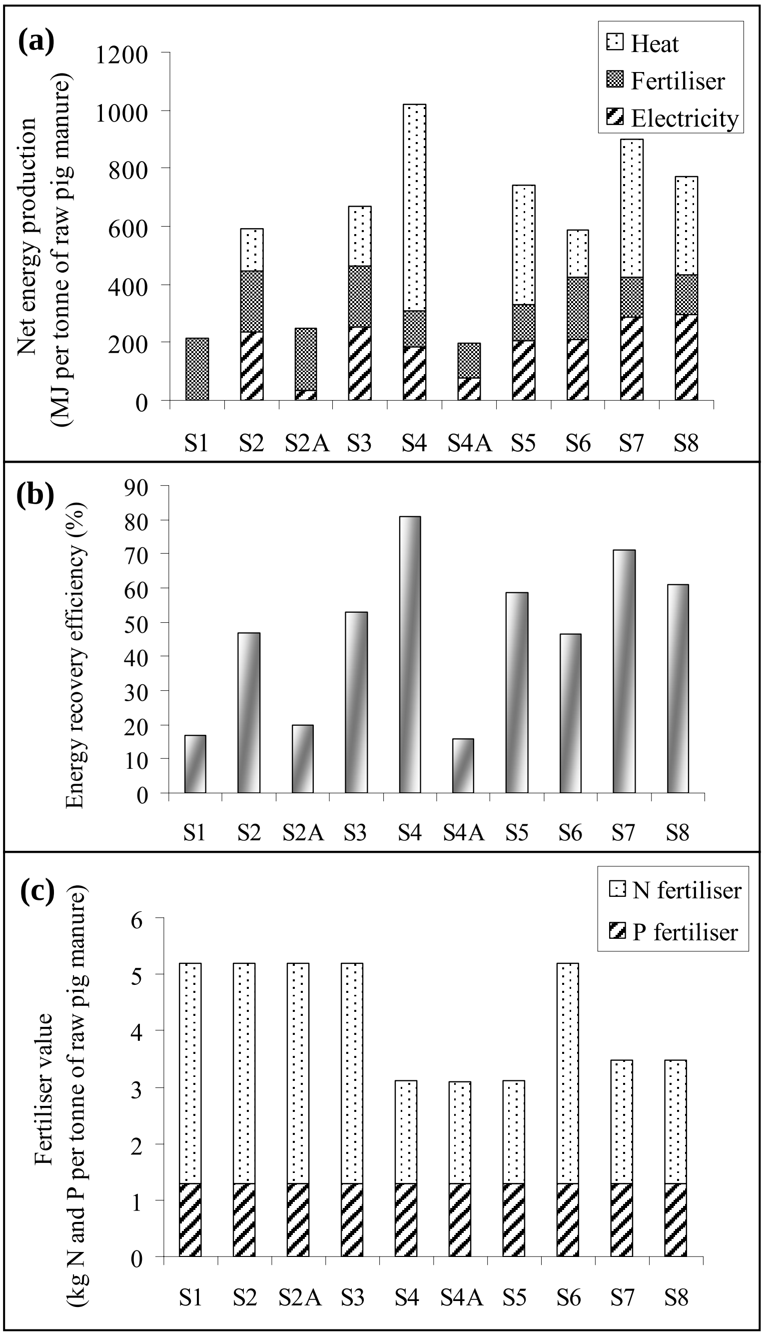


Fig.3.2 a) Net energy production, b) Energy recovery efficiencies, c) Substituted fertiliser potentials. The Danish cases are represented in scenario (S)1, S2, S3, S4, S5, S6, S7 and S8. The Thai cases are represented in S2A and S4A. See the scenario description in Fig. 3.1.

For energy recovery, the incineration based scenarios (S4 and S7) achieve the highest efficiencies with the net energy productions of 1019 and 898 MJ per tonne of fresh manure (Fig. 3.2a), corresponding to 81% and 71% of the total energy content in the manure (Fig. 3.2b), respectively. The net energy production includes electricity, heat and energy equivalents from substituted fertiliser production. Followed by the highest energy efficiencies, gasification based scenarios (S5 and S8) can extract 756 MJ per tonne of fresh manure (Fig. 3.2a; equivalent to 60%, Fig. 3.2b). Subsequently, anaerobic digestion (S2, S3, and S6) based scenarios yield 650 MJ per tonne of fresh manure on average (Fig. 3.2a; equivalent to 49%, Fig. 3.2b). The combustion processes can convert all (for incineration) or almost (for thermal gasification) organic matters to energy. With respect to the efficient drying system (72.5% of heat recovery; Table3.2), the combustions can achieve the higher energy efficiencies than the anaerobic digestion systems which are biological processes where losses can occur through bacterial growth.

Despite the lower net energy production, the electricity production rate of the gas engine in the anaerobic digestion process (38%) is higher than the electricity production rate (26%) of the steam turbine-generator in the incineration process (see Table 3.2). The addition of anaerobic digestion process can increase net electricity production up to 56% from the combustion based scenarios (S7 and S8 compared to S4 and S5, respectively; Fig. 3.2a). Finally, the reference scenario without applying treatment technology gains the lowest energy production of 212 MJ per tonne of raw pig manure with the energy recovery efficiency of 16.8% from avoided fertiliser. Compared to the reference scenario, the incineration based scenarios are the most promising ones with respect to 5.3 times of the net energy production and 60% higher energy recovery efficiency.

Nonetheless, the mentioned scenarios are based on the cases that all energy can be utilised as electricity and heat. In many cases heat can not be utilised (e.g. in the rural area) while the electricity can be transported over long distances. Subsequently, the energy efficiency may be dissimilar. However, the incineration process can maximise the electricity production efficiency (45%; Table 3.2) by cooling all produced heat away. Under the circumstance, incineration and anaerobic digestion based scenarios obtain the similar net energy production from electricity and fertiliser equivalents. This aspect will also be discussed in chapter 4.

For nutrient recovery, all scenarios can recover the same amount of P because the P content was not lost during the processes (Fig. 3.2c). In contrast, for the N fertiliser potentials, the scenarios applying the incineration or thermal gasification processes (S4, S5, S7 and S8) have lower amount of avoided N than other scenarios (S1-S3, and S6) because all N content in the pig manure encompassing the combustions were converted to N_2, N_2O and NO_x (Fig. 3.2c). Additionally, the N losses during storage for all scenarios are fairly small due to the low NH_3 emission from the storage tank with natural crust cover (2% of N content in the pig manure; Table 2.5). The higher N content kept in the pig manure can possibly emit at the land application stage leading to lower fertiliser potentials and increased environmental impacts. This issue will be further elaborated in chapter 4.

3.2.2 Comparison with the Thai cases

For the Thai case, only anaerobic digestion and incineration based treatment scenarios were discussed because there is no available data for thermal gasification (S4A and S5A; Fig. 3.2).

For energy recovery, the Thai incineration-based and anaerobic digestion-based scenarios (S4A and S2A) yield in 5 and 2 times lower net energy production/energy recovery efficiencies compared to the Danish scenarios (S4 and S2, respectively; Fig. 3.2a and b). Additionally in Thai cases, the energy can be mostly gained from substituted fertiliser due to low electricity production rate and no heat utilisation (Fig. 3.2a). The incineration process in Thailand consumes high percentage of electricity for drying the high water content (44%) in input materials whereas the Danish scenarios include the effective drying with heat recovery prior to incineration process. In respect to this low efficiency, the no treatment scenario (S1) becomes even a better choice than Thai incineration scenario (S4A; Fig. 3.2b). In anaerobic digestion process, the Thai-based scenario (S2A) can produce electricity of only 15.6% of the Danish anaerobic digestion-based scenario (S2; Fig. 3.2 a). This can be explained by the very low biogas yields due to the short retention time in Thai biogas plants in combination with the unutilised biogas and the low gas engine efficiency to produce electricity. Generally, the mesophilic anaerobic digestion process (the Thai case) often requires higher retention time to gain the same gas yield as the thermophilic conditions (the Danish case). The opposite practices in the Thai and Danish cases with the hydraulic retention time of 7 days and 20-26 days, respectively result in 3 times lower biogas yield in the Thai case.

To improve the energy efficiencies in the Thai cases, it is recommended to increase the DM inputs by effective drying systems (e.g. air-drying by sunlight or drying system with heat recovery) prior to the incineration process. For anaerobic digestion process, the suggestions include the increase of the DM inputs and the retention time or a change to the system of thermophilic conditions by utilising heat produced from the system itself. For both technologies, the total energy outputs can be substantially improved if heat utilisation is included.

The results in this dissertation were based on the application of Thai system efficiencies to pig manure characteristics in the Danish condition (Table 3.1). Consequently, the nutrient recoveries are similar for the Danish and Thai cases (Fig. 3.2c). In Thailand, the manure generally had much lower DM content (1.6% - 3% or lower; PCD, 2000) compared with the Danish manure characteristics (with the DM content of 8.3%; Table 3.1). Therefore, water saving to increase the DM content and to save the resource can both increase the energy outputs and improve farmer economy in Thailand.

3.2.3 Other organic wastes

In order to increase energy production from the waste treatment facilities (e.g. anaerobic digestion), an addition of various wastes or materials with high DM or energy content have been integrated. As described in Paper 2A, the similar set of treatment technologies were applied to pig manure mixed with the high energy wastes (glycerine and grass silage). The mixed waste scenarios yield 2 times higher net energy production than the sole pig manure scenarios because of the increased energy content per tonne of the input material (see the mixed waste characteristics in Table 3.1). Although the energy recovery efficiencies of the scenarios are the same, if compared to no treatment scenario, the usages of the high energy content in the wastes via effective treatment systems are obviously more beneficial than losing them in the field.

Furthermore, the combinations of the technologies to extract energy were applied to biodegradable household wastes. Generally, the conclusions with respect to the ranks of the treatment systems were similar to the mentioned findings from the pig manure treatment scenarios. Nevertheless, the reference scenario and some processes were different. Instead of applying the processed wastes to the fields, they were transferred to landfills. Furthermore, waste collection, transportation and landfilling systems (with the methane losses via the landfilling) were taken into consideration.

3.3 The uncertainties of the energy extraction

The sensitivities from selected input parameters were assessed to determine the uncertainties of the results in terms of energy recovery efficiencies and net energy productions. The analyses indicated that the energy recovery efficiencies and net energy productions are generally most sensitive to the dry matter content in the solid fraction from the liquid-solid separation process, and the contents of DM, energy and volatile solids in the pig manure. Consequently, the energy extraction in this investigation can be further improved by increasing manure dry matter content prior to the energy recovery or the solid-liquid separation processes. For instance, the manure handling system in pig stables with the separation of faeces and urine collection can achieve the solid manure fraction up to 29.2% DM (based on Møller *et al.* 2004).

3.4 Highlights

In relation to the integrated treatment technology systems, the highlights are.

- For the Danish cases, the incineration based treatment system achieved the highest energy recovery from the pig manure in terms of net electricity and heat production (895 MJ/tonne of the raw pig manure) as well as the energy equivalent in the substituted nutrients (124 MJ/tonne of the raw pig manure). Anaerobic digestion system was also important to maximise the electricity production. In total, the integrated treatment systems aiming at energy extraction (anaerobic digestion, incineration, thermal gasification) improved the efficiencies from the traditional system (no treatment) from 30% to 50% of total energy content in the pig manure.

- For the Thai cases, the application of the anaerobic digestion and incineration systems did not obviously increase the energy extraction as the energy equivalents of substituted fertiliser from the no treatment system. The recommendations for the Thai incineration and anaerobic digestion systems are to utilise the heat from the system (e.g. heating piglets, changing mesophilic- to thermophilic-digestion systems, thermal-preheating/drying pig manure) and to increase the DM inputs (e.g. separation, water savings, and drying via heat utilisation or natural sunlight) prior to the energy extraction. In addition, higher retention time or thermophilic conditions can improve the biogas yield from the Thai anaerobic digestion system.

- For the nutrient recovery in Denmark and in Thailand, all systems can recover almost the same amount of the N and P fertilisers (3.9 kg N and 1.3 kg P/tonne of the raw pig manure) except the incineration and thermal gasification based systems. All nitrogen encompassed the incineration and thermal gasification processes were converted to N_2 and NO_x.

4. Comprehensive assessment on the environmental impacts from pig manure management applying integrated technology systems

In order to achieve the sustainable direction in pig manure management, it is necessary to investigate the entire chain of pig manure management from generation to ultimate usage on land or as bio-fuel. Nevertheless, the assessment only considered the treatment, the storage, the transportation and the land application stage due to the well-defined systems and efficiencies as well as the included energy and nutrient recovery in the stages. Various tools to assess the environmental impacts are available but different tools (e.g. environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle assessment (LCA) and material flow analysis (MFA)) generally aim at different aspects. The EIA is a tool assessing the environmental impacts from projects which are often site-specific and relates to decision-making processes. On the more strategic level, the SEA focuses on the environmental impacts from policies, plans and programmes integrating on a decision making process at an early stage. (Finnveden & Moberg, 2005). The LCA aims to assess the overall environmental impacts considering all emissions and the resource usages and productions throughout a product’s life cycle (ISO 14040, 2006) whereas the MFA emphasises only on the material flows and resources (Finnveden & Moberg, 2005). In order to conduct a comprehensive assessment of the environmental impacts from the pig manure in this study, LCA can fulfil the aim better than other tools and is thus selected as the tool for the investigation. Initially, the significant impact categories based on the assessment of a traditional pig manure management system are identified in this chapter. The environmental impacts include not only the impacts on ecosystems but also human health and resources. Afterwards, the significant impact reductions are investigated by applying different integrated technology systems.

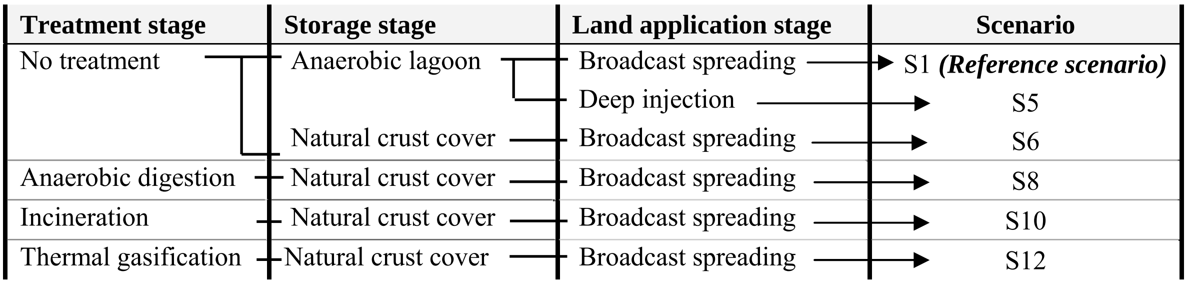
4.1 Methods

The assessment of pig manure management systems considers four LCA phases – goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation, which basically follows the general framework described in ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006).

4.1.1 Goal and scope definition

The goal or objective of this chapter is to identify how to reduce the significant environmental impacts on ecosystems, human health and resources from pig manure management towards sustainability using various integrated technology systems. Therefore, the significant environmental impacts are initially identified followed by the impact reductions from the commonly applied handling system. The functional unit is the treatment and the disposal of 1 tonne of raw pig manure (wet weight). The scope of this investigation includes the treatment, storage and land application stages (Fig.1.1). Five integrated pig manure management scenarios representing high impact reductions and a reference scenario were selected from Paper 3A to discuss here (S1, S5, S6, S8, S10, and S12; see Fig. 4.1).

Four treatment systems are based on no treatment, anaerobic digestion, incineration and thermal gasification processes, which are similar to the integrated treatment scenarios in section 3.1.1 (S1, S2, S4 and S5 in Fig. 3.1, respectively). Two storage systems – the anaerobic lagoon without concrete floor and the storage tank with natural crust cover were chosen due to their wide applications in Europe and other regions (Petersen & Miller, 2006; Rotz, 2004). For land application systems, the broadcast spreading and the deep injection are chosen for further discussion in the dissertation due to its wide application and its highest impact reduction, respectively. Three other spreading systems are shown in Paper 3A.



Treatment stage	Storage stage	Land application stage	Scenario
No treatment	Anaerobic lagoon	Broadcast spreading	S1 ***(Reference scenario)***
		Deep injection	S5
	Natural crust cover	Broadcast spreading	S6
Anaerobic digestion	Natural crust cover	Broadcast spreading	S8
Incineration	Natural crust cover	Broadcast spreading	S10
Thermal gasification	Natural crust cover	Broadcast spreading	S12

Fig. 4.1 Flow diagrams of the selected multi-stage scenarios (See full diagram in Fig.2, Paper 3A). Anaerobic digestion, incineration and thermal gasification systems are equivalent to S2, S4 and S5 in Fig.3.1, respectively.

For the investigation, the consequential approach is selected to capture the actual consequences of the chosen pig manure management scenarios by including the affected suppliers (or marginal suppliers) and by avoiding co-product allocation through system expansion (Weidema & Ekvall, 2009; Paper3A). This modelling can assess the environmental impacts from the changes of the system alternatives better than the attributional (or descriptive) approach does because it does not exclude the downstream processing and products and focuses on the relevant or actual affected suppliers instead of the average ones. The by-products in this case are electricity, heat and N and P fertiliser in which the marginal suppliers in Denmark are identified. The marginal electricity production includes the energy sources from 51% of coal, 43% of natural gas, and 6% of wind (Lund et al., 2008). The average marginal heat is made up of 40% coal-based combined heat and power (CHP) plant, 29% natural gas-based CHP plant, 12% biomass-based CHP plant, 15% biomass-fired boilers and 4% natural gas-fired boilers (the estimation based on a report on Danish heat plan; Rambøll *et al.*, 2008). According to Schmidt (2007), the marginal heat suppliers produce electricity in the production system. Hence, the marginal heat production also includes avoided electricity production. For the avoided N and P fertilisers, the marginal suppliers are determined as calcium ammonia nitrate and triple super phosphate production using modern technologies (Schmidt, 2007). The calculations were based on mass balances of N, P, C and DM.

4.1.2 Life cycle inventory

The data inventory of pig manure in the included life cycle stages (treatment, storage and land application) were established with regards to the data collected from existing waste treatment facilities, pilot scale research facilities, technical reports and literature mainly based on Danish/European conditions. First of all, Pig manure characteristics in this chapter are mainly based on a European database (Søgaard et al., 2002; Table 4.1) and different from the ones in chapter 3, which were primarily measured at a Danish farm (see Table 3.1).

Table 4.1 Pig manure characteristics

Pig manure characteristics	Values
Dry matter, DM (%)	4.04 (2.41) [1]
Total ammoniacal N (g kg^{-1})	2.54 (0.99) [1]
N (g kg^{-1})	3.67 (1.32) [1]
P (g kg^{-1})	0.99 (0.12) [2]
C (% of DM)	40 [3]
VS (% of DM)	76 [4]
Energy content (GJ $tonne^{-1}$ DM)	15.2 [5]

[1] Søgaard *et al.*, 2002, [2] Murto *et al.* (2004), [3] Azam (2007), [4] Poulsen & Kuligowski (2007)

Second, the technological data of different treatment systems and the losses at the treatment stage were collected from the existing waste treatment facilities supplemented with pilot scale studies and literature (see Tables 3.1 and 3.2). The energy and nutrient recovery per tonne of raw pig manure from the six chosen scenarios is shown in Table 4.2. Nonetheless, with respect to the different pig manure characteristics, the parameters relating to the manure characteristics (e.g. % DM of separated solid manure, and energy consumption for drying process) are not the same in chapter 3 and in this chapter.

Table 4.2 Avoided net energy and nutrient production from the selected scenarios (per ton of raw pig manure)

Scenarios*	Electricity (MJ)	Heat (MJ)	N fertiliser (kg N)	P fertiliser (kg P_2O_5)
S1 (No treatment)	0	0	0.842	0.916
S5 (No treatment)	0	0	1.067	0.916
S6 (No treatment)	0	0	1.139	0.916
S8 (Anaerobic digestion)	124	31	1.139	0.916
S10 (Incineration)	62.5	292	0.521	0.295
S12 (Gasification)	73.1	146	0.521	0.295

* See the detailed description in Fig. 4.1

Third, the data relating to the emissions in terms of NH_3, N_2O, NO_3^-, N_2 and CH_4 at the storage and land application stages from various systems are presented in Table 2.5 and in Table 4.3, respectively. In addition, CO_2 emission from pig manure is excluded from the calculations since it is considered as biogenic. As mentioned before, for the spreading methods, only the broadcast spreading and the deep injection are discussed in the dissertation. Finally, other supplementing inventories and assumptions are further explained in Paper 3A.

Table 4.3 Emission factors at the land application stage in Denmark

Systems	Emission factors (EF)					
	NH_3-EF (kg NH_3-N/kg of remaining N)	**Uncertainties** (kg NH_3-N/kg of remaining N)	**N_2O-EF** (kg N_2O-N /kg of remaining N)	**NO_3^-EF** (kg NO_3^--N /kg of remaining N)	**N_2-EF** (kg N_2-N /kg of remaining N)	**CH_4-EF** (%)
Broadcast spreading	0.208 [1][a]	0.150-0.400 [2]	0.01 [4]	1-25 [2]	0.030 [6]	0 [7]
Bandspreading : trailing hoses	0.120 [1][a]	0.103-0.140 [1]	0.01 [5]	1-25 [2]	0.030 [6]	0 [7]
Fast incorporation	0.100 [2]	0.060-0.130 [2]	0.015 [5]	1-25 [2]	0.045 [6]	0 [7]
Shallow injection	0.057 [1][a]	0.041-0.078 [1]	0.027 [5]	1-25 [2]	0.081 [6]	0 [7]
Deep injection	0.020 [2]	0.010-0.050 [2]	0.027 [5]	1-25 [2]	0.081 [6]	0 [7]
Artificial fertiliser	0.020 [3]	-	0.010 [4]	-	0.030 [6]	-

[1] Søgaard *et al.*, 2002, [2] Rotz, 2004, [3] Payraudeau *et al.*, 2007, [4] Klein *et al.*, 2006; Based on direct N_2O emissions. Indirect emission is excluded, [5] Wulf *et al.*, 2006; Based on percentage of N_2O emission of using trailing hose application, [6] EMEP-CORINAIR, 2001; The values are derived from the presented calculation method as 3xN_2O-N, [7] Rodhe *et al.*, 2006, [a] the values are calculated from applying ratio of total ammoniacal nitrogen and total nitrogen in Table 2 to the original EF.

4.1.3 Life cycle impact assessment (LCIA)

The data of emissions, materials and energy from various integrated pig manure management systems are classified and characterised into different impact categories. For example, for global warming the emissions potentially causing the impacts are classified which mostly are fossil CO_2, CH_4 and N_2O in this study. Subsequently, they are converted to the unit of kg CO_2 equivalent by using the identified conversion factors, mostly based on IPCC (2001). Afterwards the characterised results in different impact categories can be further converted into a single unit by normalisation or weighting methods. However, the characterised results (mid-pointed level) are focused here due to high uncertainties and biases from normalised or weighted results. The STEPWISE 2006 method (Weidema, 2009) is selected as the LCIA method. Other LCIA methods (EDIP2003, EDIP97, IMPACT2002+) are also taken into account in the identification of impact significance and sensitivity analyses.

4.1.4 Interpretation

Interpretation includes the discussion of results, the analyses of uncertainties and recommendations. Detailed discussions of LCIA results will be discussed in the following section. The effects of influencing chosen parameters are analysed to determine the result uncertainties. Finally, the recommendations are drawn as the main keys for the impact reduction in highlights (section 4.4).

4.2 Environmental impacts from integrated pig manure management systems

4.2.1 Identification of significant impact categories

To determine the important impacts, the reference scenario (S1) was assessed with three LCIA methods (STEPWISE2006 excluding biogenic carbon dioxide, IMPACT2002+ (Jolliet *et al.*, 2003) including biogenic methane, EDIP2003 (Hauschild & Potting, 2005)). Based on the percentage of single scores for each impact in Fig. 4.2, the significant impact categories are global warming, respiratory inorganics, terrestrial eutrophication, aquatic eutrophication, respiratory organics, photochemical ozone on vegetations, acidification, and human toxicity (carcinogens and non-carcinogens). For the aquatic eutrophication, the percentage present in Fig. 4.2 using the EDIP2003 method represents the sum of 88% from N-related emissions (e.g. nitrate, ammonia) and -80% from the avoided P emission (during the P fertiliser production system). Only the four more significant impacts (global warming, respiratory inorganic, terrestrial eutrophication, and aquatic eutrophication) were included in Paper 3A. The LCIA results of every significant impact will be discussed in the next section.

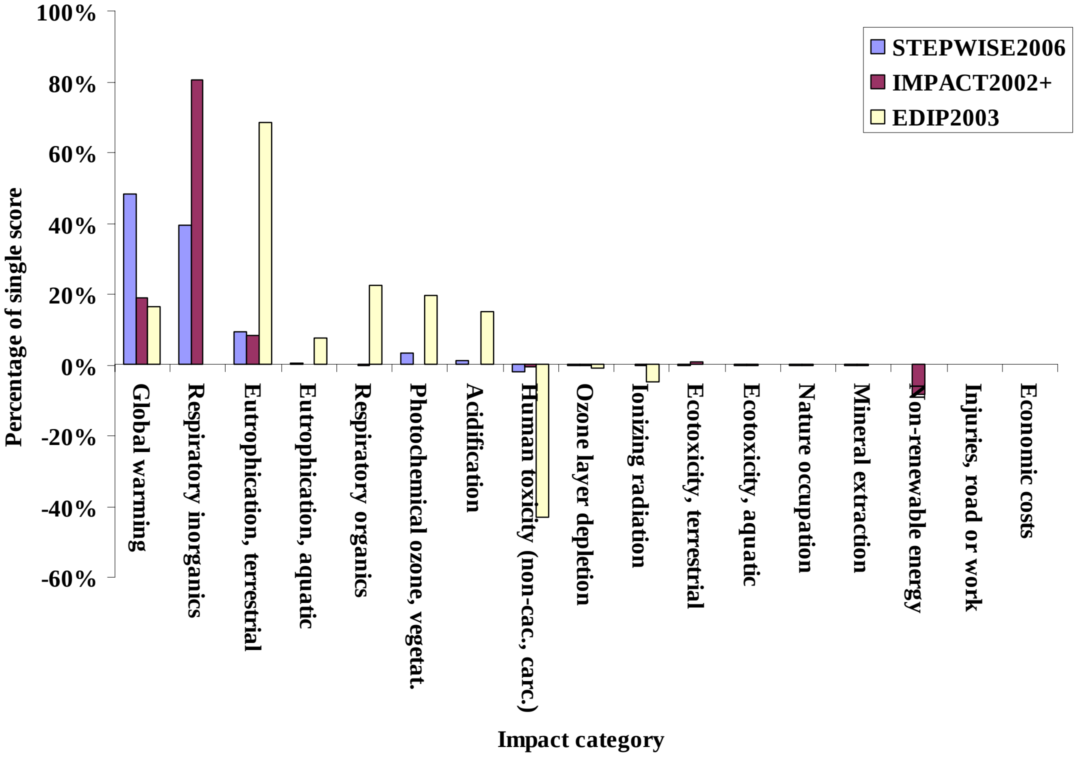


Fig. 4.2 Comparative LCIA results from the three LCIA methods - STEPWISE2006, IMPACT2002+ and EDIP2003. The IMPACT2002+ method is modified by including biogenic methane and the STEPWISE2006 method is modified by excluding biogenic carbon dioxide (vegetat. = vegetation, carc. = carcinogens) (Paper 3A).

4.3.2 Significant environmental impacts and impact reductions

The characterised results for the significant impacts are presented in Fig.4.3. In order not to exclude the important aspects possibly arising from different impacts, the magnitude of each impact and its reduction will be discussed initially as follows.

Global warming potential (GWP)

For GWP, the scenarios aiming at energy recovery (S8, S10 and S12) can reduce the impact from the reference scenario (S1) up to 144 kg CO_2-eq./tonne raw pig manure (Fig. 4.3a). The anaerobic digestion based scenario (S8) yields the highest impact reduction due to the recoveries of energy and nutrients (N and P) from pig manure. Although incineration and gasification based scenario (S10 and S12) can extract higher energy than anaerobic digestion (see Table 4.2), the less substituted N and P fertiliser to plants due to the combustion process results in lower GWP saving. In addition, without energy recovery system, the scenario with natural crust covering storage (S6) can reduce 94 kg CO_2-eq./tonne raw pig manure from the reference scenario (S1) using anaerobic lagoon. This is caused by methane oxidation which can occur in the storages with natural crusts resulting in reduced CH_4 emissions (Petersen *et al.*, 2005). The findings present the significance of the recoveries of energy and nutrients and the controls of GHG emissions in GWP emission reductions.

Respiratory inorganic potential (RIP)

RIP is the respiratory effect on human health caused by inorganic substances such as particulate matters (Anderson *et al.*, 2002). From the assessment, S5, S10 and S12 can reduce RIP from S1 up to 0.077 kg $PM_{2.5}$ (particulate matter with a diameter smaller than 2.1 μm)-eq./tonne raw pig manure (Fig. 4.3b). The main contributor for RIP in this study is ammonia emission followed by NO_x emission. Ammonia is the well known precursor for secondary particulate formation such as ammonium nitrate and ammonium sulphate (Anderson *et al.*, 2002). The combustion based scenarios (S10 and S12) have less N content left in the processed manure resulting in less ammonia emissions. The scenario without treatment system using an effective spreading method aiming at reduction of ammonia emission (deep injection; S5) can also reduce this impact considerably. In the anaerobic digestion based scenario (S8), it causes slightly higher RIP than in S1 because of the NO_x emission during the biogas combustion process (see Table 3.3).

Terrestrial eutrophication potential (TEP)

TEP is the eutrophying impact on terrestrial ecosystems such as native vegetation, forests, and agricultural crops. Increased deposit of limiting nutrient (N) to the terrestrial environment can influence the biodiversity due to the fact that this may favour some species in spite of the others (Krupa, 2003). From the assessment, S5, S10 and S12 can reduce TEP from S1 up to 86 m^2 UES (m^2 in which critical load values of ecosystem is exceeded)/tonne raw pig manure (Fig. 4.3c). In accordance with RIP, the scenarios with less ammonia emission yield the lower TEP since the main contributor for this impact is ammonia emission.

Aquatic eutrophication potential (AEP)

AEP is the eutrophying impact caused by releases of limiting nutrients (N and P) to biological growth in aquatic ecosystems (Hauschild & Potting, 2005). From the assessment, S6 and S8 can reduce AEP from S1 1.9 kg NO_3^--eq./tonne raw pig manure (Fig. 4.3d). The main contributors for AEP are emissions of nitrate, phosphate and ammonia. The reduced AEP in S6 and S8 is due to the restricted nitrate emission (from the storage tank), and the avoided phosphate emissions (from P fertiliser production). Combustion based scenarios (S10 and S12) can reduce this impact less than S6 and S8 since the P content in the burnt manure has lower plant availability than raw or digested manure resulting in lower avoided P fertiliser (see Table 4.2).

Photochemical ozone on vegetation potential (POP)

POP is the impact of photochemical ozone formed by the reaction between volatile organic compounds (VOCs), NO_x, and sunlight resulting in reduced agricultural yields (Hauschild & Potting, 2005; Weidema *et al.*, 2007). From the assessment, S10 and S12 can reduce POP from S1 up to 1600 m^2*ppm*hours/tonne raw pig manure (Fig. 4.3e). The main contributor of POP is methane emission followed by NO_x and CO emissions. S10 and S12 yield the lowest POP reduction due to the lowest methane emission whereas S8 has biogas (methane) losses and higher NO_x and CO emissions from the process (see Table 3.3).

Acidification potential (ACP)

ACP is caused by acidifying emissions such as nitrogen (NO_x and NH_3) and sulphur (SO_2) and the deposition may increase acidity in the water or soil (Hauschild & Potting, 2005). From this assessment, S5, S10 and S12 can reduce ACP from S1 up to 19 m^2 UES/tonne raw pig manure (Fig. 4.3f). The main contributor for ACP is ammonia emission. As explained in RIP and TEP, S5, S10 and S12 have the lowest ammonia emissions and thus yield the highest reduction in ACP.

Respiratory organics potential (ROP)

ROP is the impact of photochemical ozone on humans, for example, the respiratory problems from photochemical smog in cities (Hauschild & Potting, 2005; Weidema *et al.*, 2007). From the assessment, S10 and S12 can reduce ROP from S1 up to 0.20 persons*ppm*hours/tonne raw pig manure (Fig. 4.3g). The main contributor of ROP is methane emission followed by NO_x and CO emissions. For ROP, the scenarios yield the same rank with POP because of similar impact contributor (Fig.4.3e and g). However, the anaerobic digestion based scenario (S8) yield slightly lower ROP than S6 in contrast with the impact order in POP because, in ROP, the NO_x emission (from the biogas combustion) has lower influencing weight.

Human toxicity potential (HTP)

HTP is chronic toxicological effects from toxic carcinogens and non-carcinogens on human health (Jolliet *et al.*, 2003). From the assessment, S8 can slightly reduce HTP from S1 (0.2 kg C_2H_3Cl-eq./tonne of raw pig manure). The main contributors of this impact are arsenic ion, zinc, and aromatic hydrocarbons. S8 have the reduced HTP from avoided arsenic ion (from P fertiliser production) and avoided aromatic hydrocarbons (from N fertiliser production).

Overall potential environmental impacts

The findings imply that the main contributors for the reduction of overall potential environmental impacts are the recoveries of energy and nutrients and the restricted controls of emissions in terms of GHG, NH_3, NO_3^-, and NO_x. Therefore, the best option for pig manure management is the scenario which yields the highest energy and nutrient recoveries with the lowest GHG, NH_3, NO_3^-, and NO_x emissions.

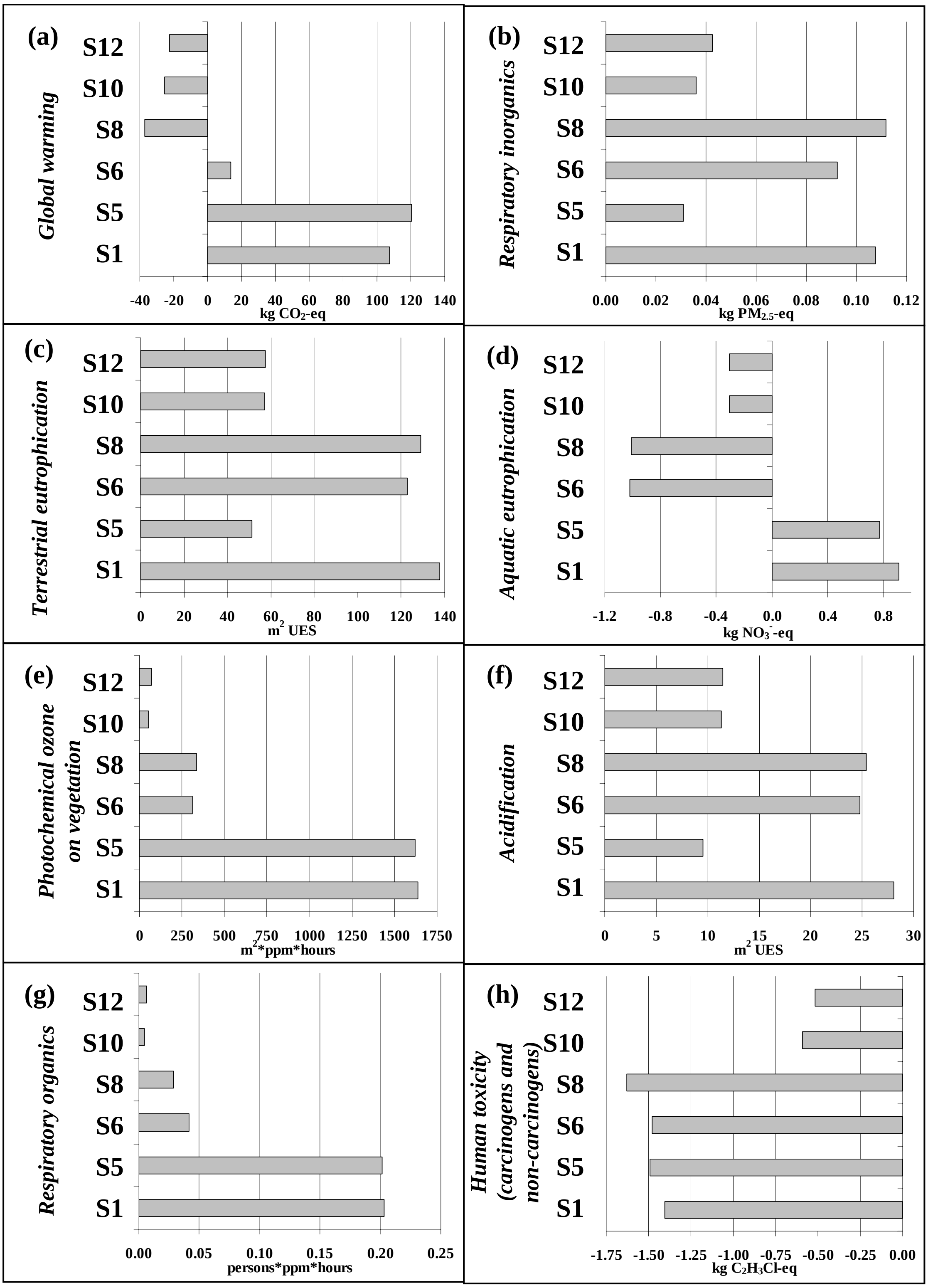


Fig. 4.3 Life cycle impact assessment results of selected 6 integrated scenarios. a) global warming potentials, b) respiratory inorganics, c) terrestrial eutrophication potential, d) aquatic eutrophication potential, e) photochemical ozone on vegetation, f) acidification, g) respiratory organics, h) human toxicity (carcinogens, non-carcinogens). The reference scenario is S1. See detailed scenario diagram in Fig. 4.1.

