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From waste problem to renewable energy resource

Exploring horse manure as feedstock for anaerobic digestion

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Abstract

A sustainable energy system requires, according to energy policies, reduced emissions of greenhouse gases, increased ratio of renewable sources of energy and more efficient use of energy. Horse manure could be regarded as waste, but also as a resource for renewable energy and plant nutrients. This thesis explores the potential of horse manure as a renewable energy source, and its possibilities to support and contribute to energy and environmental objectives. To do this, data was collected from literature, simulations, study visits and interviews.

A number of horse keeping activities were identified in the assessment of horse manure as a feedstock for energy and as a plant nutrient resource: feeding, indoor housing, outdoor keeping, manure storage, fertilizing and transport, all with effect on amount and content of horse manure. Results indicated that choice and amount of bedding are important for both energy performance and plant nutrient content in the biofertilizer. Operational conditions such as long hydraulic retention time and high temperature had less impact for horse manure as a biogas feedstock. Anaerobic digestion resulted in the lowest global warming potential compared to incineration and composting, while large-scale incineration reduced primary energy demand, acidification potential and eutrophication potential. In a subsequent simulation, anaerobic digestion had lower potential environmental impact than unmanaged composting, regarding all chosen environmental impact categories in the study. Experiences from energy companies suggest that horse manure can be used in small quantities in co-incineration, with suitable incineration technology, but odor was mentioned as a problem. Farm-scale incineration required continuous maintenance and monitoring and mixing with pellets. As a feedstock for anaerobic digestion horse manure was regarded as suitable for plug-flow processes while stirred processes experienced more technical problems leading to increased cost for plants. With adaption of horse manure to the energy recovery technology to be used, and adaption at energy conversion plants to homogenous materials, this not yet fully utilized bioenergy resource has potential to contribute with renewable energy to the energy system, and thereby also reduce environmental impact from horse manure treatment.

Keywords: horse manure, environmental systems analysis, energy systems, renewable energy, environmental impact, anaerobic digestion, biogas, biofertilizer, systems perspective, bedding, incineration, composting, horse manure utilization

Sammanfattning

Ett hållbart energisystem kräver, enligt energipolitikens uppsatta mål, minskade utsläpp av växthusgaser, ökad andel förnybar energi och mer effektiv användning av energi. Hästgödsel kan ses som avfall, men också som en resurs av förnybar energi och näringsämnen. Denna avhandling undersöker hästgödsels potential som förnybar energiresurs, och hur hästgödsel kan stödja och bidra till uppsatta energi- och miljömål. För att genomföra detta har information insamlats från litteratur, simuleringar, studiebesök och intervjuer.

Vid bedömningen av hästgödsel som energiråvara och näringsresurs identifierades ett antal aktiviteter i hästhållningen med påverkan på mängden och innehållet i hästgödseln. Dessa var utfodring, hästhållning inomhus och utomhus, lagring av gödseln, gödselspridning och transport. Resultaten indikerade att valet och mängden av strömaterial hade betydelse för energibalans och metanutbyte och för innehållet i biogödseln. Driftsaspekter som lång uppehållstid och hög temperatur visade sig ha mindre inverkan vid bedömningen av hästgödsel som biogassubstrat. Jämfört med förbränning och kompostering gav biogasprocessen lägst potentiell klimatpåverkan, medan storskalig förbränning reducerade använd energi, samt potentiell försurning och eutrofiering. Vid en senare simulering uppvisade biogasprocessen lägre potentiell miljöpåverkan inom alla miljöpåverkanskategorierna, jämfört med kompostering. Enligt erfarenheter från energiaktörer kan hästgödsel i små mängder användas vid samförbränning i lämplig förbränningsugn, men lukt nämndes som ett problem. Förbränning på gårdsnivå behövde ständigt underhåll, övervakning och en inblandning av pellets. Som ett biogassubstrat ansågs hästgödsel lämpligt för pluggflödesteknik, medan omblandade processer innebar tekniska problem och därmed dyrare anläggningar. Resultaten visar att hästgödsel har möjlighet att bidra till en förnybar energiomvandling och till minskad miljöpåverkan. Detta kräver både anpassning av hästgödseln till den energiomvandlingsteknik som den ska användas i och lämpliga anläggningar för att behandla heterogena material.

Keywords: hästgödsel, miljösystemanalys, energisystem, förnybar energi, miljöpåverkan, rötning, biogas, biogödsel, systemperspektiv, strömedel, förbränning, kompostering, tillvaratagande av hästgödsel

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List of Papers

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 planning and data collection, wrote and revised the paper with support from co-authors, 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. Simulations were planned in cooperation with the co-author. Åsa Hadin performed the analysis of final simulations, wrote major parts, revised the paper with support from the co-author and was the corresponding author.

Paper III
Eriksson, O., Hadin, Å., Jonsson, D., Hennessy, J. (2016). Life cycle assessment of horse manure treatment. *Energies* (9): 1011
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Åsa Hadin contributed to data collection, analysis of results from simulations, writing the paper, revision of the paper, and was the corresponding author.

Paper IV
Hadin, Å., Hillman, K. & Eriksson, O., (2016). Prospects for increased energy recovery from horse manure – a case study of management practices, environmental impact and costs. *Energies* (10): 1935 (Feature paper)
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Åsa Hadin performed study design, contributed to planning, data collection and analyzed case data. Åsa Hadin extracted adapted case data for environmental impact simulations and calculations, and performed calculations of environmental impact from transports. Åsa Hadin analyzed data and wrote the paper with support from co-authors, revised the paper and was the corresponding author.

Paper V

Hadin, Å, Ryrholm, N. Energy recovery from horse manure - exploring energy actors' experiences. Manuscript.

Åsa Hadin performed the study design, contributed to data collection, performed analysis of results from interviews, wrote major parts of the paper, and was the corresponding author.

Other Publications

Abstract and presentation at Green Gas Research Outlook Sweden, 24th of March, 2014, Gävle, Sweden.

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.

Hadin, Å. (2016). *Anaerobic digestion of horse manure : renewable energy and plant nutrients in a systems perspective* (Licentiate thesis). Gävle University Press, Gävle. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-22716

Abstract and presentation at EUBCE 2018, 26th European Biomass Conference and Exhibition, 15th of May, 2018, Copenhagen, Denmark.

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Nomenclature

Abbreviations

AP	Acidification Potential
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
CH_4	Methane
C	Carbon
C/N	Carbon to Nitrogen Ratio
Cr	Chromium
CSTR	Continuous Stirred Tank Reactor
EP	Eutrophication Potential
ESA	Environmental Systems Analysis
GHG	Greenhouse Gases
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
IPCC	Intergovernmental Panel for Climate Change
K	Potassium
L-AD	Liquid Anaerobic Digestion
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
Mg	Magnesium
N	Nitrogen
NO_x	Nitrous Oxides
OLR	Organic Loading Rate
ORWARE	ORganic WAste Research
P	Phosphorus
POP	Persistent Organic Pollutant
SFA	Substance Flow Analysis
Si	Silicon
SRT	Solids Retention Time
SS-AD	Solid State Anaerobic Digestion
TS	Total Solids
TOC	Total Organic Carbon
UC	Unmanaged Composting
UASB	Upflow Anaerobic Solid Bed
UASS	Upflow Anaerobic Solid-State Reactor
VS	Volatile Solids
Zn	Zinc

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1. Introduction

1.1 Background

World primary energy use is mainly supplied by non-renewable resources (oil, coal, gas and nuclear energy) (Grubler et al., 2012), and causes substantial environmental impact due to land use and emissions to air and water (Emberson et al., 2012). The energy sector, together with the transport sector, accounted for 49% of the global anthropogenic greenhouse gas (GHG) emissions in 2010 (IPCC, 2014). In 2016, 26.9% of EU-28 gross electricity consumption was produced from renewable energy sources. Renewable energy accounted for 19.1% of heating and cooling, while 7.1% was the share of renewables in transport (European Commission, 2018). The European Commission stated in 2010 that a more sustainable and secure energy system is one of the greatest challenges for Europe. Energy savings and increased energy efficiency were mentioned as measures to reduce greenhouse gas emissions, together with control of European energy consumption and increased use of renewable energy. Use of energy from renewable sources was also mentioned as an effective tool to reduce dependence on imported oil and thereby improve energy supply security (EC No 1096/2009). The renewable energy directive (RED) promotes energy from renewable non-fossil sources (e.g. wind, water, solar and biomass) (2009/28/EC). A target of 27% renewable energy consumption in the European Union in 2030 is part of the transition of the European energy system to renewable sources of energy (European Council, 2014). There are several reasons for a transition to more renewable energy in the energy system, e.g. emissions of GHG and associated GWP, health risks with combustion of fossil fuels, depletion of fossil fuels and energy supply security (European Commission, 2017; Mathiesen et al., 2015; Yang, Ge, Wan, Yu, & Li, 2014). Biomass comprising organic matter from plants and animals, material with biological origin, (Ba, Prins, & Prodhon, 2016; Mafakheri & Nasiri, 2014) is one of the most widely used renewable energy sources (Mafakheri & Nasiri, 2014). This raises the question of sustainable use of biomass and an interest in society and academe in use of organic waste and other organic material as feedstock for renewable energy production. Biogas produced from organic waste uses material for energy not intended for food or feed, and does not compete for land use as biofuel crop cultivation (2015/1513/EU; Hellmann & Verburg, 2010; Mönch-Tegeder, Lemmer, & Oechsner, 2014).

