

Anaerobic digestion of horse manure – renewable energy and plant nutrients in a systems perspective

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– renewable energy and plant nutrients
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Abstract

In horse keeping horse manure is produced, which can be utilized as a fertilizer or considered a waste. Horse manure constitutes a resource in terms of both plant nutrients and energy. In addition energy policies and objectives aim at replacing fossil fuels with renewable energy sources. The interest to improve resource recovery of horse manure increases due to various incentives for renewable vehicle fuels, legal requirements on management of manure, and environmental impact from current horse manure management.

This thesis aims at describing horse manure management in a life cycle perspective. This is made by (1) identifying factors in horse keeping affecting the possibility to use horse manure as a biogas feedstock and to recycle plant nutrients, (2) analysing factors in anaerobic digestion with influence on methane potential and biofertilizer nutrient content and (3) comparing the environmental impact from different horse manure treatment methods. Literature reviews, systematic combining, and simulations have been used as research methods.

The results show that horse keeping activities such as feeding, indoor keeping, outdoor keeping and manure storage affect the amount and characteristics of horse manure and thereby also the possibilities for anaerobic digestion horse manure. Transport affects the collected amount and spreading affects loss of nutrients and nutrient recycling. Simulation results indicate the highest methane yield and energy balance from paper bedding, while straw and peat gave a higher nutrient content of the biofertilizer. The highest methane yield was achieved with a low rate of bedding, which in the cases of woodchips and paper is also preferable for plant nutrient recycling. Still, results indicate the best energy balance from anaerobic digestion with a high ratio of bedding. The environmental impact assessment indicates a reduction in global warming potential for anaerobic digestion compared to incineration or composting.

Keywords: Horse manure, horse keeping, anaerobic digestion, nutrient recycling, systems perspective, bedding, methane potential, feedstock, biogas, biofertilizer

Sammanfattning

Vid hästhållning alstras hästgödsel som kan användas som växtnäring eller anses vara ett avfall. Hästgödsel utgör både en växtnäringresurs och en energiresurs. Dessutom styr uppsatta energimål mot att förnybar energi ska ersätta fossila bränslen. Intresset för att öka resursutnyttjandet av hästgödsel ökar på grund av olika incitament för förnybara drivmedel, lagstiftning om gödselhantering och miljöpåverkan från dagens hantering av hästgödsel.

I den här avhandlingen beskrivs hästgödselhantering i ett livscykelperspektiv genom att (1) identifiera olika faktorer vid hästhållningen som påverkar möjligheten att utvinna biogas ur hästgödsel och återföra näringen till jordbruksmark, (2) analysera faktorer i biogasprocessen som påverkar den specifika metanmängden och innehållet av växtnäring i gödseln och (3) jämföra olika gödselhanteringsmetoders miljöpåverkan. Metoderna i avhandlingen har varit litteraturstudier, systematisk kombination av teori och empiri samt simulering.

Resultaten visar att utfodringen, hästhållningen inomhus och utomhus och hur hästgödsel lagras påverkar mängden hästgödsel och dess egenskaper, och därmed också hur den fungerar som ett biogassubstrat. Transporterna har betydelse för hur mycket gödsel som kan samlas in och spridas, medan gödselspridningen påverkar näringsförluster och näringsåterföring. Resultaten från simuleringarna indikerar högst metanutbyte och bäst energibalans från papper som strömmaterial, medan halm och torv gav högre växtnäringssinnehåll i biogödseln. De högsta resultaten på specifik metanmängd nåddes med låg andel strö, vilket också var positivt för växtnäringssinnehållet vid scenarierna med spån och papper. Samtidigt indikerar resultaten att en hög andel strömmaterial ger den bästa energibalansen. Miljöpåverkansbedömningen indikerar att potentialen för klimatpåverkan minskar om hästgödsel behandlas i en biogasprocess jämfört med förbränning eller kompostering.

Nyckelord: Hästgödsel, hästhållning, rötning, näringsåterföring, systemperspektiv, strömmaterial, metanpotential, biogassubstrat, biogas, biogödsel

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To all supportive colleagues, PhD-students, project members and university lecturers at the University of Gävle I send a special thank you.

And last, but not least, I want to thank my family for all their support and my friends with four hooves for all inspiration.

List of papers and author's contribution

This thesis is based on the following papers, which are referred to in the text by Roman numerals:

Paper I

Hadin, Å., Eriksson, O., & Hillman, K. (2016). A review of potential critical factors in horse keeping for anaerobic digestion of horse manure
Renewable and Sustainable Energy Reviews (65): 432-442
<http://dx.doi.org/10.1016/j.rser.2016.06.058>

Åsa Hadin performed data collection, wrote and revised the paper with support from coauthors, and was the corresponding author.

Paper II

Hadin, Å., Eriksson, O. (2016). Horse manure as feedstock for anaerobic digestion
Waste Management (56): 506-518
<http://dx.doi.org/10.1016/j.wasman.2016.06.023>

Åsa Hadin performed data collection and wrote major parts. Simulations in ORWARE were made in cooperation with the coauthor. Åsa Hadin performed the analysis of final simulations, revised the paper with support from coauthor and was the corresponding author.

Paper III

Eriksson, O., Hadin, Å., Jonsson, D., Hennessy, J. (2016). Life cycle assessment of horse manure treatment
Energies (submitted)

Åsa Hadin contributed in data collection, analysis of results from simulations, writing the paper, revision of the paper and was the corresponding author.

Other publications

Hadin, Å., Eriksson, O., & Jonsson, D. (2015). *Energi och växtnäring från hästgödsel: Förbehandling, rötning och biogödselavsättning*. FOU-rapport Nr 42. Gävle, Sweden.

Eriksson, O., Hadin, Å., Hennessy, J., & Jonsson, D. (2015). *Hästkrafter och hästnäring-hållbara systemlösningar för biogas och biogödsel: Explorativ systemanalys med datormodellen ORWARE*. FOU-rapport Nr 43. Gävle, Sweden.

Nomenclature

Abbreviations

| | |
|--------|--|
| AP | Acidification Potential |
| CHP | Combined Heat and Power |
| C/N | Carbon to Nitrogen Ratio |
| CSTR | Continuous Stirred Tank Reactor |
| EP | Eutrophication Potential |
| GHG | Greenhouse gases |
| GWP | Global Warming Potential |
| HRT | Hydraulic Retention Time |
| IPCC | International Panel for Climate Change |
| L-AD | Liquid Anaerobic Digestion |
| LCA | Life Cycle Assessment |
| OLR | Organic Loading Rate |
| ORWARE | ORganic WAste REsearch |
| POP | Persistent Organic Pollutants |
| SRT | Solids Retention Time |
| SS-AD | Solid State Anaerobic Digestion |
| TS | Total Solids |
| UASS | Upflow Anaerobic Solid-State reactor |
| VS | Volatile Solids |

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1. Introduction

Horse keeping is of economic, environmental and social importance in Swedish society, e.g. in turnover, employment, requirements in education, contribution to tourism, leisure, and health and care (Bonorden, 2008). Horse keeping as a leisure activity, lifestyle and industry leads to development and diversification in farming between urban and rural locations, so called peri-urban areas (Elgåker et al., 2010). Zasada et al. (2013) found peri-urban horse keepers diversify between traditional farms, keeping horses as additional income to other grazing animal husbandry and hobby farmers, private persons keeping horses for personal leisure and not considered agricultural enterprises. Beside these also extensive farms established for horse keeping purposes such as horse tourism and intensive equine service farms offering leisure, education and therapy are found. The first has agricultural status and the latter has higher intensity of employment and more limited farm land.

Regardless, all types of horse keeping produce horse manure. Left on the ground, collected, stored and utilised it causes emissions to air, water and soil, followed by potential environmental effects such as acidification, increased global warming, eutrophication, resource depletion and risk for bacterial pollution of water resources (Prokopy et al., 2011). Horse manure can be categorized as organic waste causing costs for horse owners (Böske et al., 2015), but it may also be a source for renewable energy, plant nutrients for crop cultivation and organic matter (Moreno-Casselles et al., 2002). Figures for Sweden in 2010 show that the amounts of nitrogen and potassium in solid horse manure corresponded to the amounts in pig manure (solid and slurry), while phosphorous content in horse manure was estimated at approximately 50% in relation to pig manure (Edström et al., 2013).

Indications of an increasing number of horses in Sweden and other countries are stressed as an elevated risk for environmental impact from horse manure (Prokopy et al., 2011; Parvage et al., 2015). Despite more land used for horse operations, non-existent agriculture and location leads to lack of arable land for spreading of horse manure. Approximately 75% of Swedish horses are kept in or close to urban areas, resulting in a necessity for horse manure management agreements with contractors, farmers or manure treatment companies (Enhäll et al., 2012; Baky et al., 2012; Femling, 2003; Swinker et al. 2009; Prokopy et al., 2011).

Protection of water resources is a driver to reduce leakage from horse manure in horse paddocks and in manure management (Prokopy et al., 2011; Zeffner n.d; Westendorf et al., 2013). Storage as well as utilization practices of horse manure differ between horse keepers. Piling, on concrete plates

or on the ground, followed by spontaneous composting, and spreading on arable land is the most common horse manure practice in Sweden (Enhäll et al., 2012). Other manure management systems as formulated by IPCC, also apparent in horse manure management, are e.g. manure left unmanaged deposited in pastures, stored in unconfined piles or stacks or stored in paved or unpaved confined areas and removed periodically (Dong et al., 2006). Unmanaged composting during storage is important for the ability to spread horse manure since decomposition of bedding material consumes plant nutrients, with nutrient deficiency in the soil the first year after spreading (Malgeryd & Persson, 2013). Managed co-composting, of horse manure with other manure or vegetable waste, takes place in specific composting sites, e.g. in drum composts (Sindhøj & Rodhe, 2013; Rodhe et al., 2015). Transporting horse manure to waste management companies for soil treatment, soil production, or landfill cover, constitutes a costly horse manure treatment alternative for horse keepers due to the landfill ban on organic waste and a subsequent deposition fee (Bonorden, 2008). Incentives for small-scale horse manure combustion plants are, besides lack of land for spreading, when horse manure is perceived to have a low value for fertilizing, when costly transports are needed for treatment, and as replacement for electricity or fossil fuels in heating systems (Lundgren & Pettersson, 2009; Baky et al., 2012). Horse manure is often moist and needs pre-drying before small-scale combustion (Baky et al., 2012).