4.3 Uncertainties of the impact reductions

To determine the uncertainties of the found results, the major influencing factors are analysed and described in this section. The main factors included are the LCIA methods, dry matter controlling, energy reference systems, unutilised heat, treatment system efficiencies, and ammonia emission uncertainties. The analyses include only the more significant impact categories (GWP, RIP, TEP and AEP), which are significantly affected from the considered factors. Hence, the sensitivity scenarios, relating to energy production, will consider only GWP because it is the most influenced one.

4.3.1 Effects from different LCIA methods

Dissimilar LCIA methods have various approaches and weighting factors which may lead to unlike conclusions. However, to reduce the bias from using one LCIA method, this study identifies the impact significances from three LCIA methods (STEPWISE2006, IMPACT2002+, and EDIP2003) and the more significant impact categories could be similarly drawn to some extent. This implies that there is not a major influence of the LCIA methods on this assessment. Furthermore, the EDIP97 method was also applied to assess global warming potentials (Paper 3B) and it did not change the concluding results when using the STEPWISE2006 method.

4.3.2 Effects from dry matter controlling

In case that the pig manure is controlled with higher DM content such as the DM content of 8.3% measured from a Danish farm in Paper2A (see Table 3.1), the recoveries of energy and nutrients from anaerobic digestion, incineration and thermal gasification based scenarios are increased resulting in higher reduction of GWP per ton of raw pig manure (with a factor of 3 on average).

In the same time, the emissions of GHG, NH_3, NO_3^-, and NO_x are increased resulting higher negative impacts on RIP, TEP, and AEP per ton of raw pig manure (with a factor of 2 on average for each impact; see Paper 3A for further description). If the emissions are well controlled (e.g. by applying natural crust storage and deep injection method), the benefits from the high DM controlling will be apparent.

4.3.3 Effects from varied energy reference systems

The electricity and heat production systems applied in this chapter are based on the technologies which are most likely to be affected from a replacement (marginal technologies) with the combinations of different energy sources (e.g. coal and natural gas) including the avoided electricity in the heat production system. In Paper 3B, the business-as-usual marginal technologies (coal and natural gas based technologies for electricity and heat production, respectively) were applied whereas in Paper 2A, the natural gas power CHP plant were applied in both electricity and heat production. The effects from applying dissimilar marginal technologies or energy reference systems are thus determined and presented in Fig. 4.4 (S8, S10 and S12 for the marginal technologies in this chapter; S8A, S10A, and S12A for the business-as-usual marginal technologies in Paper 3B; S8B, S10B, and S12B for the energy reference system in Paper 2A).

For the marginal technologies in Paper 3B, the GHG saving is slightly higher because the coal-based electricity production contribute to higher CO_2 rate than the marginal electricity in this chapter (see S8, S8A, S10, S10A, S12, and S12A; Fig. 4.4). However, this does not change one of the main findings that the anaerobic digestion based scenario yields higher GHG saving than other scenarios.

In contrast with the energy reference system in Paper 2A, the incineration based scenario (S10B) yields higher GHG reduction than anaerobic digestion based scenario (S8B) (Fig. 4.4). This reveals the need to identify the marginal technologies applied in environmental assessment studies because it may influence the conclusions.

4.3.4 Effects from unutilised heat

In case that the produced heat cannot be utilised and only the electricity production can be sold to the grid because it can be transported over the long distances, the incineration process can be optimised by cooling the heat away to obtain an electricity production rate of 45% (see Table 3.2). The sensitivity scenarios without heat utilisation are presented in Fig. 4.4 (S8C, S10C and S12C). For S8C and S12C, although the net energy production are reduced substantially (31 MJ and 146 MJ/tonne raw pig manure, respectively), GWP values are only slightly decreased (1 kg CO_2-eq. and 6 kg CO_2-eq./tonne raw pig manure, respectively; Fig. 4.4) when compared to S8 and S12. This can be explained by the avoided marginal heat. The replaced marginal heat contributes to GWP much lower than the replaced marginal electricity does (0.038 and 0.22 kg CO_2-eq/1 MJ of marginal heat and electricity, respectively). This can be seen in the incineration scenario with optimisation that GWP is increased from the improved electricity production despite additional heat requirements (S10C; Fig. 4.4).

4.3.5 Effects from the efficiencies of treatment systems

As the selected treatment technologies represents the state-of-art with very high energy recovery efficiencies, the actual performances of these technologies may be lower. The minimum efficiencies of treatment technologies based on biological and combustion processes in this study (anaerobic digestion and incineration) were selected from biogas and incineration plants in a developing country –Thailand (see the system efficiencies and losses at the treatment stage in Tables 3.2 and 3.3, respectively). In Thai efficiency incineration based scenario (S10D), GWP saving is lower than in the normal scenario (S10) with a factor of 3 (Fig. 4.4). As discussed in section 3.2.2, the input materials with the high water content for the Thai incineration process consumes a lot of energy for evaporation (62% of total energy consumption in the Thai plant; Table 3.2). In combination with no heat utilisation, it resulted in low energy recovery efficiency and GHG savings.

For Thai efficiency anaerobic digestion based scenario (S8D), the low biogas production results in lower energy recovery (see section 3.2.2) and lower GWP saving (Factor of 2, Fig. 4.4) compared to S8. Furthermore, more than 75% of the GHG savings from the Thai plant scenarios (S8D and S10D) are derived from the avoided N and P fertilisers and these scenarios (S8, S8D, S10, and S10D) apply the natural crust cover storage tank with low GHG emissions. If pig manure is stored in anaerobic lagoon (the traditional system in Thailand and in many other countries around the world), there will be GHG emissions rather than GHG saving in the Thai efficiency scenarios. Thus, it is important to consider overall handling systems. In case that the incineration and anaerobic digestion plants have very low efficiencies and cannot be improved, it might be better to apply manure as fertiliser with a tight control for ammonia and GHG emissions.

4.3.6 Effects from uncertainties of ammonia emissions from the storage and land application systems

As assessed in Paper 3A, the uncertainties of the storage and land application systems (see Table 2.5 and 4.3) do not significantly effect on GWP and AEP but influence RIP and TEP. The two storage systems (anaerobic lagoon and storage tank with natural crust cover) presented the similarity in RIP and TEP according to the uncertainty intervals. Nonetheless, it does not affect the concluding results because the initial difference in ammonia emissions from the storage systems are not obvious compared to the ammonia emission reduction from applying different spreading systems. However, the ammonia emissions from the storage and spreading systems substantially depend on weather conditions, soil conditions and manure characteristics. Since the ammonia emission factors applied in this study are based on Danish/European studies, the actual application in other countries/regions (e.g. in Thailand) requires more data collection.

Notwithstanding the effects from different sensitivity factors, the main keys for impact reductions are still the effective energy and nutrient recovery systems and the tight controls of emissions (GHG, NH_3, NO_3^-, and NO_x). However, the sensitivity analyses reveal the need to identify marginal technologies, treatment technology efficiencies and emission factors locally to make comprehensive and accurate assessments.

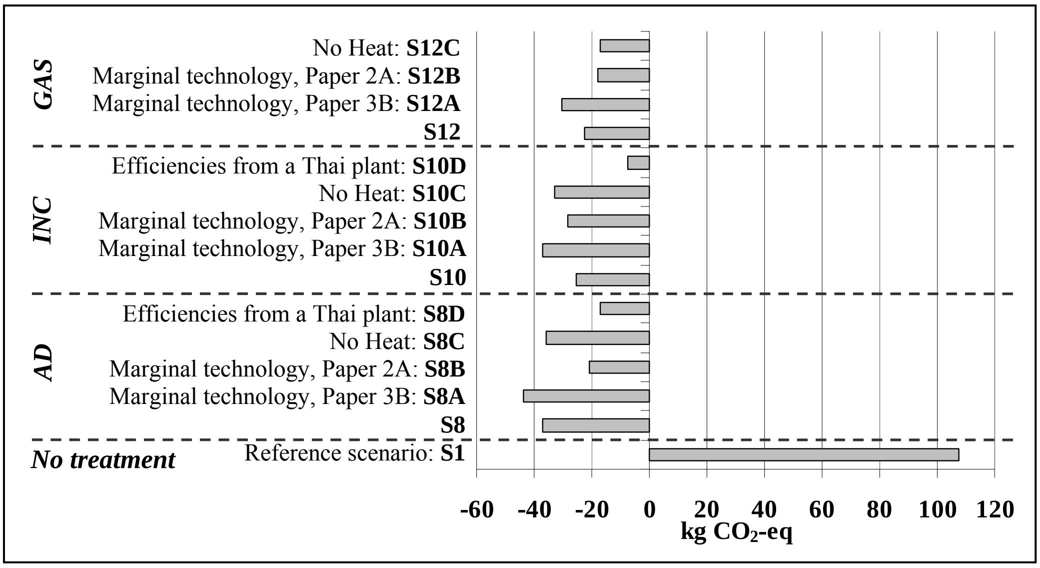


Fig. 4.4 Global warming potentials of sensitivity scenarios. See the scenario diagram in Fig. 4.1. (AD = anaerobic digestion, INC = incineration, GAS = thermal gasification).

4.4 Highlights

The highlights regarding the comprehensive environmental assessment are.

- The more significant impacts for pig manure management are global warming, aquatic eutrophication, respiratory inorganics (respiratory effects on human health from inorganic substances), and terrestrial eutrophication. There are also other 4 significant impacts included. This shows that the effective assessments require the consideration of overall environmental impacts in order not to cause another problem when solving the other one.

- The main keys for overall environmental impact reductions and sustainable pig manure management are the integration of effective treatment technologies aiming at energy and nutrient recovery (anaerobic digestion, incineration and thermal gasification); and the controls of emissions (greenhouse gases, ammonia, nitrate, and nitrogen oxides) at every handling stage (e.g. by applying natural crust storage tank and deep injection).

- With respect to the global warming potential, it completely relates to the amount of CO_2-eq. savings from the systems which depend on energy sources in the reference systems. The varied energy reference systems, which are 1) the combinations of different energy sources from coal and natural gas including the avoided electricity from the heat production system, and 2) the natural gas power CHP plant, changed the conclusions. This confirms the need to identify the actual affected suppliers (marginal suppliers) of the substituted energy production systems to assess the environmental impacts more accurately.

5. Conclusions

This PhD study was carried out in order to analyse and suggest possibilities for the more sustainable direction in pig manure management.

First of all, the fundamental for the potential sustainable alternatives is to deal with the most important aspects, which were chosen as the environmental impacts on ecosystems, human health and resources. From the LCA assessment, the more significant environmental impacts potentially arising from pig manure management were global warming, respiratory effects on human health from inorganic substances (respiratory inorganics), and terrestrial and aquatic eutrophication. Based on COM (2001) and Rockström *et al.* (2009), these impacts have also been of high concern as the main threats to sustainable development at a global level both directly (global warming; resulting in climate change) and indirectly (respiratory inorganics, and terrestrial and aquatic eutrophication; indirectly regarded as the interfered nitrogen cycle and the losses in biodiversity). To reach the sustainable solutions in term of the overall significant impact reductions, the assessments revealed that the recoveries of energy and nutrients and the control of emissions were crucial.

With the aim to lessen the significant environmental impacts, the various treatment technology systems were integrated and assessed to maximise the energy extraction and the nutrient recovery from pig manure. The considered technologies were anaerobic digestion, incineration, thermal gasification in combination with thermal pre-treatment, separation, and drying. The system efficiencies were based on Danish and Thai cases. For the Danish case, the treatment system applying the incineration with efficient drying yielded the highest net energy production in terms of net electricity and heat production and the energy equivalent of the avoided fertiliser production. If the aim is to maximise the electricity production, the anaerobic digestion system is important because the system can recover the energy as electricity at a higher rate than the incineration. Alternatively, the by-products (combustible gases) from the anaerobic digestion and the thermal gasification systems can be stored for later usage. All in all, the integrated treatment systems for energy extraction applying anaerobic digestion, incineration or thermal gasification improved the energy recovery efficiencies from the traditional system (do nothing) from 30% to 50% of total energy content in the pig manure with the DM content of 8.3%. In contrast with the Danish case, for the Thai case, the treatment system aiming at energy recovery (anaerobic digestion and incineration) did not obviously increase the energy recovery from the no treatment system due to their low plant efficiencies. Hence, it is recommended for the Thai treatment systems to utilise the heat produced from the systems and to increase the DM contents of the pig manure before the energy extraction processes. For the nutrient recovery, all systems in Denmark and in Thailand can substitute the same amount of the N and P fertilisers except the systems including the incineration and thermal gasification processes which yield less N and P fertiliser replacement.

Regarding the global warming potential in the unit of kg CO_2 equivalent, the assessments suggested that it was crucial to identify the actual affected energy production systems (marginal systems) of the electricity and heat substitution. The different systems (the identified affected electricity and heat with the combination of different energy sources and with the avoided electricity production in the heat production compared to the natural gas power CHP plant) can influence the conclusions. With respect to the replacement of the marginal electricity and heat production systems from pig manure management (with 4% DM content of the pig manure), the anaerobic digestion based system yielded the highest CO_2-eq. saving despite lower net energy production compared to the incineration based system.

Subsequently, another essential aspect for the impact minimisations – the control of emissions at every handling stage - was included and presented throughout the whole thesis. The decreased emissions of greenhouse gas, ammonia, nitrate and nitrogen oxides resulted in the reductions of the more significant impacts. Mostly based on the Danish/European studies and IPCC reports, the emission factors at the housing, treatment, storage and land application stages were listed. The findings illustrated that the slatted floor housing system, the storage tank with a cover/natural crust cover and the deep injection system can limit the losses better than the other considered systems. As a result, the potentials for nutrient (the N content) and energy (the C content) recovery were also increased.

Furthermore, in order to provide the effective choices for pig manure management systems, the known nutrient and energy contents in pig manure are important. This study provided tools to predict the direct excretions, which are the main compartment of pig manure both causing the pollutions and being a potential resource for nutrients and energy, from the pigs by using diet compositions. Based on the developed and selected tools, the direct excretions in term of N, P and C can be quantified and restricted via the controlled amounts of the DM intake and dietary fibre content (for the C content), N/protein intake (for the N content) and P intake (for the P content).

Finally, the integrations of technology systems aiming at the recovery of energy and nutrients as well as the restricted N and C emissions are the effective approaches to protect resources, ecosystems, and human health in pig manure management. The developed and selected tools to predict the pig excretions also allow farmers to control this resource more precisely. These alternatives and tools facilitate better piggery waste management towards sustainability. Furthermore, the organised units enable users to easily apply the technology systems on other wastes, in other countries, or with other efficiency/emission ranges. Nevertheless, for the applications, local data is required in order to estimate the magnitude of the improvements in terms of the recoveries of energy and nutrients, the controls of emissions and the reductions of the environmental impacts more precisely.

6. Perspectives for future research

On the basis of the results and conclusions from this dissertation, the future improvements are.

Sustainable pig production systems incorporating available and up-to-date technologies will be beneficial both for farmers and for the environment. The broadened scope of the environmental assessment considering how “1 kg of pork” can be produced with a better way including the sustainable alternatives for pig manure management in this study will improve the overall chain of pig productions. Towards a more comprehensive assessment, the pig manure management should consider 1) pig manure generation influenced by diet compositions and other handling systems (e.g. cleaning system or in-house separation resulting in different dry matter content) and 2) the losses at housing stage. This assessment allows us to compare environmental impacts from pork consumption with other kind of food products such as vegetables and chicken meat and provides better information for ordinary people who want to protect the environment.

The drivers and barriers to apply the integrated systems in reality are very important. No matter how integrated systems considerably reduce the environmental impacts and extract the large amount of energy and nutrients, constraints in practice (e.g. high investment costs, regulations, know-how technologies, and educated workers) can limit the applications very easily. This kind of study must be known to effectively transfer scientific studies to the real World. Therefore, the identification of drivers and barriers in terms of technical, financial, regulative, normative and cultural-cognitive aspects on different piggery waste management systems will provide better information for decision-making processes and thus increase the possibilities for actual developments leading to better environment and sustainable piggery waste management.

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Paper 1A

Title:

Prediction of manure nitrogen and carbon output from growing-finishing pigs.

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Prediction of manure nitrogen and carbon output from grower-finisher pigs

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ABSTRACT

Intensive pig production may be a hazard to the environment due to plant nutrient leakage and losses. To facilitate efficient and sustainable manure management and reduce oversupplying of crops with nutrients, there is a need for precise assessment of nutrient content in manure and manure excretion. This study has developed algorithms for predicting the amount of excreta and manure content of nitrogen (N) and carbon (C). Data compiled from 285 digestibility and N balance experiments with growing-finishing pigs diets fed diets varying widely in chemical composition were used to establish algorithms. The main input variables were analysed nutrients contents together with intake of dry matter and digestibility of organic matter (diOM). The accuracy and prediction power of the obtained prediction equations were tested with another dataset consisting of 116 digestibility and N balance experiments with varying chemical compositions. Prediction equations related to C was tested using 26 digestibility experiments.

The dietary fibre (DF) fractions like crude fibre, non-starch polysaccharides (NSP), analysed DF and calculated dietary fibre (cDF) were all highly negatively correlated to digestibility and positively to manure output. Including more than one or two predictors only marginally improved predicting the C and N content in excreta as well as the daily excretion rates. The best predictor for estimating

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the daily amount of faeces and daily faecal N and C excretion was diOM, and the second best predictor was cDF. However, the equations became more precise when dry matter intake or animal body weight was added as independent variable. For urine N equations, the dietary protein intake was the best predictor. The partitioning of N between faeces and urine was related to the concentration of cDF with a shift in N excretion in urine to N excreted in faeces as more carbohydrate was fermented. The ratio of C/N in faeces was depending on cDF in the diet. The wide variation in the diets included in the predictions ensures that the equations also are relevant and applicable in developing as well as developed countries as a useful tool for efficient handling and use of manure nutrients in practice.

1. Introduction

Livestock farming has become increasingly industrialized in both developed and in developing countries to meet the growing demand for livestock products and is no longer always related to the plant production (Steinfeld et al., 2006). Industrialization has increased the specialization and size of livestock production and as a consequence there is often local accumulation of manure, which cannot be used sustainably as a source of nutrients for crops. Consequently, there is an increasing surplus of nutrients from animal manure that cannot be utilized as fertilizers to plants which can be a hazard to the environment.

Research and efforts are focusing on development of methods and strategies that can be used for an environmentally friendly management of animal manure. Recently, models were developed that contribute to supporting decisions regarding balanced nutrient recycling in Europe. In the “Danish animal manure normative system” (Poulsen et al., 2006), a whole-system analysis is carried out, and nitrogen (N) and phosphorus (P) excretions from pigs are estimated as the difference between nutrient input and output. In this system, storage losses from pig manure are estimated, to provide data on N and P under ex-animal, ex-housing and ex-storage conditions. In the Netherlands, whole-farm N balances play a crucial role in N management (Schröder et al., 2003). However, these models have been developed for livestock production in developed countries and cannot be used in developing countries without adaptation.

Previously, research has shown that equations can be developed for assessment of the daily excretion of faeces and N by using dietary data, animal body weight (BW) and dry matter intake (DM intake) in the calculations (Kirchgessner et al., 1991a,b; Fernández, 1997; Fernández et al., 1999). The studies proved that manure DM and N excretion were positively correlated to DM intake and BW but negatively correlated with dietary organic matter digestibility (diOM).

In Asia, dietary protein and fibre contents of pig feed vary widely between farm categories. Small scale farms use local feedstuffs and agricultural by-products varying in protein and fibre contents, while concentrate feeds higher in protein and lower in fibre content are used on large scale farms (Anon, 2003). Excretion is related to both dietary fibre (DF) and protein contents of diets, and the amount of excreta from pigs fed diets with high contents of low fermentable fibre is almost twice the amount from pigs fed standard diets containing low levels of DF (Jørgensen et al., 1996; Sørensen and Fernández, 2003).

High carbon (C) content in the faeces is an indicator of a potential large methane production from the manure (Sommer et al., 2004). Moreover, changes in C content will affect the C/N ratio, that is an indicator of manure compost stability and N availability for plants, thus increasing the C/N ratio will reduce the N fertilizer value of manure (Sørensen and Fernández, 2003). When anaerobic digestion and biogas production is a treatment option, both C and N are important process and residual management parameters.

Therefore there is a need for models or equations to predict manure quality and quantity at the animal level that is applicable for example in the Asian context. Such excretion data will be very important input data for whole-system models used in decision support for sustainable manure management. The current study focuses on developing prediction equations for estimating the daily amount of faeces, N and C excretion from growing-finishing pigs based on simple diet characteristics and diet composition. The aim is to contribute to the decision support for appropriate management of nutrients in pig manure and slurry. Data are provided from the very extensive database containing digestive/metabolic studies carried out at the department of Animal Health, Welfare and Nutrition over the past 25 years.

2. Materials and methods

2.1. *Feedstuffs and diets*

The diets used in the study were composed of 75 different feed ingredients shown in Table 1 and put into different categories. The ingredients/studies were selected from the very extensive database at the Department of Health, Welfare and Nutrition in order to cover a broad variety of feedstuffs used both in Europe and Asia (Just et al., 1983b; Simpson, 1990). The ingredients were combined to provide 285 different diets that were used in digestibility and balance experiments with growing-finishing pigs.

2.2. *Pigs and sample collections*

Two hundred and eighty-five diets were fed in replicates to Danish growing pigs weighing from 28 to 94 kg for a period of 12 days, including initial 5–7 days for adaptation to feed, metabolic cage and environmental conditions.

Daily faeces and urine were collected quantitatively during the last 5–7 experimental days of each replicate. Faeces were collected immediately following morning and afternoon feeding, placed in pre-weighed airtight plastic buckets and refrigerated. The next morning's collections were added to the previous afternoon's collection and weighed. Each morning, urine collections were weighed and an aliquot proportional to the volume voided that day were taken, placed in airtight plastic bottles and

Table 1
Feedstuffs used in formulating the diets used in the prediction.

Feedstuff class	Feedstuff	Main dietary characteristic
Protein rich feedstuffs	Casein, fish meal, meat and bone meal, coconut cake, cotton seed cake/meal, horse bean, linseed/cake, lupine, pea, potato protein, rapeseed cake/meal, soy bean meal, sunflower cake/meal, wheat germ, maize gluten, maize gluten fodder	Protein (g/kg DM) (440, 233–900; mean and range)
Grain and starch/sugar rich feedstuffs	Barley/naked/dehulled/hulls, wheat/starch/middlings/fodder meal/meal, rye/middlings, oat/dehulled/polishing/hull meal, maize/starch/meal/germ, sorghum, rice/fodder meal, cassava, D-tagatose, potato starch, sucrose, sugar, sugar beet molasses, sugar cane molasses, sweet potato, wheat starch, whey powder	Starch + sugar (g/kg DM) (733, 421–1000; mean and range)
Fibre rich feedstuffs	Barley hulls, barley–pea–silage, brewer's spent grain, cellulose, clover grass, clover grass silage, grass meal, green meal, alfalfa green meal, pea fibre, pea hulls, pectin/residue, potato fibre/pulp, seed residue, soy bean fibre, palm cake, sunflower, wheat bran, maize bran, rye bran, citrus pulp	Fibre (g/kg DM), crude fibre (247, 65–778; mean and range), total fibre (557, 382–1000; mean and range)
Fat rich feedstuffs	Animal fat (pig, fish), vegetable fat (rapeseed, soy bean)	Fat (g/kg DM) (1000; mean)

refrigerated. Before collecting urine, 40 ml 30% sulphuric acid was added each morning to the urine containers to avoid ammonia emission. After completion of the collection period, the collected faeces and urine were homogenised and a representative sample of each was taken for chemical analyses.

2.3. Chemical analysis of diets, faeces and urine

DM and ash content were determined according to the Association of Official Analytical Chemists (1990). Nitrogen was measured by the Kjeldahl method using Kjell-foss 16200 autoanalyser (Foss Electric, Hillerød, Denmark) and protein was calculated by multiplying the N content with the factor 6.25. Fat was extracted with diethyl ether after hydrochloric acid hydrolysis (Stoldt, 1952). Crude fibre (CF) was determined by the Weende method (Tecator, Höganäs, Sweden). Starch and sugar were analysed by the method of Christensen (1980). Starch was analysed by an enzymatic-colorimetric method according to Bach Knudsen (1997) and sugars (glucose, fructose and sucrose) and fructan by the enzymatic-colorimetric method of Larsson and Bengtsson (1983). Non-starch polysaccharides (NSP) and their constituent sugars were determined by gas liquid chromatograph described by Theander and Åman (1979), and Englyst et al. (1982). DF is the sum of total NSP plus Klason lignin which was measured gravimetrically (Theander and Åman, 1979). Carbon was measured as described by Neergaard et al. (1969).

2.4. Calculation and statistical analysis

Calculated dietary fibre (cDF) was calculated as the residual from ash, crude protein, crude fat and starch + sugar. Similarly, carbohydrate (CHO) was calculated as the residual from ash, crude protein and crude fat. Digestibility of dry matter (diDM) and diOM were calculated as dietary DM and dietary organic matter, subtracted from faecal DM and faecal organic matter, respectively.

Data were analysed using SAS software (SAS Inst. Inc., Cary, NC). Correlation and regression analyses were performed using PROC CORR and PROC GLM of SAS, respectively. If dependent variables were highly correlated they were not simultaneously included in the same equation. Equations were developed by stepwise regression and removing dependent variables without significant effect ($P \geq 0.01$) in order to simplify the equations.

Validation of the developed prediction models was done using test set validation by calculating the performance of the models by its prediction error in terms of root mean square error of prediction (RMSEP) and by testing any systematic difference (bias) between the average values of the test dataset (Esbersen, 2002; Jørgensen and Lindberg, 2006). Models regarding faeces, urine and nitrogen excretion (Tables 5–7) were tested using 116 diets (Just, 1982b,c,d,e; Just et al., 1983a,b; Oksbjerg et al., 1996). Models concerning carbon excretion (Table 8) were tested with 26 diets (Thorbek, 1975; Just, 1982a).

3. Results

3.1. Variability of feeds and excretions

Chemical composition of diets and excreta are presented in Table 2. The average N excretions were 34.7 g/kg of faecal DM and 6.40 g/kg urine. The contents of starch and sugars in faeces were in most cases very low (average 16 g/kg DM). The variation in daily excretions was large (CV 61 and 44 for fresh faces and faeces DM, respectively), which indicates a good database for the development of prediction equations for the content of N and C in excreta and the faecal and urine excretion. In comparison to the daily faecal C excretion, the daily urine C excretion was only 0.15 of faecal C. Therefore, the prediction of the daily amount of urine C excretion was not considered in the current study.

3.2. Correlation between chemical composition and dry and organic matter digestibility in diets

The correlation between the dietary chemical characteristics is presented in Table 3. As all fibre fractions (CF, NSP, DF and cDF) are indicators of the indigestible part of the diets, they are highly negatively correlated to the diDM or diOM and positively correlated to the amount excreted. Digestibility of

Table 2
Variations in the parameters used as dependent (faeces and urine excretion) and independent (dietary composition and animal traits) variables in the predictions.

Item	*n*	Mean	Minimum	Maximum	CV
Dietary composition (g/kg DM)					
Crude protein	285	184	23.4	535	32.8
Crude fat	285	55.5	12.2	207	58.8
Starch and sugar	285	499	196	892	26.8
Ash	285	68.7	37.3	152	26.5
Crude fibre	230	55.1	7.27	193	59.3
Calculated Dietary fibre (cDF)	285	189	19.9	510	48.9
Analysed dietary fibre (DF)	37	172	18.0	346	63.2
Non-starch polysaccharides (NSP)	37	146	5.0	318	65.3
Dietary carbon	74	448	400	503	4.3
Animal variables					
Body weight, kg	285	57.2	28.3	93.7	19.4
Dry matter intake (kg/day)	285	1.50	0.83	2.39	15.8
Metabolisable energy intake (MJ/day)	285	26.5	14.1	35.9	18.6
Digestibility of dry matter (diDM), coefficient	285	0.811	0.434	0.976	10.2
Digestibility of organic matter (diOM), coefficient	285	0.835	0.450	0.986	9.7
Urine composition (g/kg)					
Urine nitrogen	285	6.40	1.37	23.0	51.4
Urine carbon	59	5.48	2.16	10.7	37.2
Faeces composition (g/kg DM)					
Dry matter (g/kg)	285	343	183	611	20.0
Faecal nitrogen	285	34.7	12.7	60	20.7
Faecal fat	283	106	30.9	355	33.0
Starch and sugar	211	16.4	5.48	204	113
Ash	285	207	91.8	469	32.5
Crude fibre	211	161	53.7	383	33.6
Calculated dietary fibre (cDF)	285	459	84.5	772	22.7
Faecal carbon	74	438	306	508	10.5
Faecal C/N	74	12.8	5.8	19.7	24.6
Daily excretion (g/day)					
Fresh faeces	285	0.90	0.10	3.42	61.1
Faecal DM	285	0.28	0.04	0.82	43.7
Faecal N	285	9.39	2.15	20.4	36.5
Faecal C	74	126	23.3	372	51.4
Urine N	285	19.2	5.51	83.3	50.7
Urine C	74	18.5	7.60	32.3	30.0

Table 3
Correlations between dietary chemical components and digestibility coefficient of dry matter (diDM) and organic matter (diOM).

Dietary variables	Crude protein	Crude Fat	Starch and sugar	Ash	Crude fibre	DF	cDF	Carbon	NSP	diDM
Crude fat	0.06									
Starch and sugar	−0.62	−0.31								
Ash	0.32	−0.09	−0.52							
Crude fibre	0.16	0.01	−0.72	0.34						
DF	0.11	−0.26	−0.88	0.49	0.85					
cDF	0.14	−0.00	−0.79	0.42	0.88	0.98				
Carbon	0.24	0.59	−0.08	−0.01	−0.28	−0.34	−0.32			
NSP	0.08	−0.29	−0.85	0.45	0.84	0.99	0.97	−0.37		
diDM	−0.17	−0.09	0.75	−0.58	−0.79	−0.91	−0.85	0.04	−0.88	
diOM	−0.16	−0.10	0.75	−0.51	−0.81	−0.91	−0.86	0.03	−0.88	0.99

N = 285, except for crude fibre (*n* = 230), carbon (*n* = 74), DF and NSP (*n* = 37).

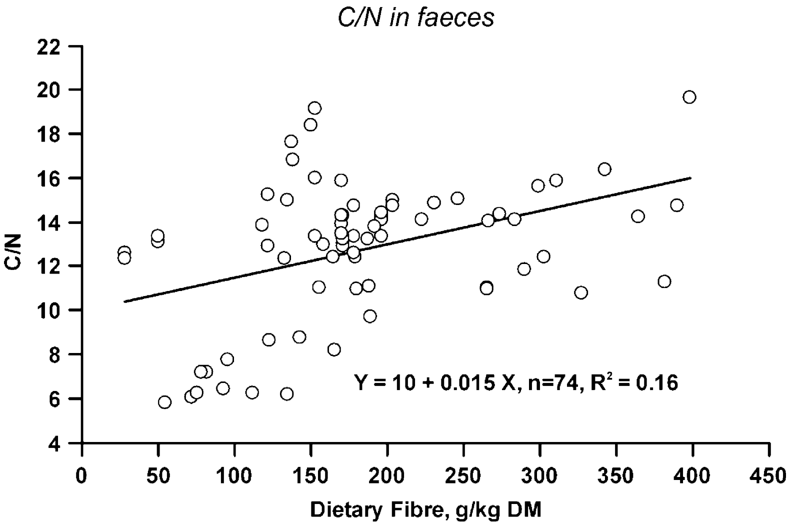

Fig. 1. The C/N relation in faeces depending on dietary fibre (cDF).

DM and OM is highly correlated ($r = 0.99$). The current study also shows a closely inverse relationship between the DF fractions and the dietary starch and sugar content.

3.3. Correlation between dietary variables and excreta

The correlations between dietary variables and daily excreta components are presented in Table 4. Results indicate a strong correlation between both diOM and cDF and the daily faeces excretion ($r = 0.90$). Similarly, there was a negative correlation between DF content and digestibility of DM and OM due to high lignifications of the fibre fraction. diOM and cDF were also significantly correlated to daily faecal N and C excretion but not to daily urinary N excretion. However, the excretion variables were not correlated to dietary fat. Neither was C excretion nor the daily faeces amount correlated to dietary protein. The C/N relation depends on the concentration of DF (Fig. 1) although the correlation is relatively low.

3.4. Prediction of faecal excretion

The linear and multiple prediction equations developed for assessing the daily faeces amount are presented in Table 5, the equations are ranked by R^2 and residual mean square error (RMSE) values. DM in faeces was mainly correlated to DF and can be predicted with reasonable accuracy (Equation 1). This may have important implications as prediction of faeces DM excretion can be obtained by use of table values of DM digestibility.

The R^2 value for dietary CF (Equation 2) was lower than for cDF (Equation 3) when only one predictor was used for estimating the daily fresh faeces excretion. The DM intake or BW was then considered to be included as independent variables in order to improve the equations. In the experiments performed in this study, pigs were fed according to the ‘scale feeding’ method, i.e. the amount of feed was related to the pigs’ BW. Thus, DM intake and BW were highly correlated and consequently not simultaneously included in an equation. However, the inclusion of BW or DM intake to Equation 3 only increased the R^2 value slightly to 0.75 and 0.76, respectively (Equations 4 and 5). The RMSE decreased to 0.27 in both equations.

Using diOM as the only predictor accounted for 81% of the variation in the daily faeces excretion (Equation 6). The relationship was negative because indigestible feed will be excreted as faecal material. When DM intake or BW were added to Equation 6, the R^2 values increased to 0.85 and RMSE was reduced to 0.21 (Equations 7 and 8). Including the product of BW and diOM increased the R^2 to 0.90 and reduced the RMSE to 0.17 (Equation 9). Among the dependent variables: diOM, cDF, CF, BW and DM intake, the best predictor of daily amount of fresh faeces was diOM ($R^2 = 0.81$, RMSE = 0.24), the second best was cDF ($R^2 = 0.74$, RMSE = 0.28), and the third best was CF ($R^2 = 0.55$, RMSE = 0.38).

Table 4
Correlations between dietary variables and daily excretion.

	Crude protein	Crude fat	Starch and sugar	Ash	Crude fibre	DF	cDF	Carbon	NSP	diDM	diOM
In faeces (g/day)											
Nitrogen	0.37***	0.00 NS	−0.74***	0.48***	0.66***	0.94***	0.73***	−0.34**	0.92***	−0.79***	−0.78***
Carbon	−0.15 NS	−0.10 NS	−0.57**	0.42***	0.59**	0.87***	0.77***	−0.18 NS	0.84***	−0.91***	−0.92***
In urine (g/day)											
Nitrogen	0.84***	−0.03 NS	−0.35***	0.18**	−0.03 NS	−0.16 NS	−0.05 NS	−0.21 NS	−0.17 NS	0.01 NS	0.00 NS
Carbon	0.09 NS	−0.17 NS	0.04 NS	0.02 NS	−0.45 NS	−0.33*	−0.16 NS	−0.03 NS	−0.35*	−0.03 NS	−0.05 NS
Faeces amount (kg/day)											
Fresh	0.11 NS	−0.03 NS	−0.67***	0.42***	0.74***	0.89***	0.86***	−0.27*	0.86***	−0.89***	−0.90***
DM	0.14*	0.12 NS	−0.70***	0.43***	0.76***	0.89***	0.81***	−0.19 NS	0.86***	−0.93***	−0.93***

NS: none significant. $N = 285$, except for crude fibre ($n = 230$), Carbon ($n = 74$), DF and NSP ($n = 37$).

[*] Significant correlation is indicated by $P<0.05$.

[**] Significant correlation is indicated by $P<0.01$.

[***] Significant correlation is indicated by $P<0.001$.

Table 5
The prediction of amount of faeces voided daily by growing pigs, $N = 285$.