Objectives by the Swedish parliament for climate and energy include increased renewable energy share, increased energy efficiency and reduced greenhouse gases. This is specified with at least 50% renewable energy of total energy, at least 10% renewable energy in the transport sector, 20% less energy intensity and 40% reduced emissions of greenhouse gases by 2020 (Regeringens skrivelse 2015/16:87). In 2016 the share of renewable energy in Sweden was about 30% for transport fuels and about 70% in heating and cooling, while the share of electricity from renewable sources was about 65% (European Commission, 2018). A milestone in the Swedish environmental objectives is 70% reduction of greenhouse gas emissions by 2030 from transport within Sweden. To reach this there is a need for a transport-efficient society, with more efficient vehicles and increased share of renewable fuels (Regeringens skrivelse 2017/18:238). In 14 member countries of the IEA (International Energy Agency), the produced biogas was mainly used for heating and electricity in 2015, with Sweden as the exception (Svensson, Hoyer, & Murphy, 2016). Biogas produced in Sweden in 2016 was mainly used for vehicle fuel (64% of produced biogas) and heat production (about 20% of produced biogas 2016) (Swedish Energy Agency, 2017). Biogas represented 1.1 TWh of a total of 16.9 TWh biofuel in the Swedish transport sector in 2015 (Swedish Energy Agency, 2018). According to Swedish studies biogas used as vehicle fuel leads to the highest environmental benefits because of replacement of fossil fuels (Berglund, 2006; Lantz, Svensson, Björnsson, & Börjesson, 2007).

Biogas is a renewable fuel with GHG emission-reduction potential, which also contributes to rural sustainable development and new income opportunities for farmers according to the Renewable Energy Directive (RED) (2009/28/EC). Biogas content of methane (about 60%) and carbon dioxide (about 40%) (Berglund, 2006) is used for heat, electricity production, vehicle fuel after upgrading, and in the natural gas grid (Berglund & Börjesson, 2006). Biogas in Europe is produced from landfill, agricultural waste and energy crops (Ahlberg-Eliasson, Nadeau, Levén, & Schnürer, 2017). Organic waste (residuals from forestry, agriculture, and organic waste from industry and municipalities) is regarded as a significant resource for renewable energy, and agricultural residues have the greatest biogas potential of biomasses in the EU (Meyer, Ehimen, & Holm-Nielsen, 2016). Organic waste from agriculture includes manures from livestock, of which cattle and hog manures are most common as feedstock for anaerobic co-digestion (Mata-Alvarez et al., 2014). In Sweden the majority of biogas plants in 2016 were wastewater treatment plants, but the greatest proportion of biogas was produced from co-digestion plants with different mixes of feedstock (food waste, manure, food industry waste, slaughter waste, energy crops, etc.) (Swedish Energy Agency, 2017).

Lantz et al. (2007) stated that agricultural organic material in Sweden was underutilized as biogas feedstock, and Meyer et al. (2016) suggested that European agricultural residues, including manure, represented a potential for doubling the European biogas production in 2030, compared to 2015. Manure represented 11% of the total wet weight biogas feedstock in Sweden 2016 (Swedish Energy Agency, 2017), while Edström, Hansson, Olsson & Baky (2013) reported manure to represent 38% of the theoretical biogas potential feedstock in Sweden and horse manure to be 23% of this theoretical potential. Increased interest in horse manure as a biogas feedstock was reported in e.g.

Mönch-Tegeder et al. (2013) and Wartell et al. (2012), related to large quantities of stall waste, i.e., bedding and dung, for horse keepers to handle. A horse produces about 9 tonnes of dung and urine per year (Lawrence, Bicudo, & Wheeler, 2003) or about 11 tonnes of faeces and bedding annually (Nitsche, Hensgen, & Wachendorf, 2017). In the literature bedding ranges between 25% (Cui, Shi, & Li, 2011) and 90% (Malgeryd & Persson, 2013) in the mix of collected horse manure. Horse manure potential as a biogas feedstock calculated from 363,000 horses diverged between 220-440 GWh in Sweden (Edström et al., 2013). This was the number of horses defined in the 2010 estimated statistics (Enhäll, Nordgren, & Kättström, 2012) and compared to the total energy use in Sweden in 2016 it represented 0.1% of the energy use (Swedish Energy Agency, 2018). Nitsche et al. (2017) presented gross energy yields from anaerobic digestion of horse manure (horse dung and bedding) of 10.8 GJ per horse annually for horse manure with wood shavings, and 22.0 GJ per horse and year for horse manure with straw. Europe's about 7 million horses (World Horse Welfare and Eurogroup for Animals, 2015) would then represent a gross energy potential of about 21 TWh–42 TWh, if anaerobically digested. These figures would represent 5.6-11% of the total energy use in Sweden in 2016.

1.2 Horse keeping and horse manure

The horse sector is a heterogeneous group of organizations differing in orientation of horse activities and organization. Horse-related activities include riding, trotting, tourism, breeding, and/or education. Horse activities are important for rural areas (Zasada, Berges, Hilgendorf, & Piorr, 2013), women and youth (Forsberg, 2007; Hedenborg, 2015; Thorell & Hedenborg, 2015), education and rehabilitation. Horse keeping farms consist of traditional farms, extensive horse-oriented farms, hobby horse keeping farms and extensive equine service farms. The variation includes differences in horse activities, farming, number of horses and areas for pastures (Zasada et al., 2013). Despite differences, all horse facilities produce horse manure, for some perceived as waste, and for others a valuable resource. Horse manure as a waste fraction from horse facilities produces odors (Haeger-Eugensson, Ferm, & Elfman, 2014), costs for off-site hauling (Wartell et al., 2012), and is detrimental to water quality (Airaksinen, Heiskanen, & Heinonen-Tanski, 2007; Parvage, Ulén, & Kirchmann, 2013; Prokopy, Perry-Hill, & Reimer, 2011). From another point of view it is a resource for energy (Böske, Wirth, Garlipp, Mumme, & Van den Weghe, 2014, 2015; Kusch, Oechsner, & Jungbluth, 2008; Linné et al., 2008; Luostarinen, 2013; Wartell et al., 2012) and plant nutrients (Keskinen et al., 2017).

Horse manure is in general a mix of horse dung, used bedding material and urine soaked in used bedding material as described in e.g. Airaksinen, Heinonen-Tanski, & Heiskanen (2001). This mix was called stall waste in Wartell et al. (2012), which investigated horse manure with or without bedding. Horse dung was explained as feces without bedding in Mönch-Tegeder et al. (2013).

In this thesis horse manure was used for a mix of horse dung and used bedding, but the variations and specific definitions are visualized in the data from the literature review. In simulations horse manure represented a mix of horse dung and fresh bedding. Horse manure management, storing and spreading is regulated in environmental and agricultural legislation, e.g. Swedish Environmental Code (SFS 1998:808) and legislation about environmental consciousness in agriculture (SFS 1998:915) in Sweden. Legislation regulates horse manure storage capacity, environmentally conscious storage and spreading in agriculture, applicable to most horse facilities in Sweden. Temporary storage and composting in fields are allowed. If used as a fertilizer horse manure should be applied according to regulations on the amount of plant nutrient loads and soil incorporation. Requirements on manure management at horse facilities not classified as agricultural holdings are guided by potential environmental risks and follow local adjustments. Defined as an animal by-product horse manure is allowed to be incinerated, landfilled, used for fertilizer production and composting, used as a biogas feedstock and applied to land (2011/142/EU; EC No 1096/2009). Landfill of organic waste is prohibited in Sweden since 2005 and instead horse manure disposed of is used for contaminated soil treatment or as cover material at waste treatment plants. If disposed as a waste, horse manure can be incinerated in a combustion plant with permission for waste combustion (Edström, Schüßler, & Luostarinen, 2011).