Researchers have paid attention to the waste problem in the horse industry and studied the possibilities to anaerobically digest horse manure, since it is regarded as a rich supply of substrate for renewable energy (Kusch et al., 2008; Wartell et al., 2012; Böske et al., 2014; 2015). Horse manure in Sweden represents a theoretical renewable energy potential of 0.77-1.55 TWh annually and the technical-economical potential represents 0.22-0.44 TWh annually (Edström et al., 2013). In anaerobic digestion both renewable energy and biofertiliser are produced. Recycled biofertiliser replacing mineral fertilisers leads to avoided greenhouse gas emissions (GHG) (Evangelisti et al., 2014), and avoided contamination of soil with heavy metal (cadmium) which is found in mineral fertilisers derived from the raw material phosphate rock. Phosphate is a limited resource, even though researchers and institutes differ somewhat in their predictions for how long the resource will last (Linderholm et al., 2012). Natural cycles of plant nutrients such as N and P are mentioned in Rockström et al. (2009) as one of the earth system processes threatened by human interference. Börjesson & Berglund (2007) showed both indirect and direct environmental improvements of biogas replacing fossil fuels for transportation in an environmental systems analysis. Combustion of fossil fuels releases toxic compounds, nitrogen and sulfur oxides which in turn affects acidification and also carbon dioxide which contributes to global warming (Chynoweth et al., 2001).

2. Aim of thesis

The aim of this thesis is to describe and discuss how horse manure treatment may contribute to an ecological sustainable development by energy recovery and recycling of nutrients to agricultural land, generally called resource recovery below. Focus is on biogas production from horse manure in a systems perspective, comprising factors that influence how horse manure performs as a biogas feedstock and a fertilizer. In addition environmental impact from horse manure management including different treatment options is included.

In this thesis the research questions are:

- What factors in horse keeping constitute drivers and barriers for resource recovery of horse manure?
- What crucial factors affect the performance in anaerobic digestion of horse manure related to resource recovery?
- What is the potential environmental impact from anaerobic digestion of horse manure in comparison to other treatment methods?

3. Scope and limitations

The scope of this thesis covers the life cycle of horse manure management, from production to different manure treatment methods including utilization of energy and biofertilizer and potential environmental impact. Manure production relates to horse keeping practices that affect amount and characteristics of horse manure and also how horse manure characteristics affect anaerobic digestion performance and the possibility of nutrient recycling (Figure 1).

In Paper I a qualitative environmental systems analysis was made on the system of horse keeping activities related to one specific environmental aspect: horse manure, consisting of faeces, urine and used bedding material. Paper II comprises a quantitative systems analysis of horse manure related to nutrient content, specific methane yield and energy balance in a biogas system. In Paper III potential environmental impact from different treatment options for horse manure were examined using life cycle assessment. These systems are compiled and visualized in Figure 1 where manure production,

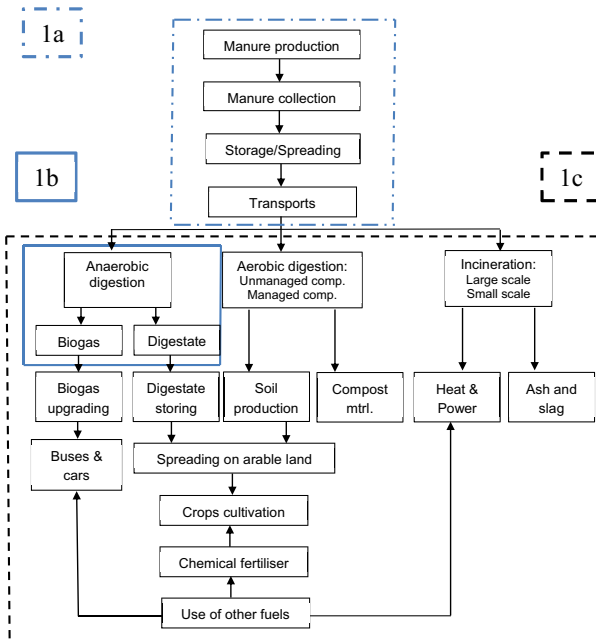


Figure 1. The studied system in this thesis, compiled from Paper I (1a), II (1b) and III (1c).

collection, storage/spreading and transportation represents the horse keeping system (blue dotted line) and anaerobic digestion, biogas and biofertilizer (digestate) represents the studied system in Paper II (blue line). Paper III system boundaries are visualized with a black dashed line.

The results in the qualitative study of horse keeping are compiled from different studies in different countries, some performed in a qualitative manner and some with a quantitative design. National variations and particularities in each of the practices could occur. The results are relevant as a general description of environmental impact of horse keeping but each horse keeper has unique practices and great variations exist. The quantitative simulations are made in a Swedish context regarding type of bedding, while retention time in the digester (HRT) and temperature are generic based on findings in the literature study. The results should be seen as indicative, due to data insufficiency and also poor validation in the absence of other studies on LCA of biogas from horse manure. Investigated scenarios indicate possible pathways to be used in planning of systems for biogas from horse manure.

This thesis does not give absolute values of emissions from horse industry but comparisons between different alternatives of bedding and treatment methods. Simulations in ORWARE use current process technology and annual values for process characteristics. Key parameters for specific methane yield in relation to tonnes of VS are used in the systems analysis while energy potential and plant nutrients are measured in relation to a chosen amount of treated horse manure. However information about numbers, size, location and types of horses could not be determined for a specific area. With this follows assumptions of distances for transport of substrate and bio-fertilizer (digestate) in the simulations.

4. Methods

Methods for collecting and analyzing data used in the studies (Paper I, II and III) were literature reviews, systematic combining and simulations, all described below. In Paper I and II data from literature were enriched with informal observations by study visits at, and observations of, horse keepers (e.g. riding schools); and also a survey of horse keepers in the municipality of Gävle. Findings were qualitatively analysed by systematic combining. In Paper II and III quantitative data from the literature review was used in simulations in ORWARE (Table 1).

Table 1. Methods used in the papers.

| Method/Paper | I | II | III |
|-----------------------|---|----|-----|
| Literature review | x | x | x |
| Systematic combining | x | | |
| Simulations in ORWARE | | x | x |

4.1 Literature review

The review was performed as consecutive literature searches and studies. In the review process for Paper I, literature on horse keeping and environmental impact from horse keeping was included. Focus was set on horse manure management, aiming to describe horse keeping effects on horse manure amount and content. A qualitative analysis of content in literature led to the identified activities and related critical factors as results of Paper I.

Literature about horse manure characteristics and biogas technology was reviewed with the aim to compile information and data on horse manure as a biogas feedstock presented in literature (Paper II). Relevant papers and reports on combustion and composting were also included (Paper III). The literature search for peer-reviewed scientific articles was made by using databases such as Discovery, Science Direct, Google Scholar and search services for journal papers, conference papers and e-books. Materials selected for inclusion are peer-reviewed scientific papers, reports from research centers, like the Swedish Institute of Agricultural and Environmental Engineering, and agencies, e.g. the Swedish Board of Agriculture.

Information from relevant papers was related to horse manure and the suitability for biogas production, content of bio-degradable material and its character with respect to biogas aspects. Information on biogas technology and processes were studied in literature in relation to operational systems

(temperature), reactor configurations (single- or two-stage reactors), operational mode (batch or continuous) and biofertilizer management.

4.2 Systematic combining

Systematic combining is a qualitative research method, described in Dubois & Gadde (2002), pointing at the need for direction and redirection of studies, a process where literature and theories are combined and compared to visits in and information from reality, as in case studies. The concept of systematic combining was raised from a discussion of advantages and disadvantages of case studies and criticism against case studies as research method (Dubois & Gadde, 2002). A variant of systematic combining was used to describe horse keeping and environmental impact in a qualitative manner in Paper I. In this study information in literature was supplemented with field observations, through visits at biogas plants and empirical observations of horse manure management (Table 2).

Table 2. Study visits performed in the study.
Numbers within brackets refer to number of facilities included

| Focus | Type of facility | Location |
|-------------------------|---------------------------------------|--|
| Biogas | Farm-scale (2) | Sötåsen, Uppsala (Sweden) |
| | Municipal organic waste (4) | Uppsala, Mörrum, Linköping, Söderhamn (Sweden) |
| Horse manure management | Riding schools (3) | Gävle (Sweden) |
| | Harness racing/trotting racetrack (1) | Gävle (Sweden) |

A survey was conducted with 83 horse keepers in the municipality of Gävle, Sweden, about their horse manure management practices. Field observations and information from the survey added empirical information to the study and directed the literature search and the analysis of literature in a process of systematic combining of literature and empirical observations. Through matching theory and reality the crucial factors in horse keeping for environmental impact and biogas utilization were extracted (Figure 2).

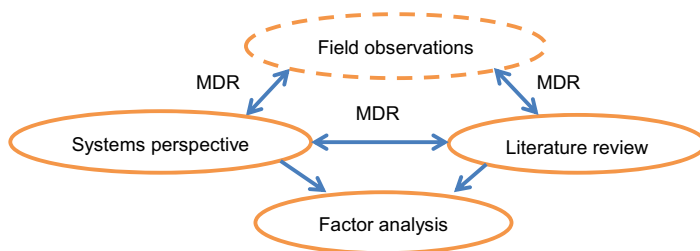


Figure 2. The modified systematic combining approach used in this project (after Dubois & Gadde, 2002). Arrows represent matching, direction and redirection (MDR).

Recurring contacts with horse keepers in combination with literature studies facilitated a wide-ranging investigation of factors affecting horse manure content and amount. Horse keepers with differing number of horses and experience from horse manure, biogas plant operators and information in literature contributed to categorized data representing the crucial factors presented in Paper I.