No.	Equations	R^2	RMSE	Bias	RMSEP
Faeces DM (g/kg DM)					
1	Faeces DM = 442.4 – 0.524 cDF	0.50	48.81	–28	44.6
Fresh faeces (kg/day)					
2	Faeces* = 0.236 + 0.0130 CF	0.55	0.38	0.0	0.68
3	Faeces = –0.0692 + 0.00510 cDF	0.74	0.28	0.1	0.64
4	Faeces = –0.313 + 0.00508 cDF + 0.00436 BW	0.75	0.27	0.2	0.59
5	Faeces = –0.523 + 0.00515 cDF + 0.297 DM intake	0.76	0.27	0.1	0.51
6	Faeces = 5.966 – 6.08 diOM	0.81	0.24	0.1	0.57
7	Faeces = 5.405 – 6.31 diOM + 0.505 DM intake	0.85	0.21	0.1	0.36
8	Faeces = 5.469 – 6.20 diOM + 0.0105 BW	0.85	0.21	0.2	0.44
9	Faeces = –2.835 + 3.62 diOM + 0.155 BW – 0.171 diOM × BW	0.90	0.17	0.2	0.37
Faeces DM (kg/day)					
10	Faeces DM* = 0.137 + 0.00286 CF	0.58	0.08	0.0	0.19
11	Faeces DM = 0.0763 + 0.00108 cDF	0.67	0.07	0.0	0.18
12	Faeces DM = 0.0185 + 0.00108 cDF + 0.00103 BW	0.67	0.07	0.0	0.17
13	Faeces DM = –0.105 + 0.00111 cDF + 0.118 DM intake	0.72	0.07	0.0	0.13
14	Faeces DM = 1.463 – 1.42 diOM	0.87	0.04	0.0	0.16
15	Faeces DM = 1.349 – 1.44 diOM + 0.00242 BW	0.92	0.04	0.0	0.13
16	Faeces DM = 1.274 – 1.50 diOM + 0.171 DM intake	0.98	0.02	0.0	0.08

*$N = 230$. RMSE: root mean square error; Bias: accuracy of the prediction; RMSEP: residual mean square error of prediction using the test data (Just, 1982b,c,d,e; Just et al., 1983a,b; Oksbjerg et al., 1996; $n = 116$); BW: body weight (kg); DM intake: dry matter intake (kg/day); CF: crude fibre (g/kg DM); cDF: calculated dietary fibre (g/kg DM); diOM: digestibility of organic matter (coefficient).

As the daily amount of faecal DM excretion is closely related to the amount of faeces, similar variables were selected for equations to predict the daily amount of faecal DM (Equations 10–16). Equation 16 using diOM and DM intake as predictors gave the highest R^2 (0.97) and the lowest RMSE (0.02).

The validation of the equations using the test dataset consisting of 116 diets varying greatly in chemical composition (Just, 1982b,c,d,e; Just et al., 1983a,b; Oksbjerg et al., 1996) showed much less variation (RMSEP) between the equations than the variation (RMSE) from the regression and all had zero bias. This indicates that using a model with one or two parameter is just as good as a model with several parameters.

3.5. *Prediction of faecal N excretion*

Equations for the predictions of daily faecal N excretion are presented in Table 6. The daily faecal N excretion was significantly higher in rations with increased fibre content because of a reduced N digestibility. As a result the daily faecal N excretion was positively correlated to either dietary cDF or diOM which, as a single independent variable, accounted for 54% and 61% of the variation (Equations 1 and 6, respectively). However, the precision of the prediction of daily faecal N excretion was increased by including N intake and DM intake (Equations 3, 4 and 6–9). All independent variables used for predicting daily faecal N excretion had a positive relationship with the dependent variables, except dietary diOM. A higher diOM resulted in lower daily faecal N output because indigestible material was excreted in the faeces.

Validation of the equation indicated that either cDF or diOM as single variables was comparable and addition of N intake as supporting predictor improved the accuracy. Including more variables, i.e. from Equations 3 and 4 or from 7 to 9 did not improve the prediction accuracy to any extent.

3.6. *Prediction of urine N excretion*

The daily urinary N excretion was positively related to dietary protein level, which, as the only single variable, resulted in a quite high R^2 value of 0.67 (Table 7, Equation 1). As a result of the stepwise

Table 6
The prediction of daily faecal N excretion by growing pigs, $N = 285$.

No.	Equations	R^2	RMSE	Bias	RMSEP
N in faeces (g/day)					
1	Faecal N = 4.132 + 0.0275 cDF	0.54	2.34	0.6	3.74
2	Faecal N = 0.685 + 0.0264 cDF + 0.0855 N intake	0.67	1.98	0.1	2.81
3	Faecal N = –1.072 + 0.0264 cDF + 0.0772 N intake + 1.366 DM intake	0.68	1.96	0.2	2.36
4	Faecal N = 3.553 + 0.00640 cDF + 0.0107 N intake + 0.000487 cDF × N intake	0.72	1.84	0.0	2.33
5	Faecal N = 37.20 – 33.4 diOM	0.61	2.15	0.4	3.70
6	Faecal N = 32.15 – 32.0 diOM + 0.0887 N intake	0.75	1.72	0.0	2.62
7	Faecal N = 11.34 – 7.92 diOM + 0.593 N intake – 0.586 diOM × N intake	0.78	1.62	0.2	2.14
8	Faecal N = 25.37 – 33.5 diOM + 0.0163 dPROT + 4.678 DM intake	0.78	1.63	1.8	2.07
9	Faecal N = 30.17 – 33.4 diOM + 0.0728 N intake + 2.59 DM intake	0.78	1.63	–0.1	1.99

RMSE: root mean square error; Bias: accuracy of the prediction using the test data; RMSEP: residual mean square error of prediction using the test data (Just, 1982b,c,d,e; Just et al., 1983a,b; Oksbjerg et al., 1996; $n = 116$); DM intake: dry matter intake (kg/day); dPROT: dietary crude protein (g/kg DM); N intake: nitrogen intake (g/day); cDF: calculated dietary fibre (g/kg DM); diOM: digestibility of organic matter (coefficient).

regression procedure, urinary N predictions were improved by including BW, DM intake, cDF and the product of dietary crude protein (PROT) and BW (Equations 2–6). The PROT, BW and DM intake were positively correlated to daily urinary N excretion, whereas cDF was negatively correlated.

The complete dataset included diets both high and low in dietary protein not fulfilling the pigs protein/amino acids requirement. In order to predict urine N excretion in pigs fed diets where the protein requirement was fulfilled, a smaller dataset was obtained with protein contents from 150 to 260 g/kg and protein retention between 70 and 160 g/day. The prediction equations using this smaller dataset (Equations 7–12) show lower R^2 but the precision illustrated by RMSE was higher.

The partitioning of N excretion between faeces and urine depending on cDF is illustrated in Fig. 2 for the reduced dataset. The figures show that a higher content of cDF resulted in a simultaneous increase in faeces N and decrease in urine N.

Validation of the two set of prediction showed more or less the same picture. The reduced dataset failed to predict more accurate than prediction model based on the whole dataset. Furthermore including more variables than dPROT and DM intake into the prediction did not improve the prediction power.

Table 7
The prediction of daily urine N excretion by growing pigs on the complete dataset both balanced and unbalanced ($N = 285$) or a subset of balanced diets with the dietary protein between 150 and 260 g/kg dry matter and retained protein between 70 and 160 g/day ($N = 125$).

No.	Equations	R^2	RMSE	Bias	RMSEP
N in urine—whole dataset (g/day)					
1	Urine N = –5.213 + 0.136 dPROT	0.67	5.70	–2.3	11.15
2	Urine N = –17.46 + 0.135 dPROT + 0.216 BW	0.73	5.17	–1.1	6.99
3	Urine N = –21.20 + 0.134 dPROT + 10.15 DM intake	0.73	5.18	–1.2	6.50
4	Urine N = –18.47 + 0.143 dPROT + 9.84 DM intake – 0.0149 cDF	0.75	5.01	–2.2	6.57
5	Urine N = –15.23 + 0.139 dPROT + 0.224 BW – 0.0176 cDF	0.76	4.92	–0.8	7.05
6	Urine N = 19.16 – 0.0627 dPROT – 0.436 BW + 0.00352 dPROT × BW	0.76	4.86	0.9	5.06
N in urine—reduced dataset (g/day)					
7	Urine N = –2.803 + 0.111 dPROT	0.23	4.71	0.6	10.73
8	Urine N = –20.34 + 0.133 dPROT + 0.239 BW	0.48	3.87	1.0	6.54
9	Urine N = –28.50 + 0.143 dPROT + 13.23 DM intake	0.56	3.59	–0.5	5.60
10	Urine N = –27.90 + 0.147 dPROT + 14.09 DM intake – 0.0137 cDF	0.59	3.45	–0.3	5.14
11	Urine N = –19.27 + 0.134 dPROT + 0.243 BW – 0.00854 cDF	0.50	3.83	1.4	6.53
12	Urine N = 47.90 – 0.231 dPROT – 0.953 BW + 0.00639 dPROT × BW	0.61	3.38	4.3	5.54

RMSE: root mean square error; Bias: accuracy of the prediction using the test data; RMSEP: residual mean square error of prediction using the test data (Just, 1982b,c,d,e; Just et al., 1983a,b; Oksbjerg et al., 1996; $n = 116$); BW: body weight (kg); DM intake: dry matter intake (kg/day); dPROT: dietary crude protein (g/kg DM); cDF: calculated dietary fibre (g/kg DM).

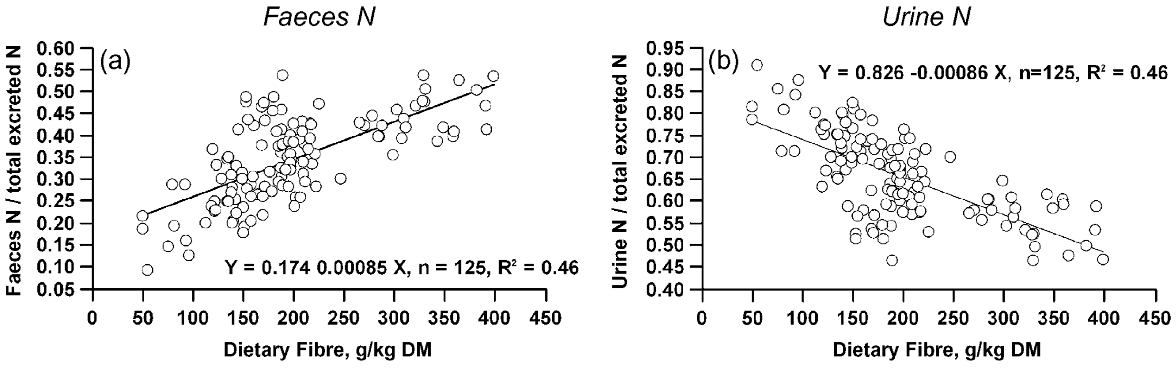

Fig. 2. The shift in N excretion between faeces to urine depending on dietary fibre (cDF) using the dataset with balanced diets ($n = 125$) with regard to protein requirement.

3.7. Prediction of C in feed and faeces

Dietary C is a component of protein, fat and carbohydrate and can be predicted from these components but the R^2 value was only 0.45 and the RMSE 14.6% or 3.3% of the mean dietary C (Table 8, Equation 1). However, the prediction of C in faeces was associated with a higher R^2 of 0.98 and smaller RMSE 6.4% or 1.4% of the mean faecal C using the same chemical characteristics (Equation 2).

Equations for daily faecal C excretion are presented in Equations 3–8. A simple linear equation using cDF as the only independent variable indicated a close positive relationship between daily faecal C and cDF (Equation 3). The equation was more accurate giving a higher R^2 value of 0.74 and a lower RMSE of 32.7 when DM intake was included (Equation 4). Subsequently, the equations became more precise and resulted in higher R^2 value by adding BW, DM intake and PROT or N intake. The equation including diOM and DM intake was the best equation resulting in the highest R^2 value of 0.96 and the lowest RMSE of 12.4.

Prediction of C was associated with higher variation (RMSE) than similar prediction of N (Table 7), however, these latter equations was also based on a smaller number of observations. There was also less data available to test the prediction equations ($n = 26$ from Thorbek, 1975; Just, 1982a), however, including more than two predictor variables did not reduce the bias or increase the accuracy to any extent. The relative large bias as an indicator of systematic deviation of prediction of dietary C and faecal C (3.5% and 4.6%, respectively) when using the test dataset could partly be explained by differences in

Table 8
The calculation of C in diet and faeces dry matter and prediction of daily faecal C excretion by growing pigs, $N = 74$.

No.	Equations	R^2	RMSE	Bias	RMSEP
C in feed (g/kg DM)					
1	Dietary C = 0.713 dPROT + 0.720 dFAT + 0.384 dCHO	0.45	14.6	15.6	8.7
C in faeces (g/kg DM)					
2	Faecal C = 0.523 fPROT + 0.787 fFAT + 0.494 fCHO	0.98	6.4	20.0	12.7
C in faeces (g/day)					
3	Faecal C = 10.53 + 0.590 cDF	0.62	39.2	−8.8	14.3
4	Faecal C = −98.82 + 0.541 cDF + 69.95 DM intake	0.74	32.6	4.7	9.5
5	Faecal C = 834.8 − 914 diOM + 1.17 BW	0.92	18.1	−4.5	8.9
6	Faecal C = −46.69 + 106.4 diOM + 15.08 BW − 16.1 BW×diOM	0.95	14.2	−2.1	5.6
7	Faecal C = 922.8 − 927 diOM + 0.960 BW − 0.344 dPROT	0.93	17.3	−4.0	8.1
8	Faecal C = 727.6 − 861 diOM + 0.591 BW + 1.968 N intake	0.96	12.4	−3.5	10.8

RMSE: root mean square error; Bias: accuracy of the prediction using the test data; RMSEP: residual mean square error of prediction using the test data (Thorbek, 1975; Just, 1982a; $n = 26$); dPROT: dietary protein (g/kg DM); dFAT: dietary fat (g/kg DM); dCHO: dietary carbohydrate (g/kg DM); fPROT: faecal protein (g/kg DM); fFAT: faecal fat (g/kg DM); fCHO: faecal carbohydrate (g/kg DM); BW: body weight (kg); DM intake: dry matter intake (kg/day); N intake: nitrogen intake (g/day); cDF: calculated dietary fibre (g/kg DM); diOM: digestibility of organic matter (coefficient).

chemical analysis of fat. In the test dataset fat was extracted without any previous hydrochloric acid hydrolysis.

4. Discussion

In general, the standardized deviation residuals were normally distributed. However, two observations were considered outliers with large residuals in the equations of total faecal amount, daily urinary N and daily faecal N excretion and subsequently not included in the prediction models.

A large coefficient of variation (CV) for the NSP, DF, CF, crude fat, cDF, and crude protein content in the experimental diets ensured a potential for developing prediction equations representative for diets with a large variation in composition. The equations may therefore also be used in developing countries like Thailand and Vietnam where pig feed varies greatly, as many by-products are used instead of whole cereal feedstuffs (Lekule et al., 1990). Especially, the wide range in CV of CF (59.3%) and crude protein content (32.8%) is particularly relevant in the Asian context (Anon, 2003).

In general including more predictors into a prediction model increase the R^2 and amount of variation explained which also was demonstrated in the present study. However, when testing the accuracy and prediction power of the various models on a new dataset, including more than one or two predictors do not gain very much. This was the case on all the prediction independent of prediction of faeces amount or excretion of N and C. The present validation indicated that DF (CF or total DF) or diOM alone (urine N dietary protein) could produce accurate prediction of manure, N and C output in growing pigs and that the addition of DM intake or N intake as supporting predictors had little improvement on the prediction accuracy.

The content of N in faeces DM in relation to dietary content N in diet is relative high as both starch and sugars in faeces in most cases is very low. These results are in agreement with other studies confirming pigs' great capacity for fermenting carbohydrate in the hind-gut (Fernández, 1997; Just et al., 1981, 1983a), with the exception of diets containing potato starch where the starch in the raw form is difficult for the digestive enzymes to assess (Sun et al., 2006).

As all fibre fractions (CF, NSP, DF and cDF) are indicators of the indigestible part of the diets, they are highly negatively correlated to the digestibility of DM or OM (Just et al., 1984; Len et al., 2007) and positively correlated to the amount excreted. The fibre fractions are all highly correlated and only one component at a time should be selected as predictor. The number of observations for dietary cDF totalled 285 but only 37 were analysed for DF (Table 2). Therefore, dietary cDF rather than DF was selected as a predictor. Even though a closely inverse relationship (−0.72) exists between dietary CF and dietary starch and sugar the predictive power of the CF is higher as also shown by Fernández and Jørgensen (1986).

Results published by Kirchgessner et al. (1991a) showed agreement with the current findings in that the daily amount of faecal DM could be assessed by using diOM and DM intake. The selection of digestibility of DM and or OM as predictors has great potentials. Digestibility of DM and OM can thus both be assessed relatively easily from the digestible DM/organic matter of individual feed ingredients (Just et al., 1983c), or by *in vivo* methods: i.e. total collection (Le Goff and Noblet, 2001), by use of markers (Sales and Janssens, 2003), or by *in vitro* methods (Boisen and Fernández, 1997; Noblet and Jaguelin-Peyraud, 2007). Therefore, digestibility of both DM and OM together with cDF is excellent and useful predictor.

The strong correlation between both diOM and cDF and the daily faeces excretion ($r = 0.90$) can be explained by the observed negative correlation between DF content and digestibility of DM and OM that is due to high lignifications of the fibre fraction (Just, 1982a; Bach Knudsen, 1997).

Velthof et al. (2005) and Kerr et al. (2006) found in agreement with the present study that a higher content of dietary protein did not influence daily faecal C content. Canh et al. (1998) reported that there was no impact of dietary protein on the daily amount of excreted faeces. However, dietary protein content was more correlated to daily urinary N excretion (0.84) than to faecal N excretion (0.37), which agrees with the finding of Canh et al. (1998). Therefore, dietary diOM or cDF were selected as the main factors determining the daily amount of faeces, daily amount of faecal N and C excretion. Dietary protein was selected as the main factor affecting the daily urinary N excretion. The daily faecal N excretion was significantly higher in rations with increased fibre content because of a reduced N digestibility. Moreover, increased fibre content resulted in higher faecal excretion of microbial protein (Fernández and Jørgensen, 1986). Similarly, Kerr et al. (2006) reported that increasing dietary cellulose increased manure C content.

The positive relation between the C/N ratio in faeces material and the DF indicates an increase in the greenhouse methane gas production in the pigs' digestive tract (Jørgensen, 2007) and a potential very large methane production from the stored manure (Sommer et al., 2004).

The daily urinary N excretion was strongly and positively related to dietary protein level. This result shows the importance of improving the dietary amino acid balances to meet specific dietary requirements for growing pig as the excessive intake of N beyond daily requirements is excreted via the urine (Just, 1982b).

Fermentable substrate available for microbial digestion in the large intestine of pigs increase faecal N output, which, in turn is balanced by a reduction in urine N output (e.g. Misir and Sauer, 1982; Mosenthin et al., 1990). The shift from N excretion in urine (as urea) to N excretion in faeces (as organic bound) demonstrated in the present study on the dataset with balanced diets with regard to protein requirement can be explained by a higher microbial fermentation of the fermentable carbohydrates when pigs were fed diets rich in DF (Mosenthin et al., 1992; Kirchgessner et al., 1994; Canh et al., 1997). Similarly, Sørensen and Fernández (2003) found that urinary N was lowest in pigs fed diets with the highest fibre content.

5. Conclusion

The current study showed that with relatively few input variables that can quite easily be obtained and/or measured, it is possible to assess the C and N content in excreta as well at the daily excretion rates.

The best predictor for estimating the daily amount of faeces and daily faecal N and C excretion equations was digestible organic matter, and the second best predictor was calculated DF. In general, the equations became more precise when DM intake or animal BW was added as independent variable.

For the urine nitrogen equations, the dietary protein content was the best predictor. Such prediction will produce a good estimate but it can be improved if DM intake is included as supporting variable.

The provided equations could be used to establish tools for appropriate management of pig manure and slurry with regard to nutrient utilisation in order to avoid environmental problems. The equations should be selected with respect to the available characteristic of the diets.

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Paper 1B

Title:

Comparison of methods for quantification of excretions of dry matter, nitrogen, phosphorus and carbon in growing pigs fed regional diets.

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Comparison of methods for quantification of excretions of dry matter, nitrogen, phosphorus and carbon in growing pigs fed regional diets

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Running head: Methods for quantification of excretion in growing pigs

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ABSTRACT

Modern pig production contributes to many environmental problems that relate to manure, especially in areas with highly intensive production systems and in regions like Asia where the regulative control is not effective. Therefore, the objective of this study was to use three different pig diets as representative for Danish (DK), Thai (TH) and Vietnamese (VN) pig production to demonstrate the potential of different approaches to predict/calculate excretion from growing pigs in comparison with the experimentally determined values. Excretion of dry matter (DM), nitrogen (N), phosphorus (P) and carbon (C) of the experimental diets were determined in balance experiments with growing pigs. Due to the highest dietary fibre content, VN had the lowest digestibility of N, P and C (73, 49, and 73%, respectively) compared with the DK and TH pig diets. From the known diet composition using standard table values on chemical and nutrient digestibly, high accuracy (bias) and low variation was found and the results could be used for prediction of the amount of nutrient excretion in faeces and urine in growing pigs. Another approach was to predict nutrient excretion in faeces and urine using recent published equations from Vu et al. (2009). Calculation based on standard values regarding nutrient retention in the pig body as used in the Danish manure normative system showed to be quite useful for quantifying the total excretion of N and P. Overall, the results demonstrate that simple models that require cheap and normally available information on dietary nutrients can give useful information on nutrient excretion in growing pigs.

KEY WORDS: excretion, faeces, urine, Nitrogen, Phosphorus, Carbon

INTRODUCTION

Many environmental problems like surface water eutrophication, groundwater pollution, greenhouse gas emissions and odour relate to livestock manure especially in regions with intensive production systems. Highly intensive pig production has in many countries around the world resulted in a higher risk of negative environmental impact (Poulsen, 2000; Sørensen et al., 2006; Devendra, 2007). In fact, there are legislative measures to limit environmental impacts in many countries, e.g. Denmark, The Netherlands, and France where restrictions on animal density have been imposed (Jongbloed et al., 1999). However, the amount of nutrients in manure may exceed the amount that can be assimilated by crops resulting in nutrient accumulation in agricultural areas in those countries (Jongbloed et al., 1999; Kyllingsbæk, 2005). The situation is worse in Asian countries such as Thailand and Vietnam because there are no effective regulations or the regulations are poorly enforced (FAO/LEAD, 2004).

Nevertheless, pig manure has potential for resource recoveries in terms of energy, such as biogas production, and nutrients, such as nitrogen (N) and phosphorus (P) fertilizers. The challenge is how to manage the resource recoveries more efficiently with lower effects on the environment. Many studies have shown that different feeding strategies can reduce nutrient excretions and greenhouse gas emissions by use of lowered dietary nutrient supplies adapted to the actual physiological requirements in pigs (i.e. phase feeding), use of synthetic amino acids to replace crude protein, or microbial phytase supplementation combined with reductions in inorganic feed phosphates (Nahm, 2002; Jondreville et al., 2003; Sutton and Richert, 2004; Monteny et al., 2006). Nahm (2002) reported that manure N can be decreased up to 60% by the addition of synthetic amino acids to replace crude protein.

Tools to quantify inputs, outputs, and flows of nutrients at animal level is very useful for global design of manure management systems that efficiently take into account diet composition and productivity, resource recovery and environmental protection as well as economy. Therefore, the objective of this study was to use three different pig diets as representative for Danish (DK), Thai (TH) and Vietnamese (VN) pig production to demonstrate the potential of different approaches to predict/calculate excretion from growing pigs in comparison with the experimentally determined values.

MATERIALS AND METHODS

In vivo experiments

Composite diets simulating practical diets used in Denmark, Thailand and Vietnam with varied contents of dietary protein, dietary fibre and fat, respectively were formulated on the basis of raw ingredients purchased in Denmark (Table 1). Representative samples of diets were stored at -18˚C for chemical analyses.

The experimental procedure was similar to Sørensen and Fernández (2003). Nine sibling female pigs were allocated individually to metabolism cages. Three growing pigs were subjected to two balance periods for each diet - at 40 to 45 kg and 55 to 60 kg body weight - and fed 1.7 and 2 kg feed per day, respectively. Each balance period consisted of 5 days adaptation and 7 days complete collection of faeces and urine. Faeces and urine were collected quantitatively each day during the 7 experimental days and stored at 5˚C. Urine was collected through indwelling Foley catheters. After 7 days the faeces collected from each pig were homogenized and samples were stored at -18˚C until further analysis.

The diets, faeces and urine were analyzed chemically. Dry matter was determined by drying samples to a constant weight at 103ºC, and ash was analyzed by incineration at 525ºC. Nitrogen was measured by the Dumas procedure and protein was calculated as Nx6.25 (Hansen, 1989). Carbon was analyzed according to Leco Corporaton Application Bulletin (1987). P was determined by the vanadomolybdate colorimetric procedure. Crude fat (HCl-fat) was extracted with diethyl ether after acid hydrolysis (Stoldt, 1952). Crude fibre (CF) was assessed by the Weende method (Tecator, 1978). Starch was assayed by an enzymatic procedure according to Bach Knudsen (1997) and sugar was analyzed by the method of Jacobsen (1981). Based on the obtained chemical results, the digestibility, retention, utilization and excretions of N, P and C were determined according to Sørensen and Fernández (2003) and shown in Table 2.

Calculations and predictions of excretions of faeces, N and C

In addition to the experimentally obtained results, two different models were used to quantify the excretions of faeces DM, N and C. First, the excretions were quantified using published table values on nutrient contents in the feedstuffs used in the *in vivo* experiment. Proximate analysis and digestibility of the used feedstuffs were derived from Just et al. (1983), except pearl millet (NRC 1982), cereals (Vils and Sloth 2005) and dietary fibre (Bach Knudsen 1997). The calculated results are shown in Table 3.

Second, the excretions of faeces, DM, N and C were predicted using published equations. Vu et al. (2009) proposed equations to calculate amounts of faeces and faeces composition derived from datasets of 285 diets assayed in digestibility experiments at the Faculty of Agricultural Sciences, Aarhus University. Vu et al. (2009) showed that the calculated values using these equations did not differ significantly between equations with one, two or three parameters. Therefore, Vu et al., 2009 defined the following criteria for parameterization of the equations, (i) easily obtainable parameters, (ii) as few parameters as possible, and (iii) a diminutive difference between the calculated and the experimental determined results. The selected equations from Vu et al. (2009) used in the present study are shown below.

Faeces DM (kg/day) = -0.105 + 0.118*DMintake (kg/day) +0.00110*DF (g/kg DM)

Faeces N (g/day) = 0.685 + 0.0260*DF (g/kg DM) + 0.0855*Nintake (g/day)

Faeces C (g/day) = -98.82 + 68.95*DMintake (kg/day) + 0.541*DF (g/kg DM)

There were two sets of equations to calculate urinary N given by Vu et al. (2009). The equation representing dietary protein contents from 15 to 26% of DM and protein retention between 70 to 160 g/day was selected for the present study.

Urine N (g/day) = –28.50 + 0.143*Crude protein (g/kg DM) + 13.23*DMintake (kg/day).

The predicted values are shown in Table 4 and Figures 1 to 3.

Estimation of N and P based on the Danish manure normative system (DMNS)

The Danish manure normative system calculating N, P, and potassium (K) contents in manure has been established in order to provide Danish farmers and authorities with tools for fertilizer planning and control. The system calculates the nutrient flows by considering *ex animal*, *ex housing*, and *ex storage* contents of N, P and K (Poulsen et al., 2006). First, the system includes standard values for dietary nutrient content, nutrient digestibility, feed intake, and nutrient retention in the pig body in order to calculate the excretion of the nutrients (*ex animal*). Then, the system accounts for losses due to emissions during housing to get *ex housing* values and finally, losses from emissions and denitrification during storage are subtracted (*ex storage*). In the present study, the excretion of N and P was calculated for a standard (mean) Danish pig based on the current mean values for dietary protein (N) and P content, digestibility of protein and P, daily feed intake, and daily N and P retention to give the actual daily excretion of N and P for a standard Danish growing-finishing pig in the interval from 30 to slaughtering at 105 kg (Fernández, 1997; Poulsen et al., 2006; Poulsen, 2009). In addition, the excretion of N and P was calculated for the experimental diets (DK, VN, TH) using the same principles but by use of the recorded daily intake and the dietary protein (N) and P content (given by the calculated composition from tables (Table 3)) in order to mimic the situation on a farm where the farmer has the declared dietary contents but does not know the actual retention and digestibility of the nutrients. The results from the estimation of N and P based on DMNS are shown in Table 5 and Figures 1 to 3. Aarnink et al. (1992) also estimated the P excretion in pig manure and proposed an equation for calculation of P retention that accounts for the effects of physiological stage (P retention = $0.005467 x W^{-0.025} x$ daily gain, g where W is the body weight of the pig). Otherwise, the Aarnink et al. (1992) equations correspond to the DMNS equations. The excretion of P was also calculated by use of Aarnink et al. (1992) and is shown in Figures 1 to 3.

Calculations and statistical analyses

Validation of the predicted/estimated results (Tables 3 and 4) was done by test set validation (Esbersen, 2002) using the present experiment. The performance of the prediction was evaluated by its prediction error in terms of root mean square error of prediction (RMSEP):

$$RMSEP = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_{i,ref})^2}{n}}$$

Bias represents the average difference between predicted and measured Y-values for all samples in the validation or reference data set (ref) and measure the accuracy of the prediction model. If there is no systematic difference between the average values of the two data sets, the bias will be zero:

$$Bias = \frac{\sum_{i=1}^{n}(\hat{y}_i - y_{i,ref})}{n}$$

RESULTS AND DISCUSSION

In vivo experiment with pigs fed Danish, Vietnamese and Thai based diets

The chemical composition of the experimental diets is shown in Table 1. Generally, the protein and fat content were higher in the Asian pig diets compared with the Danish diet whereas the fibre content was highest in the Vietnamese diet compared with the Thai and the Danish diets. Furthermore, the analyzed contents for most nutrients reflected the calculated contents (Table 3) showing that table values on nutrient contents are quite reliable for the most common feedstuffs. Main feedstuffs in TH were maize and sorghum which are not typically used for pig feeding in Denmark and the use of these feedstuffs resulted in minor deviations from the standard values.

In general, no health problems were observed among the pigs throughout the experiment. Average feed intake for the Danish diet (DK) and the Vietnamese diet (VN) was almost identical whereas the Thai diet (TH) intake was lower (Table 2). Feed refusals were observed for the TH group during the first period and these pigs consumed 20% less than the other groups, which might be related to the inclusion of pearl millet that is known to contain tannins affecting palatability and reducing feed intake (FAO, 1995). Therefore, vanilla flavour was added to TH during the second period resulting in increased feed intake to almost the same level as the VN and DK diets. The average body weight gain of pigs fed the TH diet was lower than the VN and DK pigs reflecting the lower feed intake of the pigs fed the TH diet without added flavour.

Nutrient digestibility, retention and excretion

Nutrient balances in terms of intake, retention and excretion per day, total excretion in percentage of intake and the digestibility of dietary nutrients are summarized in Table 2. The digestibility of N, P and C in the Thai and Danish diets was very much alike whereas the digestibility was the lowest in the VN diet which might be related to the high crude fibre content in feed. The low P digestibility in VN might also be caused by the fact that feed phosphate (dicalcium phosphate, DCP) was solely added to the DK and TH diets, and it is known that DCP has a higher P digestibility than plant feedstuffs (Poulsen, 2007). Previous studies have shown that high fibre levels decrease nutrient and energy digestibility in pigs (Just et al., 1984; Noblet and Perez, 1993; Len et al., 2007). Fibre can hinder the access of digestive enzymes to the cell contents (Bach Knudsen et al., 1993) and can furthermore increase the passage rate of digesta (Low, 1993). This may also decrease the digestibility of nutrients and energy because of less access and time available for the digestive enzymes.

The N, P and C excretions in faeces and urine are presented in Table 2 and differed to some extend between diets although the total daily excretion of N and P did not differ significantly between diets. In contrast, the total C excretion was 50% higher in VN compared with DK and TH which was due to a much lower C digestibility in VN. The present study did not result in statistical differences in the urinary N and C excretion between the experimental diets whereas the faecal excretion of N and C was significantly different. The opposite was valid for the P excretion. The retention of N and P was almost the same for all diets and was similar to the values of growing pigs reported by Fernández et al. (1999) (21.0 g N and 4.15 g P per day). Excreted urinary P represents excessive dietary P in relation to the pigs' physiological requirement. However, the small amount of excreted P in urine for VN can be regarded as obligatory losses (Table 2), but it seems likely that VN provided sufficient available P to fulfil the pigs' P need. In general, excessive protein (N) and P intake results in higher daily excretion of N and P in urine. Many studies show that reductions in unavailable and/or excess N and P in diet can decrease the excretion of N and P (Jongbloed and Lenis, 1992; Knowlton et al., 2004; Portejoie et al., 2004).

Table 3 compares the analyzed values and values obtained from feedstuff tables on dietary nutrients. In general, the difference is very small which resulted in correspondingly small bias when the digestibility of DM, OM, C and N (protein) was calculated based on either the analyzed values or standard values from feedstuff tables (NRC, 1982; Just et al., 1983; Bach Knudsen, 1997; Vils and Sloth, 2005). Thus, the cheap and quick approach using table values seems reasonable for obtaining indicative values on digestibility.

Calculation of the daily excretions by use of table values or equations

The predicted amount of daily excretion of faeces DM, N, C and urine N using either information from tables (NRC, 1982; Just et al., 1983; Bach Knudsen, 1997; Vils and Sloth, 2005) or equations (Vu et al., 2009) is shown in Table 4 and Figure 1 and 2. In general both methods of prediction show values within the standard error (SE) for the measured in vivo values. However, the variance (RMSEP) was smaller when using table values than when using equations. Bias or accuracy for prediction of faeces DM was negative for both methods showing a slight overestimation in average 7 and 3% when predicted was based on table values or equations, respectively. Faeces N were underestimated on average by 17% using the information from tables because of an underestimation of the N digestibility (Table 3). However, using the equations the bias was much smaller. Contrary to faecal N the prediction of faecal C showed an underestimation of 2% when using tables and 11% when prediction was based on equations by Van et al. (2009). However, the predicted N excretion in urine based on Vu et al. (2009) was higher (especially in the VN diet) than in the experiment: 17 and 30% of bias for tables and equations, respectively (Table 4 and Figure 2). The predictions assume an average utilization of 50% of the digested N which can be expected in average in practice (Just, 1982; Just et al. 1983). In the current experiment, the utilization of N was higher (mean 58% N retained of digested N; Table 2) and as urinary N normally is higher than faecal N, it is evident that a reduction in N excretion can be obtained by feeding the pigs close to their requirement. Biases in total N excretion (1 to 17%) were mainly influenced by the N content in urine (Figure 3); however, the predictions were within the standard error found in the present experiment.

Calculation of the daily excretions by use of the Danish manure normative system

The N and P balances in terms of intake, retention and excretion are shown in Table 5 and are compared with the experimental or calculated values in Figures 1 to 3. Table 5 shows the actual mean values on N and P balances for a Danish grower-finisher pig (DK standard) in comparison with the calculated N and P balances based on the DMNS system for the experimental pigs fed DK, VN or TH in the present experiment. In general, the DK and VN diets mimicked the DK Standard, whereas the TH pigs showed a much higher excretion of N and P due to the higher feed conversion ratio (feed intake per kg gain).

Comparison of the experimental results with the model results

The experimental results on N, P, C and DM excretions are compiled and compared with predictions from (i) DMNS (regarding N and P), (ii) Vu et al. (2009) (regarding DM, N and C), (iii) calculated amounts based on table values (regarding DM, N and C), and (iv) Aarnink et al. (1992) (regarding P) in Figures 1 to 3. Figure 1 shows that the predictions of faecal DM and P content for all models fall within the standard error seen in the experiment for all diets, but the DMNS model was not able to predict the faecal N excretion and the Vu et al. (2009) equation was not able to predict the faecal C excretion within the experimental standard errors indicating that more variation of predicting faecal N and C can be expected. Thus, the different models seem to be quite valid for predictions of faecal DM and P excretions. Furthermore, the success of the models to predict faecal N and C excretion depended on the type of diet. Generally, the predictions of urinary excretions of N and P only showed results within the experimentally determined standard errors for DK and not for VN or TH (Figure 2). In contrast, all the models resulted in predictions of the total N and P excretions that fell within the experimentally obtained standard errors (Figure 3). Thus, all the tested models could be used to predict the N and P excretions in these diets representing regional different pig diets. Taken as a whole, the very simple models (DMNS and Aarnink et al. 1992 which are principally very alike) were quite useful to predict the overall excretion of N and P whereas the equations given by Vu et al. (2009) resulted in more precise predictions for the separate excretions of N and P in urine and faeces. Vu et al. (in press) also shows that models based on the equations proposed by Vu et al. (2009) are suitable for predictions of nutrient contents in manure for pigs fed Vietnamese diets. Although the present experiment was of limited duration and number of diets, it is anticipated that the conclusions can be expanded to a longer period reflecting e.g. the grower-finisher period of pigs.

This study also emphasizes that both the simple models and the more complex models may be used for evaluation of the potential for improvements in nutrient utilization and thus reductions in nutrient excretions. The provision of essential amino acids has been used to lower the protein contents in pig diets while maintaining adequate supply of essential amino acids without negative effects on pig performance (Portjoie et al., 2004; Canh et al., 1998). However, this potential has not been fully utilized worldwide.