A broad range of stakeholders are part of a bioenergy system, and include producers and suppliers of feedstock but also utilities and producers of transport fuels, end users, the financial community, technology providers, community members, policy makers, regulators and planners (Elghali, Clift, Sinclair, Panoutsou, & Bauen, 2007). Horse manure stakeholders are encompassed by horse keepers, as producers and suppliers of feedstock, end users as energy actors, transport planners with experience from horse manure transports, and officials working with the compliance of regulations regarding horse manure.

1.3 Challenges related to horse manure management

1.3.1 Horse keeping

Use of horses and locations of horse facilities have implications for horse manure management. Horse manure has been described as a substantial waste problem, and an abundant source of organic waste that causes costs for the horse industry (Böske et al., 2014, 2015; Mönch-Tegeder et al., 2013; Wartell et al., 2012). Used bedding material has been noted as an emerging issue, causing environmental and hygiene risks (Cui et al., 2011) and concern about nutrient runoff effects on water quality (Westendorf & Williams, 2015). Horses were previously used as draught animals for transport, agriculture and forestry, and horse manure was part of the natural cycle of plant nutrients to crops, from livestock and humans to arable land. During urbanisation local transport in cities relied on horses and environmental and health problems with horse manure management occurred, e.g. flies and smell nuisance because of manure piles (Biehler, 2010; McShane & Tarr, 2003). It is also described in literature how horse manure was used in extensive cultivation in compost beds, so called glass-enclosed hotbeds, which utilized the generated heat for plant growing (Smith, Aber, & Rynk, 2017). Horse industry today consists of hobby farmers, small-scale entrepreneurs and professionals that keep horses for leisure, breeding, sport and recreational purposes. This causes land-use related problems in densely populated areas, or peri-urban areas, where horse riding schools and racing tracks are located due to user accessibility. In rural areas conflicts occur when new equine activities disturb agricultural activities or new residential areas (Elgåker, 2012; Elgåker, Pinzke, Lindholm, & Nilsson, 2010).

1.3.2 Nutrients

Inflow of nutrients, conversion and addition of N and P due to human activities interfere with natural flows and cycles of nutrients, and cause undesired changes in natural ecosystems (Rockström et al., 2009). Phosphorus inefficiency and use of limited phosphate rock causes depletion of the resource, unused and lost P followed by human health problems and environmental impact (eutrophication) (Linderholm, Tillman, & Mattsson, 2012; Withers et al., 2015). When mineral fertilizer is used instead of biological nutrients, the material important for soil condition and for plant growing is not supplied. Moreno-Caselles, Moral, Perez-Murcia, Perez-Espinosa, & Rufete (2002) mention the problems faced if soil is depleted and humidifying soil is not recycled and the problems if heavy metals are added to agricultural land with use of mineral fertilizers which contaminates soil with cadmium derived from the raw material phosphate rock (Linderholm et al., 2012). Similarly, it is important in biogas systems to have a feedstock of a certain quality for low levels of contaminants in the digestate (Gregson, Crang, Fuller, & Holmes, 2015). This can be met by exclusion of unsuitable feedstock, with contents of e.g. heavy metals and persistent organic pollutants (POPs) (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009) to accomplish a digestate from co-digestion and farm-based biogas plants that meets the quality requirements as biofertilizer.

1.3.3 Transports

Transportation is a condition in the development of biomass energy systems (Forsberg, 2000). Transports create a biomass supply chain together with collection, storage, pre-treatment and finally energy conversion. The biomass supply chain management objectives are to ensure continuous feedstock supply, as well as minimize costs and environmental impact (Mafakheri & Nasiri, 2014). Use of biomass energy resources contribute to feedstock diversification and thereby security in energy supply (McKendry, 2002). Utilization of local resources was one of the issues mentioned in Poeschl, Ward, & Owende (2010) to reach expanded biogas production and sustainable feedstock supply. That increased transport of feedstock needs to gain public acceptance together with other aspects of concern for location of biogas plants, e.g. noise and odor, was also highlighted in Poeschl et al. (2010). Transports are also necessary in an energy system where horse manure is considered a bioenergy source. A key issue is if transportation to energy conversion could be regarded as environmentally viable. This is affected by factors such as distance, quantity, timing and location of suppliers. Transportation is regarded as a prerequisite for the development of a bioenergy system while it also means an increased level of emissions and energy input which reduces the benefits from bioenergy (Forsberg, 2000). Freight shipments by truck over short and medium distances (below 300 km) need to be improved in efficiency e.g. efficient engines, cleaner fuels and intelligent transport systems (European Commission, 2011b). In general larger and fewer transports are positive from an environmental point of view (Aronsson & Huge Brodin, 2006). Centralized distribution systems enable reduced environmental impact by so called consolidated flows of goods. Larger and more stable transport flows lead to better utilization of vehicles, which reduces fuel consumption and thereby emissions from transports (Kohn & Brodin, 2008). The need for policy measures to promote bioenergy in general, mentioned in Elghali, Clift, Sinclair, Panoutsou, & Bauen (2007) also applies to horse manure, regarded as an underused source of biomass feedstock (Svanberg, Finnsgård, Flodén, & Lundgren, 2016).

1.4 Opportunities related to horse manure as energy resource

The EU encourages a shift from a linear to a circular economy in a Roadmap to a resource efficient Europe (European Commission, 2011a), i.e., shift to circular economies with closed material loops similar to natural ecosystems. Resource recovery of energy (mentioned above) and of plant nutrients in horse manure close material loops in line with circular economy systems. The study of products from cradle to grave with life cycle assessment and material flow analysis enables measures to turn waste to resource as a means for a circular economy. Anaerobic digestion of animal manure combines reduced emissions with energy generation and nutrient recycling (Meyer et al., 2016) which contributes to a circular economy in turning waste to resource (Gregson et al., 2015). In a circular economy, waste management strategies follow the waste hierarchy that states the priority order in waste prevention, legislation and policy: reduce, reuse, recycle, energy recovery and disposal of waste (2008/98/EC). To decrease the amount of waste to disposal the order of the waste hierarchy should be followed with activities for reduction first. Prevention, and other measures, could also be applied to horse manure, which in legislation is considered agricultural organic waste (SFS 2011:927) if it is collected and treated off-site. The classification as an animal by-product (Commission regulation 1069/2009) still motivates reduction followed by use as an organic fertilizer and energy recovery. By-products could be described as secondary resources according to Djuric Ilic et al. (2018) and this is in line with a circular economy to turn waste into resources (European Commission, 2011a).

1.5 Aim of thesis

This study is motivated by the anticipated increased use of bioenergy, and need for efficient waste management at horse facilities. This study aims to explore resource recovery from horse manure in a systems perspective, i.e., energy performance and potential environmental impact from various horse manure treatment. Resource recovery in this study comprises energy recovery and recycling of plant nutrients to agricultural land. Focus is on critical factors for horse manure as a feedstock in anaerobic digestion, given the conditions in specific simulations, literature and field observations. The study and systems comparisons are conducted to provide information to facilitate future choices and decision making about horse manure management for horse keepers, energy actors and policy makers.

Research questions are:

1. What potentially critical factors in horse keeping affect the amount and characteristics of horse manure?
2. How do feedstock characteristics and biogas process parameters affect energy performance and nutrient content in biofertilizer?
3. What is the potential environmental impact from anaerobic digestion of horse manure in comparison to other treatment methods?
4. How do potential energy actors view horse manure as an energy resource?

1.6 Scope and limitations

The scope of this thesis covers horse manure treatment. The studied systems, visualized in Figure 1, comprise a system where horse manure is treated in different treatment options and contributes fertilizer and biofuel. System boundaries are set to visualize treatment options for horse manure. Environmental impact from horse keeping is qualitatively discussed in the system, with data and descriptions collected from literature studies on horse manure and horse keeping. The literature study added both qualitative and quantitative information about horse keeping and horse manure production. The descriptions in this study are general descriptions, necessitating interpretations for each specific case. In the simulations horse manure (horse dung and bedding) was treated as a waste feedstock for bioenergy with zero environmental impact entering the studied systems. Simulations aimed to quantify the environmental impact for different treatment options and the energy balance in the biogas process for a chosen amount of horse manure. Simulation results should be interpreted as indicative due to the uncertainties in input data, although sensitivity analyses were performed. The study was performed in a regional Swedish view, with local respondents in the case study, and with international outlooks in literature reviews.