4.3 Simulations in ORWARE

Environmental systems analysis methods or tools are developed to provide information about environmental impact of decisions, as part of a basis for making decisions (Ahlroth et al., 2003; Moberg et al., 1999). In systems analysis a system is defined with system boundaries, components, a surrounding environment and often sub-systems (Ingelstam, 2012) as displayed in Figure 1. In Paper II the ORWARE tool was used for simulations of anaerobic digestion and production of biogas and plant nutrients from horse manure in a full scale continuous stirred tank reactor (CSTR). In Paper III ORWARE was used to calculate, compare and evaluate environmental impact from anaerobic digestion in comparison to other possible horse manure treatment methods.

ORWARE is a computer-based tool for environmental systems analysis and environmental costs of waste management processes (Eriksson, 2002). The tool describes the waste streams, with respect to chemical compositions of nutrients, carbon, pollutants etc. The flow of substances and energy from waste sources, collection, treatment and transports to utilization of products, like nutrients and recovered energy, are described in changeable and graphically displayed sub-models (Eriksson et al., 2014; Eriksson & Bisallion, 2011). Emissions are characterised with LCA (life cycle assessment) into potential environmental impact categories and environmental costs are calculated with LCC (life cycle cost) (Eriksson et al., 2014).

In Ahlroth et al. (2003), models are described as implementations of methods. As a mathematical model ORWARE implements the methods of life cycle assessment, and links together systems analysis, material flow analysis, substance flow analysis and life cycle cost (Assefa et al., 2005a, 2005b) to a quantitative analysis of waste treatment methods. Winkler & Bilitewski (2007) compared different LCA models and stated that different LCA models gave variations in result of a specific waste management case. Mentioned challenges for LCA as a science-based assessment tool is for example in describing real waste management systems processes and mass flows, and to show the spread in environmental impacts that can be found in waste management systems.

4.3.1 Sensitivity analysis of various biogas parameters

The ORWARE model is based on general figures, assumptions and equations (Eriksson et al., 2005). Adaption of waste descriptors, i.e. the chemical composition of horse manure and bedding materials', was made. The anaerobic

digestion sub-model is based on an existing liquid anaerobic digestion process (L-AD). The validity of the anaerobic digestion sub-model was tested by a comparison of methane potentials in literature (Eriksson et al., 2015). Because of the high uncertainty in input data, the simulation results should be interpreted as indicative.

Paper II consists of a quantitative analysis of horse manure as biogas feedstock using the ORWARE tool with two sets of scenarios (A and B). The process parameters hydraulic retention time (HRT) and temperature were varied to address uncertainty and simulated in ORWARE along with type of bedding and ratio of bedding representing horse manure feedstock characteristics (Table 3).

Table 3. Sensitivity analyses of process parameters and horse manure characteristics

| Simulations scenario set A | Simulations scenario set B |
|---|-----------------------------------|
| Bedding type (peat, straw, wood chips, paper) | Bedding ratio (20% and 47%) |
| Bedding ratio (20%, 47%) | HRT (20, 30 and 90 days) |
| | Temperature (37°C and 55°C) |

4.3.2 Life cycle assessment of horse manure treatment

Simulations of different horse manure treatment methods' potential environmental impact were done with existing treatment sub-models in ORWARE, adapted to relevant references. The mix of horse manure consisted of 5,000 tonnes of softwood bedding added to 10,000 tonnes of horse manure, constituting the functional unit of the analysis. This amount of horse manure was assumed to be transported 15 km to the treatment plants. The simulated treatment methods were (Eriksson et al., 2015):

- Managed composting adapted to drum compost. Active mixing, aeration and turning takes place. A bio filter reduces methane and nitrous oxides. 100% of material is assumed to be utilized as fertilizer in agricultural land.
- Unmanaged composting. Passive decomposition in piles interpreted to have emissions as landfills and 50% of the nutrients to replace chemical fertilizers while 50 % are non-utilized.
- Combustion in large scale, modelled as a Swedish waste combined heat and power plant (CHP), co-incineration of horse manure and household waste. Ash and slag are disposed to landfill. Mineral fertilizers are used on agricultural land.
- Small-scale combustion, modelled as a farm-scale combustion plant with pre-drying, generates heat.
- Anaerobic digestion, modelled as L-AD process including pretreatment (thermal hydrolysis with steam explosion), mesophilic process and HRT 30 days. The process generates biogas, upgraded for the transport sector with a scrubber, and biofertilizer, assumed to be transported 50 km.

In order to make the different horse manure treatment methods comparable and functionally equal, system expansion with compensatory systems was used (Eriksson et al., 2005). Compensatory systems are for example conventional supplies of electricity, district heating, vehicle fuel and mineral fertilizer (NPK).

5. Horses, horse manure and biogas

The reasons for keeping horses have changed over time and differ between countries and economies. Irrespectively of this, horse manure constitutes an output from horse keeping, affected by the amount of horses and horse keeping practices. In this chapter horse keeping, biogas production and legislative policy instruments are described in a Swedish-European context.

5.1 Horses for work, sports and leisure

Sweden has a history of having many horses, with about 720,000 draught horses in the 1920s (Femling, 2003) used in agriculture, forestry, the transport sector, and in the military where officers additionally used horses for riding (Hedenborg, 2009). During the twentieth century the number of horses decreased due to the mechanization in the agriculture, military, transport and forestry sectors (Hedenborg, 2015), and in the 1970s there was about 60,000 horses in Sweden. The increase in Sweden to about 300,000 horses in 2010 (Enhäll et al., 2012) follows an increased availability of equestrian sports and the development of horse riding schools. Riding clubs emerged in Europe in the late 1920s and the modern riding school took shape after World War II (Hedenborg, 2007; Thorell & Hedenborg, 2015).

The changed use of horses, from work to sports and leisure, has also turned them from being managed and used for work by men (Hedenborg, 2009) to women today dominating riding schools in Sweden (Hedenborg, 2007). Equestrian sports historically had riders from the upper-class of society or military, women being a minority in both. Decreased wages for grooms increased the number of women and the profession was feminized during the 1920s (Hedenborg, 2009). In 1952 Olympic Games women for the first time were allowed to participate in the dressage while women were excluded as professional jockeys from 1929 to the early 1970s in Sweden (Hedenborg, 2007). In 2009 68% of amateur jockeys and 7% of professional jockeys were women, while in trotting (harness racing) 5 % of the trainers are female (Hedenborg, 2015).

Horse industry plays an important role for countries in the European Union with a large variety of horse-related businesses, often in the areas of training, feed production and breeding plus livery (Liljenstolpe, 2009). The development of the sector shows more diversity of horse-related enterprises and an increased mobility of horses (sport, import/export and slaughter) followed by a requirement of horse passports for all horses in EU from 2009, to increase food safety (Liljenstolpe, 2009).

Liljenstolpe (2009) claims the number of horses per capita in Europe during the past decade as relatively constant. The study covers countries in the European Union in 2009 with the highest number of horses per capita found in Sweden and Belgium, showing Netherlands to have the highest amount of horses per 1000 ha, and the largest horse populations found in Germany and Great Britain. High numbers of horses correlate to high education level and high standard of living. In richer countries unemployment does not affect horses per capita while unemployment is connected to lower number of horses in weaker economies (Liljenstolpe, 2009).

5.2 Environmental objectives, energy targets and legal requirements

The Swedish Environmental code dictates reuse, recycling, management of raw materials and promotion of natural cycles. It comprises the general rules of consideration stating e.g. the responsibility to take precautions to prevent, hinder and counteract damage to environment or threats to human health from planned or completed activities or measures (SFS 1998:808). European and national energy targets aim at an increased share of renewable energy in the overall energy usage. The headline targets for Europe 2020 are:

Reduce greenhouse gas emissions by at least 20% compared to 1990 levels or by 30% if the conditions are right, increase the share of renewable energy in our final energy consumption to 20%, and achieve a 20% increase in energy efficiency (European Commission, 2010: 32).

The Swedish parliament has adopted four political climate and energy objectives to be reached by 2020:

- At least 50% renewable energy of total energy use
- At least 10% renewable energy in the transport sector
- 20% less energy intensity compared to 2008 and
- 40% reduced emissions of greenhouse gases from the sectors not being part of EU emissions trading. The last is an interim target to the National Environmental Quality Objective about limited climate impact (Regeringens skrivelse, 2015/16:87).

The Swedish National Environmental Quality Objectives include 16 different objectives, e.g. no eutrophication, only natural acidification and a rich cultivated landscape (Swedish Environmental Protection Agency, 2016). These objectives should be reached within a generation by measures related to activities causing these environmental effects, for example horse keeping. More specified requirements in ordinances and general guidance from authorities addresses the above mentioned objectives and targets.

Table 4 presents legal requirements with respect to horse manure management. Requirements for horse facilities not classified as farms are adapted to the risk of negative environmental impact and local adjustments (Malgeryd & Persson, 2013). Horse manure is stackable and allowed to be temporarily

stored and composted in fields because of the high content of bedding material. Animal by-products are products, e.g. manure, described as excrement and/or urine with or without litter (bedding material) from farmed animals, horses included (Commission Regulation 1069/2009). Exceptions from sanitization requirements exist for anaerobic digestion of manure if authorities assess the risk for transmission of infections as low (when manure from one or a couple of close farms are digested) but then biofertilizer should be treated as unprocessed. Co-digestion of manure from several production sites in general requires sanitization (Swedish Board of Agriculture, 2011).