Thus, reducing protein contents in DK, VN and TH may be helpful in order to decrease the N excretion but this may not always be possible at a local or regional scale due to the supply of feedstuffs or economy. Similarly, substitution of feed phosphate by phytase may also lessen the P excretion, but this requires specific knowledge of the effects of phytase on P digestibility when microbial phytase is added to different diets composed of regionally relevant feedstuffs. Johansen and Poulsen (2003) showed that the effects of microbial phytase highly depended on diet composition and the presence of plant phytase in the feedstuffs. Generally, the effect of phytase addition on P digestibility was greatest in feedstuffs with a low plant phytase activity. Nevertheless, the review showed a maximum P digestibility of not more than 60 to 65% when microbial phytase was supplemented to pig diets fed dry (Johansen and Poulsen, 2003).

CONCLUSIONS

This study showed that regional differences in diet composition simulated by three diets significantly affected manure characteristics. Due to the highest dietary fibre content, VN had the lowest digestibility of N, P and C (73, 49, and 73%, respectively) compared with the DK and TH pig diets. Very simple input-output models using either standard table values of the feedstuffs or standard values regarding nutrients retention in the pig body (like DMNS) seem quite useful in order to quantify the total excretion of N and P whereas the newly developed equations derived from datasets of almost 300 diets were very useful to predict the divided excretions of DM, N and C in faeces and in urine. In conclusion, these simple models seem to be quite robust and thus very useful as they are based on parameters and information that are available at a low cost under practical conditions. However, more experimental data have to be available and integrated if the effects of e.g. microbial phytase additions should be included in a further refined model.

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Table 1. Composition and chemical analysis of the experimental diets

Diet	DK	VN	TH
Ingredients, %			
Barley	26.04	-	-
Wheat	55.00	15.00	-
Oats	-	28.76	-
Pearl millet	-	-	42.50
Maize	-	-	22.05
Soybean meal	15.91	15.90	15.00
Wheat bran	-	15.00	10.00
Green meal	-	12.85	-
Vegetable oil	-	8.00	-
Fishmeal	-	3.00	8.00
Limestone ($CaCO_3$)	0.41	1.07	0.76
Salt	0.39	0.22	0.31
Dicalcium phosphate	1.00	-	1.18
Minerals and vitamins	0.20	0.20	0.20
Lysine, methionine, threonine mix	1.05	-	-
Chemical analysis, % of DM			
Dry matter, %	90.1	91.5	90.0
Ash	5.0	5.9	5.7
Crude protein (Nx6.25)	17.5	19.6	23.8
Crude fat	3.1	13.3	5.6
Crude fibre	4.2	9.8	3.7
Starch and sugar	56.2	32.6	48.2
Total dietary fibre[1]	18.9	28.7	16.2
Phosphorus	0.57	0.52	0.77
Carbon	43.4	47.2	44.4

DM = Dry matter, DK = Danish diet, VN = Vietnamese diet, TH = Thai diet.

[1] The content of total dietary fibre was calculated as the residual fraction after subtraction of the analyzed content of sugars, starch, crude protein, crude fat and ash from the dry matter content.

Table 2. Mean body weight, feed intake and experimentally determined nutrient balances and excretions in the in vivo experiment with pigs fed the three different diets (LS Mean values for six pigs)

Composition	Diet			SE[1]
	DK	VN	TH	
Mean liveweight, kg	59.7	60.2	57.1	
Feed intake, kg/d	1.80	1.78	1.43	
Feed DM intake, kg/d	1.62	1.63	1.29	
N				
N intake, g/d	45.5	51.2	49.2	4.23
N retention, g/d	21.2	23.5	21.2	2.03
Faecal N, g/d	8.79 ^{a}	13.8 ^{b}	10.0 ^{ab}	1.33
Urine N, g/d	15.5	13.9	18.0	2.43
N excretion, % of intake	52.9	54.1	56.1	3.54
N Digestibility, %	80.6 ^{a}	72.9 ^{b}	79.9 ^{a}	1.94
P				
P intake, g/d	9.17	8.55	9.99	0.84
P retention, g/d	3.91	4.12	4.34	0.38
Faecal P, g/d	4.39	4.37	4.41	0.42
Urine P, g/d	0.87 ^{a}	0.05 ^{b}	1.53 ^{c}	0.22
P excretion, % of intake	57.2	51.8	59.0	2.69
P digestibility, %	51.9 ^{ab}	48.7 ^{a}	55.9 ^{b}	2.21
C				
C intake, g/d	705 ^{ab}	770 ^{a}	573 ^{b}	53.3
Faecal C, g/d	108 ^{a}	208 ^{b}	93 ^{a}	12.5
Urine C, g/d	19.8	20.7	20.7	2.83
C excretion, % of intake	18.2 ^{a}	29.7 ^{b}	19.5 ^{a}	1.00
C digestibility, %	84.6 ^{a}	72.9 ^{b}	84.1 ^{a}	1.03

DK = Danish diet, VN = Vietnamese diet, TH = Thai diet

[1] Pooled standard error.

LS Means values within a row with the same letter are not significantly different at $P<0.05$ (Least Square Means test).

^{abc}: Values in a row with different superscripts differ significantly ($P<0.05$).

Table 3. Analyzed and calculated chemical composition and digestibility of nutrients of the experimental diets (DK, VN and TH)

	Analyzed/Estimated (in vivo)			Calculated from feedstuff Tables[1]				
	DK	VN	TH	DK	VN	TH	Bias[2]	RMSEP[3]
Chemical composition, % DM								
Dry matter, %	90.1	91.5	90.0	86	89	87	3.2	0.5
Ash	5.0	5.9	5.7	5.7	6.2	6.6	-0.6	0.2
Crude Protein (Nx6.25)	17.5	19.6	23.8	17.5	19.3	22.6	0.5	0.4
Crude fat	3.1	13.3	5.6	2.4	12.5	4.0	1.0	0.3
Starch and sugar	56.2	32.6	48.2	54.7	35.8	48.5	-0.7	1.4
Total dietary fibre	18.3	28.6	16.7	16.9	27.5	15.0	1.4	0.2
Crude fibre	4.2	9.8	3.7	4.1	9.4	3.4	0.3	0.1
Phosphorus	0.57	0.52	0.77	0.64	0.55	0.77	-0.06	0.02
Total digestibility, %								
Dry Matter (DM)	85	73	85	82	71	82	2.3	0.4
Organic Matter (OM)	86	74	86	86	75	87	-0.9	0.4
Carbon	85	73	84	84[4]	72	85	0.1	0.6
Protein	81	73	80	83	76	82	-2.6	0.3

DM = Dry matter, DK = Danish diet, VN = Vietnamese diet, TH = Thai diet.

[1] NRC (1982), Just et al. (1983), Bach Knudsen (1997), Vils and Sloth (2005).

[2] Bias, systematic difference between the experimental estimated value and that calculated using table values.

[3] RMSEP, root mean square error of prediction.

[4] Carbon digestibility calculated by the equation: dcCarbon (%) = -12.15 +1.117 dcOM (%), using data from Jørgensen (2007).

Table 4. In vivo estimation and calculated/predicted amount of excreted faeces DM, N, C and urine N of the experimental diets (DK, VN and TH)

	In vivo estimation				Calculated from Tables[1]					Predicted from equations[2]				
	DK	VN	TH	SE[3]	DK	VN	TH	Bias[4]	RMSEP[5]	DK	VN	TH	Bias	RMSEP
Faeces DM, kg/d	0.24	0.44	0.20	0.027	0.28	0.46	0.22	-0.022	0.01	0.29	0.40	0.23	-0.012	0.03
Faeces N, g/d	8.8	13.8	10.0	1.33	7.4	11.7	8.1	1.82	0.2	9.3	12.5	9.2	0.52	0.6
Faeces C, g/d	108	208	93	12.5	105	209	85	3.4	3	114	170	82	14.6	13
Urine N, g/d	15.4	13.9	18.0	2.43	18.0[6]	18.7	18.5	-2.59	1.2	18.0	21.2	22.6	-4.81	1.4

DK = Danish diet, VN = Vietnamese diet, TH = Thai diet.

[1] Based on feed intake shown in Table 2 and values calculated from tables (NRC, 1982; Just et al., 1983; Bach Knudsen, 1997; Vils and Sloth, 2005) shown in Table 3.

[2] Based on feed intake shown in Table 2 and equations from Vu et al. (2009).

[3] Pooled standard error.

[4] Bias, systematic difference between the experimental estimated value and that calculated using either table values or predicted values.

[5] RMSEP, root mean square error of prediction.

[6] Urine N calculated assuming a 50% utilization of the digested N.

Table 5. Calculated intake, retention and excretion of nitrogen (N) and phosphorus (P) based on the Danish Manure Normative System using standard values or the experimental values for DK, VN and TH treatments regarding N and P contents in the diets and feed intake

Diet	DK Standard[1]	DK	VN	TH
Weight gain, g/d	840	719	810	465
Feed intake, kg/d	2.26	1.80	1.78	1.43
Nitrogen:				
N intake, g/d	52.7	45.4	51.1	49.0
N retention, g/d	24.9	21.3	24.0	13.8
N excretion, g/d (total)	27.8	24.1	27.1	35.2
In faeces, g/d	10.0	8.63	9.70	9.31
In urine, g/d	17.8	15.5	17.4	25.9
Phosphorus:				
P intake, g/d	9.18	9.24	8.47	9.91
P retention, g/d	4.62	3.96	4.45	2.56
P excretion, g/d (total)	4.56	5.29	4.02	7.35
In faeces, g/d	4.59	4.62	4.02	4.95
In urine, g/d	0.03	0.67	0[2]	2.40

[1] Mean values for the weight interval 30 to 105 kg. Diet content: protein 145.8 g/kg (23.3 g N/kg); phosphorus 4.06 g/kg. Digestibility: protein 81%; phosphorus 50%. Retention per kg gain: 29.6 g N; 5.5 g P (Fernández, 1997).

[2] The urinary excretion was calculated to be -0.22 g/d and was set to 0.

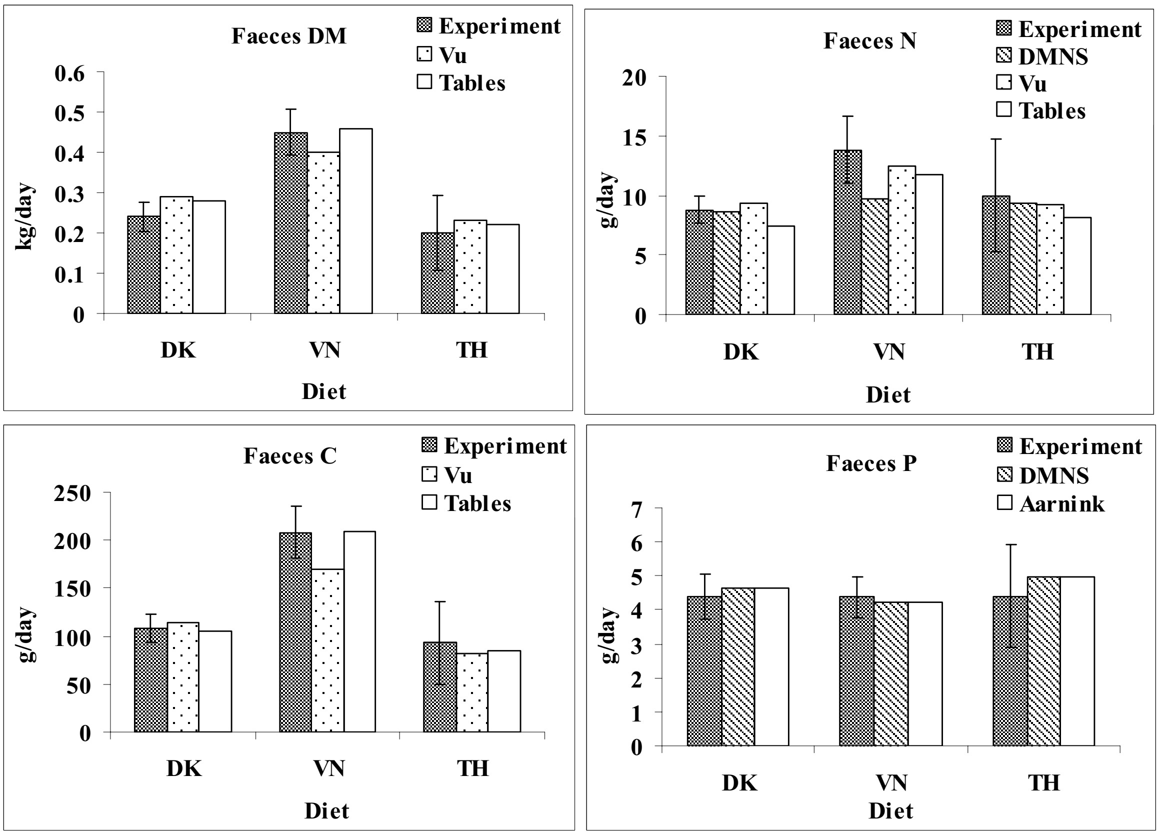


Figure 1. Comparison of the daily excretion of faeces DM, N, C and P obtained in the present experiment (Experiment) with the Danish manure normative system (DMNS), Vu et al. (2009) (Vu), calculated amounts based on table values (Tables) and Aarnink et al. (1992) (Aarnink). The experimental values are expressed as least square means (n=6) with pooled standard errors. DK = Danish diet, VN = Vietnamese diet, TH = Thai diet.

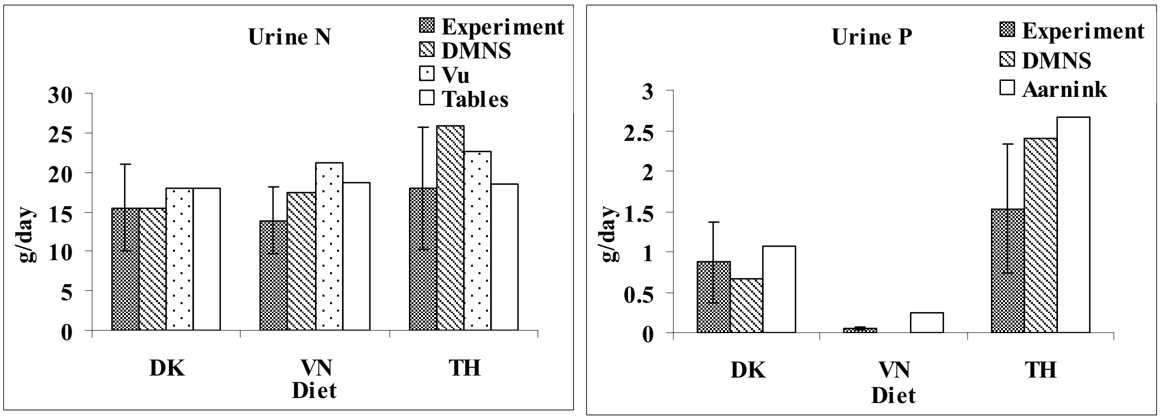


Figure 2. Comparison of daily urine excretion of N and P obtained in the present experiment with the modified Danish manure normative system (DMNS), Vu et al. (2009) (Vu), calculated amounts based on table values (Tables) and Aarnink et al. (1992) (Aarnink). The experimental values are expressed as least square means (n=6) with pooled standard errors. DK = Danish diet, VN = Vietnamese diet, TH = Thai diet.

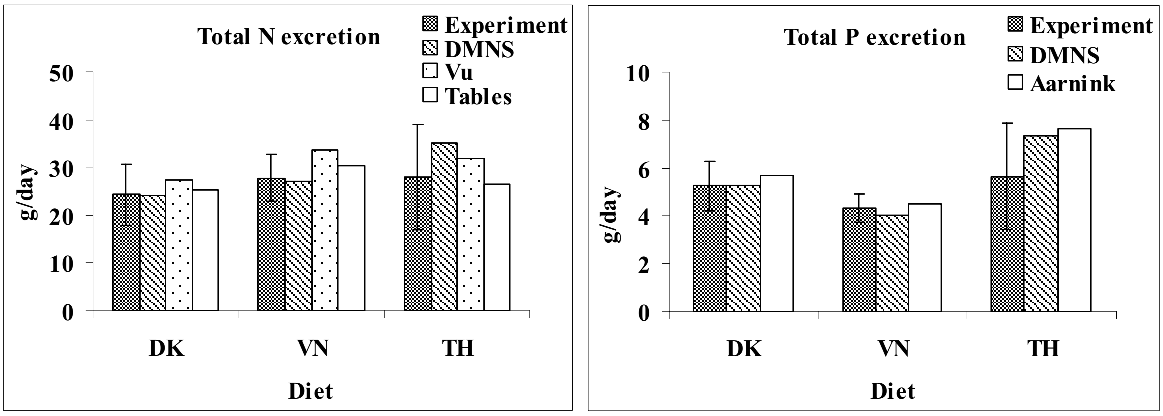
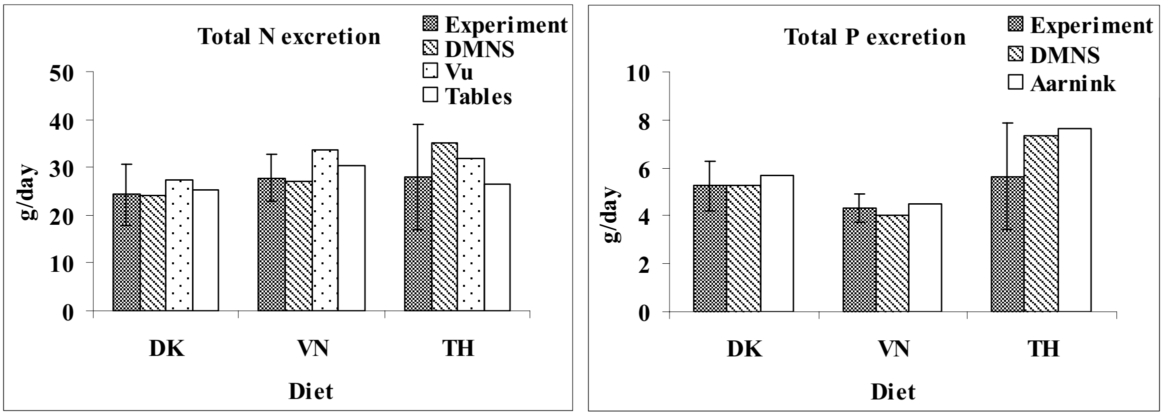


Figure 3. Comparison of daily total N and P excretion obtained in the present experiment (Experiment) with the modified Danish manure normative system (DMNS), Vu et al. (2009) (Vu), calculated amounts based on table values (Tables) and Aarnink et al. (1992) (Aarnink). The experimental values are expressed as least square means (n=6) with pooled standard errors. DK = Danish diet, VN = Vietnamese diet, TH = Thai diet.



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Paper 1C

Title:

Nitrogen, phosphorus, and carbon utilization and excretion in growing pig fed Danish and simulated Asian diets.

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Nitrogen, Phosphorus and Carbon Excretion and Losses in Growing Pigs Fed Danish or Asian Diets

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Abstract

The objectives of this study were to determine inputs and outputs of nitrogen (N), phosphorus (P) and carbon (C) and to estimate the nutrient losses during housing and storage in order to address these important parts of the whole manure management systems in pigs fed different diets. Digestibility and balance experiments were conducted to identify N, P and C utilization and excretion from growing pigs fed Danish diet (DK), Vietnamese diet (VN) or Thai diet (TH). Due to the highest dietary fibre content, VN showed the lowest digestibility of N, P and C (72.9%, 48.7% and 72.9%, respectively). Nevertheless, total N and P excretion in % of intake among the 3 diets were similar because the amount of digested protein and P in the DK and TH diets was in excess of pig requirements resulting in excretion via urine. Losses during housing and storage from pigs fed the DK and TH diets were calculated using emission factors (Dong et al., 2006; Hutchings et al., 2001; Velthof et al., 2007). Danish system 1 with slatted floor and storage system with cover emitted less N and C (17 % of N excretion and 10% of C excretion) than deep litter (Danish system 2) and solid storage and anaerobic lagoon (Thai system). This study demonstrates that diet composition significantly affects manure characteristics, while housing and storage systems influence the magnitude of nutrient losses. Reductions in dietary fibre, protein and P content can reduce nutrient excretion. Slatted floor and storage system with cover can be applied to limit N and C emissions.

Introduction

Manure management has contributed to many environmental problems around the world such as surface water eutrophication, groundwater pollution, greenhouse gas emissions, and odor. Nutrient accumulation from pig manure occurs in many European and Asian countries (Gerber and Menzi, 2006; Jongbloed et al., 1999; Kyllingsbæk, 2005). Appropriate manure management can reduce the detrimental environmental effects due to potential for resource recoveries in terms of energy and nutrients. Previous studies have shown that diet composition, such as protein, fat, and fibre contents, affect manure composition, but housing and storage systems also affect nutrient losses significantly (Canh et al, 1998; Portejoie et al., 2004; Dong et al., 2006; Hutchings et al., 2001). Quantification of inputs, outputs, and flows of nutrients at different stages is therefore very necessary for precise and proper development of manure management systems. This study is conducted (i) to determine the excretion of N, P and C in growing pigs fed 3 different diets considered representative for Denmark, Thailand, and Vietnam and (ii) to continuously estimate nutrient losses at housing and at storage level. Controlled excretion and storage are essential parts of all manure management systems.

Experiments and methods

Digestibility and balance experiments were conducted to determine N, P and C utilization and excretion from growing pigs fed DK, VN, or TH diets. All diets were formulated on the basis of raw ingredients purchased in Denmark. Three sibling female pigs were subjected to two balance periods for each diet - at 35 to 40 kg and 55 to 60 kg body weight. The experimental period consisted of 5 days adaptation and 7 days total collection of faeces and urine. The diets were analysed chemically. Daily amount of N, P and C in faeces and urine (Table 2) were calculated based in feed intake, excretion of faeces and urine and the corresponding analysed composition (Poulsen et al., 2007). Losses at housing and storage level were estimated by emission factors from literature studies. N losses were determined as NH_3 and N_2O emissions and N leaching. Emission factors of NH_3-N and N_2O-N were derived from Hutchings et al. (2001) and Dong et al. (2006), respectively. Calculations of nitrate leaching were based on the integrated nitrogen model MITERRA-EUROPE (Velthof et al., 2007). C losses were considered as CH_4 and CO_2 emissions and CH_4 emission estimated according to the method adapted from Dong et al. (2006). Since many studies show different magnitudes of CO_2 emission even from the same storage systems (Loyon et al., 2007; Møller et al., 2004; Sommer and Dadl, 1999; Wolter et al., 2004), CO_2 emission was estimated by its ratio in biogas from anaerobic condition (55% CH_4 and 45% CO_2 by volume; Tchobanoglous et al., 1993). P losses were considered insignificant based on previous findings (Petersen et al., 1998; Sommer and Dahl, 1999).

Results and discussion

The chemical diet composition is shown in Table 1. VN and TH present the highest crude fibre and crude protein contents, respectively. Daily nutrient intake and excretion, total excretion in percentage of intake, and the nutrient digestibility are presented in Table 2.

Total N and P excretion in % of intake among the 3 diets are similar. The lowest digestibility of N and P is found where pigs are fed the VN diet, resulting in a smaller urinary excretion compared with pigs fed the DK and TH diets. Pigs fed the VN diet exhibit the highest total C excretion in % of intake caused by the high fibre content in the diet. Furthermore, VN results in the lowest N and C digestibility which might also be related to the high crude fibre content in feed. Many studies have shown that high dietary fibre content reduces nutrient and energy digestibility in pigs (Len et al., 2007; Just et al., 1984). Fibres can obstruct the access of digestive enzymes to the cell contents (Bach-Knudsen et al., 1993) and increase the passage rate of digesta (Low, 1993) which may decrease digestibility of all nutrients because of less access and time available for the digestive enzymes to act. For P digestibility, the low value for VN is partially derived from no addition of feed phosphate which has a higher digestibility of P than typical feedstuffs. A high urinary P excretion implies that the dietary P content exceeds the physiological need of the pig. Despite a lower N intake, daily N excretion in urine from pigs fed the DK and TH diets are numerically higher than in pigs fed the VN diet. This is due to the higher N digestibility resulting in more N absorption and thus urinary N excretion. However, the N excretion also depends on the content of essential amino acids. In general, an oversupply of protein and phosphorus results in higher daily excretion of N and P via urine.

The obtained results confirm that diet composition significantly affects manure characteristics, i.e. dietary modifications can decrease nutrient losses via faeces and urine. As such, reduction of fibre content in the VN diet, reduction of protein content in all diets and reduction of feed phosphate in DK and TH have potential to increase nutrient digestibility, and to reduce N and P excretion, respectively. Similarly, it has previously been presented that reduction of unavailable and excess dietary N and P can decrease N and P excretion (Jongbloed and Lenis, 1992; Knowlton et al., 2004; Portejoie et al., 2004). Other studies also showed that lowering dietary protein content in order to reduce total N excretion while maintaining adequate essential amino acids can be done without negative effects on pig performance (Canh et al, 1998; Portejoie et al., 2004). Furthermore, many studies showed that supplementation of phytase at the expense of feed phosphate has potential to reduce P excretion.

Nitrogen and C losses during housing and storage of manure from pigs fed DK and TH diets were calculated for one Thai and two Danish housing systems (Table 3). The N losses from the Danish systems 1 and 2 and the Thai system were 17%, 41% and 46%, respectively.. The observed range is in accordance with former studies which showed that nitrogen losses during storage varied from 10% to 50% (Eghball et al. 1997; Oenema et al., 2007; Petersen et al., 1998). Ammonia volatilization during storage has been found in many studies to be the major loss cause (Loyon et al, 2007; Oenema et al, 2007). The calculated losses of C in the Danish systems 1 and 2 and the Thai system were 10%, 17% and 27%, respectively (Table 3). In terms of global warming, emission of CH_4 has a higher potential than CO_2. The calculated amount of CH_4 emission in this study is in contrast to some studies where the CH_4 emission from pig manure was insignificant during storage (Hansen et al, 2006; Sommer and Dahl, 1999; Wolter et al., 2004). This could be explained from the fact that in those studies aerobic conditioning was predominant, resulting in oxygen inhibited methanogenesis.

Table 3 shows that the calculated emissions of N and C were lowest from pigs kept on slatted floors (Danish system 1). Many studies demonstrate that the use manure storage on covered concrete floors can reduce gaseous emissions and leaching tremendously (e.g. 10% – 99%, Dong et al., 2006; Hansen et al., 2006; Velthof et al., 2007). Solid manure storage and anaerobic lagoons in Thai systems result in the highest C and N losses (Table 3). Anaerobic lagoons at elevated temperatures and without cover significantly induce methane emission. Although many studies presented insignificant nitrate leaching during storage (Sommer and Dahl, 1999; Wolter et al., 2004),storage systems without concrete floor and cover (e.g. Thai system) have high risk for NO_3^- leaching (Velthof et al., 2007). The Danish deep litter system has considerably higher losses than slatted floor systems (20% and 7% difference of N and C emission, respectively). Hence, housing systems with slatted floor can be applied to limit N and C emission in comparison to the Danish system 2 or the Thai system.

Conclusions

Diet composition as well as housing and storage systems affect nutrient losses. The nutrient excretion can be lowered by reducing the dietary protein (i.e. essential amino acids) and P content according to the pigs' requirement and/or by reducing the dietary fibre content. In this study, although the VN diet has the lowest digestibility of N, P and C (72.9%, 48.7% and 72.9%, respectively), total N and P excretion in % of intake among the 3 diets were not different since the amount of digested nutrients in DK and TH was in excess of pig requirements and thus excreted via urine. Slatted floor and storage system with cover have a smaller emission of N and C (17% of N and 10% of C excretion) in terms of NH_3, N_2O, NO_3 and CH_4 compared to other systems (deep litter, solid storage and anaerobic lagoons). Since some assumptions of calculations were based on European information, country-specific information is required for further application in Asia. To improve the assessment of the entire manure management system, further studies on inputs, outputs, and input-output functions of different types of integrated treatment technology systems need to be carried out.

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Table 1. Analysed chemical composition of the experimental diets

Composition	Diet		
	DK	VN	TH
Dry matter (%)	90	92	90
Ash (% of DM)	5.0	5.9	5.7
Crude protein (Nx6.25, % of DM)	18	20	24
Crude fat (% of DM)	3.1	13	5.6
Crude fibre (% of DM)	4.2	9.8	3.7
Phosphorus (% of DM)*	0.6	0.5	0.8
Carbon (% of DM)	43	47	44

DM = Dry matter, DK = Danish diet, VN = Vietnamese diet, TH = Thai diet

* Dicalcium phosphate was added: 1%, 0% and 1.18% (by weight) for DK, VN and TH, respectively.

Table 2. Nutrient intake and excretion, and the digestibility of dietary nutrients

Composition	Diet			SE[1]
	DK	VN	TH	
N				
N intake (g/day)	45.5	51.2	49.2	4.23
Faecal N (g/day)	8.79 a	13.8 b	10.0 ab	1.33
Urine N (g/day)	15.5	13.9	18.0	2.43
N excretion (% of intake)	52.9	54.1	56.1	3.54
N Digestibility (%)	80.6 a	72.9 b	79.9 a	1.94
P				
P intake (g/day)	9.17	8.55	9.99	0.84
Faecal P (g/day)	4.39	4.37	4.41	0.42
Urine P (g/day)	0.87 a	0.05 b	1.53 c	0.22

P excretion (% of intake)	57.2	51.8	59.0	2.69
P digestibility	51.9 ab	48.7 a	55.9 b	2.21
C				
C intake (g/day)	705 ab	770 a	573 b	53.3
Faecal C (g/day)	108 a	208 b	93 a	12.5
Urine C (g/day)	19.8	20.7	20.7	2.83
C excretion (% of intake)	18.2 a	29.7 b	19.5 a	1.00
C digestibility	84.6 a	72.9 b	84.1 a	1.03

DK = Danish diet, VN = Vietnamese diet, TH = Thai diet

The results are presented as Least square means (LSM)

LSM within a row with the different letters are significantly different at P<0.05 (Least Square Means test)

[1] Pooled standard error (SE)

Table 3. Calculated nitrogen and carbon losses from housing and storage systems

	Manure management systems		
	Danish system 1	Danish system 2	Thai system
Housing system[1]	Slatted floor (Slurry)	Deep litter	Solid floor
Storage system[1]	Slurry tank with surface cover	Deep litter	Solid fraction manure and anaerobic lagoon[2]
Total N losses (g/day)[3]	4 (17%)	9 (37%)	13 (46%)
NH_3-N	4 (17%)	9 (36%)	10 (35%)
N_2O-N	0.1 (0%)	0.2 (1%)	0.1 (0%)
NO_3-N $_{leaching}$	0 (0%)	0 (0%)	3 (11%)
Total C losses (g/day)[3]	13 (10%)	22 (17%)	31 (27%)
CH_4-C	7 (5%)	12 (9%)	17 (15%)
CO_2-C	6 (5%)	10 (8%)	15 (13%)

[1] Adapted from Hutchings et al. (2001) for Danish systems and from Gerber and Menzi (2006) for Thai system

[2] Applied assumptions from Poulsen and Kristensen (1997). 5% of faeces ex animal was in urine ex animal. 0.5 kg of urine per kg faeces ex animal was absorbed in pig faeces.

[3] Numbers in parenthesis represent losses in % of initial content

Paper 2A

Title:

Energy production, nutrient recovery and greenhouse gas emission potentials from integrated pig manure management systems.

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Energy production, nutrient recovery and greenhouse gas emission potentials from integrated pig manure management systems

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Improper management of pig manure has resulted in environmental problems such as surface water eutrophication, ground water pollution, and greenhouse gas emissions. This study develops and compares 14 alternative manure management scenarios aiming at energy and nutrient extraction. The scenarios based on combinations of thermal pretreatment, anaerobic digestion, anaerobic co-digestion, liquid/solid separation, drying, incineration, and thermal gasification were compared with respect to their energy, nutrient and greenhouse gas balances. Both sole pig manure and pig manure mixed with other types of waste materials were considered. Data for the analyses were obtained from existing waste treatment facilities, experimental plants, laboratory measurements and literature. The assessment reveals that incineration combined with liquid/solid separation and drying of the solids is a promising management option yielding a high potential energy utilization rate and greenhouse gas savings. If maximum electricity production is desired, anaerobic digestion is advantageous as the biogas can be converted to electricity at high efficiency in a gas engine while allowing production of heat for operation of the digestion process. In conclusion, this study shows that the choice of technology has a strong influence on energy, nutrient and greenhouse gas balances. Thus, to get the most reliable results, it is important to consider the most representative (and up-to-date) technology combined with data representing the area or region in question.

Keywords: pig manure, integrated waste treatment, energy recovery efficiency, greenhouse gas reduction, nutrient recovery potential

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Introduction

Global pig meat production has been increasing considerably within recent decades. From 2000 to 2006, global pig meat production has increased by over 19% and reached approximately 100.6 million tonnes in 2007 (Best 2008). This rapid increase in combination with highly intensive production systems have resulted in increased environmental problems due to improper management of the large quantities of pig manure generated during production. Estimated global pig manure production was around 125 million tonnes dry matter in 2007 (based on ASAE 2003, Danish Meat Association 2007, Danish Pig Production 2007, Best 2008). Key environmental problems are surface water eutrophication, ground water contamination, and greenhouse gas (GHG) and odor emissions. For instance, livestock manure has contributed to surpluses of nitrogen (N) and phosphorus (P) being applied to farmland which has lead to eutrophication in European countries (Jongbloed *et al*. 1999).

Manure, however, has not only negative environmental effects as it is potentially a source of both energy and nutrients. Several technologies are available for treatment aiming at extraction and utilization of energy and nutrients contained in the manure. Anaerobic digestion, liquid/solid separation, drying, incineration and thermal gasification are technologies that have been applied in nutrient and energy

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recovery strategies for different types of biodegradable wastes from agriculture, industry and households such as animal manure, kitchen waste, sewage sludge and slaughterhouse waste (Tafdrup 1994, Møller *et al.* 2000, 2007a, Stasta *et al.* 2006, Van Lier *et al.* 2001). To improve the economy in anaerobic digestion, anaerobic co-digestion of pig manure with other materials such as energy crops (*e.g.* grass and maize silage) and industrial waste (*e.g.* fats and glycerin) is often used as biogas yield from manure alone can be quite low (Amon *et al.* 2006, Nielsen *et al.* 2002, Weiland 2006). On the other hand, pig manure has a high buffer capacity and, therefore, helps to maintain stable and optimal conditions during digestion (Murto *et al.* 2004). Thermal pretreatment of manure prior to anaerobic digestion can improve biogas yield by up to 60% (Raju 2005). Liquid/solid separation of manure can increase biogas production per volume of input material and reduce input volume leading to improved economy, reduced transportation and digester construction costs, and increased income from energy sales (Møller *et al.* 2000, 2007a). Separation can also be used to extract nutrients (N and P) as P is present mainly in the solid fraction whereas most of the N is present in the liquid fraction. Separation can enable application of nutrients to match crop requirements. Drying uses heat to evaporate water reducing manure water content resulting in reduced material volume and mass for more ease and better economy in further processing (Stasta *et al.* 2006). Incineration and gasification are based on thermal processing at different temperatures, pressures and oxygen concentrations for extracting energy and nutrients (McKendry 2002a).

Environmental impacts of pig manure management have been assessed both at the farm and national levels (Basset-Mens & van der Werf 2005, Melse & Verdoes 2005, Sørensen *et al.* 2003). Melse & Verdoes (2005) evaluated environmental impacts from four farm-scale systems with experimental installations of treatment systems at different pig farms. Nevertheless, the measurements only aimed at nutrient recovery and direct greenhouse gas emissions from the systems without considering energy balances. Many studies have investigated environmental impacts of pig manure management but generally without considering manure management in detail. For instance, manure treatment was not considered at all or only single unit processes (*e.g.* either composting or anaerobic digestion) were considered (Basset-Mens & Van der Werf 2005, Van der Werf *et al.* 2007). However, anaerobic co-digestion has been studied intensively for pig manure with different kinds of organic waste but most of the studies focused on process performance and optimization in experimental, pilot-plant and plant scales (Amon *et al.* 2006, Angelidaki & Ellegaard 2003, Murto *et al.* 2004). Although Edelmann *et al.* (2005) presented a life-cycle assessment study dealing with co-digestion, the environmental impacts were compared between applying varied processes in anaerobic digestion and manure handling and were not compared with other technologies such as incineration and thermal gasification. Incineration and gasification combined with drying systems have been extensively applied to biodegradable materials although not for pig manure (Stasta *et al.* 2006, Stolarek & Ledakowicz 2001). Thus, knowledge about the environmental impacts using these treatment processes or combinations of these technologies for pig manure management is limited. Further studies are, therefore, needed to assess fully the impact of different manure management options on the environment to provide a basis for decision-making aimed at reducing environmental burdens, securing high nutrient and energy recovery, and improving economic feasibility at the same time.

The objective of this study was to determine the comparative energy and nutrient recovery, and GHG emissions from pig manure management using different combinations of existing technologies that are applicable for manure treatment aiming at energy and nutrient extraction. Sets of practically applicable manure management scenarios based on combinations of these technologies are developed and analyzed with respect to net energy production, energy recovery efficiency, nutrient recovery, and greenhouse gas emissions. The analysis includes scenarios for management of both pure pig manure and manure mixed with a high-energy industrial by-product and a crop residual. Data characterizing the different technologies were collected from full-scale existing waste treatment facilities wherever possible supplemented with data from experimental plants, laboratory measurements and literature.