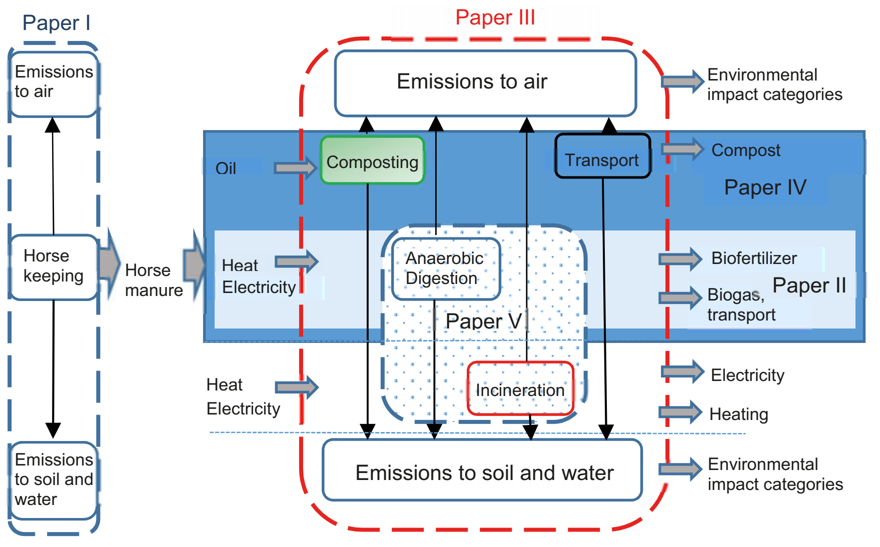

Figure 1. Energy analysis and material flow analysis in Papers I, II, III and in Paper IV. Paper I illustrated with blue dashed line, Paper II light blue shaded, Paper III red dashed line, Paper IV dark blue shaded. The interview study in Paper V is illustrated with dots.

1.7 Appended papers

1.7.1 Paper I

Paper I (Hadin, Eriksson, & Hillman, 2016) identified factors of significance for horse manure as a biogas feedstock and environmental impact from horse keeping (Figure 1). Paper I addressed research question 1, and increased the understanding of the underlying conditions in manure generation in using horse manure as a feedstock for combined energy recovery and nutrient recycling in anaerobic digestion. The literature review provided data describing environmental impact from horse manure management, and horse keeping effects on horse manure characteristics and amount. Critical factors identified were feeding, indoor housing, outdoor keeping, manure storage, fertilization and transport.

1.7.2 Paper II

Paper II (Hadin & Eriksson, 2016) addressed research question 2. Important aspects for anaerobic treatment of horse manure were identified, described, analyzed and discussed. Methods applied for this were a combination of literature review and mathematical modelling. Horse manure characteristics as a biogas feedstock were described in terms of total solids (TS), volatile solids (VS), macronutrients, micronutrients, carbon nitrogen quota, digestibility, impurities and inhibitors, from literature. Manure characteristics and biogas process parameters tested in simulations in the mathematical model ORWARE were bedding type and mixing ratio, retention time, and digester temperature. Simulations pointed to the important choice of bedding and amount of bedding, both for energy aspects and plant nutrient content in the biofertilizer. Long hydraulic retention time and high temperature had less impact.

1.7.3 Paper III

In Paper III (Eriksson, Hadin, Hennessy, & Jonsson, 2016) life cycle assessment, through simulations in ORWARE, was used to compare environmental impact from unmanaged and managed composting, small and large-scale incineration, and anaerobic digestion. This paper addressed research question 3. While anaerobic digestion was suggested to give the lowest global warming potential (GWP) compared to incineration and composting, large-scale incineration reduced primary energy demand, acidification potential (AP) and eutrophication potential (EP). The results add information to the study's aim to describe environmental impact from alternative treatment methods of horse manure.

1.7.4 Paper IV

Paper IV (Hadin, Eriksson, & Hillman, 2017) explored horse manure treatment in a case located in a municipality and compared environmental impact from horse manure treatment in business as usual (BAU) with a treatment option in an expected biogas plant and associated transports. Data from the case was analyzed and used as input data in simulations of composting and liquid anaerobic digestion. Anaerobic digestion was indicated to have lower environmental impact than BAU, regarding all chosen environmental impact categories in the study. The study contributes to the thesis by adding the environmental and economic aspects of transports and anaerobic digestion in a case and addresses research question 3.

1.7.5 Paper V

Paper V addressed research question 4, and included an interview study with energy operators with experience of using horse manure as an energy resource. Energy actors' experiences from anaerobic digestion and incineration of horse manure diverged depending on process. This information was used to explore constitution of horse manure for energy purposes. Conclusions were that horse manure for energy purposes needs to be dry, due to transport efficiency and incineration. It should not contain any solid impurities, which was stated as problems in anaerobic digestion, except in the plug-flow process. Furthermore, suitable bedding was wood in small-scale incineration and plug-flow process. Otherwise, straw pellets were usually mentioned as preferred type of bedding.

2. Methods

The result of the current study is the product of data collected from literature reviews, systematic combining, interviews and environmental systems analysis (Table 1). Literature reviews were performed in all appended papers. Literature review was one part in systematic combining in Paper I, and was combined with environmental systems analysis (ESA) in Paper II-IV. Systematic combining was used to connect literature reviews and field observations. In Paper IV and V interviews were added to the method. Interviews comprised telephone interviews, e-mail questionnaires, interviews at field observations and study visits, and various combinations of these. Personal communication with people having specific knowledge also provided data for the study. The inventory studies resulted in qualitative descriptions as well as specific numerical data for computer simulations (environmental systems analysis in terms of LCA). By using environmental systems analysis potential environmental impact from anaerobic digestion, incineration and composting of horse manure were compared in Paper III, and anaerobic digestion and composting in Paper IV. The study in Paper IV was inspired by a case study design. The analysis of collected data in Paper V was influenced by qualitative content analysis.

Table 1. Methods used in the thesis.

Method/Paper	**I**	**II**	**III**	**IV**	**V**
Literature review	X	X	X	X	X
Systematic combining	X				
Interviews				X	X
Environmental systems analysis		X	X	X	

In the thesis, results from papers and literature were analyzed to explore the prospects for increased resource recovery of horse manure, and how to interpret the results from the different papers. Finally, the different study designs and variances in results from all papers were used to analyze whether results concurred, disagreed or complemented to each other.

2.1 Research process

The research process was gradually designed out of theory, practice and personal experience. It is for the most part an exploratory and descriptive qualitative study. It is exploratory because of the investigations included and identification of energy and environmental questions of increased resource recovery from horse manure in a system perspective. It is descriptive due to the identification and description of aspects of importance in current and optional treatment methods. Exploratory studies investigate phenomena and identify or discover categories of meaning, problems and questions while descriptive studies also describe the phenomenon of interest (Marshall & Rossman, 2016). The qualitative descriptions were complemented with quantitative results from simulations, indicating potential environmental impact from treatment options.

The investigation started with the idea to turn horse manure from a waste problem to a renewable energy resource. The plan was to define the number of horses, location and how horse manure was treated in a specific area. Whether alternative treatment methods with improved energy recovery could reduce environmental impact was part of the continued investigation (Figure 1). The research process was characterized by cooperation with participating researchers, where co-authors added data and knowledge through simulations and during calculations of energy and emissions associated to transportation of horse manure, respectively. Literature reviews resulted in theoretical data while meetings, interviews and study visits collected both qualitative and quantitative information from the field. Results from simulations added quantitative information from current and changed horse manure management.

Study visits with field observations and interviews acted as complement to literature studies and questionnaires and were performed during periods of the research process. Observations at horse facilities and interviews aimed to give a wider understanding about the horse facilities' activities and horse manure management. Other study visits took place at biogas plants in operation, treating farm-based substrates (manure) and organic fractions of municipal solid waste. A regional Swedish project (Eriksson, Hadin, Hennessy, & Jonsson, 2015; Hadin, Eriksson, & Jonsson, 2015; Hennessy & Eriksson, 2015) and additional reports (in Swedish) formed a basis for the research reporting in Papers I-III.