Table 4. Legal requirements and general guidance regarding horse manure management (Swedish-European context)

| Requirement/Guiding principle/ General rule | Description |
|--|---|
| Swedish Ordinance (1998:915) about environmental consciousness in agriculture | 6 months storage capacity (required for > 2 horses in sensitive areas and > 10 horses in non-sensitive areas) |
| Environmental Code (1998:808) 2 Ch 3 § | Storage without leakage according to the precaution- and best available technology principles. |
| Swedish Board of Agriculture regulations (SJVFS 2004:62, SJVFS 2015:21) about environmental consciousness in agriculture with respect to plant nutrients | Spreading allowed with a maximum stated nutrient load per year (nitrogen) or every fifth year (total phosphorous). Temporary storing and composting in field allowed. Documentation of removed and received manure required. |
| Commission Regulation 1069/2009 | Manure from farmed animals, e.g. horses, is classified as animal by-product. Disposal methods and use of manure is incineration, dispose to an authorized landfill, production of fertilizers or soil improver, composting, transformation to biogas, fuel for combustion and application to land |
| Commission regulation 142/2011 | Horse manure can be used as a biogas feedstock in biogas plants with required permission from authorities, e.g. comprising sanitization (feedstock treated in 70 degrees in 1 h) |
| Ordinance (SFS 2001:512) about landfilling | Prohibition to put organic waste in landfill in Sweden since 2005. With this follows a landfill deposition tax per tonne waste |
| Waste ordinance (SFS 2011:927) | Collected and treated outside the production plant, and if the intent is to dispose of the horse manure, it is considered agricultural organic waste |
| Ordinance (SFS 2013:253) about waste incineration | As organic waste horse manure can be incinerated in a combustion plant with permission for waste combustion |

5.3 Horse manure and biogas systems

Horse manure is a farm-based feedstock for biogas production. A wide range of organic material is used as feedstock for biogas: sewage sludge, food waste and agricultural waste such as manure, crop residues and energy crops. Horse manure is an agricultural waste, but is currently produced in sites other than in agricultural areas. In general, the potential of organic material as biogas feedstock is under-utilized (Lantz et al., 2007). Manure represented 10% of the total wet weight used as biogas feedstock in Sweden 2015 and energy crops represented 0.9%. (Sweden Energy Agency, 2016) although the agricultural sector represents 70 % of the potential biogas feedstock in Sweden, of which 33% consists of manure and 37% of crop residues (Lantz, 2013).

Horse manure biogas potential in Sweden has been presented in two earlier studies. Linné et al. (2008) adjusted the theoretical biogas potential with limitations for manure dropped in grazing areas while Edström et al. (2013) presented a so-called techno-economical energy potential adjusted to the availability of horse manure (Table 5).

Table 5. Calculated biogas potential from horse manure in Sweden

| Reference | Number of horses | Methane potential (Nm ³ CH ₄ /ton TS) | Theoretical potential (GWh) | Availability (%) | Limited potential (GWh) |
|-----------------------|----------------------|---|-----------------------------|------------------|-------------------------|
| Linné et al. (2008) | 283 000 ¹ | 120 | 730 | 50 | 365 |
| Edström et al. (2013) | 363 000 ² | 80-157 | 770-1510 | 29 | 220-440 |

1) 1.5 tonne TS/animal

2) 2.6 tonne TS/animal

In Edström et al. (2013) horse manure was calculated to represent 17-23% of the total biogas potential from manure in Sweden (techno-economical potential and theoretical potential respectively) while cattle manure represented 54% of the techno-economical biogas potential in Sweden.

Biogas is produced when organic material is degraded without oxygen (anaerobic digestion) (Lantz, 2013; Berglund, 2006). Biogas consists of about 60% energy-rich methane and 40% carbon dioxide and can be used for different energy purposes as is or, after upgrading, in vehicles for transport (Berglund, 2006; Appels et al., 2011). Most of the biogas utilized in Sweden in 2015 was upgraded (1 219 GWh) and mainly used as vehicle fuel (Swedish Energy Agency, 2016) which, according to Lantz et al. (2007) and Berglund (2006), leads to the highest environmental benefits if fossil fuels are replaced.

The non-upgraded biogas in Sweden in 2015 was used for heat, electricity, industrial use or flared. Biogas production in Sweden has increased during the past ten years, both in terms of produced biogas and number of biogas

producing facilities (Swedish Energy Agency, 2016). In 2005, 1.3 TWh was produced at 233 biogas plants whereas in 2015 1.9 TWh was produced in 282 biogas plants, distributed as shown in Table 6.

Table 6. Categories of biogas plants in Sweden in 2015 and proportion of production (Swedish Energy Agency, 2016).

| Category of biogas reactor | Number | Proportion (%) |
|------------------------------|-----------------------|----------------|
| Waste water treatment plants | 140 | 36 |
| Co-digestion plants | 35 | 44 |
| Farm-scale biogas plants | 40 (37 reported data) | 3 |
| Industrial biogas plants | 6 | 6 |
| Landfills | 60 (54 reported data) | 9 |
| Gasification plants | 1 | 2 |
| Sum | 282 | 100 |

Besides biogas, the output from anaerobic digestion is digestate, also called biofertilizer from co-digestion and farm-based biogas plants. Biofertilizer is the remaining non-degradable material and plant nutrients after anaerobic digestion (Arthurson, 2009). The content of feedstock contaminations needs to be kept at a low level with quality management and exclusion of unsuitable feedstock because of concentration of heavy metals, persistent organic pollutants (POPs) or other contaminants in bio-fertilizer (Holm-Nielsen et al., 2009). In 2015 99% of digestate from co-digestion and farm-scale biogas plants were used as biofertilizer in Sweden (Swedish Energy Agency, 2016).

Biogas from horse manure could contribute to generation of renewable energy and can be a valuable supplement to existing farm-based biogas production during grazing periods with less cattle manure available (Olsson et al., 2014). Co-digestion of horse manure and energy crops in continuous stirred tank reactors (CSTR) is also reported in Ruile et al. (2015). CSTR represent the most common configurations of biogas reactors, suitable for most available feedstocks, continuously fed and stirred with TS below 15 % in the mix. Other configurations are batch-fed reactors, suitable for dry feedstock. Materials with high content of TS can also be digested in a plug-flow digester where the substrate slowly moves through the process by using a mechanical screw (Banks & Heaven, 2013; Bachmann, 2013).

Research on horse manure as a biogas feedstock is focused on solid state anaerobic digestion (SS-AD) due to high total solids (TS) and fibrous content in horse manure unsuitable in continuous slurry-based biogas reactors (Kalia & Singh, 1998; Kusch et al, 2008; Böske et al., 2014). SS-AD is favorable for lignocellulosic material but has challenges in formation of volatile fatty acids (VFA), ammonia accumulation and mixing (Sawatdeenarunat et al., 2015). The categorization of biogas plants, besides the technology applied (reactor type, temperature), can also be by size and type of substrate digested (Holm-Nielsen et al., 2009) (Figure 3).

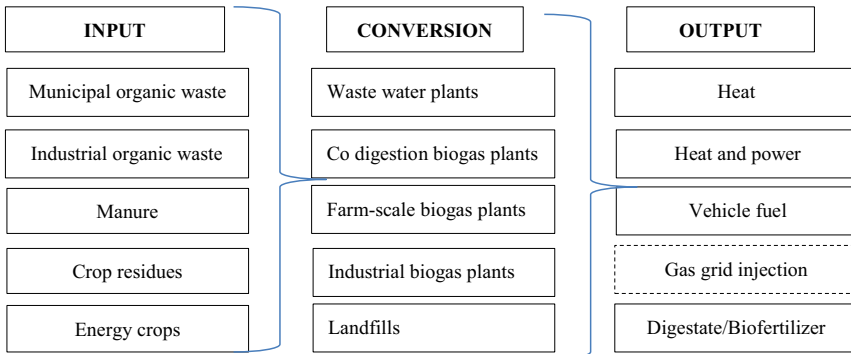


Figure 3. Overview of biogas production in Sweden 2015 (modified after Lantz et al., 2007; Swedish Energy Agency, 2016). Sweden also had one operational gasification plant in 2015.

5.4 Policy instruments for biogas production

Nutrients in manure treated anaerobically are more available for plants than untreated manure, and if co-digested with substrates with lower TS it is also more easily spread than solid manure (Lantz, 2013; Olsson et al., 2014). To seize the potential and expand biogas systems in Sweden there are challenges in strengthening the drivers for nutrient recycling and renewable energy utilization and reducing the barriers, often technical and economic (Lantz et al., 2007). Table 7 presents a summary from literature of policy instruments acting as drivers and barriers for biogas production in general. Environmental benefits are regarded as the strongest drivers for manure as a biogas feedstock, while other incentives for biogas production from manure and crops are regarded as few and weak by Lantz (2013).

It is proposed that biogas systems involve many actors, e.g. municipalities, farmers and energy companies, all affected by drivers and barriers connected to their role in the energy system (Lantz et al., 2007). In this thesis horse keepers are reflected upon as producers of a substrate, horse manure, possible to use as a feedstock for biogas utilization. Policy instruments as drivers and barriers for horse manure as a biogas feedstock are also related to current horse keeper manure management practice. For example, legal requirements apply as drivers for alternative horse manure treatment methods where risk for emissions to water and soil exists. Horse manure is the horse keepers' responsibility and manure management, comprising storing capacity designed for no leakage, is a regulated activity for Swedish agricultural facilities with more than ten horses in nonsensitive areas (SFS 1998:915; Eskilsson, 2013). Despite the fact that horses today are kept outside agricultural facilities and in smaller numbers, the general rules of consideration, like the precaution principle and choice of best available technology, are relevant for horse keepers to follow. This means that horse keepers are advised to have some storage capacity without leakage for manure (Eskilsson, 2013). Without use

for horse manure organic matter, nutrients or insufficient areas for spreading manure it may be considered as a waste, collected and treated off-site. In that case the waste hierarchy (Directive 2008/98/EC) guide waste producers, as horse keepers, to reduce (use prevention measures), reuse, recycle and recover waste.