Treatment technologies considered

Data used for the treatment technologies considered were collected mainly from existing treatment facilities or pilot-scale research facilities. All of the facilities are located in Denmark and represent state-of-the-art technologies under practical conditions. Technologies considered are anaerobic digestion (AD), thermal pretreatment (TPT), liquid/solid separation (SEP), drying (DRY), incineration (INC), and thermal gasification (GAS). Specific characteristics of the technologies selected are as follows.

Anaerobic digestion

The AD process is operated under thermophilic conditions (52°C) with post storage of the digestate under mesophilic conditions (35°C) to extract additional methane. Data describing this process were collected mostly from 20 Danish full-scale biogas plants (DEA 2005, Nielsen *et al.* 2007, Poulsen & Hansen 2003).

Liquid/solid separation

The SEP process is based on a commercial separator system marketed by Kemira Water Denmark A/S. The process is based on adding a cationic polymer (Optifloc C620) to the manure followed by separation in a filter press. Data were collected during experiments with the separator (Møller *et al.* 2007a,c). The solid fraction from SEP is assumed to be able to achieve up to 54% of dry matter (DM) content.

Table 1: Input parameters and input–output functions used as basis for technology systems.

Process/parameter	Unit	Value	Reference
Anaerobic digestion and co-digestion			
Biogas energy content (65% of CH_4)	kWh m^{-3} biogas	6.5	Christensen (1998)
Electricity production efficiency for gas engine-generator	%	38	Poulsen & Kuligowski (2007)
Heat production efficiency for gas engine	%	40	Poulsen & Kuligowski (2007)
Biogas plant energy consumption, electricity	kWh $tonne^{-1}$ biomass	6	DEA (2005)
Biogas plant energy consumption, heat	kWh m^{-3} raw material	34	DEA (2005)
CH_4 emission, biogas process	%	2	Poulsen & Hansen (2003)
CH_4 emission, gas engine	g GJ^{-1} waste	323	Nielsen *et al*. (2007)
CO_2 emission, gas engine	kg GJ^{-1} waste	83.6	Nielsen *et al*. (2007)
N_2O emission, gas engine	g GJ^{-1} waste	0.5	Nielsen *et al*. (2007)
Separation			
Separation efficiency, mass (weight)	% in solid fraction	13.0	Møller *et al*. (2007a)
Separation efficiency, DM/VS[a]/C[a]	% in solid fraction	84.4	Møller *et al*. (2007a)
Separation efficiency, N	% in solid fraction	54.3	Møller *et al*. (2007a)
Separation efficiency, P	% in solid fraction	84.6	Møller *et al*. (2007a)
Energy consumption for separation	kWh $tonne^{-1}$ input material	3	Møller *et al*. (2000)
Thermal pre-treatment			
Thermal pre-treatment CH_4 potential improvement (127°C)	%	51	Raju (2005)
Drying			
Manure drying heat consumption	MJ $tonne^{-1}$ water	2970	Simonsen (2008)
Manure drying power consumption	MJ $tonne^{-1}$ input mass	314	Poulsen & Kuligowski (2007)
Manure drying relative heat recovery	%	72.5	Simonsen (2008)
Incineration			
Electricity production efficiency	% of energy content in waste	25.9	Reno-Nord (2006)
Electricity production efficiency (without heat production)	% of energy content in waste	45	Poulsen & Kuligowski (2007)
Heat production efficiency	% of energy content in waste	71.5	Reno-Nord (2006)
Total energy consumption	% of energy production	3.99	Reno-Nord (2006)[b]
CH_4 emission, incineration	g GJ^{-1} waste	0.59	Nielsen *et al*. (2007)[c]
CO_2 emission, incineration	kg GJ^{-1} waste	94.5	Nielsen *et al*. (2007)[c]
N_2O emission, incineration	g GJ^{-1} waste	1.2	Nielsen *et al*. (2007)[c]
Gasification			
Thermal gasification chemical energy output	% of input energy	83	Poulsen & Kuligowski (2007)
Thermal gasification heat energy output	% of input energy	10	Poulsen & Kuligowski (2007)
Electricity consumption	% of energy production	10	Poulsen & Kuligowski (2007)
Electricity production efficiency for combustible gases	%	38	Assumed to be equal to AD
Heat production efficiency for combustible gases	%	40	Assumed to be equal to AD
CH_4 emission, gasification	g GJ^{-1} waste	0.59	Nielsen *et al*. (2007)[c]
CO_2 emission, gasification	kg GJ^{-1} waste	94.5	Nielsen *et al*. (2007)[c]
N_2O emission, gasification	g GJ^{-1} waste	1.2	Nielsen *et al*. (2007)[c]
Storage			
N emission factor, pig slurry with surface cover	% of total N emitted	2	Hutchings *et al*. (2001)
N emission factor, liquid fraction manure	% of total N emitted	2	Hutchings *et al*. (2001)
N emission factor, solid fraction manure	% of total N emitted	30	Hutchings *et al*. (2001)
Average temperature	°C	15	Assumption
Methane conversion factor, pig slurry/liquid slurry	%	17	Based on Dong *et al*. (2006)[d]
Methane conversion factor, digestate	%	0	Based on Dong *et al*. (2006)[d]

Table 1: Input parameters and input–output functions used as basis for technology systems. *(Continued)*

Process/parameter	Unit	Value	Reference
Energy reference systems			
CO_2 equivalent for natural gas power CHP plant–gas turbine combined cycle	kg CO_2 equivalent MWh^{-1} electricity or heat	282.77	DEA *et al.* (2005)
Others			
CH_4 global warming potential, 100 years time horizon	g CO_2 g^{-1} CH_4	23	IPCC (2001)
N_2O global warming potential, 100 years time horizon	g CO_2 g^{-1} N_2O	296	IPCC (2001)
Power conversion factor	MJ kWh^{-1}	3.6	
N fertilizer, energy equivalent	MJ kg^{-1}	42.44	Hülsbergen *et al.* (2001)
P_2O_5 (super phosphate) fertilizer, energy equivalent	MJ kg^{-1}	15.8	Hülsbergen *et al.* (2001)

DM, dry matter; VS, volatile solids; C, carbon; AD, anaerobic digestion.

[a] Assumed to be equal to separation efficiency of DM.

[b] Based on electricity and diesel consumption of the incineration plant. Energy equivalent of diesel is 42.3 MJ kg^{-1} (Haşimoğlu *et al.* 2008).

[c] Assumed identical to emissions from incineration of municipal waste.

[d] Applied for modified equation in Dong *et al.* (2006), EF = VS × B_0 × 0.67 kg m^{-3} × MCF, where EF, total methane emission (kg CH_4); VS, VS in the fraction (kg); B_0, methane yield (m^3 CH_4 kg^{-1} VS); MCF, methane conversion factor for each manure management system by climate region.

Thermal pretreatment

The TPT processes take place at 127°C which is the optimum temperature for improving biogas yield without chemical addition based on data from a full-scale test facility and laboratory experiments (Raju 2005). The heat consumption associated with TPT is assumed to replace the heat needed for heating the input materials to digester temperature due to the fact that the heat used for separated manure in TPT process is 31% of the total heat required for a thermophilic digester estimated by the data displayed in Table 1. Therefore, the combined TPT+AD process does not require any additional energy input compared to sole treatment by AD.

Drying

The DRY process evaporates water from the solid fraction produced by the SEP process. Based on data from a full-scale sewage sludge treatment plant (Simonsen 2008), DRY can achieve DM contents in excess of 95%. Using heat exchangers, it is possible to recover up to 72.5% of the heat used for water evaporation.

Incineration

The INC process is based on excess air combustion transforming combustible materials to hot flue gases and bottom ashes while extracting energy via a steam turbine and heat exchange system (McKendry 2002a). The data for the INC process were collected at a full-scale municipal waste incineration plant (Reno-Nord 2006).

Thermal gasification

The GAS process is based on partial combustion in a limited-oxygen atmosphere to produce combustible gases (*e.g.* CO, H_2 and CH_4) which can be converted to energy in a gas engine (McKendry 2002a,b). Data for GAS were collected from a pilot scale experimental plant for treating manure (Poulsen & Kuligowski 2007).

The storage system for slurry/mixed waste/digestate is a concrete tank with natural crust cover. For waste processed with INC or GAS, it is stored as ash without emissions. Further details on mass and energy input-output from the unit processes are presented in Table 1.

Manure management scenarios considered

Eight different scenarios for management of pure pig manure (labelled S1–S8) and six scenarios for management of pig manure mixed with high-energy industrial by-product and green crop (labelled MS1–MS8) are developed (Table 2 and Figures 1 and 2). The composition of the manure and materials mixed is selected to 85.8% pig slurry, 6% glycerine

Table 2: Process description of pig manure management scenarios (S) and mixed waste scenarios (MS)[a] considered using processes using liquid-solid separation (SEP), thermal pre-treatment (TPT), anaerobic digestion (AD), drying (DRY), incineration (INC), thermal gasification (GAS), and storage (STO).

Scenario	Alternative treatment process combinations
S1, MS1	STO
S2, MS2	AD – STO
S3	SEP (12% DM) – TPT – AD – STO
S4, MS4	SEP (54% DM) – DRY – INC – STO
S5, MS5	SEP (54% DM) – DRY – GAS – STO
S6	SEP (12% DM) – AD – STO
S7, MS7	SEP (12% DM)[b] – AD – SEP (54% DM) – DRY – INC – STO
S8, MS8	SEP (12% DM)[b] – AD – SEP (54% DM) – DRY – GAS – STO

[a] Numbers for MS are not in numerical order (1, 2, 4, 5, 7, 8) because they represent the same number with similar technology system for pig manure management scenarios.

[b] Excluded for MS.

DM, dry matter.

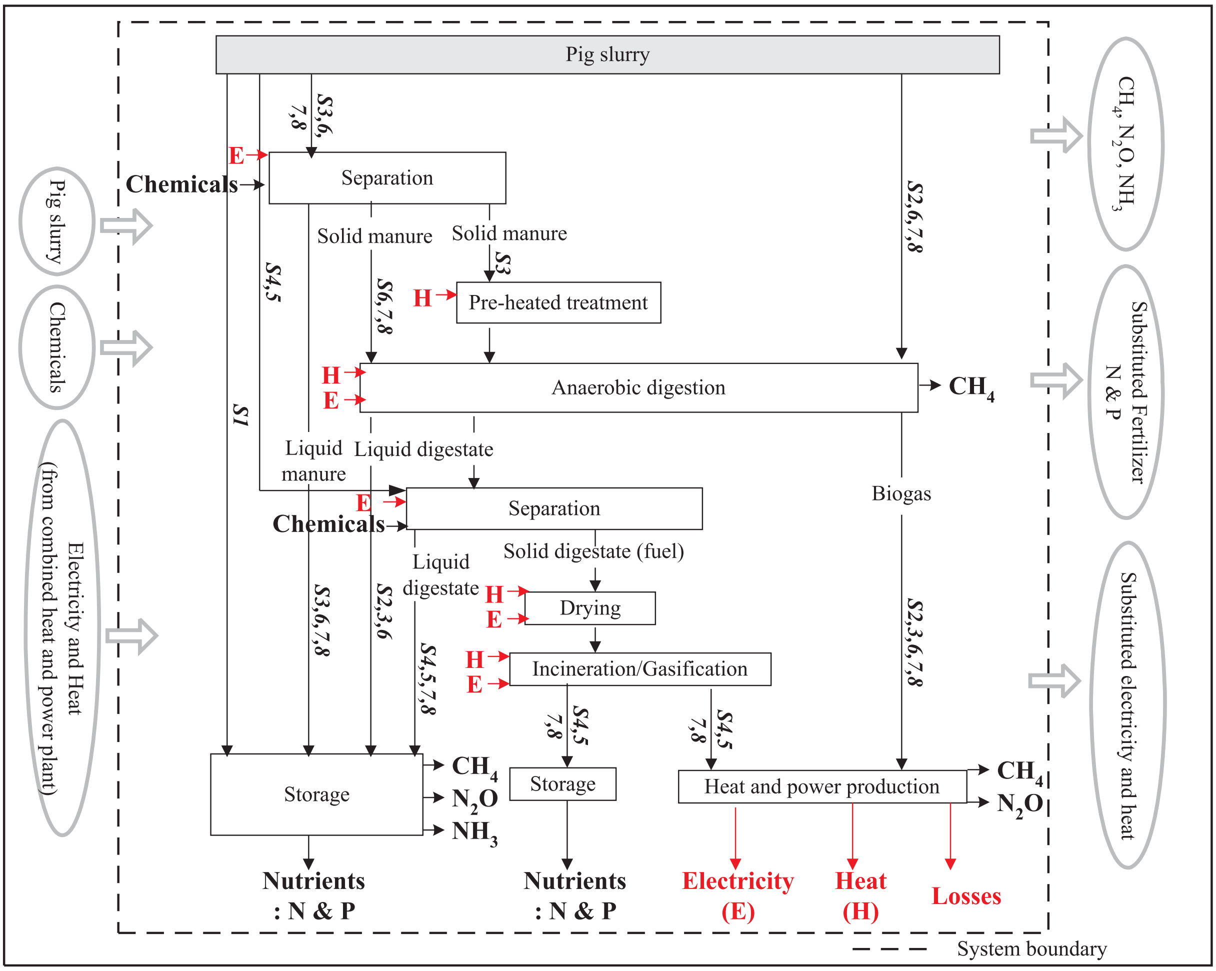

Fig. 1: Mass and energy flow diagram for pig manure management scenarios (S1–S8). Dark arrows indicate internal mass flows and red arrows indicate internal energy flows (E, electricity; H, heat) whereas gray arrows indicate mass and energy entering or leaving the system.

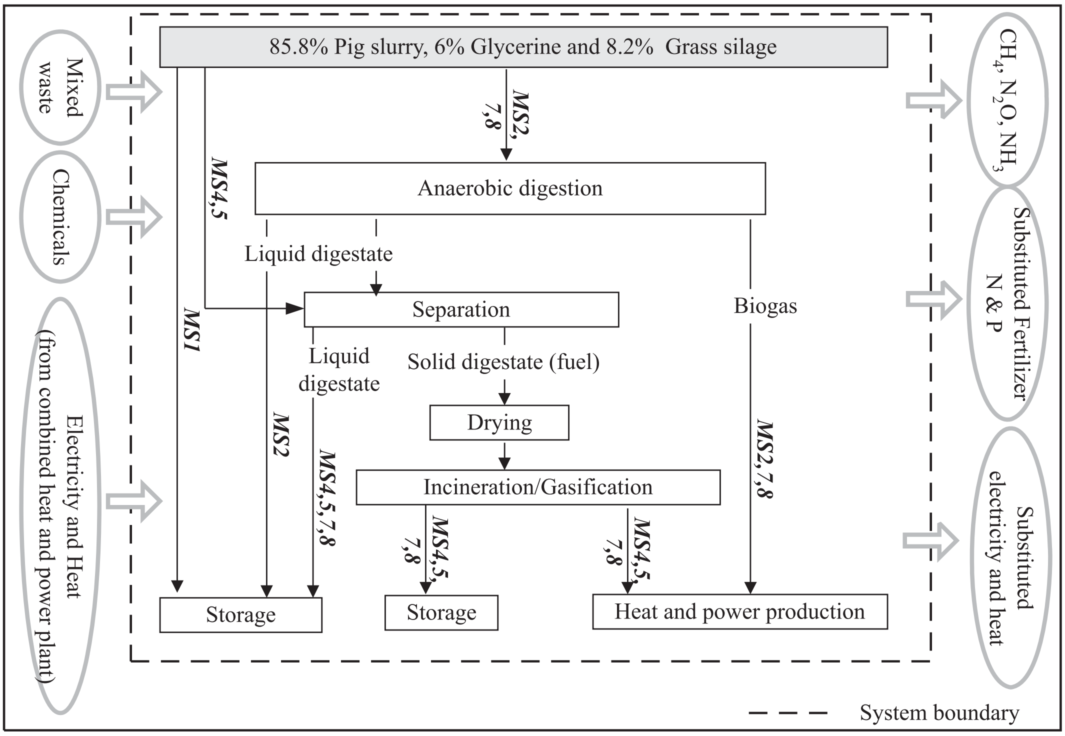

Fig. 2: Mass and energy flow diagram for mixed waste management scenarios (MS1–MS8).

and 8.2% grass silage by mass based on the optimum glycerine concentration from Amon *et al*. (2006), aiming at a DM content of 12%. The scenarios are based on practically applicable and commonly used combinations of the technologies discussed in the previous section. Mixed material scenarios do not include SEP prior to anaerobic digestion as the mix already has a sufficient high dry matter content. As the materials mixed with manure are easily degradable, TPT is also excluded for mixed material scenarios. The process diagram illustrating mass and energy flows associated with the pig manure management scenarios is presented in Figure 1. Due to the fact that the same process units have similar internal mass and energy flows, Figure 2 illustrates only the overall mass and energy flows of the mixed waste management scenarios. S1 and MS1 are chosen as baseline scenarios as they represent the most widely applied treatment of pig manure.

Evaluation approach

The system boundaries for the 14 scenarios in Table 2 and Figures 1 and 2 encompass all unit processes applied to the manure or mixed waste at farm level including treatment systems, heat and power production (optional) and storage. The evaluation does not include impacts of pig production itself or impacts associated with emissions from the pig stable, transportation and land application of the manure. The 14 scenarios are evaluated with respect to their production of energy (heat and electricity), nutrients (N and P), and greenhouse gases (non-biogenic CO_2, CH_4 and N_2O). Although a chemical is added in the SEP process, it is neglected in the assessment. The functional unit is chosen as 1 tonne of raw manure or 1 tonne of the manure mix with characteristics as presented in Table 3.

Nutrient recovery is determined as the sum of N and P quantities present in liquid and solid fractions (supernatant, digestate, manure, ash, *etc*.) leaving the treatment system. It is determined as potential fertilizer values and it is assumed that all nutrients present in these fractions are available for plant uptake and can substitute equal amounts of nutrients in commercial fertilizer (based on Laboski & Lamb 2003, Maraseni & Maroulis 2008). Energy recovery is determined as net energy (electricity, heat and substituted fertilizer) production and energy recovery efficiency. Net energy production is associated with net direct energy production and equivalent energy saved by the potential fertilizer values of nutrients recovered. The equivalent energy saved from nutrient recovery is calculated as energy required for production of N and P fertilizer. Energy recovery efficiency is defined as the ratio of net energy production to total energy content of input material.

Total GHG emission is determined as the sum of GHG emissions associated with: (i) production of mass or energy consumed by the system (upstream impacts); (ii) direct emissions by the system (direct impacts); and (iii) substitution by energy and nutrients produced by the system (downstream impacts). The reference system used for converting energy production including energy equivalent from nutrient recovery to CO_2 equivalent is a natural gas powered CHP plant using a gas engine. This system is chosen as it has a higher energy conversion efficiency and lower GHG emissions compared to most other practical energy production systems such as a coal fuelled CHP plant or power plant.

Table 3: Characteristics of the waste fraction.

	Pig manure	Glycerine	Grass silage	Solid manure	Mixed waste[a]
DM (%)	8.3[b]	40[b]	30.2[b]	53.9[c]	12.0
N (% of DM)	4.8[b]	0[b]	2.7[b]	3.1[c]	3.4
P (% of DM)	1.57[b]	0[b]	0.04[b]	1.6[c]	0.95
C (% of DM)	40[d]	39.1[b]	48.6[b]	40.1[c]	42
VS (% of DM)	73[e]	78[b]	86[e]	73[c]	77
Ash (% of DM)	–	0.2[f]	5.46[g]	5.94[h]	5.6
Methane yield ($m^3\ kg^{-1}$ VS)	0.32[i]	0.75[j]	0.36[e]	0.29[i]*	0.42
Energy content (GJ $tonne^{-1}$ DM)	15.2 (raw), 12.2 (digested)[k]	32.9[l]	17.3[g]	15.2 (raw), 12.2 (digested)[m]	19.2 (raw), 15.4 (digested)

[a] Calculated from 85.8% of pig slurry, 6% of glycerine and 8.2% of grass silage by mass.

[b] Data from a Danish biogas plant (Grøngas).

[c] Applied separation efficiency from Møller *et al*. (2007a), see Table 1.

[d] Murto *et al*. (2004).

[e] Azam (2007).

[f] Determined as fats.

[g] Determined as grass/plant from Ptasinski *et al*. (2007).

[h] Miles *et al*. (2004).

[i] Møller *et al*. (2007c); *calculated from digestion and post-digestion systems.

[j] Amon *et al*. (2006).

[k] Poulsen & Kuligowski (2007).

[l] Calculated from $C_3H_8O_3$.

[m] Assumed to be the same as pig manure.

Results and discussion

Impacts in terms of net energy production, energy recovery efficiency, nutrient recovery, and net GHG emissions from the 14 scenarios are shown in Figures 3–5.

Energy recovery

Generally, INC-based scenarios (S4 and S7) have the highest net energy production – 1019 MJ tonne^{-1} and 898 MJ tonne^{-1} of fresh manure, corresponding to 81% and 71% of the total energy content in the manure, respectively (Figure 3a,b). This includes both direct electricity and heat production and energy equivalents from substituted nutrients. INC utilizes all combustible matters for energy production and, therefore, in combination with an efficient drying method, generally yields a higher total energy output than for instance AD- or GAS-based scenarios. GAS-based scenarios (S5 and S8) have the second highest-energy production yielding 756 MJ tonne^{-1} of fresh waste corresponding to an average energy recovery

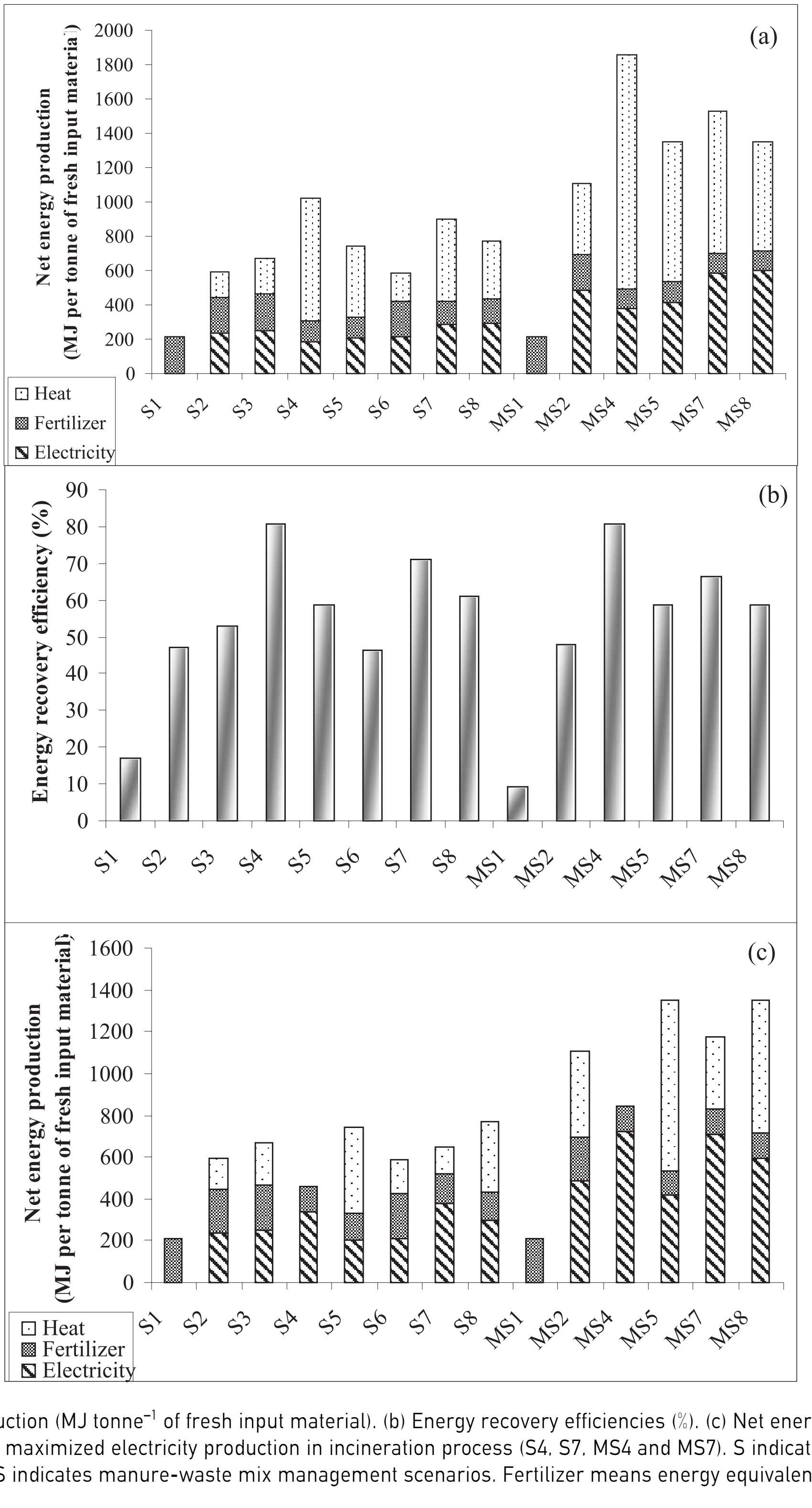

Fig. 3: (a) Net energy production (MJ tonne^{-1} of fresh input material). (b) Energy recovery efficiencies (%). (c) Net energy production (MJ tonne^{-1} of fresh input material) for maximized electricity production in incineration process (S4, S7, MS4 and MS7). S indicates sole pig manure management scenarios and MS indicates manure-waste mix management scenarios. Fertilizer means energy equivalents of the substituted fertilizer.

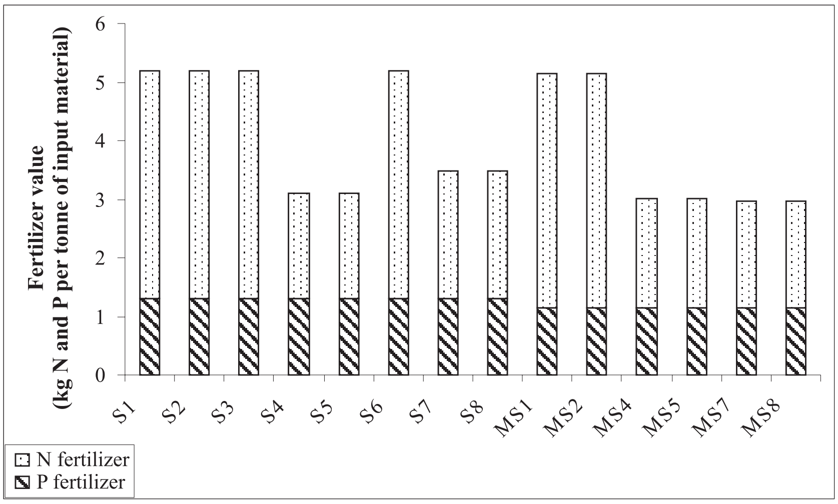

Fig. 4: Substituted fertilizer potential (kg N and P tonne^{-1} of fresh input material). S indicates sole pig manure management scenarios and MS indicates manure-waste mix management scenarios.

efficiency of 60% (Figure 3a,b). Since GAS uses part of the energy in the manure to drive the process, it yields less energy than INC. AD-based scenarios (S2, S3 and S6) recover energy equivalent to 616 MJ tonne^{-1} of fresh manure corresponding to an average energy recovery efficiency of 49% (Figure 3a,b) which is less than energy extraction from the combustion systems. This is due to the fact that AD is a biological process that is not capable of converting all organic matters into energy. If AD is combined with INC/GAS, SEP, and DRY (S7 and S8; Figure 3b), energy production can be increased by up to 24%. The lowest energy recovery system is achieved by the baseline scenario (S1) yielding 212 MJ tonne^{-1} of fresh waste corresponding to an energy recovery efficiency of 16.8% from substituted fertilizer (Figure 3a,b). The most promising energy recovery scenarios are, therefore, based on INC (S4 and S7) yielding 5.3 times more energy than the baseline scenario, S1.

Net energy production values from the mixed waste scenarios (MS1–MS8) are generally two times higher than the corresponding sole manure management scenarios (Figure 3a). However, the relative energy efficiency of corresponding scenarios is approximately the same (Figure 3b). The higher net energy production of mixed waste management is a result of the higher energy content in the added materials – glycerine and silage. This higher energy content in the mixed waste is the background for the higher net energy production; however, if there are no technologies applied (baseline scenarios, S1 and MS1), the energy content in both low- and high-energy waste will be lost in the field. Hence, the choice of technology systems is a key to efficiently use the energy contained in the waste.

Electricity production is often preferred over heat production because electricity can be transported over long distances and generates more income. If the aim is to maximize electricity production for the scenarios presented in Table 2, it is possible to optimize the INC process to achieve an electricity production rate of 45% by cooling all heat generated in the process away (Poulsen & Kuligowski 2007; Table 1). Energy recovery efficiencies for the 14 scenarios using the optimized INC process are shown in Figure 3c. It can be seen that, with optimization, the AD- and INC-based scenarios (S2, S3, S4, S6, S7, S8, MS2, MS4, MS7, and MS8) have similar efficiencies for energy production from electricity and substituted fertilizer while scenarios based solely on GAS (S5 and MS5) have somewhat lower electricity efficiencies. Furthermore, AD- and GAS-based scenarios have the advantage of producing gases that can be transported over longer distances before energy conversion which increase the energy utilization potential.

Nutrient recovery

All 14 scenarios yield very similar quantities of P regardless of treatment method (Figure 4). This is because none of the treatment processes considered loses P. Recovery of N is similar for scenarios that are not based on the INC or GAS processes (S1, S2, S3, S5, S6 and S8, MS1 and MS2). Nitrogen losses from these scenarios are fairly small and mainly associated with evaporation from storage facilities. Scenarios including the GAS or INC processes (S4, S5, S7, S8, MS4, MS5, MS7 and MS8) yield similar, but lower, N recovery due to partial conversion of nitrogen into N_2 and NO_x during the incineration and gasification processes. All N and P present in the treated manure is assumed to have the same fertilizer value as chemical fertilizer. However, in reality, it might be less available for plants due to different chemical composition and losses through emissions during land application processes (Søgaard *et al.* 2002, Møller *et al.* 2007b).

Greenhouse gas emissions

Total GHG emissions (direct emissions and substituted fossil CO_2) from all scenarios are shown in Figure 5. The values are in general proportional to net energy production (compare Figures 3a and 5). As a result, the highest GHG reduction values are achieved by INC-based scenarios, S4 and

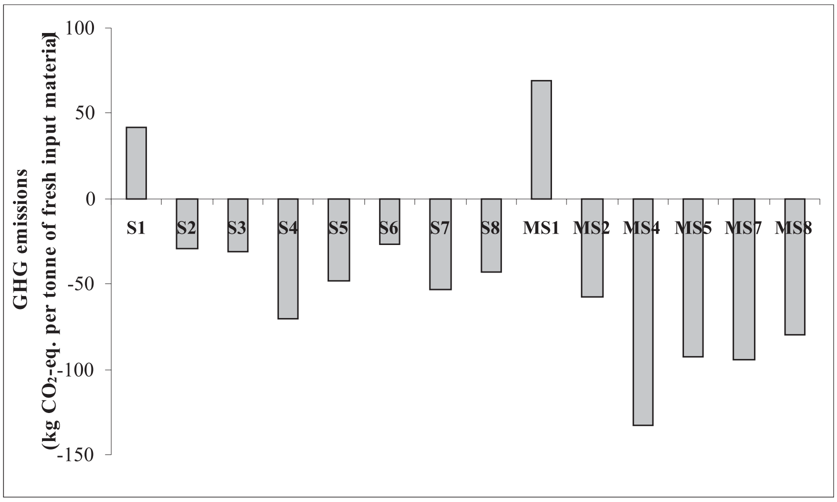

Fig. 5: GHG emissions (kg CO_2-eq. tonne^{-1} of fresh input material) of technology scenarios. S indicates sole pig manure management scenarios and MS indicates manure-waste mix management scenarios.

MS4 saving 70 kg CO_2-eq.tonne^{-1} and 133 kg CO_2-eq.tonne^{-1} of fresh input material, respectively (Figure 5). All scenarios with the exception of S1 and MS1 present reduction in CO_2 emissions. S1 and MS1 have GHG emissions of 42 kg CO_2-eq.tonne^{-1} and 69 kg CO_2-eq.tonne^{-1} of fresh waste, respectively. GHG emission savings from MS2–MS8 are generally higher than for the corresponding S-scenarios due to the higher energy content in the mix. On the other hand, emissions of GHG during storage are larger for the mix than for sole manure because of higher biological activity producing GHG. Hence, it confirms advantages from applying technology systems to the mixed waste. Furthermore, in the case that the energy production substitutes for energy produced from a coal-powered CHP plant which emits higher CO_2 equivalents than the reference system in this study, a natural-gas powered CHP plant, technology systems will be more beneficial due to higher CO_2 saving.

Parameter sensitivity

A sensitivity analysis was performed to evaluate the sensitivity of energy extraction efficiency and GHG emissions with respect to selected input parameters. Parameter sensitivity (S) is calculated using the approach of Poulsen & Hansen (2003) as:

$$S = \Delta O / \Delta P \tag{1}$$

where ΔO is the change in the output parameter, O, (energy extraction efficiency or GHG emission) induced by a change ΔP in the input parameter, P. As the difference between the S and the MS scenarios is the composition of the input materials, only the S scenarios are included in the sensitivity analysis. The input parameters resulting in the highest sensitivity values are presented in Table 4 together with the corresponding sensitivity values for the eight S-scenarios.

Table 4: The highest sensitivities of reduction of GHG emission (kg CO_2-eq. tonne^{-1} of fresh waste) and energy recovery efficiencies (%) with respect to input parameters.

No.	Input parameters	Sensitivities	S1	S2	S3	S4	S5	S6	S7	S8	Maximum
1	SE, DM (% in solid fraction)	$S_{\text{GHG reduction}}$	0	0	1.02	1.80	2.16	1.02	1.48	1.51	2.16
		S_{Energy}	0	0	0.36	1.03	1.05	0.27	0.92	0.85	1.05
2	DM (%)	$S_{\text{GHG reduction}}$	1.00	1.39	1.25	1.18	1.26	1.29	1.29	1.36	1.39
		S_{Energy}	0	0.24	0.15	0.16	0.21	0.17	0.22	0.26	0.26
3	VS (% of DM)	$S_{\text{GHG reduction}}$	1.26	1.02	0.90	0.12	0.17	0.88	0.03	0.12	1.26
		S_{Energy}	0	0.88	0.83	0	0	0.80	0.17	0.31	0.88
4	SE, mass (weight) (% in solid fraction)	$S_{\text{GHG reduction}}$	0	0	0.52	0.98	1.20	0.52	0.81	0.84	1.20
		S_{Energy}	0	0	0.01	0.14	0.20	0.01	0.12	0.14	0.20
5	Energy content, raw pig manure (GJ tonne^{-1} DM)	$S_{\text{GHG reduction}}$	0	0	0	1.11	1.15	0	0	0	1.15
		S_{Energy}	1.00	1.00	1.00	0.02	0.03	1.00	1.00	1.00	1.00
6	Thermal gasification Chemical energy output (%)	$S_{\text{GHG reduction}}$	0	0	0	0	1.01	0	0	0.51	1.01
		S_{Energy}	0	0	0	0	0.84	0	0	0.36	0.84

$S_{\text{GHG reduction}}$, sensitivity of reduction for GHG emission; S_{Energy}, sensitivity of energy recovery efficiency; S, pig manure management scenario; SE, separation efficiency.

The total GHG emission from each scenario is most sensitive to: (i) dry matter content in the solid fraction from the liquid/solid separation process; (ii) manure DM content; (iii) manure volatile solid content; and (iv) mass of solid fraction from liquid/solid separation process with maximum sensitivity values of 1.2 (Table 4). The reasons are that some of these parameters directly control the net amount of energy produced, thereby, resulting in controlled GHG balances for the scenarios and some of them influence direct GHG emissions (non-biogenic CO_2, CH_4 and N_2O). The separation efficiency for DM mainly controls the energy output from the INC and GAS processes whereas the DM in raw manure directly affects the amounts of energy that can be extracted by the INC, GAS and AD processes. Volatile solid content influences on CH_4 emission during storage and energy output from biogas production for AD process while mass of solid fraction from liquid/solid separation process affects direct GHG emissions from the untreated liquid part.

The energy recovery efficiency is most sensitive to: (i) the dry matter content in the solid fraction from the liquid-solid separation process; (ii) manure energy content; and (iii) the volatile solid content in manure. The sensitivities, however, are quite similar (Table 4). These results indicate that both energy extraction efficiency and GHG balances can be improved by increasing the manure dry matter content prior to energy extraction. This may be achieved by either designing the manure collection system in the pig stable such that faeces and urine are separated yielding a 'solid' manure fraction with up to 29.2% dry matter (based on Møller *et al.* 2004), or by improving the SEP process for instance by the use of filter press technology with chemical addition yielding up to 36% dry matter in the solid fraction (Pedersen 2005).