2.1.1 Case study design

As a part of the research process a case study designed to horse keepers' current horse manure management practices (on site collection, storage and utilization) in a Swedish municipality provided quantitative and qualitative data for a combined assessment. The study (Paper IV) was inspired by an embedded single case study design where multiple units of analysis create the context of the case (Yin, 2003). The current situation in horse manure management was explored with interviews, personal communication and field observations. Horse manure treatment was qualitatively described and a quantitative analysis was performed with environmental systems analysis. Despite several attempts it was not possible to establish the current number of horses and their location in a specific area.

Preparations started with an initial questionnaire provided to horse keepers to gather some preliminary experiences from horse manure management. This was followed by personal contacts with officials at the Administrative County Board and at a municipal council committee in the specific municipality. These provided lists of horse keepers in the municipality, not recently updated. In several attempts to find the current number of horses, data was collected from insurance companies, veterinarians and breeding associations. Furthermore, websites were studied, looking for information about horse manure management in different municipalities in one county. These investigations contributed to knowledge for continued research. Finally, the lists with information from the Administrative County Board and the municipal council committee was used as a basis for telephone interviews. The final questionnaire was developed from a first test interview, and discussions with colleagues at the university. Telephone interviews were performed with as many horse keepers as possible during one week. Experiences from data collection by questionnaires through e-mail and by telephone interviews were used later in the research process when energy actors´ experience with horse manure was investigated.

2.2 Literature review

The literature review was predominantly a document review of peer-reviewed scientific papers, but also reports, books and information material from authorities addressing themes of interest for the research project, i.e., horse keeping and manure management, biogas plant configurations, composting, incineration, and medicines in horse manure. Horse keeping comprises feeding, housing, storage, treatment and spreading of horse manure. Research centers were e.g. the Swedish Institute of Agricultural and Environmental Engineering, and agencies, e.g. the Swedish Board of Agriculture. The literature search for peer-reviewed scientific papers was made by using databases such as Discovery, Science Direct, Google Scholar and search services for journal papers, conference papers and e-books.

The literature review was performed as consecutive literature searches and studies including horse keeping environmental impact with focus on horse manure management. Literature on horse manure characteristics with respect to biogas aspects was reviewed, and qualitatively analyzed with the aim to (1) qualitatively describe horse keeping effects on horse manure amount and content, and (2) find quantitative information and data for simulations. Biogas technology in terms of operational factors (temperature), reactor configurations (single- or two-stage reactors), operational mode (batch or continuous) and biofertilizer management was also reviewed, as well as relevant papers and reports on combustion and composting of horse manure. The aims were to compile information about horse manure as an energy resource in anaerobic digestion and incineration and describe resource recovery from horse manure through composting and anaerobic digestion.

2.3 Systematic combining

A process of going back and forth between information from field observations, personal contacts, meetings, literature reviews, and data matching created direction and redirection in the research project (Figure 2). Informal meetings and open, less predetermined discussions about horse manure treatment discovered active data, while literature searches and preparing for and conducting interviews contributed to the passive data in the project. The method, predominantly used in Paper I, can be described as a "systematic combining" approach, where multiple sources of data were used and theory and reality were matched during the research process, as described in Dubois and Gadde (2002). Study visits and interviews at sites aimed to understand the reality and confront information from literature with the empirical information as a part of the research process, in the same way as the use of and shift between different research methods. Parallel with field data collection, literature about methods for performing the data collection as well as about horse manure as a biogas feedstock were reviewed.

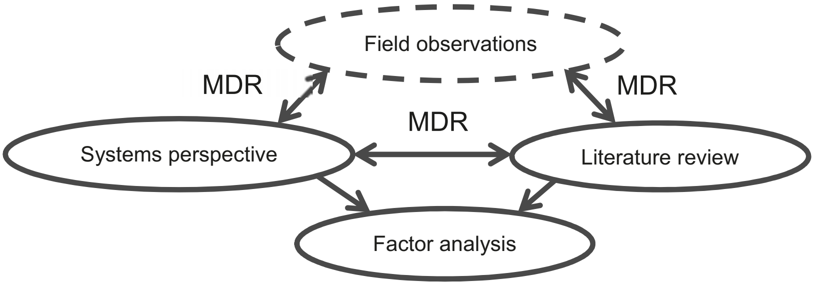

Figure 2. The modified systematic combining approach used in this project (after Dubois & Gadde, 2002). Arrows represent matching, direction and redirection (MDR).

2.3.1 Field observations

The literature reviews were used to retrieve information that directed further search for information and were matched and confirmed with field observations. During the research project three riding schools, a race trotting track, one small-scale solid state anaerobic digestion plant (garage type), two full-scale plug-flow anaerobic digestion plants, two farm-based co-digestion liquid anaerobic digestion plants, one liquid anaerobic digestion plant for municipal organic waste, and a bedding producer were visited. At the visits the organizations' process, horse manure management or biogas processes were presented, both by walk around, discussions and oral presentations, and sometimes complemented with interviews with organization representatives. Participating in meetings with farmers, horse keepers and officials from the Swedish Rural Economy and Agricultural Society (Hushållningssällskapet), Swedish Institute of Agricultural and Environmental Engineering (former JTI, now RISE, Jordbruk och livsmedel), biogas plant constructors and users acted as communication platforms. These meetings developed contacts in the area of interest, and visualized different actors' points of view about horse manure, biofertilizer and producing biogas feedstock.

2.4 Interviews

During literature review and document studies, specific stakeholders and respondents were identified as suppliers of information. Some were contacted for interviews, mainly by telephone, for informal interviews about specific topics, or for semi-structured interviews with an interview guide, a questionnaire, with a series of questions about horse manure management. In some cases semi-structured interviews were held during study visits.

2.4.1 Questionnaires

Horse keeping in one specific municipality was visualized by information gathered by a questionnaire about horse manure management in Paper IV. The questionnaire consisted of quantitative questions which were presented to the horse keepers by telephone. This aimed at describing how horse manure treatment was conducted in the specific municipality. In total information from 81 interviews was collected of which 60 respondents provided information on both the amount of horse manure and type and amount of bedding. These results were used for descriptions of bedding, storing, and for calculations of environmental impact from manure collection and in simulations of environmental impact from composting and anaerobic digestion.

In Paper V energy actors' experiences of, or knowledge about, horse manure as an energy resource was explored. A questionnaire was sent to energy actors by e-mail or used as an interview guide for semi-structured telephone interviews. Respondents represented 13 energy actors, consultants, investigators and researchers. Five had experience from incineration with horse manure as fuel, and eight had experience from anaerobic digestion of horse manure as substrate. The respondents represented, or referred to, incineration plants where horse manure was co-incinerated with wood pellets, woody biomass or solid waste. Anaerobic digestion respondents referred to anaerobic digestion in general, wet digestion processes (L-AD) or dry digestion processes (SS-AD). Experience from wet anaerobic digestion was from co-digestion with other livestock manure, full scale or laboratory scale. SS-AD represented anaerobic digestion of solely horse manure, and co-digestion with municipal organic waste in a stirred process and in a plug-flow anaerobic digestion process. Answers were compiled, categorized, complemented with information from literature and analyzed in a structured manner.

2.4.2 Personal communication

People with experience regarding horse manure were contacted by telephone and sometimes visited during information and data collection in the research process. Examples of these areas of knowledge were:

- Horse keeper's situation regarding horse manure
- Swedish statistics on horse keeping
- Anaerobic digestion of horse manure
- Use of medicines and statistics about horse-related use of medicines
- Horse manure treatment at waste and composting companies, collection and transport

2.5 Environmental systems analysis

Systems analysis is an approach for integrated analysis and evaluation of complex systems, and a systems perspective has characterized the studies in this thesis. Methods for environmental systems analysis aim to ensure that environmental factors are taken into consideration in planning and at decision points. In a system, different entities, called sub-systems, interact with each other (Björklund, 1998). The system boundaries determine what is analyzed in the systems analysis, and are defined in time, space and function (Björklund, 1998).

Two common methods for environmental systems analysis used in this thesis are substance flow analysis (SFA) and life cycle assessment (LCA). SFA, extensively used for decision making in environmental management and waste management, focuses on individual substances (chemical elements and compounds) (Brunner, 2012). This is a distinctly different focus, according to Brunner (2012) compared to material flow analysis (MFA), which presents physical flows of material, often in kg. The amount of material used in an MFA gives a rough, indirect valuation of environmental impact (Moberg, Finnveden, Johansson, & Steen, 1999). Moberg et al. (1999) describe SFA as an MFA concentrated to substances. In SFA resource management is supported by data about substance flows and the mass balance principle, matching imports and exports of substances into the system. By means of SFA scarce, depleting or accumulating resources in a system can be identified (Brunner, 2012).