Table 7. Summary of different policy instruments for biogas production (based on Lantz et al., 2007; Holm-Nielsen et al., 2009; Amiri et al., 2013; Lantz, 2013; Arthurson, 2009; Swedish Energy Agency, 2016).

| Policy instruments | Comments |
|---------------------------|--|
| Drivers | |
| Informative instruments | European and national environmental and energy objectives, policies and programs |
| Legal instruments | Manure storage capacity, waste management directive, ban on landfilling, manure application regulations |
| Economic instruments | Tax on commercial fertilizers, on landfilled material, biogas exempted from energy tax, reduced tax and subsidies for use of bi-fuel cars, free parking. European Unions' CO ₂ -trade system. Subsidies for farm-scale biogas plants and for biogas from manure |
| Others | Improved fertilization effect, reduced odor, efficiency of scale, collecting manure from several farms in farm-scale plants. Environmental benefits: reduced acidification, eutrophication |
| Barriers | |
| Economic instruments | Low cost on commercial fertilizers, high cost for handling biofertilizers, limited profitability |
| Legal instruments | Sanitization requirements in biogas plants if manure is collected from more than two sites |
| Others | Limited knowledge, biogas distribution infrastructure and storage capacity, excess biogas during summer and competition from lower costs, low refined solid biomass fuels |

6. Results

This chapter summarizes the results from Paper I-III. Chapter 6.1 describes the production of horse manure by horse keeping practices that affect amount and characteristics of horse manure. The environmental impact connected to the practices is also described in chapter 6.1. Together with chapter 6.2 regarding factors in horse keeping with influence on anaerobic digestion the result from Paper I is covered. Chapter 6.3 and 6.4 represent the main results of Paper II with characteristics of horse manure and crucial factors in anaerobic digestion of horse manure. The results from Paper III are covered in chapter 6.5 on the environmental impact of different treatment options.

6.1 Environmental impact from horse manure management

Environmental impact from management of horse manure is a product of the practices chosen by the horse keeper, from choice of feeding to management of horse manure. The combination of these horse keeping practices is here visualized as a horse manure management system (Figure 4). The identified system comprises activities such as feeding, housing indoors and outdoors, practices for storage and fertilization and also transport of horse manure, bedding material and feed.

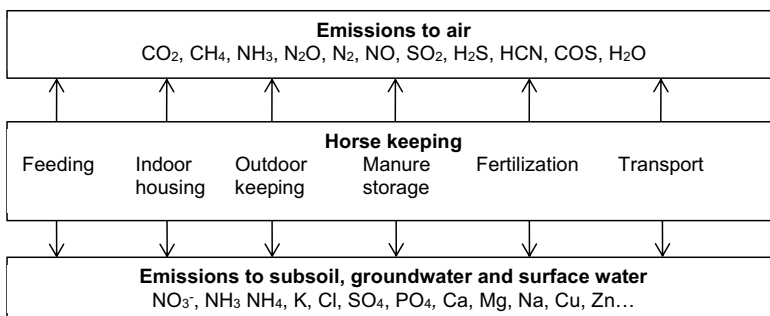


Figure 4. Environmental impact from different activities in horse keeping related to horse manure management (modified from Oenema et al. (2007), with input from Petersen et al. (2007), Parvage et al. (2015); Parvage et al. (2013), Berglund & Falkhaven (2011), Kwiatkowska-Stenzel et al. (2014), Flysjö et al. (2008) and Dong et al., (2006)).

Environmental issues like water contamination due to phosphorous leakage is raised by Westendorf & Williams (2015) where overfeeding result in

higher concentrations of phosphorous in the manure. Excess protein in horse diets leads to increased content of nitrogen in excreted manure (Williams et al, 2011; Harper et al., 2009). Wasted feed, i.e. feed left-overs, could be a resource for biogas production if collected and stored instead of left in the field (Westendorf et al., 2013).

Paddocks are areas of high to moderate risk for P and N leakage from horse manure left on the ground, high horse density and long-lasting use of land, creating problems with surface run-off water (Parvage et al., 2013; 2015; Airaksinen et al., 2006). High horse density is especially found in highly intensive horse farms with an average horse density of 9.2 horses/ha, meanwhile traditional farms, hobby farmers and extensive horse-oriented farms in peri-urban areas have an average horse density of 1.3-1.8 horses/ha (Zasada et al., 2013). Mucking outdoor areas is one measure to reduce the risk for contamination of water resources and leakage to surrounding areas (Parvage et al., 2013).

Environmental impact from storage and spreading of horse manure mainly occurs as air emissions and leakage to water and soil. About 25% of the nitrogen is lost during storage (Karlsson & Rodhe, 2002). Storage of horse manure varies between horse keepers. In Prokopy et al. (2011), storage practices ranged from directly on the ground to more proper storage in three sides of concrete. Some of the horse manure was used for fertilizing gardens and in hay fields but the majority was not used on the investigated horse keeping farms. In Sweden more than 50% of the horse keepers in 2010 stored horse manure on concrete slabs and about 25% direct on the ground. About 60% spread horse manure on their own land and about half of the riding schools and trail riding companies had agreements with farmers to manage the horse manure (Enhäll et al., 2012).

6.2 Factors in horse keeping important for anaerobic treatment of horse manure

Activities in horse keeping affecting the total weight, nutrient content and biodegradability of horse manure are in this thesis called factors. These factors influence the possibility of using horse manure for resource recovery. Identified factors in horse keeping are depicted in Figure 5.

| Horse keeping | | | | | |
|----------------|-------------------|---------------------|----------------|--------------------|------------|
| Feeding | Indoor housing | Outdoor keeping | Manure storage | Fertilization | Transport |
| - amount feed | - amount bedding | - time outside | - type | - spreading method | - distance |
| - type of feed | - type of bedding | - collection regime | - time | - soil conditions | - fuel |

Figure 5. Summary of crucial factors for using horse manure as a biogas feedstock.

Horse keeping indoors and outdoors affects the ability to collect horse manure. Choice of bedding and mucking regime results in different content and amount of collected horse manure (Werhahn et al., 2010; Airaksinen,

2001). Removal of only faeces reduces use of bedding on a daily basis and e.g. peat/wood chips as bedding material entails easier separation of used, not soaked bedding, while straw results in the highest amount of mucked out dirty bedding manure (Airaksinen et al., 2001). Results from tests of nutrient content in bedding material (Airaksinen et al., 2001) indicated highest content in straw (phosphorous and potassium) and in peat (nitrogen), and used bedding had higher nutrient content than fresh bedding material. Straw as bedding material in general shows the highest methane potential but studies are conflicting in their view of whether used bedding adds methane potential or not (Cui et al., 2011; Wartell et al., 2012; Mönch-Tegeder et al., 2013). Transports of feed, bedding material and manure takes place in the system, and affect the environmental impact and availability of horse manure. However, due to insufficient information on transport types and distances, this activity is hard to evaluate in terms of current environmental impact.

6.3 Horse manure characteristics as a biogas feedstock

Biogas feedstock in general can be described in terms of availability, suitability, digestibility and content of inhibitors and impurities (Al Seadi et al., 2013). The availability aspects of where horse keeping is situated and transport distances of horse manure to biogas plants, i.e., logistical considerations, are not covered in studied literature, neither in the sensitivity analysis of simulations in Paper II, see section 3.

Suitability of biogas feedstock is characterized by levels of total solids (TS), volatile solids (VS), and the carbon to nitrogen ratio (C/N). Total solids in horse manure (about 20-80%, Paper II) indicate solid state anaerobic digestion (SS-AD) as an interesting alternative to the more common liquid anaerobic digestion (L-AD). The amount of organic matter (volatile solids, VS) in horse manure is 30–90% (Paper II). Although the levels of VS indicate the methane potential in a feedstock, it does not provide information on the degradability. Horse manure has a high share of slowly degradable lignocellulosic organic material, stemming from the bedding material used, which delimits the degradability.

Lignocellulosic material consists of cellulose and hemicellulose enclosed by lignin in a complex (Bochmann & Montgomery, 2013). Cellulose and hemicellulose can to some extent contribute to energy production, while lignin is hardly degradable, which affects the methane potential negatively by passing non-degraded through the biogas process. Biogas production from lignocellulosic material could be enhanced by an optimal C/N ratio, established and maintained at 20-30, promoted by co-digestion with nitrogen-rich manure. Furthermore, SS-AD and/or pretreatment could enhance the biogas production from lignocellulosic material (Sawatdeenarunat et al., 2015). Horse dung is in a favorable C/N ratio range for biogas production. Whereas micronutrients levels are low (Paper II) levels of macronutrients correspond to other livestock manures with only minor differences.

Digestibility is the ability of a feedstock to decompose through anaerobic digestion (Al Seadi et al., 2013), or anaerobic degradation. The anaerobic degradability is tested in biochemical methane potential (BMP) tests where the specific methane yield from a specific feedstock is determined (Drosg et al., 2013). The literature review revealed numerous methane potential tests performed on different scales and with different technologies, experimental tests (e.g. Wartell et al., 2012; Mönch-Tegeder et al., 2013) and/or operational lab-scale processes (Böske et al., 2014, 2015) or full-scale co-digestion (Olsson et al., 2014; Kalia & Singh, 1998). Compiled results (Figure 2, Paper II) vary between about 50 L CH₄/kg VS (horse dung without bedding) to about 280 L CH₄/kg VS (horse manure and wheat straw). Methane potentials in literature show higher digestibility for unused straw and straw pellets (about 183-250 L CH₄/kg VS) than unused softwood bedding, pellets and sawdust (about 17-20 L CH₄/kg VS).

Impurities and inhibitors interfere with the biogas process and solid impurities in horse manure (e.g. horse shoes) could disturb equipment (for example stirrers), depending on chosen technology. Inhibitors are for example heavy metals, although low levels of heavy metals are found in horse manure (Henriksson et al., 2015; Moreno-Caselles et al., 2002).

6.4 Crucial factors in anaerobic digestion of horse manure

Biogas production and plant nutrient contents in biofertilizer are affected by feedstock characteristics (TS, C/N ratio, VS, content of macro- and micro-nutrients), process configuration (L-AD, SS-AD, continuous, batch, plug-flow) and operating conditions (OLR, HRT, temperature in digester). The indicative results from ORWARE simulations of bedding type, bedding ratio, hydraulic retention time (HRT) and digester temperature show the highest specific methane yield when using a low ratio of waste paper as bedding material and the most positive energy balance for a high ratio of waste paper (Table 8). This indicates a possible energy recovery potential from paper in anaerobic digestion, while in composting tests paper did not decompose during the storage period (Swinker et al., 1998; Airaksinen et al., 2001).