Conclusions

Fourteen different scenarios for treating animal manure with the aim of energy and nutrient recovery are developed and assessed with respect to their energy and greenhouse gas (GHG) balances. Based on the comparison of these scenarios, the highest energy extraction efficiency and the highest reduction in GHG emissions could be achieved by scenarios that include incineration of the manure dry matter fraction (up to 81% of total energy recovered). Scenarios based on either thermal gasification, anaerobic digestion or a combination of these yield somewhat lower total energy recovery and GHG emission savings than the incineration-based scenarios. In comparison with the no treatment scenario, manure treatment aimed at energy extraction can increase energy recovery and GHG emission saving by up to 64% and 112 kg CO_2–eq.tonne^{-1} of fresh manure, respectively. Combination of treatment processes such as incineration or thermal gasification with anaerobic digestion generally improve energy extraction efficiency compared to using each process separately.

In the case that maximum electricity production is desired, anaerobic digestion should be part of the applied treatments as this process has high electricity production efficiency. Electricity production from the incineration process can be maximized although this means that no additional heat can be produced. Combining this optimized incineration process with anaerobic digestion can convert 41% of the total energy contained in the manure into electricity. Both energy extraction efficiency and GHG balances are strongly dependent on the dry matter content in the raw input material (manure) and on the dry matter content that can be achieved in the solid fraction after liquid/solid separation of the manure. Energy extraction efficiency and GHG balances can be improved by increasing the manure dry matter content prior to energy extraction. This may be achieved by either designing in-stable manure collection systems such that faeces and urine are separated or by improving liquid/solid separation technology applied after manure collection. Alternatively, as can be seen from this study, addition of other high-energy materials such as glycerine and grass silage can also double energy recovery and reduction of GHG emissions if the scenarios apply the selected technologies. It is important to consider applying technology systems with manure mixed with available high-energy waste or processed manure with higher dry matter content. This is not only because it can improve plant economy due to higher energy yield but it can also assure effectiveness for energy extraction and greenhouse gas reduction strategy since if no technology included, like only storage system, almost all energy in terms of carbon content will be lost when applied to the field through degradation and more greenhouse gas will be emitted. For nutrient recovery, potentials for saved N and P fertilizer are not much different except less N recovered from scenarios based on incineration or gasification processes. In practice, the plant availability of nutrients in manure and processed manure might be less than in chemical fertilizer resulting in less energy equivalents saved. However, the sensitivity analysis shows an insignificant effect of nutrients on energy recovery efficiency and GHG reduction for scenarios that apply energy recovery technologies.

In summary, the results presented in this study show that, with proper management, animal manure can be converted into significant quantities of energy and potentially reduce GHG emissions. The results further indicate that energy extraction efficiency can be improved by introducing more efficient techniques to remove water from the manure. Due to the fact that this study includes some environmental impacts regarding to potentials for energy and nutrient recovery and greenhouse gas reduction and excludes some parts of manure management systems and economy consideration, further investigation (*e.g.* life-cycle assessment and economic analysis) is important for actual application with a holistic perspective.

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Paper 2B

Title:

Improved energy recovery efficiencies from piggery waste biogas plants in Thailand using Danish experiences.

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Improved Energy Recovery Efficiencies from Piggery Waste Biogas Plants in Thailand Using Danish Experiences

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Abstract: *In Thailand, pig slurry is one of the important alternative sources for renewable energy as can be seen from the increasing number of piggery waste biogas plants. This study compares performance of piggery waste biogas systems in Thailand and Denmark and thereby improved energy recovery efficiencies by utilizing knowledge and experience in both countries. Data for the Thai biogas plants and piggery wastes are from medium-size pig farms investigated by Energy Research and Development Institute and the Pollution Control Department. Data for the Danish plants are from 20 full-scale plants, one pilot plant and literature including a European data base. The results show that net biogas (methane) and total energy production per tonne of volatile solids (VS) of pig slurry from the Thai plants are 4 and 14 times lower than those from Danish system, respectively. It is concluded that the performance of Thai biogas plants can be improved through systematic and long-term studies on pilot and existing full-scale Thai systems and plants, including increased dry matter content of feed pig slurry, higher mesophilic retention times or change to thermophilic processing, and combined heat and power production. The specific goal of the improvement must be to increase actual biogas yield (per unit biomass and unit volume of reactor) as well as gas utilization and gas conversion efficiencies. Danish experiences can provide inspiration for such projects, including ways to utilize heat energy also in Thailand for heating and/or cooling purposes, at least for large-scale systems and plants.*

Keywords: Pig slurry, energy efficiency, biogas, methane yield, technology transfer

1. INTRODUCTION

Pig slurry has become one of the renewable energy sources in Thailand as can be seen from the increasing number of piggery waste biogas plants. In 2007, biogas plants operated under the biogas promotion program for medium and large scale livestock farms handled wastewater from 269 livestock farms with total estimated biogas production of 72 million m^3/year and electricity production of 0.3 PJ/year [1]. Most of the operated plants treat piggery waste due to the fact that this type of livestock waste is under regulation control with restricted standards, whereas other livestock wastes such as cow and poultry manure are not specifically regulated [2]. From existing Thai reports it can be seen that it is crucial to obtain higher gas yields and to utilize the energy to the extent possible through plant and system modifications. In order to improve the system in Thailand, benchmarking with other biogas systems with well-known high effectiveness is needed, e.g. Danish centralized biogas plants. The objective of this study is thus to compare performance of piggery waste biogas systems in Thailand and Denmark and thereby improve energy recovery efficiencies by utilizing knowledge and experience from both countries.

2. METHODOLOGY

2.1 Biogas plant performances

Data for the Thai biogas plants were collected mainly from 2 medium-size pig farms supplemented with estimated data from 44 farms investigated by Energy Research and Development Institute (ERDI). The range for a medium size pig farm is 60 – 600 Livestock Unit (LU; 1 LU = 500 kg pig, live weight) [3]. Data for the Danish piggery biogas plants were collected from 20 full-scale plants, one pilot plant and literature. The Danish centralized biogas plants use (where possible) co-digestion of different organic wastes with piggery waste to increase biogas yield per tonne of feed biomass in order to improve economy. Therefore, the biogas yield for existing Danish plants considered in this study was estimated per tonne volatile solids of pig slurry by expert assessment, supplemented with experimental studies on pig manure only. The selected biogas systems are widely applied in both countries. Internal energy consumptions of the anaerobic digestion systems (2% and 10% of total energy production from the Thai and Danish plants, respectively) are excluded because they do not significantly influence the main findings from this study.

2.2 Characteristics of piggery wastes

Characteristics of piggery waste for Thai pig farms were provided by the Pollution Control Department (PCD) and represent an average from values with wide fluctuation [4]. The Danish piggery waste characteristics are based on a European data base [5] and Danish plant data [6]; also here average values are used, but the range of fluctuation is relatively smaller.

3. DATA AND RESULTS

Key numbers and characteristics of the selected Thai and Danish plants are presented in Table 1 for comparative assessment, using m^3 CH_4/t VS (tonne volatile solids) as gas production unit and kWh/t VS as energy production unit. Characteristics of piggery waste for Thai and Danish conditions are presented in Table 2.

Table 1 System performances of the selected Thai and Danish piggery waste biogas plants

Process/Parameter	Thai plants	Danish plants
Anaerobic digestion system	CD and UASB	CSTR with post digestion system
Temperature [a]	Mesophilic condition	Thermophilic condition (55%) and Mesophilic condition (45%)
Hydraulic retention time	7 days in CD, 1 day in UASB [b]	10 – 16 days in CSTR, 10 days in post digester
Amount of input pig slurry/wastes (m^3/day)	20 – 570	40 – 550
Methane losses from biogas process and gas engine	5%	5%
Unused and burnt methane	15%	0%
Net methane production for pig slurry (m^3 CH_4/t VS) [c]	90 (80-90)	340 (340-400)
Electricity production (kWh/m^3 CH_4)	2.15	4
Electricity production (kWh/t VS)	200	1400
Heat production (kWh/m^3 CH_4)	0	4
Heat production (kWh/t VS)	0	1400

CD = channel digester, UASB = up-flow anaerobic sludge blanket,
CSTR = continuously stirred tank reactor, t VS = tonne of volatile solids
[a] Mesophilic condition = 30-40°C; thermophilic condition = 50-60°C, [b] Only the liquid fraction from CD will pass the UASB system, [c] The numbers represent the best estimation with a range in parenthesis which is done by comparison with specific methane yields from experimental data [7, 8].

Table 2 Characteristics of the piggery waste

Plants	DM (%)	VS (% of DM)
Thai plants (Medium-size pig farms)	3.3 [1]	76 [1]
Danish plants	4.04 [2]	76 [3]

DM = dry matter, VS = volatile solids, [1] [4], [2] [5], [3] [6]

Net biogas (methane) production/t VS from the Thai plants is 4 times lower than those from Danish system (see Table 1). Electricity production/t VS from the Thai systems is also significantly lower than that from the Danish plants (7 times, see Table 1). The Danish energy production will be 14 times higher than that in Thailand, if heat utilization is included.

4. DISCUSSION

4.1 Methane production

For the Thai plants, an explanation for the low methane yield/t VS may be that the assumed (PCD reporting) VS contents are higher than would be found by thorough sampling and analysis of actually treated slurry. The PCD report showed that DM and VS contents of piggery waste from medium size pig farms were 2 times than those from the large size pig farms [4]. Because the investigated farms are almost 600 LU (the maximum for medium size), the wastewater characteristics are possibly closer to large size farms. If characteristics of the piggery waste from the large-size pig farms are applied with the same methane production per tonne of slurry, net methane production will be approximately 180 m^3 CH_4/t VS.

According to the actual system configuration, it can be seen that hydraulic retention times (HRTs) for the mesophilic Thai plants are quite low. Burton and Turner [9] recommend mesophilic HRT for pig manure of 10 to 20 days. Furthermore, Sánchez et al. [10] suggest that the constant cumulative methane production, from mesophilic anaerobic digestion of piggery waste, occurs at HRT from 25 to 30 days. For the Danish plants, many studies showed that with thermophilic in stead of mesophilic anaerobic digestion you get higher gas yield per unit time and volume of reactor [11, 12]. For Thai plants it seems justified to reconsider both process and reactor design in order to improve energy efficiency, but still maintaining the goal of limited plant volumes and investment costs.

Leakages and flared gas may lower what is accounted as gas produced at the Thai plants. For the Danish plants and systems, the relatively high gas production may be attributed to long term system and technology developments, e.g. thermophilic processing, gas proof storage, tight control of DM content and composition of the slurry feed, and regular monitoring of process parameters such as pH, fatty acids and alkalinity. Some Danish plants control DM in each batch of biomass delivered to the biogas plant.

4.2 Energy production efficiency

In the Danish systems, efficiency in gas utilization for electricity production is strictly controlled and has increased over time at the same time as the technology has been improved. Combined heat and power (CHP) systems have also been promoted in the Danish systems to increase total energy recovery efficiency. In Denmark, the produced heat can often be sold to district heating systems or utilized in-plant to achieve thermophilic processing.

4.3 Recommendation for system improvements

Thai system improvement and optimization of the technology can possibly reduce the gap between the Danish 2800 kWh/t VS versus the Thai 200 kWh/t VS. To increase biogas yield/t VS, monitoring of feed waste characteristics and yield of biogas yield from existing plants should be implemented in order to understand input-output relations and systematically improve performance. Process and reactor design should be reconsidered with focus on retention times and temperature regimes (mesophilic/thermophilic) in order to increase gas yield per unit feed biomass and reactor volume. Dry matter content of feed piggery waste should be increased before entering the reactor, either by reduced water usage or dewatering. Water saving could be beneficial for the farmer economy and the environment. Co-digestion with high-energy organic wastes, which may be available nearby (e.g. rice husks/straw, tapioca waste, palm bunches) could be applied in order to increase biogas yield per unit feed biomass as has been done in Denmark. Applying CHP units could further increase total energy production. Produced heat can be used for thermal pre-treatment of pig manure, which can increase biogas yields and removal efficiencies of volatile solids [13]. Given advanced technology, heat produced could be used for cooling systems.

5. CONCLUSION

In conclusion, net methane, electricity and total energy production per unit feed of volatile solids from Thai plants are 4, 7 and 14 times lower than those from Danish plants. Possible explanations for the low Thai numbers are overestimated dry matter contents, too low retention times, and low engine efficiency for electricity production together with wasted heat. The Danish plants have been controlled and improved systematically over the last 20 years by regular monitoring of feed dry matter, energy production, and key processing parameters. The Thai systems could be improved in terms of increased methane yields both per unit feed of volatile solids by stricter monitoring of feed characteristics and biogas yield from the existing plants, increasing retention time, increasing dry matter contents of pig slurry, and adding other high-energy organic wastes. Furthermore, the Thai energy conversion efficiency could also be improved by applying combined heat and power production systems and alternatively using the produced heat for pre-treatment of slurry and/or cooling systems.

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Paper 2C

Title:

Energy and greenhouse gas balances for pig manure using alternative treatment options.

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Energy and Greenhouse Gas Balances for Pig Manure Using Alternative Treatment Options

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Executive summary

Animal manure originating from for instance pig and cattle production represents a source of both energy and nutrients and utilization of these resources can therefore help substitute fossil fuels and reduce greenhouse gas emissions. In many regions of the world large quantities of especially pig manure is produced making it one of the largest waste streams in these regions. Manure has traditionally been applied to farmland locally as fertilizer, but as feed imports and animal production has increased locally, manure production is now often matching or exceeding local farmland nutrient requirements. This means that if animal production is to continue increasing, alternative manure management strategies facilitating both utilization of energy and nutrients in the manure as well as export of nutrients are required.

In this paper a set of alternative scenarios for management of pig manure with the aim of energy and nutrient extraction is evaluated with respect to useful energy (heat and electricity) output, nutrient (N, P) extraction efficiency and impact on greenhouse gas emissions. The scenarios are selected so as to represent practically proven technologies and processes that are applied in current waste management, technologies. This means processes that are also applicable for treatment of animal manure. The scenarios include both biological and thermal manure treatment as well as combinations. Input data for the evaluation are taken from existing full scale waste and manure treatment facilities wherever possible, supplemented with pilot and lab scale measurements in cases were full scale data are not available. The results indicate that combinations of thermal and biological treatment and treatment based solely on thermal methods yield similar energy and greenhouse gas balances whereas treatment based only on biological methods yields significantly less energy output and reduction in greenhouse gas emissions.

Introduction

Animal manure from especially pig and cattle farms represents an important source of energy and nutrients (Reijnders and Huijbrects 2003; Wulf et al. 2005). As pig production has increased so has pig manure production and increased effort is therefore being put into development of improved methods for management and utilization of the nutrients and energy contained in the manure. The recent focus on global warming and increased demands for clean energy has made it even more relevant to investigate possibilities for utilizing the energy contained in pig manure.

At present only a very small amount of the manure produced in the farming industry is utilized for energy primarily through anaerobic digestion and biogas production in conventional biogas plants. Research, however, is currently under way to develop and improve other technologies for extracting energy and nutrients from animal manure.

One of the areas that have received most attention is anaerobic manure digestion with the aim of producing biogas that can be converted into heat and power. This technology has existed for several decades and is well documented (Yadvika et al. 2004).

The methane potential of pig manure can be improved by thermal pre-treatment of the manure by exposing it to high temperatures and pressures (Bonmati et al. 2001; Raju, 2005, Mladenovska et al. 2006;), however, as of present only relatively little is known about the relation between the pre-treatment temperature and methane potential.

Manure separation aiming to concentrate the nutrients in specific fractions, usually applied after anaerobic digestion, has also been investigated (Møller, 2002) although considerably less is known about this process in comparison with anaerobic digestion. The method generally separates the manure into a liquid fraction containing most of the nitrogen and a solid fraction with 15 – 30% dry matter containing most of the phosphorous. A variety of technical solutions have been developed for this process.

Two other methods for extracting the energy from manure are incineration and thermal gasification. Both these methods are well known, however, knowledge about their performance with respect to treatment of pig manure is very limited, although some preliminary studies have been carried out with respect to thermal gasification (Stoholm et al 2007).

The objective of this study is to evaluate energy and nutrient extraction potentials using different pig manure management strategies based on the technologies presented above. A set of practically applicable manure management scenarios are selected and their energy, nutrient and, greenhouse gas balances compared. A sensitivity analysis evaluating greenhouse gas balance sensitivity with respect to input parameters to the calculations is conducted to identify the most important input parameters.

Table 1. Unit processes considered in the seven manure management scenarios that are evaluated in this study

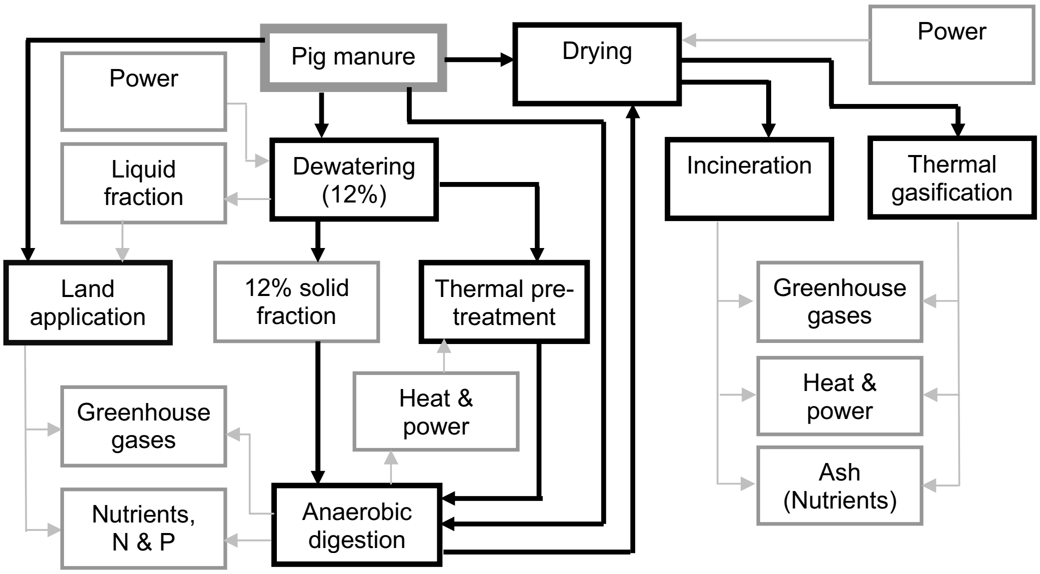
Scenario	Unit-processes in scenario
1	Dewatering to 12% dry matter – thermophilic anaerobic digestion – land application of digestate
2	Dewatering – thermal pre-treatment – digestion – land application of digestate
3	Dewatering – pre-treatment – digestion – drying – incineration – land application of ash and liquid fraction
4	Dewatering – pre-treatment – digestion – drying – thermal gasification – land application of ash and liquid fraction
5	Dewatering – drying – incineration – land application of ash and liquid fraction
6	Dewatering – drying – thermal gasification – land application of ash and liquid fraction
7	Direct land application

Scenarios and data used

Based on the technologies discussed earlier a set of seven scenarios for pig manure management deemed practically applicable are identified. An overview of the unit processes included in each scenario is presented in Table 1.

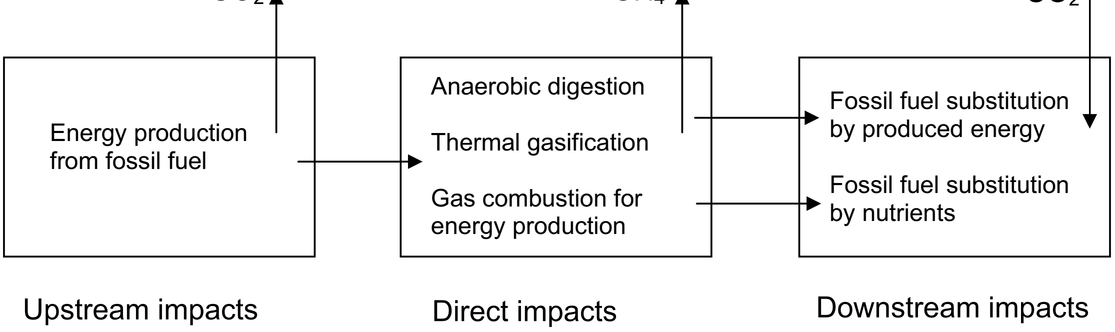
An overview of the system considered including mass and energy flows between the individual treatment processes as well as in and outputs from the system are is given in Fig. 1.

Figure 1. Schematic overview of 7 scenarios considered for manure management. Bold boxes indicate unit processes and bold arrows primary pathways of the scenarios. Boxes indicated with a thin line represent inputs and outputs to and from the individual processes.



The following assumptions were made in the calculations: The chemicals (polymers) used in the dewatering process represent only a very small contribution to the energy and greenhouse gas balances and are therefore neglected. Thermal pre-treatment of the pig manure does require energy (for heating) but as pre-treatment is used prior to anaerobic digestion energy for heating the manure to the digestion temperature is saved as the manure is hot when it comes out of the pre-treatment process. Therefore the energy consumption for pre-treatment and anaerobic digestion combined and anaerobic digestion without pre-treatment are considered the same. Manure drying is assumed to follow the same process as used in practice for drying of sewage sludge. This process actually consists of an initial dewatering to 35% dry matter followed by thermal evaporation of the water until the desired dry matter content. Nutrients (N, P) contained in the end products from the pig manure treatment are assumed to represent an amount of energy equal to that required for producing an equivalent quantity of artificial fertilizer.

Figure 2. Overview of contributions to the greenhouse gas balance considered in the evaluation of the seven scenarios for animal manure management.



It is also assumed that all nutrients present in the end products will be available for plant uptake. It is further assumed that all nitrogen contained in the solid manure fractions is lost during thermal treatment (incineration and thermal gasification) of these fractions. When estimating the impact on greenhouse gas balances, it is assumed that net energy produced replaces electricity and heat cogenerated from coal. In cases where electricity/heat ratios do not match that of cogeneration, excess electricity and heat are assumed generated from coal separately. Cogeneration efficiencies are assumed equal to those for a modern waste incineration plant. Transport usually has very little impact on energy and greenhouse gas balances (Poulsen and Hansen 2002) and is therefore neglected here. Input data for the unit processes used in each of the seven scenarios are listed in Table 2.

Table 2. Data used to evaluate the energy output from the seven pig manure management scenarios presented in Table 1.

Parameter	Unit	Value
Raw manure dry matter content	%	4
Raw manure upper fuel value	GJ/ton d.m.	15.2
Manure VS content	% of d.m.	76
Manure methane potential	Nm^3/ton VS	239
N content in manure	kg/ton wet weight	4.2
P content in manure	kg/ton wet weight	0.8
Biogas plant energy consumption (power and heat)	% total energy production	10
Dry matter reduction during digestion	% of input	30
Thermal pre-treatment CH_4 potential improvement	% of normal potential	50
CH_4 emission biogas process	% of CH_4 produced	2
CH_4 emission gas engine	% of CH_4 produced	3
Energy content biogas	MJ/kg CH_4	46.1
Electricity production rate for gas engine-generator	% of input energy	40
Heat production rate for gas engine	% of input energy	40
Dewatering, power consumption	MJ/ton input mass	7.2
N in liquid fraction	% of total content	70
P in liquid fraction	% of total content	10
Manure drying heat consumption (28-95 % d.m.)	MJ/ton water	3442
Manure drying power consumption	MJ/ton input mass	314
Manure drying relative heat recovery	%	75
Incineration efficiency at incineration plant	% of input	99
Electricity production rate at incineration plant	% of input	25
Heat production rate at incineration plant	% of input	71
Energy consumption at incineration plant	% of production	10
Thermal gasification syngas energy output	% of input energy	83
Thermal gasification heat energy output	% of input energy	10
Thermal gasification plant electricity consumption	% of production	10
N energy equivalent (electricity)	MJ/kg	42.4
P energy equivalent (oil)	MJ/kg	15.8
Coal energy equivalent	MJ/kg	24
Power production efficiency from coal	%	45
Heat production efficiency from coal	%	90
Coal CO_2 emission	kg/kg	3.8
Methane CO_2 equivalent	kg/kg	20

* d.m.= dry matter

Greenhouse gas balances are developed considering both emissions associated with production of the materials and energy consumed by the pig manure management system (upstream impacts), direct greenhouse gas emissions from the system itself (direct impacts), and avoided greenhouse gas emissions due to the materials and energy produced by the manure management system (downstream impacts). The impacts considered are associated with CO_2 emission or substitution associated with energy consumption or production and CH_4 emissions from digestion, thermal gasification and combustion of the produced gases. An overview of the greenhouse gas balance impacts considered is given in Fig. 2.

Input data for each of the seven scenarios listed in Table 1 were first collected by Poulsen and Hansen (2003) from relevant pilot and full scale treatment facilities treating manure, sewage sludge or solid waste in Denmark. In this study several of the data were updated as treatment facilities have been optimized or new technology have been developed and installed. The data therefore represent modern full-scale facilities or pilot scale research facilities and the data may be taken as the state of the art of the technology. Data for characterizing the dewatering and drying processes were taken from a full scale sewage sludge treatment facility, data for anaerobic digestion are averages based on approximately 20 Danish full-scale biogas plants, incineration process data comes from a full-scale municipal waste incinerator and data for thermal gasification, from a pilot scale experimental plant for treating manure. The data for thermal manure pre-treatment are based on both a full-scale test facility and on laboratory experiments (Raju, 2005). An overview of the data used is given in Table 2.

Results

Figure 3 shows the relative energy output in terms of heat (for district heating) and electricity as well as energy represented by nutrients (N, P) and unused or lost energy from each of the seven scenarios using the data presented in Table 2. Using traditional anaerobic digestion (scenario 1) it is only possible to capture about 25% of the energy as electricity and heat and an equal amount is represented by the nutrients in the manure. Pre-treating the manure (scenario 2) increases electricity and heat output to about 30% of the total energy content incl. nutrients. If anaerobic digestion is combined with either incineration or thermal gasification of the excess manure fibre fraction coming out of the digestion process (scenarios 3 and 4), electricity and heat output increases to between 40 and 45% with nutrients representing an additional 20%. Nutrient output from scenarios using thermal treatment (scenarios 3 – 6) are slightly lower as part of the nitrogen is lost during thermal treatment. The results also show that scenarios based on a combination of biological and thermal treatment (3 and 4) yield total energy outputs that are similar to treatment based solely on thermal methods (scenarios 5 and 6) with the incineration based scenarios (3 and 5) having slightly higher total energy outputs.

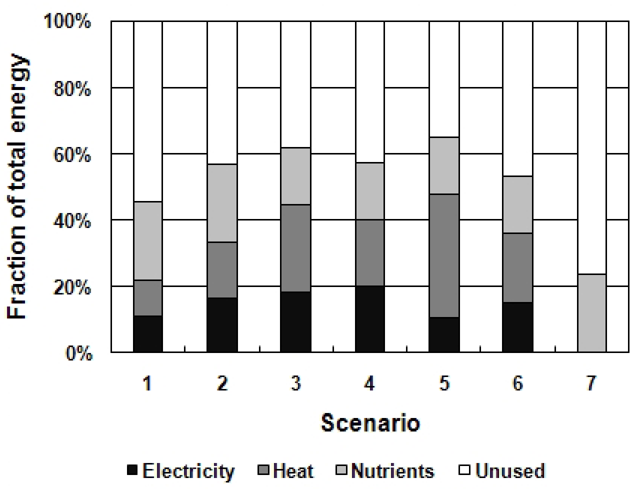


Figure 3. Relative output of energy in terms of electricity, heat and nutrients as well as unused energy for the seven manure management scenarios in presented in Table 1.

Treatment based solely on biological treatment is only competitive if thermal pre-treatment of the manure prior to digestion is used (scenario 2). The highest quantities of electricity (high value energy) are produced by scenarios based on combined biological and thermal treatment (scenarios 3 and 4). This is because the electricity production efficiency of the gas engine used in these scenarios is higher than the efficiency of converting heat to electricity via a steam turbine-generator system. Direct field application of the manure (scenario 7) only yield the energy represented by the nutrients in the manure.

Generally the results indicate that in order to maximize the total energy output, anaerobic digestion is not required, but thermal treatment (incineration or thermal gasification) alone can achieve just as good results. In order to achieve a high electricity to heat production ratio, however, anaerobic digestion is necessary. It is also noted that the use of anaerobic digestion improves the dewatering properties of the digested slurry and if digestion is omitted, dewatering and drying may consume more energy than assumed here.

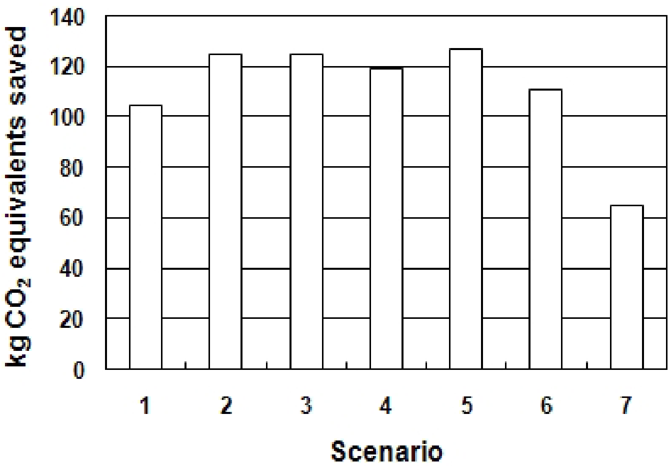


Figure 4. Net reductions in greenhouse gas emissions per ton of raw manure treated for each of the seven manure management scenarios listed in Table 1.

Figure 4 shows the net reductions in greenhouse gas emissions per ton of raw manure treated by each of the seven scenarios considered. Contributors to CO_2 savings are the net energy produced and the energy represented by the nutrients. Main contributors to CO_2 emissions are the methane emitted by the anaerobic digestion process and the thermal gasification processes. Scenarios 2 – 5 yield approximately the same CO_2 savings (120 – 130 kg CO_2 per ton of raw manure treated) while scenario 6 yields slightly smaller savings (about 110 kg CO_2 per ton raw manure treated). Direct field application of manure (scenario 7) yield only about half of the CO_2 savings achieved by scenarios 2 – 5. Based on the greenhouse gas balances, scenarios based on combinations of biological treatment (with thermal pre-treatment) and thermal treatment (scenarios 3 – 5) appear to be good choices. If treatment is based solely on biological treatment, thermal pre-treatment should be used while incineration should be used in cases where treatment is based solely on thermal treatment. Judging from both energy and greenhouse gas balances scenarios 3 and 5 appear to be the best choices. It is noted, however that the differences between scenarios in many cases are relatively small and changes in the input data therefore may change the relative succession of the scenarios with respect to both energy and CO_2 balances.

A sensitivity analysis was performed to evaluate the impact of changes in the input data in Table 2 on the greenhouse gas balance for each scenario. The sensitivity of the greenhouse gas balance S_{CO2} with respect to a given input parameter P was defined as:

$$S_{CO2} = \Delta O/\Delta P \qquad (1)$$

Where O is the output parameter (mass of CO_2 saved), ΔO is the absolute change in the output caused by an introduced change, ΔP, in the input parameter P. Table 3 lists the input parameters that results in the highest sensitivity for the greenhouse gas balance.

Table 3. Input parameters with the largest impact on the resulting greenhouse gas balance for the seven scenarios. Sensitivity values are averages over those of the seven scenarios for which the input parameter is used.

Parameter	Unit	S_{CO2}
Coal CO_2 emission	kg/kg	1.1
Coal energy equivalent	MJ/kg	1.0
Thermal gasification syngas energy output	% of input energy	0.6
Manure drying relative heat recovery	%	0.5
Power production efficiency from coal	%	0.5
Raw manure upper fuel value	GJ/ton d.m.	0.4
Manure methane potential	Nm^3/ton VS	0.3
Energy content biogas	MJ/kg CH_4	0.3
Electricity production rate for gas engine-generator	% of input energy	0.3
Heat production rate for gas engine	% of input energy	0.3
N in liquid fraction	% of total	0.3

Although the CO_2 emission and the energy output associated with coal combustion both result in a large sensitivity of the greenhouse gas balance, values for these two parameters are well established and accurate values can be found in the literature if the type of coal used is known. Greenhouse gas balances show intermediate sensitivity with respect to the energy output from thermal gasification, electricity production efficiency from coal, energy recovery during drying and the fuel value of the manure. Again the values for these input parameters are fairly well known but they do vary with the technology used. It is therefore essential to use the values that represent the technology considered. Manure methane potential, energy content of biogas, power and heat production rates for gas engine and the fraction of N present in the liquid phase after separation are parameters that have somewhat less influence on the greenhouse gas balances. For these parameters it is therefore less imperative that values corresponding exactly to the considered technology are used, although most of these values are fairly well known and documented in the literature.

Conclusions

Seven scenarios for treating animal manure with the aim of energy production and nutrient utilization were evaluated with respect to their potential energy and greenhouse gas balances. The evaluation was conducted using data from existing full- or pilot scale treatment facilities utilizing technologies such as liquid-solid separation, thermal pre-treatment, anaerobic digestion, drying, incineration or thermal gasification of the manure. Manure treatment based on either thermal treatment methods (incineration or thermal gasification) or on combinations of thermal pre-treatment, anaerobic digestion and incineration or thermal gasification yielded the highest energy outputs and CO_2 savings. These scenarios were able to utilize 55 – 65% of the energy (including energy represented by nutrients) in the pig manure and had savings of 110 – 130 kg CO_2 per ton of raw pig manure. If treatment is based only on biological methods (anaerobic digestion) thermal pre-treatment is necessary to yield similar energy utilization rates and CO_2 savings. Applying the manure directly to farmland as fertilizer without any further treatment as done for most of the manure globally yields only about half the energy utilization (only energy represented by the nutrients is utilized) and CO_2 savings as the previously described scenarios. If focus is to maximize energy output and CO_2 savings without any concern for the type of energy produced (heat or electricity) anaerobic digestion need not to be part of the treatment but thermal treatment methods such as incineration or thermal gasification seem to be sufficient. If however, the amount of electricity produced is

also of concern, treatment should include anaerobic digestion as the electricity production rate from a gas engine (used to convert biogas to energy) is higher than from a steam turbine-generator system (used to extract energy from the hot flue gases produced by incineration).
A sensitivity analysis indicated that it is important to choose values representing energy output from thermal gasification, electricity production efficiency from coal, energy recovery during manure drying, and manure fuel value, that corresponds to the technology considered in the calculations as these parameters have a relatively strong influence on the results while being relatively technology dependent.

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Paper 2D

Title:

Energy and greenhouse gas balances for organic household waste using alternative treatment options.

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Energy and Greenhouse Gas Balances for Organic Household Waste Using Alternative Treatment Options

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Executive summary

Global household waste production is increasing in response to improving standards of living and changes in consumption patterns. Household waste is traditionally disposed of either by landfilling or by incineration and the increasing waste production has therefore resulted in increasing landfill or incinerator capacity requirements. Biodegradable (food) waste constitutes a relatively large fraction (up to 50% by weight) of the household waste. Removal of the food waste prior to final disposal will improve energy recovery during incineration or reduce methane production and emission in connection with landfilling. The food waste could instead be treated by anaerobic digestion together with sewage sludge in digesters already present at many wastewater treatment plants. The waste can be supplied to the wastewater treatment plants for instance via the use of kitchen garbage disposal units and transport via the sewer system or by separate collection and transport by truck.

This paper evaluates a set of different scenarios for managing the biodegradable household waste with respect to their energy and nutrient recovery efficiency and their contribution to the global greenhouse gas balance. The scenarios are based on presently applied waste treatment technologies including anaerobic digestion, drying, incineration and thermal gasification. Input data for the evaluation are taken from existing full scale waste and sludge treatment facilities wherever possible, supplemented with pilot and lab scale measurements in cases were full scale data are not available.

Introduction

Waste generation is usually very closely related to the standard of living in a given area and as living standards have increased globally so has waste production. Although recycling and reuse is increasingly being applied, landfilling is still the principal waste disposal strategy in many regions and demands for increased landfill capacity and difficulties in locating suitable landfill space have increased. One waste type that is especially difficult to manage in an environmentally optimal way is household waste due to its very complex composition. Household waste typically contains 25 – 50% food waste by weight (Garcia et al. 2005; Burnley, 2006) and this fraction therefore represent a significant part of the waste mass that must be collected and transported for further treatment and disposal. A large fraction of the economic expenses associated with collection and transport is therefore associated with the food waste fraction. Disposal of food waste in landfills further result in emission of methane produced during anaerobic microbial degradation of the food waste. When incinerated, food waste lowers the fuel value of household waste due to its very low and sometimes negative fuel value. Thus, there are several reasons why food waste should be separated from the general waste stream and treated separately.

Several attempts have been aimed at separate collection of the food waste for energy and nutrient production based on the use of special containers and transport systems based on trucks, but these have in general not been very successful. The main reasons being that separation of the waste requires too much effort from the citizens resulting in poor quality of the separated material and the collection is too expensive compared to the benefits achieved from the separation. The use of kitchen grinders can solve most of the problems associated with poor separation and also reduce costs for transport as the waste will be transported via the sewer system. At the wastewater treatment plant the waste can then be separated from the water and digested anaerobically together with sewage sludge in digesters already present at many wastewater treatment plants for energy production.