Life cycle assessment describes the environmental aspects and potential environmental impacts from a product during the life cycle (from cradle to grave) (European Committee for Standardization, 2006). In an LCA the system boundary specifies the product system with one or several functions. Within the product system there are unit processes with inflows and outflows. Data collection is made in the life cycle inventory analysis (LCI) and the potential environmental impacts are evaluated from the LCI result (European Committee for Standardization, 2006). This is performed using the mandatory elements in what is known as a life cycle impact assessment (LCIA) of the LCA: selection of impact categories, category indicators and characterization models followed by an assignment of inventory data (LCI results) to specific environmental impact categories (classification) and calculation of category indicator results (characterization) (European Committee for Standardization, 2006; Klöppfer & Graal, 2014).

This thesis used results from the computer based tool ORWARE (Eriksson et al., 2002) to describe environmental impact of waste management processes for horse manure. In ORWARE simulations result in quantitative environmental systems analysis by compiling material flow analysis (multi-SFA) with LCA output and input inventory and characterization of emissions into potential environmental impact categories (EIC) (Figure 1). Environmental impact categories were selected based on findings in Paper I on horse manure environmental impact. The impact categories considered were climate change (GWP), acidification (AP) eutrophication (EP) and cumulative energy demand (CED). The characterization factors used for the conversion of the results to the same impact category were selected from state-of-the-art impact assessment methods such as climate change (Solomon et al., 2007), acidification (Huijbregts, 1999), and eutrophication (Heijungs et al., 1992). Cumulative energy demand (CED) is a resource accounting method that quantifies the cumulative energy use. CED accounts for energetic resources and biomass and their energy and heating value (Alvarenga, Lins, & Almeida Neto, 2016). CED is used as the energy indicator in the simulations, valued as primary energy demand/use in the life cycle (Klöppfer & Graal, 2014). Energy used in the core system (energy input) was summarized and compared to energy gained in the core system (energy output). Energy input compiles the energy used within the system (the sum of energy used for collection, transport, biogas plant operation, biogas upgrading, digestate handling and storing), while output represents the energy conversion from the feedstock (Poeschl, Ward, & Owende, 2012). Depending on system expansion, energy needed for associated energy conversion in the compensatory system was also added to the studied system. This was the case in Paper III.

2.5.1 The explored system

The explored system consisted of inflows and outflows of material and energy, waste management processes (anaerobic digestion, composting and incineration), and transport work (Figure 3). Inflows to the system consisted of heat, electricity, fossil fuels and horse manure (horse dung and bedding). Outflows consist of produced biofertilizer, biogas, compost, heat and electricity. These products create benefits when they replace mineral fertilizers and fossil fuels. Paper II had a process perspective, and studied impacts from horse manure characteristics, operational and operative aspects on energy production and plant nutrients in an L-AD, with sanitization. Results were not characterized. In Paper III, ORWARE was used to calculate, compare and evaluate potential environmental impact from anaerobic digestion with pre-treatment, production and use of biogas and plant nutrients in comparison to alternative horse manure treatment methods (incineration and composting) and their respective compensatory systems. Simulations in Paper IV were adapted to a specific case where potential environmental impact from unmanaged composting with use of organic fertilizer and avoided emissions from fossil fuels were compared to anaerobic digestion (L-AD, with sanitization) (Figure 3). In the case (scenario 2, Paper IV) the transport distances to an assumed anaerobic digestion plant were calculated from probable transport routes and size of vehicles. Environmental impact from transport was calculated based on the distances, use of fuel and amount of manure to collect.

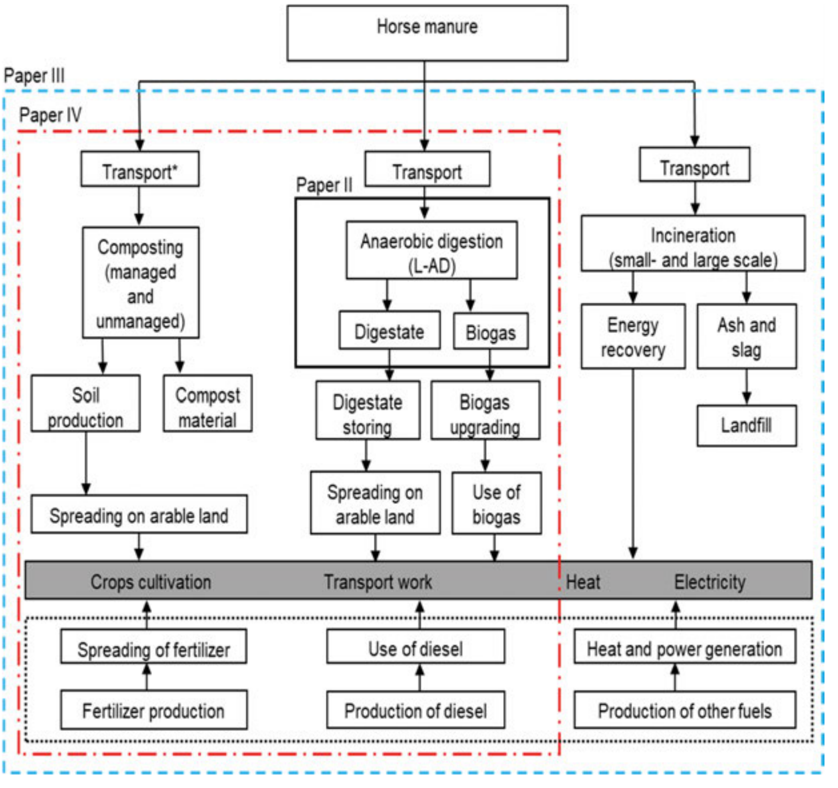

Figure 3. The studied systems, compiled from appended papers. The compensatory system is represented by a dotted black line. The studied system in Paper II is visualised with a solid black line. The studied system in Paper III is visualized with a dashed blue line, and the studied system in Paper IV is visualized with a dashed and dotted red line. *Transport to composting is not part of the systems analysis in Paper IV.

In order to make the different horse manure treatment methods comparable and functionally equal, system expansion with environmental impact from compensatory systems was used in Paper III, while an avoided burden approach (avoided emissions) from the compensatory systems was used in Paper IV. System expansion provides equal benefit by addition of functions to create equivalent functions in the systems. Compensatory systems in Paper III consisted of conventional supplies of electricity (coal condensing power), district heating from biomass, diesel oil as vehicle and mineral fertilizer (NPK). In the latter (avoided burden) the systems expansion included subtraction of environmental loads related to the compensatory system from the core system (Klöppfer & Graal, 2014). It can also be described as credits given to the anaerobic digestion system (production and use of biogas) for avoided production and use of fossil fuels (Hillman & Sandén, 2008). In Paper IV avoided burdens consisted of conventional vehicle fuel and mineral fertilizer. The mathematical model is designed to compare mineral fertilizer and residues from compost and anaerobic digestion in crop utilization (fertilization effect) and soil emissions when organic fertilizers replace mineral fertilizers (Dalemo, Sonesson, Jönsson, & Björklund, 1998).

While Paper III explored environmental impact and energy performance from different horse manure treatment methods, Paper II investigated the effects of bedding type and amount for horse manure as a biogas feedstock. Retention time and temperature were also simulated. Energy performance from, and nutrient content in, a fixed amount of horse manure consisting of horse dung and wood shavings, peat, straw or paper were tested. Paper IV added the specific circumstances from the case municipality, with a specific bedding mix and ratio and a study where treatment in a biogas process replaced composting of horse manure.

2.5.2 System characteristics

The performed life cycle assessments explored one part of the horse manure life cycle: waste management. Horse manure entered the system with zero environmental impact (zero burden), i.e., upstream environmental impact was omitted, and the environmental impact from horse manure production was assigned to the horse activity such as riding education, sport and leisure, among other horse-related activities. Horse manure characteristics and the amount of horse manure, i.e., the chemical composition of the waste stream, formed the input of feedstock treated in the different simulations. The ORWARE model is based on general figures, assumptions and equations (Eriksson et al., 2005) and adaptions in the current studies were made, depending on study, for example in input data for waste descriptors, choice of processes, and energy use in biogas upgrading. Comparisons between different treatment alternatives were studied with the help of interventions resulting from treatment of different amounts of horse manure and changes in parameters in simulations. The functional unit (treated amount of horse dung) was 10,000 tonnes in Paper II, with 25% or 90% added bedding material in the simulated scenarios. These rates was chosen as a result of data in literature. In Paper III the functional unit was 15,000 tonnes of horse dung and wood bedding. The bedding rate in the mix was about 33%, a rate of bedding in between the previous studies. Paper IV amount of horse manure correspond to the amount of horse dung and bedding in the case, in total 4179 tonnes.