In terms of nutrient recovery, waste paper is no longer the preferable choice as peat and straw indicate the highest NPK-contents (Table 8). Peat preserves most of the soluble nitrogen in bedding manure and is the only bedding decomposed enough to be spread after a compost test (Airaksinen et al., 2001). In simulations of anaerobic digestion, high peat ratio leads to the highest levels of N (Table 8). Due to a slow degradation of lignocelluloses in anaerobic digestion, impeded by e.g. lignin in cell walls (Yang et al., 2015), simulations using peat as bedding results in negative production of methane (Table 8). Straw as bedding material indicate specific methane yields at 100-128 L CH₄/kg VS (high and low amount of bedding respectively) which is somewhere in between the methane potential shown in literature, ranging from about 70 L CH₄/kg VS in a solid laboratory scale test, to 280 L CH₄/kg VS in a BMP-test.

Table 8. Comparative analysis of indicative results from simulations in the ORWARE tool. Effects on biogas production and biofertilizer (digestate) by choice of bedding material and rate of bedding material.

| Indicative results | Min | Max | Bedding | Part bedding | HRT (days) | Temp (°C) |
|--|------|------|---------|--------------|------------|-----------|
| Methane yield (L CH ₄ /kg VS) | | 151 | Paper | 20% | 30 | 37 |
| Energy Balance (MJ/ton) | | 3597 | Paper | 47% | 30 | 37 |
| N-tot (kg/ton digestate) | | 4.00 | Peat | 47% | 30 | 37 |
| P-tot (kg/ton digestate) | | 0.21 | Straw | 20% | 30 | 37 |
| K-tot (kg/ton digestate) | | 0.55 | Straw | 47% | 30 | 37 |
| Methane yield (L CH ₄ /kg VS) | -7 | | Peat | 47% | 30 | 37 |
| Energy Balance (MJ/ton) | -582 | | Peat | 47% | 30 | 37 |
| N-tot (kg/ton digestate) | 0.31 | | Paper | 47% | 30 | 37 |
| P-tot (kg/ton digestate) | 0.02 | | Paper | 47% | 30 | 37 |
| K-tot (kg/ton digestate) | 0.08 | | Peat | 47% | 30 | 37 |

Softwood bedding is the most commonly used bedding material in a Swedish context (Enhäll et al., 2012) and is often used as one of several bedding materials in studies of biogas potential from horse manure (Olsson et al., 2015; Wartell et al., 2012). Both softwood and straw beddings have been included in studies on ammonia emissions in stables (Fleming et al, 2008; 2009; Garlipp et al., 2011). Low emissions are an important advantage for horse health and different studies show different results for different beddings: wheat straw showed lower ammonia emissions in one study and straw pellets in another (Fleming et al.; 2008; 2009) while Garlipp et al. (2011) concluded that wood shavings had both the lowest gas generation (NH₃, N₂O, CO₂, CH₄, H₂O) and leachate amount compared to rye and wheat straw in a deep litter system.

A high ratio of softwood bedding is negative for specific methane yield in all simulated scenarios in Paper II as results indicate specific methane yields between 82-128 L CH₄/kg VS (high and low amount of bedding respectively). As a result of more feedstock digested (in tonnes), energy balance favors of a high ratio of softwood bedding, which results in simulations on 620 MJ (low amount of softwood bedding) to 1668 MJ (high amount of softwood bedding). This also entails that a high proportion of softwood bedding is positive for energy balance, but not for specific methane yield (Table 9).

Low share of softwood bedding, thermophilic temperature (55°C) and long retention time were favorable for specific methane yield, while high share of softwood bedding, 30 days retention time and mesophilic temperature (37°C) resulted in the highest energy balance in the simulations (Table 10). Content of N and P in the biofertilizer was positively affected by a low ratio of softwood bedding while K was not affected by the bedding ratio (Table 9).

Thermophilic reactor temperature gives a faster degradation of the feedstock which potentially can shorten the retention time (Bachmann, 2013) due to higher microbial activity in thermophilic temperatures (Böske et al.,

2015). Simulations indicate a higher degradation in 55°C compared to 37°C and a higher specific methane yield. Retention time compared to temperature is not simulated but in the simulated HRT 30 days, at 37°C, the highest energy balance is reached. Bachmann (2013) mentions the increased energy demand for higher temperatures confirmed by results from simulations indicating a lower energy balance in 55°C compared to 37°C.

Böske et al. (2015) report higher methane yields for thermophilic temperatures than mesophilic which is confirmed by the simulation results (Table 9). The highest energy balance in scenario set 2 (Paper II) are for HRT 30 days, in mesophilic temperature and 90% bedding ratio while specific methane yield is highest in HRT 90 days, thermophilic temperature and low bedding rate (Table 9). Long retention time as positive for the degradation of lignocellulosic material corresponds to studied literature, but 20 days retention time indicated only 2% less specific methane yield compared to 90 days (low rate of bedding). The increase of 3 L CH₄/kg VS indicates a small contribution to specific methane yield from HRT over 20 days. In addition, longer retention time results in increased reactor volume, which is an economic aspect not investigated in this thesis.

Table 9. Comparative analysis of indicative results from simulations in the ORWARE tool. Effect on biogas production and biofertiliser (digestate) by bedding ratio, hydraulic retention time (HRT) and temperature. Softwood bedding is used in all scenarios.

| Indicative results | Min | Max | Part bedding | HRT (days) | Temp (°C) |
|--|------------|------------|---------------------|-------------------|------------------|
| Methane yield (L CH ₄ /kg VS) | | 128 | 20% | 90 | 55 |
| Energy balance (MJ/tonne) | | 1668 | 47% | 30 | 37 |
| N-tot (kg/tonne digestate) | | 1.75 | 20% | 20-90 | 37-55 |
| P-tot (kg/tonne digestate) | | 0.11 | 20% | 20-90 | 37-55 |
| K-tot (kg/tonne digestate) | 0.32 | 0.32 | 20-47% | 20-90 | 37-55 |
| Methane yield (L CH ₄ /kg VS) | 82 | | 47% | 30 | 37 |
| Energy balance (MJ/tonne) | 620 | | 20% | 90 | 55 |
| N-tot (kg/ton digestate) | 1.25 | | 47% | 20-90 | 37-55 |
| P-tot (kg/tonne digestate) | 0.05 | | 47% | 20-90 | 37-55 |

6.5 Environmental impact of different manure treatment methods

The environmental impact from unmanaged composting, managed composting, large-scale incineration, small-scale incineration and anaerobic digestion were compared in a life cycle assessment, using the mathematical model ORWARE. To enable the comparison between a compensatory system was added, described in section 4.3.2.

Indicative results from the simulations performed in Paper III show that anaerobic digestion is the most efficient treatment method to reduce greenhouse gases (GWP), where biogas is upgraded to vehicle fuel replacing fossil

fuels (Figure 6). This conforms to previously mentioned environmental benefits from use of biogas (Lantz 2013; Berglund, 2006).

Anaerobic digestion results in lower eutrophication potential (EP) than unmanaged or managed composting. This is a result of somewhat higher leakage and emissions of nutrients from composting in comparison to biogas plants, and also higher short- and long-term nitrogen emissions from spreading of organic fertilisers. For composting some of the composted material is assumed not to be recycled, which is compensated for by using chemical fertilisers. Unmanaged composting and small-scale incineration save primary energy compared to anaerobic digestion (Figure 6).

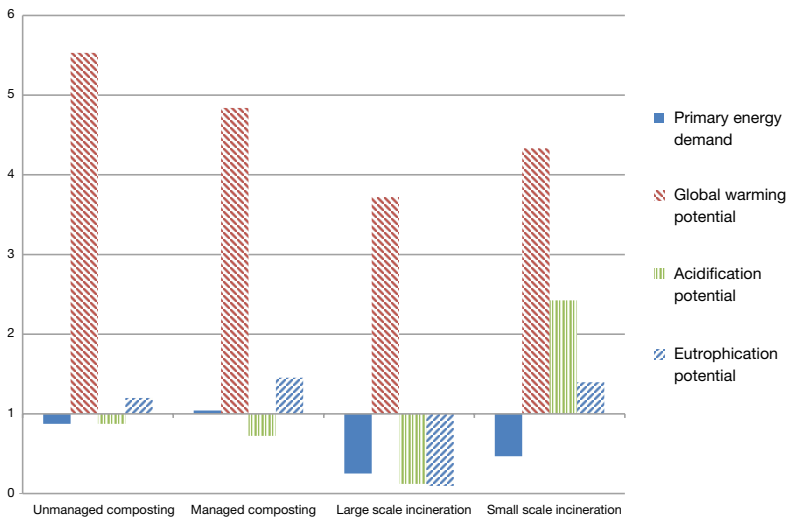


Figure 6. Comparative results for composting and incineration in relation to anaerobic digestion.

Results indicate that anaerobic digestion has lower acidification potential (AP) compared to small-scale incineration on account of higher emissions to air from small-scale incineration, compensatory vehicle fuel and plant nutrients.

Large-scale incineration contributes less to the environmental impact categories AP, EP and primary energy, in comparison to anaerobic digestion. Low AP is derived from production of electrical power and no need for compensatory heat, leading to low primary energy use. Low EP is a result of pollution control of NOx in large-scale incineration plants and that eutrophication potential to water is assumed to be low, by using chemical fertilisers.

7. Discussion

The results from papers I-III are discussed as drivers and barriers for resource recovery from horse manure in section 7.1. Table 10 illustrates covered topics, in which papers the topics appear and used methods. This table also visualizes the systems perspective in the thesis by covering environmental-, energy- and plant nutrient aspects from a life cycle perspective. Environmental impact is here indicated by emissions from the life cycle: horse manure production, -collection and -utilization (Paper I) and by impact categories (acidification potential, eutrophication potential, global warming potential and primary energy) from anaerobic digestion compared to composting, and incineration (Paper III). In resource recovery (Paper II) the outcomes methane potential, energy balance and plant nutrients are incorporated.