Due to its high degradability, food waste is well suited for anaerobic digestion with the aim of generating biogas which can be converted into energy. Although experience with digestion based solely on food waste is limited, co-digestion with other types of biodegradable wastes such as for instance sewage sludge or animal manure have been used widely and is well documented (Yadvika et al. 2004; Wulf et al. 2005; Akunna et al. 2007).

Liquid-solid separation aiming to reduce the water content of the digested material and concentrate nutrients and dry matter in specific fractions has also been investigated (Møller, 2002, Wakeman, 2007; Subramanian et al. 2007). The method generally separates the digestate into a liquid fraction containing most of the nitrogen and a solid fraction with 15 – 30% dry matter containing most of the phosphorous. A variety of technical solutions have been developed for this process.

Two other methods for extracting the energy from biomass are incineration and thermal gasification. Both these methods are well known and treatment of household waste including food waste by incineration has been a major waste treatment method in several regions globally for a long period. While incineration can treat food waste mixed with other types of waste without any further pre-treatment, thermal gasification typically requires the waste to be homogenized and dried before it can be treated (Stoholm et al 2007). Both methods, however, are well suited for treating digested and dried organic materials as these materials are very homogeneous.

The objective of this study is to evaluate energy and nutrient extraction potentials using different strategies for managing food waste from household kitchens based on the technologies presented above. A specific objective is to assess the impacts of using kitchen garbage disposal units (kitchen grinders) compared to more traditional source separation systems based on truck transport. A set of practically applicable waste management scenarios are selected and their energy, nutrient and, greenhouse gas balances compared. A sensitivity analysis evaluating greenhouse gas balance sensitivity with respect to input parameters to the calculations is conducted to identify the most important input parameters.

Table 1. Unit processes considered in six food waste management scenarios evaluated in this study

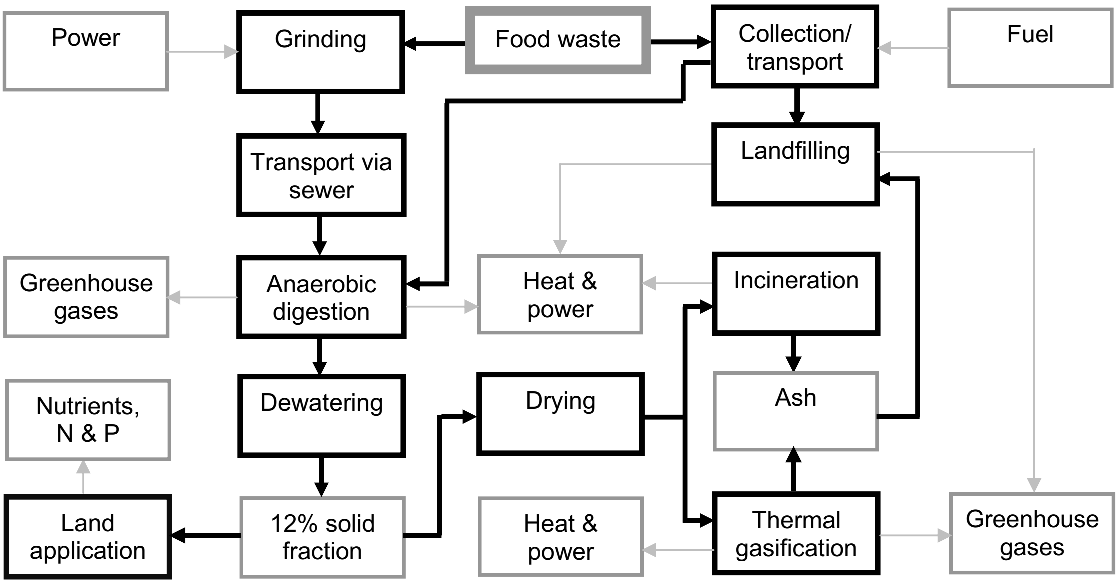
Scenario	Unit-processes in scenario
1	Collection – truck transport – landfilling
2	Collection – incineration – truck transport – landfilling of ash
3	Grinding – transport by sewer – digestion – dewatering – drying – incineration – truck transport – landfilling of ash
4	Grinding – transport by sewer – digestion – dewatering – truck transport – land application
5	Collection – truck transport – digestion – dewatering – drying – incineration – landfilling of ash
6	Collection – truck transport – digestion – dewatering – drying – thermal gasification – landfilling of ash

Scenarios and data used

Based on the technologies discussed earlier a set of six scenarios for food waste management deemed practically applicable are identified. An overview of the unit processes included in each scenario is presented in Table 1.

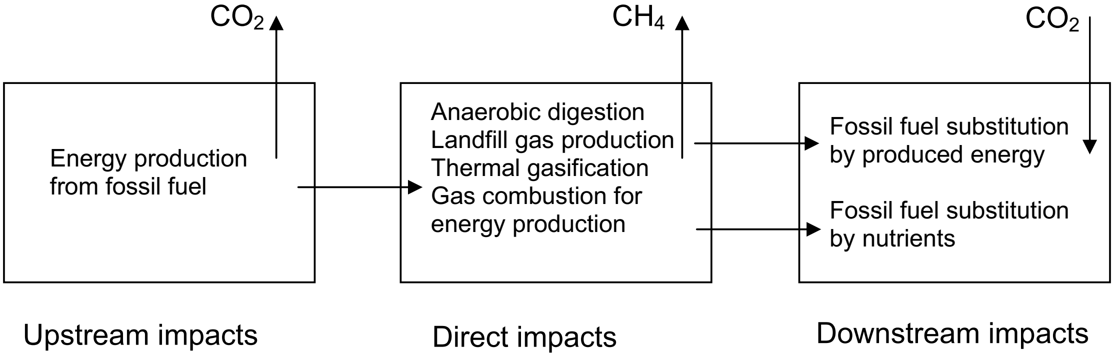
An overview of the waste treatment system considered including all unit processes, mass and energy flows between the individual treatment processes as well as material and energy in and outputs from the system are is given in Fig. 1.

Figure 1. Schematic overview of six scenarios considered for food waste management. Bold boxes indicate unit processes and bold arrows primary pathways of the scenarios. Boxes indicated with a thin line represent inputs and outputs to and from the individual processes.



The following assumptions were made in the calculations: The chemicals (polymers) used in the dewatering process represent only a very small contribution to the energy and greenhouse gas balances and are therefore neglected. The liquid fraction produced during dewatering of the digested material goes back to the wastewater treatment plant where it is treated and discharged together with the wastewater. In some practical applications the drying process actually consists of an initial dewatering to 35% dry matter followed by thermal evaporation of the water until the desired dry matter content. This is also assumed here. Nutrients (N, P) contained in the dewatered digestate applied to land are assumed to represent an amount of energy equal to that required for producing an equivalent quantity of artificial fertilizer. Finally it is assumed that the quantity of methane generated in the landfill during degradation of the waste is the same as in an anaerobic digester. It is further assumed that 50 % of this production can be extracted from the landfill and converted into heat and electricity in a gas engine while 10% will escape to the atmosphere and the remaining 40% will be oxidized to CO_2 and water before reaching the atmosphere.

Figure 2. Overview of contributions to the greenhouse gas balance considered in the evaluation of the six scenarios for food waste management.



It is also assumed that all nutrients applied to land are available for plant uptake. When estimating the impact on greenhouse gas balances, it is assumed that net energy produced replaces electricity and heat cogenerated from coal. In cases where electricity/heat ratios do not match that of cogeneration, excess electricity and heat are assumed generated from coal separately. Cogeneration efficiencies are assumed equal to those for a modern waste incineration plant.

Greenhouse gas balances are developed considering both emissions associated with production of the materials and energy consumed by the waste management system (upstream impacts), direct greenhouse gas emissions from the system itself (direct impacts), and avoided greenhouse gas emissions due to the materials and energy produced by the system (downstream impacts). The impacts considered are associated with CO_2 emission or substitution associated with energy consumption or production and CH_4 emissions from digestion, thermal gasification and combustion of the produced gases. An overview of the greenhouse gas balance impacts considered is given in Fig. 2.

Input data for each of the six scenarios listed in Table 1 were first collected by Poulsen and Hansen (2003) from relevant pilot and full scale treatment facilities treating manure, sewage sludge or solid waste in Denmark. In this study several of the data were updated as treatment facilities have been optimized or new technology have been developed and installed. The data therefore represent modern full-scale facilities or pilot scale research facilities and the data may be taken as the state of the art of the technology. Data for characterizing the dewatering and drying processes were taken from a full scale sewage sludge treatment facility, data for anaerobic digestion are averages based on approximately 20 Danish full-scale biogas plants, incineration process data comes from a full-scale municipal waste incinerator and data for thermal gasification, from a pilot scale experimental plant for treating manure.

Table 2. Data used to evaluate the energy output from the six food waste management scenarios presented in Table 1.

Parameter	Unit	Value
Raw food waste dry matter content	%	35
Raw food waste upper fuel value	GJ/ton d.m.	18
Food waste VS content	% of d. m.	85
Practical waste methane potential	Nm^3/ton VS	279
N content in digested waste	kg/ton d. m.	48
P content in digested waste	kg/ton d. m.	33
Biogas plant energy consumption (power and heat)	% of production	10
Dry matter reduction during digestion	% of input	40
CH_4 emission biogas process	$\%CH_4$	2
CH_4 emission gas engine	$\%CH_4$	3
Energy content biogas	MJ/kg CH_4	46.1
Electricity production rate for gas engine-generator	% of input energy	40
Heat production rate for gas engine	% of input energy	40
Dewatering, power consumption	MJ/ton input mass	7.2
Landfill methane extraction efficiency	% of total production	50
Landfill methane emission fraction	% of total production	10
Drying, heat consumption (28-95 % d.m.)	MJ/ton water	3442
Drying, power consumption	MJ/ton input mass	314
Drying, relative heat recovery	%	75
Incineration efficiency at incineration plant	% of input fuel value	99
Electricity production rate at incineration plant	% of input fuel value	25
Heat production rate at incineration plant	% of input fuel value	71
Energy consumption at incineration plant	% of energy produced	10
Thermal gasification syngas energy output	% of input energy	83
Thermal gasification heat energy output	% of input energy	10
Thermal gasification plant electricity consumption	% of production	10
Thermal gasification fuel conversion efficiency	% of input fuel value	95
Kitchen grinder power consumption	MJ/ton waste	19.71
Transport distance	Km	10
Transport fuel consumption	MJ/ton km	0.9
N energy equivalent (electricity)	MJ/kg	42.4
P energy equivalent (oil)	MJ/kg	15.8
Coal energy equivalent	MJ/kg	24
Power production efficiency from coal	%	45
Heat production efficiency from coal	%	90
Coal CO_2 emission	kg/kg	3.8
Methane CO_2 equivalent	kg/kg	20

* d.m.= dry matter

Results

Figure 3 shows the relative energy output in terms of heat (for district heating) and electricity as well as energy represented by nutrients (N, P) and unused or lost energy from each of the six scenarios using the data presented in Table 2. Landfilling of the food waste combined with

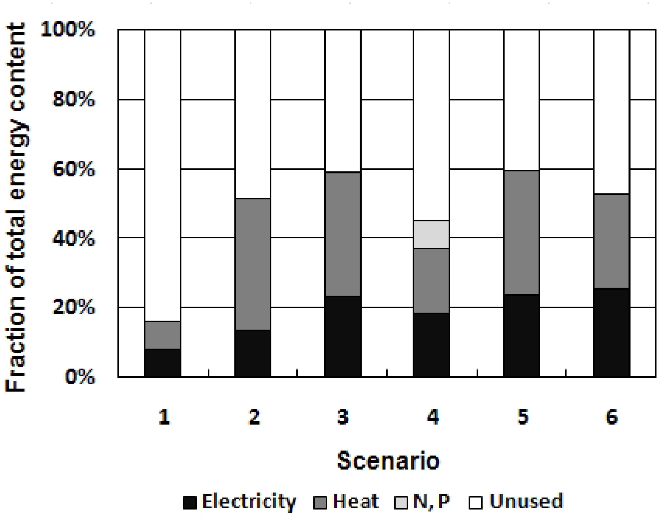


Figure 3. Relative output of energy in terms of electricity, heat and nutrients as well as unused energy for the six scenarios in presented in Table 1.

extraction and utilization of the methane produced during degradation of the waste after deposition at the landfill (scenario 1) is able to capture only less than 20% of the energy in the form of electricity and heat while any nutrients are lost. Scenarios based on thermal treatment (incineration or thermal gasification) either in combination with anaerobic digestion (scenarios 3, 5 and 6) or as sole treatment (scenario 2) yield relative energy utilization rates of 55 – 65% although they also lose any nutrients contained in the waste. Treatment based solely on anaerobic digestion (scenario 4) yields only about 45% of the potential energy output, however the nutrients are saved and can be utilized. In general the results show that the impact of nutrient utilization is small. The results also show that if thermal treatment is used it does not matter whether anaerobic digestion is also included in the treatment or not if focus is only on the total energy utilization in terms of heat, electricity and nutrients. If however, the aim is to maximize the output of electricity which is a high quality energy type compared to heat, it is clearly an advantage to include anaerobic digestion as part of the treatment as this will double the output of electricity (compare scenario 2 with scenarios 3, 5 and 6 in Fig. 3). As electricity generally has a higher economic value than heat, economy points in the direction of including anaerobic digestion especially if a digester is already available in the region, which will be the case in several European countries. The results further show that, seen from an energy perspective, it does not matter whether the waste is transported via the sewer system (using kitchen grinders) or by traditional collection and truck transport to the anaerobic digester. As kitchen grinders are significantly cheaper to install and operate than a source separation and collection system based on truck transport and that the waste likely contains much less foreign objects when grinded rather than source separated, the use of kitchen grinders seems to be advantageous. However a thorough evaluation of the economic and waste quality issues should be carried out locally before deciding which technology to use as both economy and the waste handling behaviour of citizens vary with region. Also the capacity of the sewer system for accepting and transporting increased quantities of particulate matter should be evaluated before deciding what technology to promote.

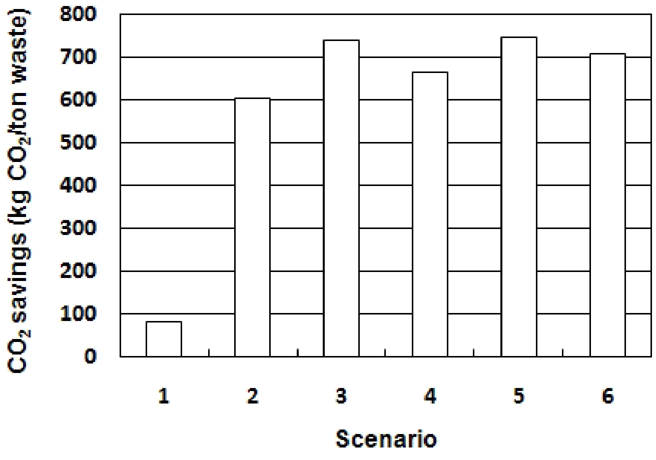


Figure 4. Net reductions in greenhouse gas emissions per ton of food waste treated for each of the six scenarios listed in Table 1.

Figure 4 shows the net reductions in greenhouse gas emissions per ton of food waste treated by each of the six scenarios considered. The main contributions to CO_2 savings comes from the net energy produced. Main contributors to CO_2 emissions are the methane emitted by the anaerobic digestion process and the thermal gasification processes. Scenarios 3 and 5 yield approximately the same CO_2 savings (about 750 kg CO_2 per ton of food waste treated) while scenario 4 and 6 yields slightly smaller savings (about 650 and 700 kg CO_2 per ton waste treated, respectively). Landfilling of the waste (scenario 1) yields the lowest CO_2 savings, primarily due to the large quantity of methane emitted to the atmosphere and the relatively low methane-to-energy utilization rate. Scenario 2 using only incineration for energy extraction achieve intermediate an CO_2 saving primarily due to the loss of nutrients.

Based on the greenhouse gas balances, scenarios based on combinations of biological treatment and thermal treatment (scenarios 3, 5 and 6) yield the best CO_2 balances with scenario 3 and 5 being the best. Again CO_2 balances do not depend on whether kitchen grinders (scenario 3) or truck transport (scenario 5) is used. Overall the results in Figs 3 and 4 indicate that anaerobic digestion combined with incineration of the remaining dry matter is the optimal choice for treatment.

A sensitivity analysis was performed to evaluate the impact of changes in the input data in Table 2 on the greenhouse gas balance for each scenario. The sensitivity of the greenhouse gas balance S_{CO2} with respect to a given input parameter P was defined as:

$$S_{CO2} = \Delta O/\Delta P \qquad (1)$$

Where O is the output parameter (mass of CO_2 saved), ΔO is the absolute change in the output caused by an introduced change, ΔP, in the input parameter P. Table 3 lists the input parameters that results in the highest sensitivity for the greenhouse gas balance.

Table 3. Input parameters with the largest impact on the resulting greenhouse gas balance for the six scenarios. Sensitivity values are averages over those of the six scenarios for which the input parameter is used.

Parameter	Unit	S_{CO2}
Landfill methane extraction efficiency	% of methane produced	3.3
Relative methane emission from landfill	% of methane produced	1.6
CO_2 emission from coal combustion	kg CO_2/kg coal	1.4
Coal energy content	MJ/kg coal	1.3
Waste energy content	GJ/ton d.m.	1.3
Waste dry matter content	%	1.2
Power production rate for gas engine generator	% input energy in gas	0.9
Energy content biogas	MJ/kg CH_4	0.9
Heat generation rate from coal	%	0.7
Power generation rate from coal	%	0.6

Methane extraction efficiency and methane emission from landfill are the two most sensitive input parameters. These parameters are also very uncertain to determine and the results for scenario 1 are therefore somewhat uncertain. Given, however, the very large difference in both energy and CO_2 balances for this scenario compared to the other scenarios it is very likely that the conclusions drawn from Figs. 3 and 4 are correct even if the input parameters may not be exact. Also the above two parameters only affects the outputs of scenario 1 and will therefore not affect the results for the other scenarios. Although the CO_2 emission and the energy output associated with coal combustion result in relatively large sensitivities, the values for these parameters are well established and can be found in the literature if the type of coal and energy conversion technology used is known. Greenhouse gas balances show intermediate sensitivity with respect to the energy content and dry matter content of the food waste and the electricity output from the gas engine. Even though waste dry matter and energy contents can vary, a relatively large amount of data is available and it is therefore relatively easy to establish reliable values. Also the electricity output from the gas engine is generally well known both by manufacturers and by biogas plants using the engines. These parameters therefore should have relatively little impact on the uncertainty in the results shown in Figs 3 and 4.

Conclusions

Six scenarios for treating kitchen food waste with the aim of energy production were evaluated with respect to their potential energy and greenhouse gas balances. The evaluation was conducted using data from existing full- or pilot scale treatment facilities utilizing technologies such as kitchen grinders, liquid-solid separation, anaerobic digestion, drying, incineration or thermal gasification of the waste. Overall energy production was highest for scenarios involving thermal treatment (incineration or thermal gasification) as sole energy extraction technology or in combination with anaerobic digestion. These scenarios were able to extract 55 – 65% of the total energy contained in the waste. For maximum electricity production anaerobic digestion should be included. In general scenarios based on thermal treatment in combination with anaerobic digestion were able to extract approximately 25% of the total energy contained in the waste as electricity. Landfilling of the waste even with extraction and utilization of methane produced in the landfill had the lowest energy extraction efficiency. Scenarios based on combinations of anaerobic digestion and thermal treatment also had the best CO_2 balances and were able to substitute CO_2 emissions corresponding to 700 – 750 kg of CO_2 per ton of waste treated. Scenarios based on either anaerobic digestion or thermal treatment had intermediate CO_2 savings and landfilling had the smallest CO_2 savings primarily due to its poor energy extraction efficiency combined with a relatively high methane emission rate. Neither energy, nor CO_2 balances depended on whether kitchen grinders/sewer system transport or traditional source separation/collection and truck transport were used for transporting the waste to the anaerobic digester. This means that selection of one transport technology over the other will depend on the practical implications combined with economic expenses.

A sensitivity analysis indicated that it is important to choose values representing methane extraction efficiency and methane losses to the atmosphere at the landfill carefully as the estimates of energy and CO_2 balances for scenarios involving landfilling and landfill gas (methane) utilization are very dependent on these parameters. As these parameters are quite difficult to assess accurately this will likely require extra effort. Other parameters that are important to assess accurately, although being less sensitive, are waste dry matter and energy content as well as the electricity generation efficiency of the gas engine.

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Paper 3A

Title:

LCA of comprehensive pig manure management incorporating integrated technology systems.

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LCA of comprehensive pig manure management incorporating integrated technology systems

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Abstract

Increased and intensified pig production has raised the needs for proper pig manure management systems in order to reduce negative environmental impacts. The objectives of this study were to identify the most significant environmental impacts from pig manure management considering a wide range of impact categories and to determine which integrated technology system at which handling stage can achieve the highest impact reduction. Twelve scenarios applying various treatment, storage and land application systems were developed and compared. Life cycle assessment (LCA) with the aim of capturing the actual consequences of the considered scenarios was selected as the tool for impact quantification. The most important impact categories in this investigation are global warming (GWP), aquatic eutrophication (AEP), respiratory inorganics (RIP), and terrestrial eutrophication (TEP). The two latter impacts, caused by ammonia emissions, have not been widely considered in most of previous LCA studies on pig manure management. The main keys for the effective impact reduction are the integration of treatment technology systems aiming at energy recovery with high nutrient recovery and control of greenhouse gas, ammonia, and nitrate emissions at every handling stage. For GWP and AEP, the anaerobic digestion-based scenario with natural crust storage achieves the highest impact reduction because of high efficiencies in energy and nutrient recovery with restricted emissions of GHG and nitrate. For RIP and TEP, the incineration and thermal gasification based scenarios and the scenario without a treatment system applying the deep injection method yield the highest impact minimisation due to the lowest ammonia emissions. This study further indicates the need to consider all significant impacts to decide the best management options taking into consideration local conditions.

Keywords: Pig manure; Integrated technology systems; Anaerobic digestion; Combustion; Spreading techniques

1. Introduction

Livestock production has increased and intensified as a result of higher food demand, due to the rapidly increasing world population, with limited farming land [1,2]. Pig meat is one of the most important livestock products, which represented 37% of the global meat production in 2007 [3]. In 2007, global pig manure generation was estimated to be approximately 125 million tonnes of dry matter [4]. With the large generated amount and farming intensification, improper manure management has contributed to significant environmental problems. According to Lopez-Riduara et al. [5] and Sandars et al. [6], the main environmental impact concerns are global warming from greenhouse gas (GHG) emissions, aquatic eutrophication and acidification from ammonia emissions.

However, recently studies have indicated that ammonia emissions can potentially contribute to other types of impacts, which have not been included before [7,8]. This includes respiratory effects on human from inorganic substances (respiratory inorganics) and terrestrial eutrophication – both potentially caused by ammonia emission from pig manure [7,8]. Ammonia is a well-known precursor of particulate matter formulation and can form secondary particulate matters such as ammonium sulphate or ammonium nitrate - contributing to respiratory effects [7]. In the case of eutrophication, terrestrial eutrophication refers to impacts on native vegetation, forests and agricultural crops. Since nitrogen (N) is often a limiting nutrient, an additional N deposit (through ammonia and N-related emissions) on soils or vegetation can affect the terrestrial ecosystems. Increased N deposits may favour some species over others and hence may influence the biodiversity [9,10]. The evidence of these impacts confirms the need to include the additional impacts in environmental assessments of piggery waste management.

To reduce the environmental impacts, many technologies have been developed and applied to decrease the emissions of greenhouse gases and ammonia, and to recover energy and nutrients. Different treatment technologies (e.g. anaerobic digestion) applied to pig manure management can reduce and save greenhouse gas emissions from reduced methane (CH_4) emissions and displaced electricity and heat production [4,8]. Different manure storage systems are able to reduce ammonia emissions (e.g. 2% to 70% of nitrogen (N) content from pig manure [11,12]). Furthermore, spreading technologies at the land application stage have contributed to the reduction of ammonia emissions. For example, injection systems may reduce ammonia emissions by more than 70% compared with a broadcast spreading system [12]. Nonetheless, the reduction of ammonia emissions can induce N emissions in other forms, such as N_2O or nitrate (NO_3^-), especially in the case of high unavailable N contents remaining in the pig manure and the subsequent N surplus in the soil after spreading the manure on the land.

Despite the existing research into technological improvements, the focus has been relatively narrow and only encompassed one or a few handling stages such as treatment and land application stages [5,13]. Also some studies did not consider manure treatment at all, or considered only a single unit process (e.g. either composting or anaerobic digestion) [14,15]. Although whole farm perspective assessments have been performed, the results have often disregarded the specific details on mass and energy flows of pig manure management systems [8]. Hence, there is a need for a detailed assessment of overall environmental impacts from pig manure management incorporating available technologies applied at different handling stages in order to reduce the environmental burdens.

1.1 Purposes of the study

In order to reduce the environmental impacts effectively, the objective of this study is primarily to identify the most significant environmental impacts arising from pig manure management taking into consideration of a wide span of different impact categories. Subsequently, the aim is to determine which technology system at which handling stage can significantly minimise the impacts. With respect to facilitating future improvements, it is important to be site specific and this study is based on a case in Denmark. Specifically, Danish conditions for electricity and heat systems, treatment, storage and spreading technologies are considered. To take the wide range of environmental impacts into consideration, life cycle assessment (LCA) is applied as a tool for the impact quantification.

1.2 Functional unit

The functional unit applied in this assessment is the treatment and disposal of 1 tonne of raw pig manure (wet weight). This investigation considers pig manure management from cradle to grave. The cradle is defined as when manure leaves the pig barns. The grave is defined as when pig manure residuals are transformed into emissions.

2. Methods

The general framework for LCA is described in the ISO 14040 and 14044 standards which are basically followed in this study [16,17].

2.1 Consequential system delimitation

Consequential modelling, applied in this study, is characterised by including the affected suppliers (sometime referred to as marginal suppliers) and by avoiding co-product allocation by system expansion [18-20]. Consequential modelling strives towards including relevant suppliers, e.g. the actual affected (or marginal) suppliers on markets, instead of the average suppliers on these markets. In the case of modelling the effects of manure treatment, the choice of consequential modelling also has the effect that for all the by-products of the pig manure system, the product substitutions are taken into account. The by-products of the pig manure system are: electricity, heat, and N and P fertiliser. In the following the marginal suppliers of some important products in Denmark are given. Marginal suppliers for electricity production are identified as long-term yearly average marginal technologies with a combination of energy sources from coal, natural gas and wind with the ratio of 51%, 43% and 6%, respectively [21]. The data of marginal electricity production relating to efficiencies of coal- and natural gas-based plants are described in [22]. For wind power plants, the data in the Ecoinvent database are applied. Marginal heat is composed of a weighted average of several different local supplies made up of small individual oil-fired boilers and a district heating system based on small combined heat and electricity plants as well as large central power plants based on gas, coal and wood (based on [22]). According to a report on the heat plan in Denmark [23], the average marginal heat suppliers are determined for the period 2010 to 2020 as 40% of coal-based combined heat and power (CHP) plants, 29% of natural gas-based CHP plants, 12% of biomass-based CHP plants, 15% of biomass-fired boilers and 4% of natural gas-fired boilers. Due to data limitation, the energy efficiency of the different heat plants is based on a coal-fired CHP plant in Denmark [22]. Marginal supplies of artificial fertilisers (nitrogen and phosphorus) are identified as modern technologies for ammonia nitrate and triple super phosphate [22].

2.2 Method for life cycle impact assessment (LCIA)

LCIA is performed using the STEPWISE2006 method [24,25]. Stepwise is chosen because it is based on several recent LCIA methods: EDIP2003 [26] and IMPACT2002+ [27]. In addition the Stepwise method includes a new consistent weighting method based on the budget constraint approach [24]. The STEPWISE2006 method includes both midpoint and end-point (damage) impacts and provides a monetarisation approach for impact assessment. The method considers 17 impact categories. The present article identifies the most significant impact categories by using three different weighting methods (STEPWISE2006 excluding biogenic CO_2, EDIP2003, and IMPACT2002+ including biogenic CH_4; see the compared impact equivalents in [28]). Based on this, the significant impact categories are selected and assessed at the midpoint level. The presented LCIA does not include all the impact categories because of constraints on the length of the article.

2.3 Pig manure management system and scope definition

The included life cycle stages are treatment, storage, transportation and land application as presented in Figure 1.

Figure 1

The modelled changes consider the treatment, storage and land application stages (Figure 1). Since the handling stages prior to the treatment stage, such as housing, are not affected by the considered changes, they are excluded from this assessment. The considered technologies at different handling stages are listed in Table 1. The reference systems at different stages are chosen, with respect to wide application in many countries and named the TRE1, STO1 and LA1 systems (Table 1).

Table1

At the treatment stage, the four systems (TRE1 to 4) are selected from the most promising and traditional integrated treatment scenarios according to [4], where the systems are described in detail. At the storage stage, the chosen reference system (STO1; anaerobic lagoon without a concrete floor) is commonly applied in many countries in Europe, the United States and Canada. The alternative system (STO2; storage tank with a natural crust) has also been extensively used in Denmark [12,29]. For STO2, when the slurry is stored in a tank without mechanical agitation, the crust of organic fibres can be formed naturally if the dry matter content of the slurry is high enough [30]. At the transport stage, the considered distance has two ranges: short (4.5 km) and long (10 km) (assumptions based on [31]) to represent the practical condition in

Denmark which has environmental restrictions on land application. In the systems without solid/liquid separation (incorporated in TRE1 and 2, see Table 1), all the liquids are transported long distance. In the systems including solid/liquid separation units (incorporated in TRE3 and 4, see Table 1), the liquids are transported short distance and the solids incorporated with the long distance transport. At the land application stage, there are five spreading techniques considered. The broadcast spreading system (LA1), where manure is spread to the soil surface through a splash plate, is widely used for manure application [32]. Other chosen systems (LA2 to 5) are the methods that have been used for the reduction of ammonia emissions [12]. The band spreading system (LA2) applies manure close to the soil surface in narrow bands via a number of hoses [33]. Rapid incorporation (LA3) is the method that incorporates the manure into the topsoil (e.g. via cultivators with rigid tines, spring tines, disc, etc.) after surface spreading within 6 hours [12,34]. Additionally, injection methods that inject manure under the ground via open slots up to 50 mm deep (shallow injection, LA4) and via closed slots more than 150 mm (deep injection, LA5) are considered [33].

2.4 Considered scenarios

Twelve scenarios are considered and illustrated in Figure 2. A reference scenario (S1) is established, which applies the chosen reference systems explained formerly for treatment, storage and land application (TRE1, STO1 and LA1; Table 1). To assess changes at the treatment stage, four scenarios (S1, S7, S9, and S11) applying TRE 1 to 4 with the anaerobic lagoon and broadcast spreading systems (STO1 and LA1, respectively) were chosen. For changes at the storage stage, eight scenarios (S1 and S6 to S12) were selected by applying the two storage systems (STO1 and STO2) to the four treatment systems (TRE 1 to 4) with the broadcast spreading system (LA1). Finally, changes at the land application stage are considered in five scenarios (S1 to S5) with no treatment and the anaerobic lagoon system applying five spreading systems (LA1 to LA5).

Figure 2

2.5 Data inventory and assumptions

The data of pig manure composition are selected from a European database and Danish full-scale biogas plants (Table 2). The emission factors and net energy recovery at the treatment, storage and land application stages are presented in Table 3. The selection is primarily based on a Danish context. In the case that the relevant data of the chosen systems in such context are not available, the European context or international scientific publications are considered. The data, specifically, in terms of N, P, and C contents, are inventoried with a mass balance approach in which all inputs and outputs are balanced.

For N flows, the total N content in manure is categorised into the emissions of NH_3, N_2O, NO_3^-, N_2 and the N uptake by harvested plants. For NO_3^- emissions at the land application stage, the values are varied with the same ranges among different application techniques (see Table 3). Furthermore, the data for the NO_3^- emission is very limited and the applied approach has considered only a farm-gate balance without indicating specific sources such as organic or artificial fertilisers [35]. It is thus assumed that the NO_3^- emissions at the land application stage from pig manure and artificial fertiliser are the same and excluded from the calculations. For the N uptake by the plants, it is assumed that the N content left in processed manure is 100% equivalent to the content in artificial fertiliser (based on experimental results in [36,37]). Only uncertainties of NH_3 emissions are presented and included in the sensitivity analysis to determine the robustness of selected storage and land application systems since this parameter highly influences the results.

For P balance, the total P input in pig manure is balanced to the available and unavailable P outputs for cultivated plant uptake compared with artificial fertiliser. Based on [38], the P content in pig manure is 100% equivalent to mineral fertiliser except pig manure encompassing incineration (INC) and thermal gasification (GAS) processes. P availability for INC and GAS is determined as 20% of the content of artificial fertiliser (based on [39,40]).

For C balance, the main emission considered is only CH_4 because CO_2 is determined as biogenic and excluded from the calculations. Although the C content in organic fertiliser can be sequestered and determined as carbon saving in the long term, C sequestration for pig manure is insignificant possibly due to its easy degradability [41,42].

Other inventories for energy and material consumptions and transport are based on the existing database in SimaPro, such as Ecoinvent data v2.0 [43]. All the inputs in terms of materials and energy are considered except capital goods for separation and thermal pre-treatment processes due to a lack of information.

Table 2

Table 3

3. Impact assessment results and interpretation

3.1 Impact identification

In order to identify significant impact categories, the baseline scenario (S1) is assessed with three LCIA methods (STEPWISE 2006, IMPACT2002+ including biogenic methane, and EDIP2003). The comparison is based on the percentage of single scores for each impact. On average, the most significant impact categories for the methods are global warming, respiratory inorganics and terrestrial eutrophication. In fact, aquatic eutrophication using the EDIP2003 method represents a large percentage of the single score but the sum of the positive value from the N emissions (88%) and the negative value from the avoided P emissions (-80%) results in low contribution in Fig. 3. Furthermore, the IMPACT2002+ method excludes aquatic eutrophication in the calculation of the single score and cannot be used to identify the significance of this impact category. Hence, in the later assessment, the results will be presented in the four most important categories - global warming, respiratory inorganics, terrestrial eutrophication and aquatic eutrophication.

Figure 3

3.2 Changes at the treatment stage

The characterised results of the changes at the treatment stage (S1, 7, 9, and 11) are presented in Figure 4.

For global warming potentials (GWP), the anaerobic digestion-based scenario (S7) performs the highest reduction of greenhouse gas emissions compared with the reference scenario/S1 (147 kg CO_2-eq.; Figure 4a). The main contributor to the saved CO_2 is avoided energy and heat production followed by fertiliser substitutions. Although, the incineration- and gasification-based scenarios (S9 and 11) have higher substituted energy production than the anaerobic system (S7), the methane emission during the storage stage from the liquid manure part separated prior to the combustion results in the lower CO_2 savings. However, S9 and 11 are still able to save up to 119 kg CO_2 eq. per ton of raw pig manure compared with S1 (Figure 4a). The impact results for GWP show that both efficient energy recovery systems with controls of GHG emissions at every handling stage are crucial for effective GHG reduction strategies.

For respiratory inorganics potentials (RIP), the incineration-based scenario (S9) has the lowest impact (0.043 kg $PM_{2.5}$-eq.; Figure 4b). From the detailed inventory analysis, the most significant contributor to this impact is ammonia emissions followed by nitrogen oxides (NO_x) emissions. Since ammonia can potentially form a secondary particulate matter such as ammonium nitrate and ammonium sulphate [58], it is the important parameter to control if the aim is to reduce RIP. S9 and S11 emit less ammonia than S1 and S7 because most of the N content is burnt during the combustion process. Although NO_x and sulphur dioxide (SO_2) emissions during the combustion process contribute to RIP, the effect on the impact is less significant compared with the ammonia emissions. However, the RIP from the anaerobic digestion-based scenario (S7) is higher than the value from the reference scenario (S1). This is because S7 and S1 have the same ammonia emission rates but there is an NO_x emission from the biogas combustion process for S7 (see Table 3). All in all, to reduce RIP from the pig manure management, the main key is to control ammonia emission at different handling stages.

For terrestrial eutrophication potentials (TEP), S9 and S11 have the lowest impacts (64 m^2 UES; Figure 4c) whereas S1 and S7 have more or less the same higher results (140 m^2 UES, approximately; Figure 4c). From the detailed inventory analysis, the main contributor to this impact is ammonia emission. The reduction of this impact coincides with RIP due to the fact that ammonia emissions are the main influencing factor. Hence, the results from this part further elaborate on the needs to reduce ammonia emission.

For aquatic eutrophication potentials (AEP), S9 and S11 have the lowest impacts (0.6 kg NO_3^--eq.; Figure 4d) whereas S1 and S7 have the same higher results (0.9 kg NO_3^-eq.; Figure 4d). The main contributors to this impact are nitrate and phosphate emissions followed by ammonia emission. High nitrate loss during storage in the anaerobic lagoon (20%, see Table 3) results in the higher values of AEP for S1 and S7 than the values for S9 and S11 where less N content is left in the processed manure. However, the impacts are reduced by the avoided phosphate emission during the fertiliser production. In the case that the nitrate emission is eliminated, the reduced AEP from the avoided P fertiliser will be noticeable.