Simulated treatment methods were anaerobic digestion (Paper II) composting, anaerobic digestion and incineration (Paper III), and composting and anaerobic digestion (Paper IV) (Table 2). Unmanaged composting, representing an assumed base scenario, was modelled as an open windrow composting with 50% (Paper III) or 26% (Paper IV) of the composted horse manure left in a landfill-like treatment while the remaining part is used as biofertilizer on agricultural land. Managed composting was modelled as reactor compost adapted to drum composting with active mixing, aeration, turning and a biofilter to reduce methane and nitrous oxides. With managed composting, 100% of compost material was assumed to be transported and utilized as fertilizer on agricultural land. The effectiveness in plant availability for organic fertilizers corresponds to

100% of phosphorous, 80% of mineral nitrogen and 30% of organic nitrogen in comparison to mineral fertilizers (Sundqvist et al., 1999). Losses of nutrients from spreading on soil depend on spreading equipment, time span, climate and soil (drainage). In the case of incineration no residues were spread on farmland, resulting in no modelled influence from soil emissions from fertilizers.

Simulations of anaerobic digestion in Papers II and IV included anaerobic digestion in a full-scale continuously stirred tank reactor (CSTR), with sanitization (Table 2). In Paper III the simulated anaerobic process represented a liquid anaerobic digestion process (L-AD) including pretreatment (thermal hydrolysis with steam explosion), more energy efficient than the sanitization process in Papers II and IV. Other differences between the studies were functional unit, bedding rate, biofertilizer to agricultural land and energy demand for upgrading. The anaerobic digestion process included mesophilic process and HRT 30 days, but was sensitivity tested with respect to temperature and retention time in Paper II (Table 2). The validity of the anaerobic digestion sub-model was tested by a comparison of methane potentials in literature (Eriksson et al., 2015). Generated biogas was upgraded for the transport sector with a water scrubber, and transported 50 km to fuel station. Fuel was used for buses and cars in Paper III, and for buses in Paper IV. Biofertilizer was assumed to be transported 50 km to field application. In Paper IV input data for upgrading was adapted to upgrading technologies with lower energy demand, and emissions of nitrous oxide (NO_x) data was adapted to biogas buses.

Table 2. Description of parameters used in simulations in Papers II, III and IV.

Parameters	Paper II	Paper III	Paper IV
Functional unit (tonnes)	10,000	15,000	4,179
Feedstock	Horse dung and 25% and 90% added bedding (wood, straw, peat, paper)	Horse dung and 33% wood bedding in the mix	Horse dung with 13% bedding (mix of wood, straw and peat)
Process(es)	L-AD with sanitization	L-AD with thermal hydrolysis Upgrading Composting Incineration	L-AD with sanitization Upgrading Composting
Sensitivity analysis	Amount and type of bedding, HRT, temperature	Fuels for district heating and electricity Biogas offset	Trp distance Amount manure in transports Trp vehicles Trp fuel Type of bedding

Incineration comprised large and small-scale incineration (Table 2). Large-scale incineration corresponded to about 500,000 tonnes added waste resulting in 1.5×10^6 of MWh heat and 200×10^3 MWh electricity. In the large-scale incineration plant, horse manure was co-combusted with household waste in a waste CHP plant equipped with efficient air pollution control. Ash and slag were disposed in landfill and mineral fertilizers were used on agricultural land. Small-scale incineration (about 350 kW), modelled as a heat generating farm-scale combustion plant with pre-drying, lacked air pollution reduction equipment.

Sensitivity analysis of various parameters was performed in the studies to address uncertainties and to test potentially important assumptions (Table 2). In Paper II and Paper IV different bedding types (peat, straw, wood chips, paper) were varied. In Paper II bedding ratios (20%, 47%), HRT (20, 30 and 90 days) and temperature (37°C and 55°C) were varied as well. Variations in alternative heat source, from biomass to coal, change of fuel for electricity from fossil to renewable and change from upgrading and vehicle fuel to combustion of biogas in a gas engine producing heat and electricity were performed in Paper III. In Paper IV transport distance, amount of manure, and type of vehicle fuel were also sensitivity checked, not in simulations but in calculations of variations of the aspects.

3. Horse manure as feedstock for resource recovery

It was stated in Paper I that activities in horse keeping determine the amount (total weight) and characteristics (nutrient content and biodegradability) of horse manure. Thereby these activities also determine the potential for anaerobic digestion. Important horse keeping activities were identified as feeding, indoor housing, outdoor keeping and manure storage, fertilization and transport (Figure 4).

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 4. Summary of activities and crucial factors for using horse manure as a biogas feedstock (Hadin, 2016).

It was concluded that the amount of feces and urine, as well as the content of nutrients in the manure, are related to type of feed, age, size of horses and their exercise level (Paper I). Non-working (sedentary) horses are in general fed with forages while exercised horses are also fed with supplementary feed, up to twice as much in energy amount as sedentary horses (Lawrence et al., 2003; Muhonen, 2008). Although exercised horses increase retention of nitrogen, and growing foals, pregnant and lactating mares use nutrients for growth and milk production (Cichorska, Komosa, Nogowsk, Maćkowiak, & Józefia, 2014; Malgeryd & Persson, 2013), high protein diets and excess dietary phosphorous lead to higher ammonia levels in stables and increases the excretion of phosphorous in excreta (Bott et al., 2015; Westendorf & Williams, 2015).

Outdoor keeping was another identified factor of importance for amount and content in horse keeping (Paper I). Horses kept outside in paddocks and grazing areas leave their droppings on the ground while urine infiltrates the ground, or is soaked to bedding material in loose housing. Time spent outside varies between 1 hour per day up to more than 12 hours per day (Parvage et al., 2013). Collection and removal of manure outside, in paddocks, is recommended in literature (Airaksinen et al., 2007) because of indicated high risk of phosphorous leaching from feeding and excretion areas (Parvage et al., 2013).

Horse manure characteristics are affected by type and amount of bedding (Paper I). Nutrient content is added or diluted by the bedding material, and digestibility is also affected. Bedding material for stabled horses, or in sleeping areas in loose housing, are chosen with respect to ammonia absorption, water-binding capacity, generation of airborne particles, comfort for the animal, degradation and suitability for land application and incorporation into the soil, economy and availability (Airaksinen, Heinonen-Tanski, & Heiskanen, 2001; Komar, Miskewitz, Obropta, Bamka, & Mickel, 2010; Fleming, Hessel, & Van den Weghe, 2008). From Paper I it was concluded that the collected amount (total weight) of horse manure was influenced by how easy it is to separate clean and used bedding material and the mucking regime. Reported variations of manure amount per horse annually are e.g. 19.5 m^3 when straw is used as bedding and 9.8 m^3 when peat is used as bedding. Total urine and fecal output was estimated in Lawrence et al. (2003) at 25.5 kg per day and per 500 kg sedentary horse, of which 8-10 kg is urine. The bedding material absorbs urine, and daily mucking out has been shown in studies to increase the air emissions in comparison to a regime where only feces are mucked out on a daily basis (Fleming, Hessel, & Van den Weghe, 2009). Manure produced indoors is a potential resource as it is mucked out and thereby collected.

Plant nutrient content in the collected horse manure is not only a consequence of feeding practices and added bedding material, but also storage and fertilization (Paper I). Type and time of storage, application technique, season, drainage conditions, spreading and incorporation of manure into soil affects losses, leakage, and emissions of nitrogen and methane (Hijazi, Munro, Zerhusen, & Effenberger, 2016; Karlsson & Rodhe, 2002).