Table 10. Illustration of content and connections in the discussion.

| Topics covered in papers | Part of life cycle of horse manure management | | | |
|---|---|---|--|---|
| | Manure production | Manure collection | Nutrients utilization | Energy recovery |
| Resource recovery potential -Manure amount -Manure characteristics | -Feed type -Feed amount -Bedding amount -Bedding type | -Mucking regime -Indoor collection -Outdoor collection -Transports | -NPK -Transports -Storage -Spreading technology -Soil conditions | -NPK -Anaerobic digestion -Methane yield -Energy balance |
| Resource recovery potential -Manure characteristics -Process characteristics | -Volatile Solids -Total Solids -Bedding ratio | | -Hydraulic Retention Time -Digester temperature | |
| Environmental impact -Emissions -Impact categories | Emissions to air, soil and water | | Environmental impact categories | |
| Methods in papers | Paper I Literature review and systematic combining (variant) | | | |
| | Paper II Literature review and simulations | | | |
| | Paper III Literature review and simulations | | | |

7.1 Drivers and barriers for resource recovery of horse manure

According to the results in this thesis resource recovery potential from horse manure could be described as the specific methane yield and energy balance of horse manure as a biogas feedstock, and also the total amount of NPK to which horse manure can contribute. The results are based on the indicative results from simulations (Paper II) and results from literature.

Specific methane yield is affected by the characteristics of the feedstock. There are indications that hay-fed horse manure mixtures have higher methane potential than mixtures from silage-fed horses (Böske et al., 2014; Böske et al., 2015). When it comes to horse manure, simulations show specific methane yield to be positively influenced by low content of bedding with high digestibility (Table 11). A low content of bedding in horse manure requires an active choice of bedding material, and a resource effective mucking regimen. Literature mentions bedding in general as a barrier for effective biogas production, for example softwood bedding is almost resistant to anaerobic digestion and long straw disturbs stirrers and pumps in liquid anaerobic digestion (L-AD) plants. Manure storage reduces the methane potential in the feedstock for anaerobic digestion due to composting of organic material and thereby acts as a barrier from an energy point of view, while storing is a prerequisite for solid manure with high content of bedding before plant nutrients can be recycled to agricultural land.

Energy balance is positively affected by a high amount of feedstock (Table 11). Availability of horse manure as feedstock is derived from produced, but also collected, horse manure amounts (Table 10). Time outdoors and manure dropped outside affect the amount of horse manure, as barriers if not collected, otherwise contributing, and acting as a driver, to higher energy balance. Collecting horse manure outdoors is positive for the amount of feedstock but could lead to disturbances from impurities (barriers) in the anaerobic digestion process, depending on biogas plant configuration. As L-AD processes are more sensitive to solid impurities these configurations act as drivers for sorting at source, reducing the risk for impurities, e.g. horseshoes, in horse manure. A high content of bedding is a driver for increased energy balance according to simulations, as it results in more feedstock and this outweighs the increase in heat and electricity demand in the anaerobic digestion process.

NPK in manure is affected by feed and bedding. Type of feed, depending on type of horse and horse workload, affects the content of N and P in manure. Amount and characteristics of horse manure affects the plant nutrient content, and a high plant nutrient content increases the incentives for treatment methods enabling recovery of plant nutrients in the manure. Bedding material adding plant nutrients to horse dung, e.g. peat and straw, thereby could be seen as drivers for nutrient recycling (Table 11). Risks for leakage and emissions of plant nutrients increase with longer storage periods. Storing manure covered, on concrete plates or in containers, and slow degradation of horse manure reduces these risks in storage (Table 11).

Plant nutrients are more available in digested manure, seen as a driver for anaerobic digestion even though not shown in simulations. In L-AD solid horse manure is converted to liquid phase mentioned as a driver for spreading and incorporation into soil. Transport distances from horse manure production sites to biogas facilities and biofertilizer transport to arable land could act as a barrier for resource recovery due to costs, but these issues are not further investigated in this thesis.

Table 11. Drivers and barriers for high methane yield, high energy balance and high NPK-tot.

| Outcome | Driver | Barrier |
|-------------------------------|---|--|
| Specific Methane Yield | Feed type Low amount of bedding (mucking, time indoors/outdoors) Type of bedding (1.paper, 2. straw, 3. wood chips) Thermophilic temperature 90 d HRT | High amount of bedding Type of bedding (peat) |
| Energy balance | High amount of horse manure (feed amount, type of bedding, mucking, collection, time indoors/outdoors) High amount of bedding (paper, straw, woodchips) Type of bedding (paper, straw) Mesophilic temperature 20-30 d HRT | High amount of peat. Long transport distance |
| NPK-tot | Amount of feed Type of feed Low amount of bedding (wood chips, peat) High amount of bedding (straw, peat) | Storage nutrient losses. Time / type Spreading losses |

With focus on resource recovery potential, a bedding material with high specific methane yield per tonne VS and high NPK per tonne should be used. In using anaerobic digestion as a waste management method energy balance still constitutes an interesting parameter as it shows the relation between horse manure as a biogas feedstock and that more feedstock, although with a low specific methane yield, favors energy balance. Optimization could be to maximize the specific methane yield from a minimum of treated horse manure or to aim at a better result than some other treatment alternatives (Banks & Heaven, 2013). As specific methane yield benefit from low ratio of bedding and straw is the second-best performing in the simulations and adds P, straw is to be considered as the most preferable bedding material in a resource recovery point of view. Simulations with high amount of straw bedding (47%) indicate a high energy balance and K-tot. Literature indicates an ability of higher specific methane yield performance for straw, not reached however in the simulations. In practice the theoretical methane yield

never may be achieved due to different reasons, e.g. parts of substrate passing through the reactor undigested, insufficient retention time and a weak balance of nutrients (Banks & Heaven, 2013). Simulations indicate specific methane yields for softwood bedding in the range of straw, while in literature softwood bedding more commonly is reported as a poorer feedstock than straw. Simulation with softwood bedding is of great interest as it is the most common bedding material for horses in Sweden. Long hydraulic retention time, high temperature and low rate of bedding are all positive, and act as drivers for a high specific methane yield from softwood bedding in simulations. Still, with a high share of softwood bedding, more energy is produced because of a high amount of material digested, and therefore more VS, although with an indicated low methane yield per kilogram of volatile solids in the feedstock.

The simulations indicate the energy balance to increase with more feedstock digested. In waste management, resource efficiency is applied by reduction of waste. Waste still produced after reduction measures should be reused, recycled or energy recovered, according to the waste hierarchy (Directive 2008/98/EC). With this follows that a reduction of horse manure, by mucking and choice of bedding type and amount, is preferable. Horse manure never produced, is the horse manure with least potential environmental impact. Environmental impacts from bedding production are not incorporated in this thesis, but less consumption of products in general leads to a reduction of environmental impact. Because of the abovementioned horse keeping factors, horse manure characteristics as a biogas feedstock differ between types of horses and between horse keepers (stables). Efficient use of resources, feeding due to horse needs, enough bedding for horse comfort and keeping air contaminants low, additional recycling of nutrients to agricultural land, possibly after recovery of energy, are means by which horse keeping facilities can contribute to ecological sustainability. Spreading biofertilizer on agricultural land is of interest if it adds plant nutrients and soil and not impurities. Spreading and incorporation should be done according to best practice. However it is of great importance to produce a high-quality biofertilizer and thereby enable recycling of nutrients to agricultural land. Choice of substrates in co-digestion should be done with consciousness in order not to make it more difficult to recycle plant nutrients in horse manure to agricultural land due to impurities.

Literature covers the waste problem which the horse industry is facing due to increasing numbers of horses (Wartell et al., 2012). Measures to reduce waste amounts and hazardous contents are of both environmental and economic importance. Horse manure produced on horse keeping sites without using it on, or off, the site represents an unutilized resource, while when recycled to agricultural land it is a utilized resource. The perception of horse manure varies depending on where it is produced and if there is a use for the organic material by the horse keeper or another interested party. Lack of knowledge of numbers and locations of horses complicates the descrip-

tion of the magnitude of horse keeping and environmental impact of horse manure management. The results in this thesis do not answer the question if the total environmental impact is reduced by changed horse manure treatment methods but indicates a reduced environmental impact from treatment methods other than unmanaged composting. Horse manure represents a left over from horse activities, in many cases produced outside the agricultural sector. As in any other activity the aim should be to reduce environmental impact in relation to the benefits from the activity.

Results from the simulations indicate a reduced contribution to local-regional environmental problems (acidification, eutrophication) and global warming with changes in horse manure management, such as a change from unmanaged composting to other manure treatment methods. If unmanaged composting, and all simulated treatment methods for that part, is replaced by anaerobic digestion, environmental benefits in terms of reduced GWP will be reached according to simulations. Anaerobic digestion utilizes renewable energy, enables nutrient recycling of organic material and could thereby replace inadequate management or management without energy and/or nutrient recycling. Combustion eliminates the possibility of plant nutrient recycling disturbing the natural biogeochemical cycles of N and P, but simulations indicate that large-scale combustion has a potential for lower impact in three out of four environmental impact categories in comparison to anaerobic digestion. The importance to find renewable energy sources and horse manure considered in literature as an abundant source of organic waste (Böske et al., 2015) are drivers for using horse manure as a biogas feedstock. The indicative results in the simulations allow for other horse manure treatment methods, e.g. depending on availability in specific areas, and whether local, regional or international environmental impacts are regarded as most important.

7.2 Methods applied

Literature review

The result in Paper I is a combination of field observations and qualitative information collected from peer-reviewed literature material and reports from research institutes and authorities. Information from a number of sources, from different countries and studies about horse keepers, and their knowledge about horse keeping and horse manure in particular, have been analysed in detail. Data on horse manure characteristics as a biogas feedstock from a number of papers is compiled in Paper II. The literature review conducted for Paper II focused on quantitative data, extracted to enable comparisons, and for simulations in the ORWARE tool. The investigated literature covers information about horse manure characteristics and methane potential from unique experimental tests or operational tests on laboratory scale. This means that in this compilation there are some limitations in comparability. Despite these challenges the analysis and categorization of horse keeping

factors, environmental impact and operational process factors has been compiled showing the critical factors for biogas utilization from horse manure.