Influential handling stages: In order to determine which stage most influences the environmental impacts, impact assessment results for S1, S7, S9 and S11 are separated into the four handling stages (Table 4).

For GWP, the most important stage for the scenarios with energy recovery is the treatment due to avoided heat and electricity production, whereas, for the no treatment scenario (S1), it is the storage due to methane emissions. Nevertheless, for anaerobic digestion-based scenario (S7), the land application stage is also important for GWP reduction due to the avoided N and P fertiliser. For RIP and TEP, the most significant stage is the land application followed by the storage due to the high amount of ammonia emissions during both stages for all scenarios. For AEP, the most significant stages are the storage and land application stages due to nitrate and avoided phosphate emissions, respectively. In addition, at the transport stage, the different transport distances do not significantly affect the considered impacts.

Table 4

3.3 Changes at the storage stage

The LCIA results of the eight integrated scenarios at the storage stage (S1 and S6 to S12) are shown in Figure 4. When comparing scenarios applying the same treatment systems; for instance, S1 compared with S6, the scenarios using the storage tank with a natural crust (S6, S8, S10, and S12) can reduce GWP up to 94 kg CO_2 eq. (Figure 4a). Pig slurry stored in anaerobic lagoons (STO1, Table1) is typically a significant source of methane, ammonia and nitrate losses resulting in less capacity for nutrient recovery through land application as can be seen from the emission factors in Table 3. The natural crust covering the storage tank (STO2, Table 1) can reduce the emissions significantly (57% for CH_4, 66% for NH_3, and 100% for NO_3^-; Table 3). Petersen et al. [30] presented the direct evidence of methane oxidation in slurry storage with surface crusts resulting in lower methane emissions. The methane oxidation could occur in a porous surface crust with an access to O_2 from the atmosphere. Negatively, from STO2, N_2O can emit due to nitrification and denitrification activities from the coverage [29]. However, the N_2O emission is insignificant when considering the positive environmental impacts from lower methane emissions resulting in the GWP reduction of the natural crust storage scenarios. For RIP and TEP, they can be slightly decreased by an average of 12% when applying the same treatment systems (Figures 4b and c). The impact reduction is derived from less ammonia volatilisation due to the crust coverage [12]. The relatively low efficiency for the reduction of RIP and TEP from different storage systems is due to the kept N content in pig manure at the storage stage resulting in the higher ammonia emission at the land application stage. Furthermore, when manure is stored in a tank (STO2) or lagoon lined with a concrete floor, it can eliminate the nitrate emissions to soil and water at the storage stage [52]. Therefore, the scenarios without nitrate emissions and with lower ammonia emissions (S6, S8, S10 and S12) result in avoided AEP from the substituted P fertiliser (-0.3 to -1.0 kg NO_3^--eq.; Figure 4d). It can be seen that S10 and S12 can reduce AEP less than S6 and S8 due to the lower P availability in the combusted manure [39,40].

3.4 Changes at the land application stage

The midpoint results of the five integrated scenarios at the land application stage (S1 to S5) are shown in Figure 4. The scenarios with chosen alternative spreading systems (S2 to S4) can significantly reduce RIP and TEP from the reference scenario (S1) due to lower ammonia emissions (Figure 4b and c) whereas GWP and AEP of the scenarios are similar (Figure 4a and 4d). S5 applying deep injection system can most reduce RIP and TEP from S1 using broadcast spreading with an average of 67%. The spreading techniques can limit ammonia volatilisation through a reduced contact area between the manure and the ambient air, and a larger surface area for infiltration of the manure into the soil [34]. The reduction of ammonia emissions can also occur as a result of other climate conditions near the soil surface such as lower wind speeds and temperature [59]. The deep injection scenario (S5) can reduce more contact area between the manure and the ambient air than the other methods because the manure is completely covered by the soil [12,34]. Furthermore, the infiltration of the manure can considerably reduce the influence from climate conditions. For AEP, the impact can be slightly decreased from the less ammonia emission because the most significant contributor to this impact is not the ammonia emissions but the nitrate and phosphate emissions. For GWP, all the LA systems result in similar impact values but the scenarios with the injection methods (S4, and S5) have slightly higher GWP from higher N_2O emissions than the other methods. The N_2O emission can occur as a result of the denitrification process due to the higher available N content in the soil [12]. Nonetheless, in general, the GWP values are more or less the same among the different methods.

3.5 Comparative changes at the treatment, storage and land application stages

The twelve scenarios representing all the considered changes are compared with the reference scenario (S1) with respect to each significant impact category (Figure 4). For GWP, the anaerobic digestion-based scenarios (S7 and S8) yield the highest reduction values (144 to 147 kg CO_2-eq; Figure 4a) due to the high efficiencies of both energy and nutrient recovery with restricted GHG emissions. For RIP and TEP, the scenarios using the incineration and thermal gasification systems (S10 and S12) achieve the highest reduction values (RIP: 0.04 kg $PM_{2.5}$-eq, TEP: 60 m^2 UES, approximately; Figure 4b and 4c) due to the restricted ammonia emissions with less N content left in the pig manure. However, the scenario without a treatment system applying the deep injection method (S5) also yields the similar lowest RIP and TEP (Figure 4b and 4c). For AEP, the scenarios with no treatment and anaerobic digestion systems applying the natural crust cover storage (S6 and S8) have the highest impact saving (1.9 kg NO_3^--eq.; Figure 4d) because of limited nitrate loss and high P fertiliser substitution.

The findings imply that the main key for impact reduction is the effective treatment systems aiming at energy recovery with high available nutrients (N and P), and the control of ammonia, nitrate and GHG emissions at every handling stage.

Figure 4

3.6 Sensitivity analysis

In order to determine how robust the results are, the major influencing parameters are selected and described below.

Uncertainties of ammonia emissions at the storage and land application stages: Due to the fact that the emission factors of different storage and spreading systems considerably depend on many factors such as weather conditions, soil conditions and manure characteristics, the uncertainties of ammonia emissions - the main influencing factor for RIP and TEP – are included in the life cycle impact assessment and presented as ranges of intervals in Figures 4 and 5 (see uncertainty ranges of the emission factors in Table 3). The uncertainties of land application systems are included in S1 to S12 in Figure 4 whereas those of the storage systems are included in S1 and S6 toS12 in Figure 5. The effect of the uncertainties both of land application and storage systems on GWP and AEP is insignificant (Figures 4a, 4d, 5a and 5d). For RIP and TEP, the uncertainties of land application systems show large intervals of values but do not generally influence the results except the changes at the storage stage (Figure 4b and 4c). The uncertainty ranges indicate that the two storage systems are not different. Furthermore, with respect to the uncertainties of the storage systems, the RIP and TEP with the uncertainty ranges present the similarity between the two storage systems when comparing the same treatment scenarios (e.g. S1 versus S6, and S7 versus S8; Figure 5b and c). However, the similarity in RIP and TEP can be explained by the slightly less amount of ammonia emissions in the lower interval of the uncertainties of the storage systems because of the other loss of nitrogen content (nitrate) for the anaerobic lagoon system resulting in the higher AEP. Therefore, it implies the need to consider all the significant impacts to identify the best management options.

Dry matter content: Prapaspongsa et al. [4] showed that the DM content in pig manure highly influenced on the environmental outcomes (net energy recovery and CO_2 savings). The DM content of 8.3% measured at a Danish farm [4] is thus selected to identify the sensitivity from high DM controlling. The nutrient content is calculated proportionally to the DM content. In Figure 8, the sensitivity scenarios of the high DM content (S1A, S7A, S9A, and S11A) and the treatment scenarios in this study (S1, S7, S9, and S11) are compared. It shows that the higher the DM content in the pig manure is, the higher RIP, TEP and AEP occur, when comparing the same treatment scenarios (e.g. S1 and S1A; Figure 8b, c and d). The higher N content in pig manure induces higher ammonia and nitrate emissions resulting in the increased RIP, TEP and AEP. However, GWP can be saved increasingly for the higher DM scenarios with energy recovery (S7A, S9A, and S11A; Figure 7a) because of the increased net energy production. In the case that the emissions of GHG, ammonia and nitrate are well controlled by using a proper storage and spreading systems such as the natural crust covering and deep injection, the benefits from increased DM content will be obvious.

Although the sensitivity factors affect the degrees of the impacts, they do not change the main keys for impact reduction, which are the effective energy recovery systems (anaerobic digestion, incineration and thermal gasification) and the control of GHG, ammonia and nitrate emissions at every handling stage.

Figure 5

4. Conclusion

This LCA study presents and compares twelve integrated technological changes at the treatment, storage and land application stages, and also considers new significant impact categories in pig manure management. On the basis of the life cycle impact assessment (LCIA) results, it appears that the most important impact categories arising from pig manure management are global warming (GWP), aquatic eutrophication (AEP), respiratory inorganics (RIP, respiratory effects on human health from inorganic substances), and terrestrial eutrophication (TEP). The latter two are caused by ammonia emissions and have generally not been considered in LCA studies on pig manure management before. The importance of RIP and TEP suggest that there is a need for ammonia emission controls to reduce the overall environmental burdens from the piggery waste. The main keys for the effective impact minimisation from pig manure management are 1) integration of treatment technology systems aiming at energy recovery in combination with high nutrient recovery for GWP saving and 2) control of greenhouse gas, ammonia, and nitrate emission at every handling stage for GWP, REP, TEP and AEP reduction. For GWP, the anaerobic digestion-based scenarios achieves the highest reduction values from the reference scenario (144 to 147 kg CO_2-eq. per tonne of raw pig manure) because of the high efficiencies in energy and nutrient recovery with restricted GHG emissions. For AEP, the anaerobic digestion- and no treatment-based scenarios with natural crust storage have the highest impact reduction (1.9 kg NO_3^--eq. per tonne of raw pig manure) due to the high nutrient recovery and limited nitrate and ammonia emissions. With respect to the least ammonia emissions, for RIP and TEP, the incineration- and thermal gasification-based scenarios and the scenario without a treatment system applying the deep injection method yield the highest reduction values (RIP: 0.07 to 0.08 kg $PM_{2.5}$-eq, and TEP: 80 to 86 m^2 UES per tonne of raw pig manure). To assess the robustness of the findings, sensitivity analyses were performed. Uncertainties of ammonia emissions from the land application systems are large and the sensitivity scenarios with a high DM content result in the different ranges of the considered environmental impacts. Nevertheless, they do not change the main keys for the impact reduction in this investigation.

With respect to the integration of effective technologies and the new considered environmental impacts, arising when applies the LCIA method is applied, this study is useful for engineers, researchers and also decision makers to plan or research how to improve pig manure management systems at both national and global levels. In addition, it enables us to consider proper pig manure management as an abatement method for the particulate matter reduction. However, the results are based on emission factors published in selected literature and they significantly depend on many factors such as weather conditions, soil conditions and manure characteristics. The application of this research requires further local data collection and considerations of investment costs and capacities to implement the technologies in practice.

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Figure captions

Fig. 1. Pig manure management system with system boundaries and considered changes. Crossed boxes illustrate the considered life cycle stages and production systems for avoided products. Dotted boxes with italic characters illustrate avoided products.

Fig. 2. Flow diagrams of the considered multi-stage scenarios. See the complete process description for the TRE, STO and LA systems in Table 1

Fig. 3. Comparative LCIA results from the 3 LCIA methods - STEPWISE2006, IMPACT2002+ and EDIP2003. The IMPACT2002+ method is modified by including biogenic methane and the STEPWISE2006 method is modified by excluding biogenic carbon dioxide. (vegetat. = vegetation, carc. = carcinogenic).

Fig. 4. Life cycle impact assessment results of 12 integrated scenarios. a) global warming potentials, b) respiratory inorganics, c) terrestrial eutrophication potential, d) aquatic eutrophication potential. The reference scenario is S1. See the detailed scenario diagram in Figure 2. The intervals represent uncertainties of ammonia emissions of the land application systems. (AD = anaerobic digestion, INC = incineration, GAS = thermal gasification).

Fig. 5. Sensitivity scenarios with uncertainties of the storage systems, and with 8.3% of dry matter. a) global warming potentials, b) respiratory inorganics, c) terrestrial eutrophication potential, d) aquatic eutrophication potential. The intervals of S1, S6 and S9 to S12 represent uncertainties of ammonia emissions of the storage systems. (AD = anaerobic digestion, INC = incineration, and GAS = thermal gasification).

Tables

Table 1

Process description of technology systems at different stages

System	Process Description
	At the treatment stage: integrated treatment systems
TRE1	No treatment (***reference system***)
TRE2	Anaerobic digestion
TRE3	Solid/liquid separation to 26% dry matter – drying – incineration
TRE4	Solid/liquid separation to 26% dry matter – drying – thermal gasification
	At the storage stage: liquid storage systems
STO1	Anaerobic lagoon without concrete floor (***reference system***)
STO2	Storage tank with natural crust
	At land application stage: Liquid spreading systems
LA1	Surface application: broadcast spreading/splash plate (***reference system***)
LA2	Surface application: band spreading/trailing hoses
LA3	Fast incorporation (within 6 hours)
LA4	Shallow injection: open slot
LA5	Deep injection: closed slot

Treatment system (TRE), storage system (STO), land application system (LA)

Table 2

Characteristics of the waste fraction

Pig manure characteristics	**Values**
Dry matter (%)	4.04 (2.41) [44]
Total ammoniacal nitrogen (g kg^{-1} raw pig manure)	2.54 (0.99) [44]
Total – nitrogen (g kg^{-1} raw pig manure)	3.67 (1.32) [44]
Phosphorus (g kg^{-1} raw pig manure)	0.99 (0.12) [45]
Carbon (% of dry matter)	40 [46]
Volatile solids (% of dry matter)	76 [47]
Methane yield (m^3 kg^{-1} volatile solids)	0.36 [48]
Energy content (GJ tonne^{-1} dry matter)	15.2* [49]

* Raw pig manure. The standard deviation is present in the parentheses.

Table 3

Emission factors and net energy recovery from integrated technology systems

Systems	**Emission factors (EF)**						**Net energy recovery**[b]	
	NH_3-EF	**Uncertainties**[a]	**N_2O-EF**	**NO_3-EF**	**N_2-EF**	**CH_4-EF**	**Electricity**	**Heat**
Unit			(MJ/tonne raw pig manure)			(MJ/tonne raw pig manure)	(MJ/tonne raw pig manure)	(MJ/tonne raw pig manure)
1. At the treatment stage[c]								
TRE1	-	-	-	-	-	-	0	0
TRE2	-	-	0.0002 [b]	-	-	0.287 [b]	124	31
TRE3	-	-	0.0006 [b]	-	-	0.0003 [b]	62.5	292
TRE4	-	-	0.0006 [b]	-	-	0.0003 [b]	73.1	146
Unit	kg NH_3-N/kg of remaining N	kg NH_3-N/kg of remaining N	kg N_2O-N /kg of remaining N	kg NO_3-N /kg of remaining N	kg N_2-N /kg of remaining N	(%)		
2. At the storage stage								
STO1	0.09 [50][d]	0.04-0.13 [50]	0 [51]	0.2 [52]	0 [53][f]	74 [51][g]	-	-
STO2	0.02 [50][e]	0.01-0.03 [50]	0.005 [51]	0 [52]	0.015 [53][f]	17 [51][g]	-	-
3. At the land application stage								
LA1	0.208 [44][h]	0.150-0.400 [12]	0.01 [55][i]	1-25 [12]	0.030 [53][f]	0 [57]	-	-
LA2	0.120 [44][h]	0.103-0.140 [44]	0.01 [56][j]	1-25 [12]	0.030 [53][f]	0 [57]	-	-
LA3	0.100 [12]	0.060-0.130 [12]	0.015 [56][j]	1-25 [12]	0.045 [53][f]	0 [57]	-	-
LA4	0.057 [44][h]	0.041-0.078 [44]	0.027 [56][j]	1-25 [12]	0.081 [53][f]	0 [57]	-	-
LA5	0.020 [12]	0.010-0.050 [12]	0.027 [56][j]	1-25 [12]	0.081 [53][f]	0 [57]	-	-
Artificial fertiliser	0.020 [54]	-	0.010 [55][i]	-	0.030 [53][f]	-	-	-

[a] The uncertainties of NH_3-EF presented here are a range of values or approximate 95% confidence limits. [b] The calculations are based on the pig manure characteristics in Table 2 and emission factors/system efficiencies in [4]. [c] The presented emission factors at this stage are not complete and the other factors are shown in [4]. [d] The storage system determined as slurry without surface cover. [e] The storage system determined as slurry with surface cover. [f] The values are derived from the presented calculation method as $3xN_2O$-N. [g] CH_4-EF for digested/ incinerated/ gasified slurry = 0%; based on MCF values at 15˚C and applied to the modified equation - $EF = VS*B_0*0.67kg/m^3*MCF$; EF = total methane emission (kg CH_4); VS = VS in the fraction (kg); B_0 = methane yield (m^3 CH_4/kg of VS); MCF = CH_4-EF. [h] The values are calculated by applying the ratio of total ammoniacal nitrogen and total nitrogen in Table 2 to the original EF. [i] Based on direct N_2O emissions and indirect emission is excluded. [j] Based on percentage of N_2O emissions using trailing hose application.

Table 4

Impact assessment results at different handling stages

Scenarios/impact category	Unit	Handling stage				Total
		Treatment	Storage	Transport	Land application	
S1: No treatment, anaerobic lagoon, broadcast spreading						
Global warming	kg CO_2-eq.	0	125.8	1.4	-19.8	107.3
Respiratory inorganics	kg $PM_{2.5}$-eq.	0	0.049	0.002	0.057	0.108
Terrestrial eutrophication	m^2 UES	0	56.0	0.4	81.4	137.8
Aquatic eutrophication	kg NO_3^--eq.	0	1.998	0.001	-1.086	0.913
S7: Anaerobic digestion, anaerobic lagoon, broadcast spreading						
Global warming	kg CO_2-eq.	-21.5	0.0	1.3	-19.8	-40.0
Respiratory inorganics	kg $PM_{2.5}$-eq.	0.019	0.049	0.002	0.057	0.127
Terrestrial eutrophication	m^2 UES	6.1	56.0	0.4	81.4	143.8
Aquatic eutrophication	kg NO_3^{-}eq.	0.013	1.998	0.001	-1.086	0.925
S9: Incineration, anaerobic lagoon, broadcast spreading						
Global warming	kg CO_2-eq.	-24.1	19.7	0.5	-7.9	-11.8
Respiratory inorganics	kg $PM_{2.5}$-eq.	-0.008	0.022	0.001	0.029	0.043
Terrestrial eutrophication	m^2 UES	0.9	25.6	0.1	37.4	64.1
Aquatic eutrophication	kg NO_3^--eq.	0.002	0.913	0.000	-0.335	0.580
S11: Gasification, anaerobic lagoon, broadcast spreading						
Global warming	kg CO_2-eq.	-21.1	19.7	0.5	-7.9	-8.8
Respiratory inorganics	kg $PM_{2.5}$-eq.	-0.002	0.022	0.001	0.029	0.050
Terrestrial eutrophication	m^2 UES	1.2	25.6	0.1	37.4	64.4
Aquatic eutrophication	kg NO_3^--eq.	0.002	0.913	0.000	-0.335	0.581

S = integrated scenario, $PM_{2.5}$ = particulate matters with a diameter smaller than 2.5 µm, m^2 UES = m^2 in which the critical load values of the ecosystem are exceeded. See the detailed scenario diagram in Figure 2.

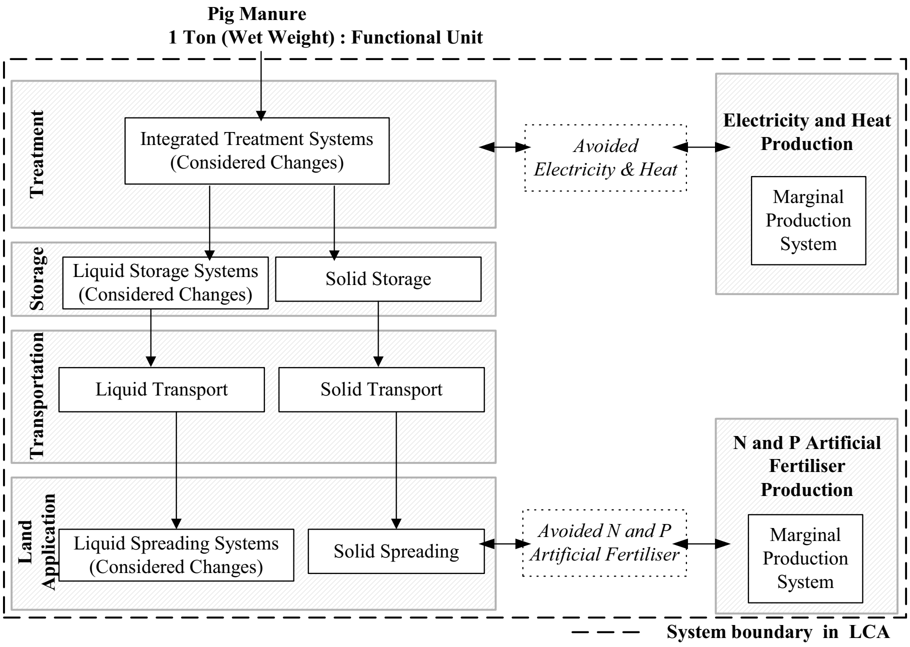
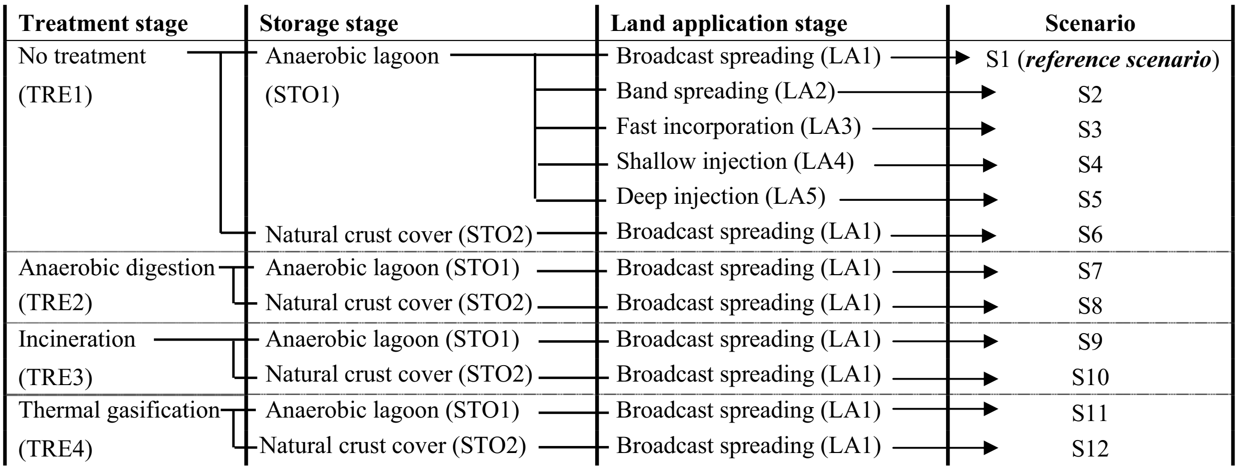


Fig. 1. Pig manure management system with system boundaries and considered changes. Crossed boxes illustrate the considered life cycle stages and production systems for avoided products. Dotted boxes with italic characters illustrate avoided products.



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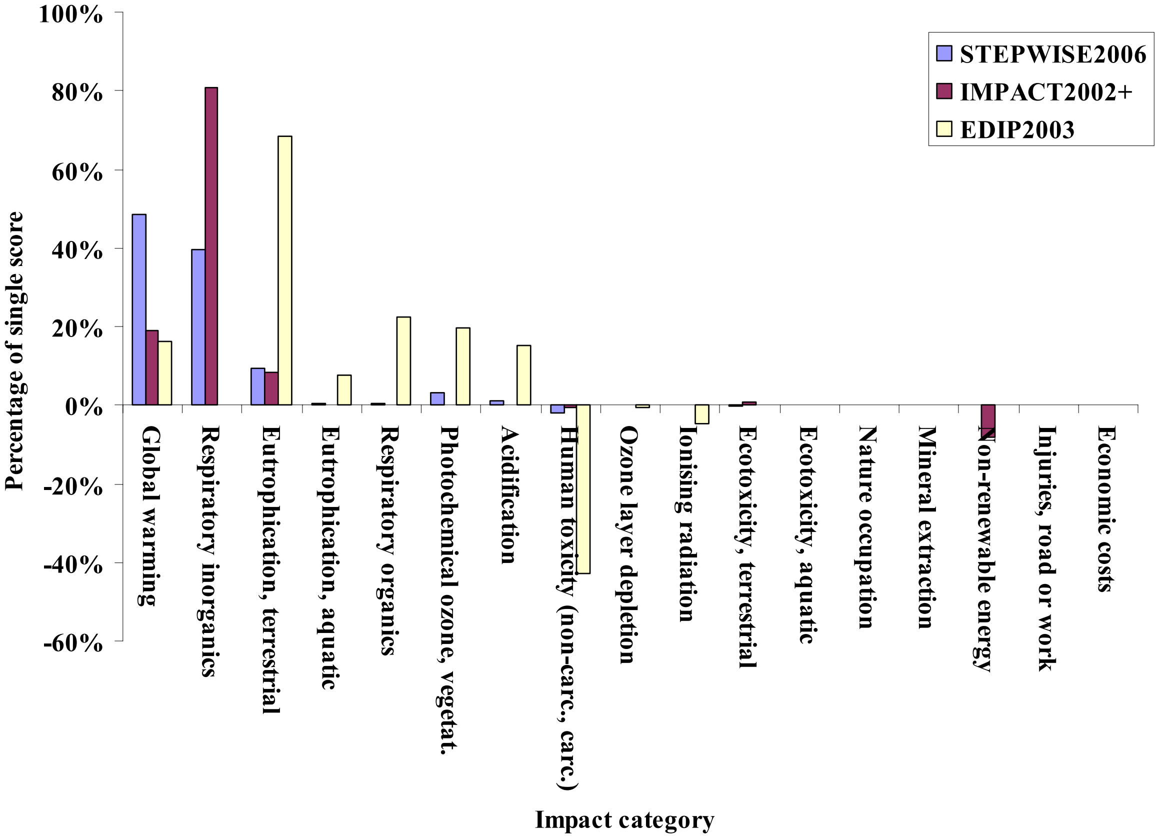

Fig. 3. Comparative LCIA results from the 3 LCIA methods - STEPWISE2006, IMPACT2002+ and EDIP2003. The IMPACT2002+ method is modified by including biogenic methane and the STEPWISE2006 method is modified by excluding biogenic carbon dioxide. (vegetat. = vegetation, carc. = carcinogenic).

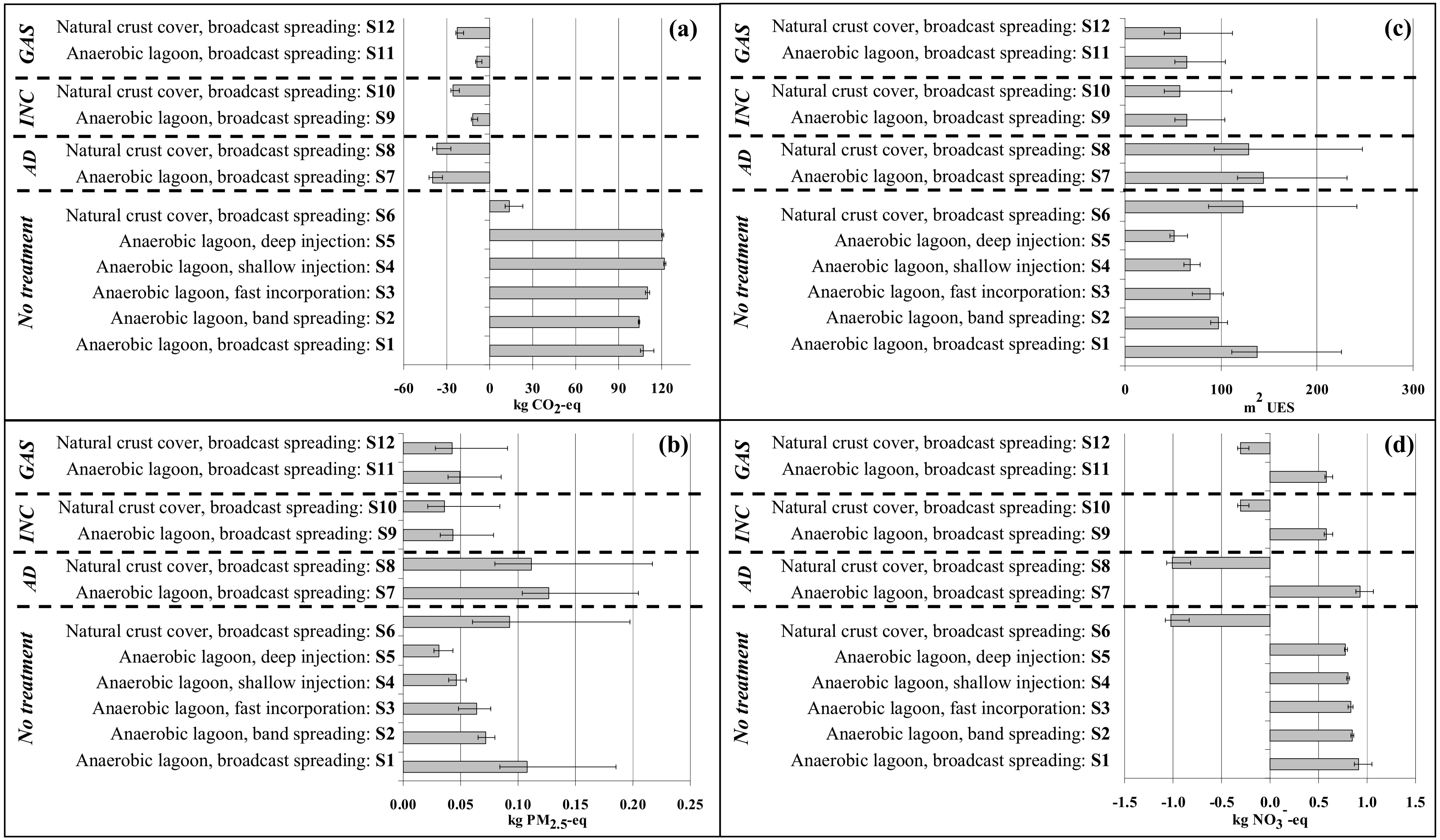

Fig. 4. Life cycle impact assessment results of 12 integrated scenarios. a) global warming potentials, b) respiratory inorganics, c) terrestrial eutrophication potential, d) aquatic eutrophication potential. The reference scenario is S1. See the detailed scenario diagram in Figure 2. The intervals represent uncertainties of ammonia emissions of the land application systems. (AD = anaerobic digestion, INC = incineration, GAS = thermal gasification).

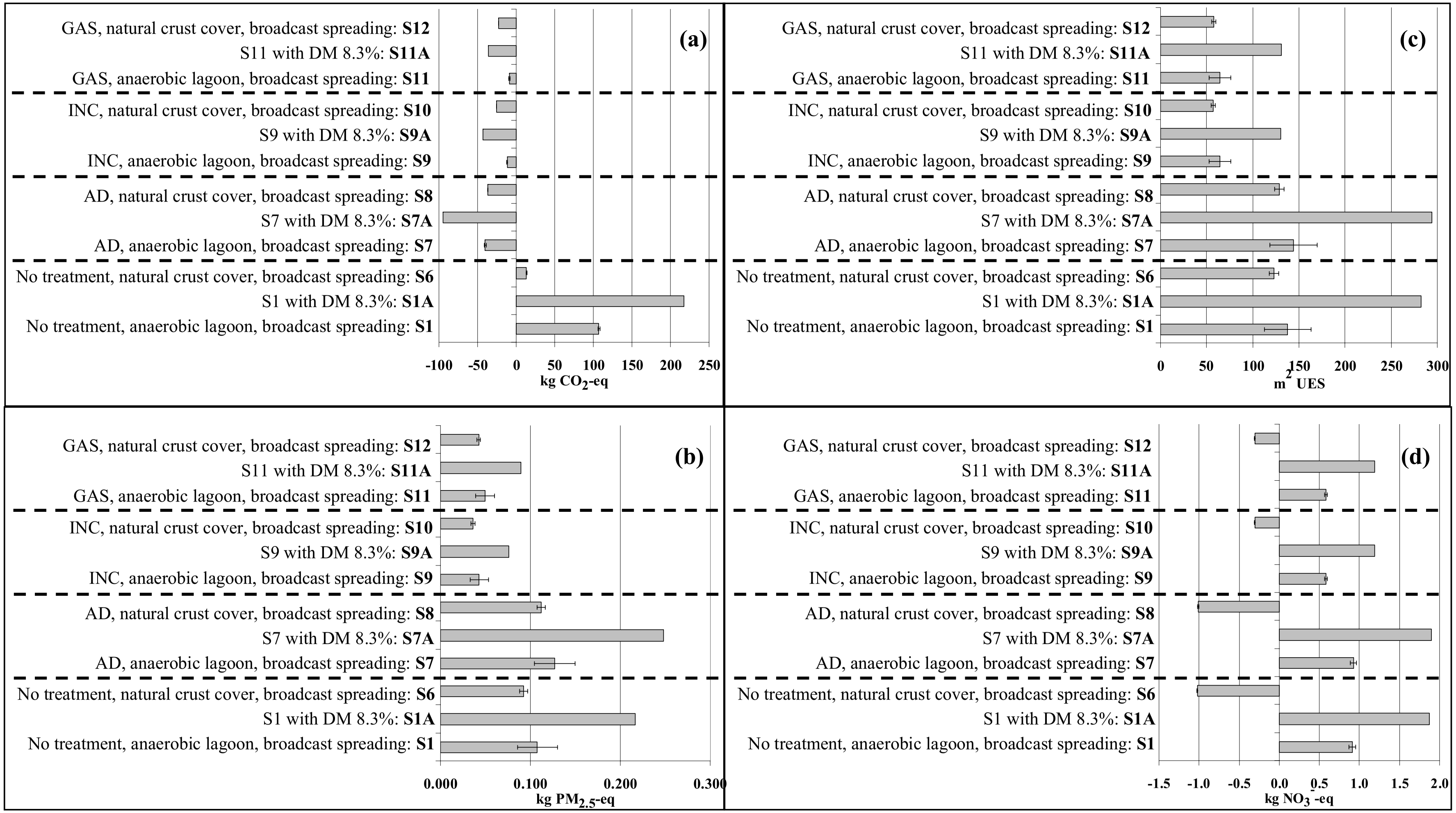

Fig. 5. Sensitivity scenarios with uncertainties of the storage systems, and with 8.3% of dry matter. a) global warming potentials, b) respiratory inorganics, c) terrestrial eutrophication potential, d) aquatic eutrophication potential. The intervals of S1, S6 and S9 to S12 represent uncertainties of ammonia emissions of the storage systems. (AD = anaerobic digestion, INC = incineration, and GAS = thermal gasification).

Paper 3B

Title:

Greenhouse gas emission reduction by integrated technology systems applied to piggery waste.

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Greenhouse Gas Emission Reduction by Integrated Technology Systems Applied to Piggery Waste

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Proper handling systems for the large amounts of pig manure generated globally – 125 million tonnes of dry matter in 2007 – is important in order to control greenhouse gas (GHG) emissions. The objective of this study was to assess how integrated technology systems for pig manure management can reduce GHG emission and achieve energy and nutrient recovery. Eight scenarios were developed by combining existing technologies (anaerobic digestion, separation, thermal pre-treatment, drying, incineration and thermal gasification) and aiming at energy and nutrient recovery. Life Cycle Assessment (LCA) aiming at describing the consequences of the changes from the selected scenarios was applied to quantify the global warming potentials (GWP) and to investigate how the different stages of treatment contribute. The life cycle impact assessment was performed by the EDIP97 method. The LCA in this study comprised 4 stages: treatment, storage, transportation and land application. The functional unit was 1 ton of raw pig manure (wet weight). Data were collected from full-scale existing waste treatment facilities supplemented with data from experimental plants, laboratory measurements, literature and the existing database in SimaPro. The results show that all of the scenarios applying treatment technologies aiming at energy recovery (incineration, gasification and anaerobic digestion) are preferable to the direct land application (or no treatment) scenario due to their contribution to the saved GWP (70 – 100 kg CO_2 equivalents/ton of raw pig manure). Incineration based scenarios yield the highest reduction in GWP, followed by gasification and anaerobic digestion based scenarios, respectively. Incineration and gasification in combination with an efficient drying yield higher energy recovery than anaerobic digestion based scenarios since they directly utilize almost all combustible matters for energy production. High energy recovery through substituted electricity and heat production from those systems most significantly influences GWP. For anaerobic digestion based systems, substituted energy production and substituted nitrogen and phosphorus fertilizer production are the main parameters reducing GWP. In conclusion, LCA in this study shows that incineration and gasification based technology systems are the most promising with the highest potentials for the reduction of global warming impacts due to high efficiency in energy recovery. This implies, however, that energy produced as electricity and heat can be utilised, which will depend on local circumstances. Additionally, the GHG savings will depend on the fossil fuel substituted and this will vary with locations as well. Therefore, decision-making as to best pig manure management system must be based on an LCA type of assessment that takes into account local conditions and other parameters than just GHG emission reduction.