Systematic combining

In Paper I literature reviews and field observations were combined in order to describe the factors in horse keeping affecting volume and characteristics of horse manure. Study visits at horse riding schools, a trotting racetrack and interviews with horse keepers were chosen due to their experiences and insights in horse manure management. The method used is inspired by the systematic combining approach where observations supported literature review and vice versa. Combinations of information were done in a systems perspective, where all activities in a life cycle perspective on horse manure were part of the analysis, which resulted in important factors affecting horse manure quantity and characteristics.

The systematic combining approach was chosen to direct and redirect literature search and enable a control of the feasibility of the results. Observations, study visits and interviews were done in a specific municipality in Sweden, but the investigated literature shows conformity with Swedish statistical data about horse keepers. Nonetheless a Swedish context is adopted in the thesis and the indicative results need to be transferred to specific conditions in horse keeping practices before being transmitted to other countries or specific horse keepers or horse manure treatment sites.

Simulations in ORWARE

In Paper II the simulations were performed to indicate the importance of various process parameters for resource recovery from horse manure. In Paper III potential environmental impact from different treatment methods was simulated. The best performing manure treatment methods are those with a high outcome and low environmental impact from the expanded system. Simulations allow studies of scenarios and the effect of changes in parameters on outcome and environmental impacts in a life cycle perspective, but due to assumptions and simplifications in models the results only give a general idea about the real conditions, important to have in mind when interpreting the results (Winkler & Bilitewski, 2007).

The performed biogas process simulations indicate that the best energy balance is reached if the content of bedding is high in the mix of horse manure. Specific methane yield, on the other hand, is increased by a low grade of bedding, as degradability decreases with higher amount of bedding. Simulations are made with a functional unit of 10,000 tons of horse dung and results are calculated per tonne digested horse manure, but the total digested amount varies. Either 25% or 90% bedding material was added, resulting in different digested amount of feedstock in different scenarios. To add 90% bedding material almost doubles the total amount of digested feedstock, leading to more produced energy in total even though the specific methane yield was lower in scenarios with high amount of bedding.

Studied literature claims solid state anaerobic digestion (SS-AD) as a suitable biogas technology for horse manure (Böske et al., 2014; Böske et al., 2015). However, in Paper II and III liquid anaerobic digestion (L-AD) simulations were performed as the default anaerobic digestion sub-model in ORWARE is a L-AD process, continuous stirred tank reactor (CSTR). To enable simulations of SS-AD further configuration and adaption of ORWARE are needed. In simulations of different treatment methods some waste management processes in the model are well defined, e.g. large-scale incineration, while e.g. the small-scale incineration process lacked information about electricity use and ash and slag. Due to data uncertainties the results from the simulations should be interpreted with caution.

Examinations of emerging technologies tend to have more uncertain data than more mature technologies and data quality aspect problems occur when technologies do not exist in full scale and estimations of data are made by using literature (Assefa et al., 2005a). The operational conditions HRT, digester temperature, bedding type and ratio were chosen based on limitations in data and model constraints. ORWARE, as a mathematical model, still benefits from enabling sensitivity tests of these process parameters. Despite indication of low methane potential from peat found in literature, the negative specific methane yield and energy balance for peat in simulations are unrealistic results derived from model constraints. ORWARE was originally constructed for simulations of household waste and simulations of horse manure showed very high methane production. This was followed by adjustments in methane production according to methane potential mentioned in literature. The choice of bedding in simulations was region- and Sweden-specific, and could lead to weaker external validity (generalisability) in the study. For wood shavings the results are valid but only indicative due to uncertainties in data.

In the L-AD simulations performed the choice and amount of bedding material affected specific methane yield, energy balance and nutrient content in the biofertilizer while retention time and temperature did not affect plant nutrient content in the biofertilizer. Literature mentions plant nutrients to be more plant-available in biofertilizer than in manure but this is not visualized in simulations in Paper II. This is a result of the chosen system boundaries in Paper II, set before the spreading of biofertilizer where plant-available nutrients replace chemical fertilizers. In ORWARE waste is assumed to have no environmental burden and the environmental impact from production of bedding is not included, which otherwise could have added environmental impact related to the bedding material.

8. Conclusions

Results indicate that improved horse manure treatment may contribute to an ecological sustainable development by comprising recovery of energy and plant nutrients to agriculture and thereby reduced potential environmental impact. Resource efficiency measures in horse keeping favors energy recovery and reduced environmental impact, with the prerequisite that horse health aspects need to be taken into account. Below conclusions are presented with respect to the research questions.

What factors in horse keeping constitute drivers and barriers for resource recovery of horse manure?

Horse keeping practices affect the possibility to use horse manure as a biogas feedstock as the activities have effects on total weight and characteristics of the manure.

- Feeding acts as a driver for nutrient content in manure.
- Mucking regimen acts as a driver for low amount of bedding as well as choice of bedding.
- Time spent indoors acts as a driver for high amount of collected manure and higher bedding content which is a driver for higher energy balance.
- Long time spent outdoors reduces the amount of horse manure if no mucking takes place, and it reduces the content of bedding in collected manure, the latter a driver for higher specific methane potential.
- Storing time is a barrier for energy recovery but a driver for nutrient recovery before spreading.
- Transport enables collection of manure and spreading (utilization) of horse manure.

What crucial factors affect the performance in anaerobic digestion of horse manure related to resource recovery?

Identified factors of importance for biogas production and plant nutrient content in biofertilizer from horse manure are feedstock characteristics and anaerobic digestion process parameters. Feedstock characteristics are total solids (TS), volatile solids (VS), carbon to nitrogen ratio (C/N), macro- and micronutrients, digestibility, impurities, and inhibitors. Anaerobic digestion process parameters are pre-treatment, operating conditions, process design, mix of substrates, organic loading rate (OLR), retention time, and temperature in digester.

Results from simulations of process parameters (hydraulic retention time and temperature) and feedstock characteristics (type of bedding and ratio of bedding) indicate an increased nutrient content in biofertilizer originating from a high amount of peat (N) and straw (K) as bedding material. Bedding scenarios of paper and softwood bedding indicate less plant nutrient content with more added bedding. Paper as bedding material gave both the highest specific methane yield and the most positive energy balance but was lacking in plant nutrients. Straw is indicated to be the second best according to specific methane yield and energy balance and adds plant nutrients to the biofertilizer. If softwood bedding is used, a high amount of bedding material acts as a driver for energy balance and as a barrier for specific methane yield and nutrient content. Mesophilic temperature acts as a driver for higher energy balance. Long HRT and thermophilic temperature act as drivers for higher specific methane yield but the contribution in comparison to shorter HRT and lower temperature is limited.

What is the potential environmental impact from anaerobic digestion of horse manure in comparison to other treatment methods?

The indicative results from simulations suggest that anaerobic digestion reduces GWP in comparison to composting and incineration. Eutrophication potential is reduced in comparison to composting and small-scale incineration as well as acidification potential from small-scale incineration. Compared to large-scale incineration, anaerobic digestion increases the potential for eutrophication and acidification potential. Also potential primary energy demand increases with anaerobic digestion in comparison to large- and small-scale incineration.

9. Further research

Interesting areas for further research regarding biogas from horse manure is to investigate if, and how, the choice of bedding material affects the potential environmental impact in anaerobic digestion. Logistics connected to collection, storage and transport to existing, or planned, biogas plants, to evaluate the possibility of collecting and transporting horse manure as a feedstock for anaerobic digestion could also be studied. In this thesis ecological sustainability is in focus, but future studies about correlations between economic, ecological and social aspects in sustainable horse keeping are of interest as well as economic and social aspects of resource recovery in biogas plants. Doing this in future studies will deepen the connection to sustainable development.

During this project the interest of testing SS-AD for horse manure arose. This requires a development of the ORWARE model to SS-AD, as a model research project. The question of whether there are configurations more suitable for small-scale anaerobic digestion, as a complement to large-scale anaerobic digestion plants, could be an interesting topic for future research.

Environmental management often starts with interested parties acting as drivers, e.g. suppliers, customers and legislation. Policy instruments of different types are often apparent: informative, legislative and economical. Legislative policy instruments are partly described in this thesis, leaving an interesting area for future research about information and economic policy instruments connected to horse manure management.

Producers of horse manure (horse keepers) and the potential users of horse manure (biogas facilities/energy companies, farmers) need to cooperate in the question of bedding material and this forms an interesting area for future research. In the case of energy utilization, suppliers of bedding, feed and entrepreneurs managing horse manure together with the above-mentioned actors, develop a horse manure biogas energy system. The drivers and barriers for development of systems like this is an interesting area for future studies.

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Papers

Associated papers have been removed in the electronic version of this thesis.

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Anaerobic digestion of horse manure – renewable energy and plant nutrients in a systems perspective

Horse manure is a plant nutrient resource, but could also be a resource for renewable energy. This thesis analyses factors in horse keeping and anaerobic digestion and their influence on the possibility to recover energy and biofertilizer from horse manure. Different bedding materials, amount of bedding, time and temperature in digestion are analysed with respect to energy- and plant nutrient recovery. This thesis also compares environmental impact from anaerobic digestion, incineration and composting of horse manure. The analysis indicates that paper performs best with respect to energy recovery, but lacks plant nutrients. Straw is favourable for both energy recovery and plant nutrient content. Peat adds plant nutrient but results in low energy recovery. Softwood bedding in small amounts performs almost as straw in the energy recovery aspect and small amounts also favour the plant nutrient content. Longer retention time and higher temperature in the digester increase the methane yield but only to a limited extent. To treat horse manure in a biogas process is indicated to reduce global warming potential in comparison with combustion and composting, while large-scale combustion, without nutrient recovery, has advantages when it comes to some other environmental impacts studied.

Åsa Hadin