In the case reported in Paper IV, data from 81 horse keepers with a total of 623 horses revealed that 84% of the horse-keeping sites had fewer than 10 horses. In the case, 66% of the horses were located at horse-keeping facilities with more than 11 horses. On average the 60 respondents that brought information about both type and amount of bedding and total amount of horse manure had 13% bedding in the mix of horse manure (horse dung and used bedding). This is lower compared to 25-90% in literature (Cui et al., 2011; Malgeryd & Persson, 2013). Regarding site collection and storage, horse keepers in the case collect horse manure outside and inside to a large extent. Whether manure is collected from outdoor areas affected the amount of collected horse manure in the case. In sites where horse manure was collected throughout the year 12 tonnes per horse per year was collected on average. In horse facilities where manure outside was left in paddocks and grazing areas 7-8 tonnes per horse annually was collected on average. The time of no collecting outside varied between 1-12 months per year (Paper IV). Storing was characterized by storing on concrete slabs, in containers and directly on the ground. Storing on concrete slabs represented about 59% of the horses in the case, in containers about 18%, and directly on the ground about 9%. Horse keepers' current horse manure utilization in the case comprised spreading on agricultural land, off-site disposal and other uses. Manure from about 70% of the horses was spread on agricultural land, of which manure from about 15% of the horses was spread on horse keeper's own agricultural land. The rest was spread on other people's agricultural land. The next common practise, representing about 25% of the horses, was to use horse manure for other purposes, i.e., soil production for gardens and unknown use (Paper IV). Most horse keepers in the case used wood shavings as bedding material, followed by peat and bedding mixes. With wood shavings as bedding material, in a plant nutrient perspective it is preferable to reduce the content of bedding material in the horse manure (Paper II). This can be achieved by a mucking regime which, as far as possible, reduces the spillage of unused bedding.

3.1 Suitability for anaerobic digestion

Horse manure suitability as a feedstock for anaerobic digestion was described in Paper II by parameters such as total solids (TS), carbon to nitrogen C/N ratio, volatile solids (VS) content of nutrients and trace elements, particle size, pH and contaminants. Biogas feedstock characteristics are also a product of carbon content and biodegradability, both of importance for biogas production. The characteristics of the feedstock affects the portion of methane (CH_4) and carbon dioxide in the biogas and presence of other gases such as hydrogen sulfide (Murphy & Thamsiriroj, 2013). Theoretical maximum specific methane yield determined by the carbon content (Banks & Heaven, 2013) is hard to achieve. In the complex anaerobic microbial processes where organic material is converted to methane (Murphy & Thamsiriroj, 2013), anaerobic microorganisms use some of the carbon and energy. Additionally, some carbon is not converted due to protection from degradation because of chemical structure or location, i.e., inside lignin. Fiber-rich feedstock, such as cellulose, has a slow start in methane production corresponding to the hydrolysis of long-chain polymers before methanogenesis can begin (Banks & Heaven, 2013). Most of the macronutrients C, H and O are converted to CH_4 and CO_2 while N and S could reduce toxic substances to methanogens, and inhibit the biogas process. At the same time N is important for microbial growth, and C/N ratios in the range 20-30:1 are often referred as in an optimal range (Banks & Heaven, 2013).

Horse manure feedstock characteristics for anaerobic digestion could, like other feedstock, be described with TS, VS, C/N, micro- and macro-nutrients, and profile of C fractions. In literature feedstock characteristics are sometimes described for horse dung without bedding, or for mixes of horse dung and bedding, then called horse manure. Feed and the content and amount of bedding affect feedstock characteristics e.g. silage horse manure showed somewhat higher TS, lower VS and higher C/N ratio than hay horse manure in Böske et al. (2014), and TS rates about 50-90% were reported for bedding material (Paper II). Horse manure total solids vary between 20-50% (Böske et al., 2014; Mönch-Tegeder et al., 2013). High VS (volatile solids) level at about 80-90% of TS characterized horse manure while bedding material alone had above 90% of TS (Paper II). In general horse manure showed a high C/N ratio (about 20-40:1) in literature. Bedding material alone showed higher C/N ratios (Paper II). VS represents the organic material that could produce energy, and a high VS indicate a good methane potential. VS in horse manure has been revealed as resistant or only slowly degradable due to high content of lignocellulosic organic material with origin from bedding material (Karthikeyan & Visvanathan, 2013; Mönch-Tegeder et al., 2013). The content of lignin makes it hard to degrade by anaerobic digestion, though different studies in the area do not always show the same correlation between lignin and biodegradability (Kusch, Schumacher, Oechsner, & Schäfer, 2011; Liew, Shi, & Li, 2012).

The literature review in Paper II revealed the highest methane potential, 277 L methane per kg VS, in experimental tests with straw as bedding (Kusch et al., 2008) (Figure 5). BMP tests, indicating degradability, showed a lower methane yield for horse manure and wood chips, about 70 L CH_4/kg VS, compared to 235 L CH_4/kg VS for horse manure with straw as bedding material (Böske et al., 2014). Low performance in biogas production and methane amount is often connected to the presence of wood bedding (Figure 5). In comparison, methane potential for food waste ranges between 178 to 531 L CH_4/kg VS (Hadin et al., 2017). In an analysis of Swedish farm-scale biogas plants of manure, specific methane production of cattle manure resulted in 178 L CH_4/kg VS, and pig manure in 191 L CH_4/kg VS (Ahlberg-Eliasson et al., 2017).

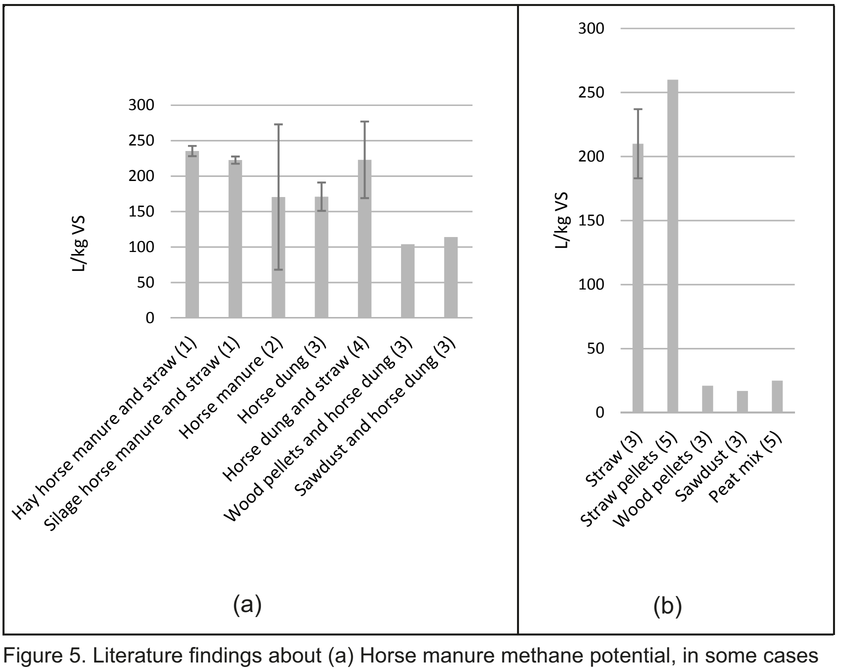

Figure 5. Literature findings about (a) Horse manure methane potential, in some cases with different mixes of bedding; (b) Bedding material methane potential. (1) Böske et al. (2014); (2) Wartell et al. (2012); (3) Mönch-Tegeder et al. (2013); (4) Kusch et al. (2008); (5) Olsson et al. (2014)

3.2 Suitability for composting

Horse manure mucked from stables and paddocks is collected and stored in unconfined piles, open static piles (heaps), turned piles, paved (concrete slabs) or unpaved piles (directly on ground) or in containers (Hadin, 2016). It is stored to enable composting of the material and to await suitable time for spreading, or transportation to other treatment and use off-site. Lack of land in peri-urban areas (Elgåker, 2012) and the fact that horses today are kept in the close vicinity of cities result in problems in manure disposal (Fleming et al., 2008).

Aerobic degradation of the organic material, composting, starts spontaneously in piles of organic material under the right conditions. Favorable conditions for composting are sufficient air supply, moisture and a carbon nitrogen ratio of 25-30. Managed composting, with turning and aeration of piles or drum composting stimulates the process (Rodhe et al., 2015) and also mixing of material with different temperature and age (Heinonen-Tanski, Mohaibes, Karinen, & Koivunen, 2006). In the compost process the temperature rises, which reduces pathogens present in the manure (Romano, Krogmann, Westendorf, & Strom, 2006), as well as volume, odor, moisture, parasites and flies (Keskinen et al., 2017).

Horse manure has slow spontaneous decomposition according to the results in Paper I. The type and amount of bedding material in horse manure affects the compost process. While horse manure with peat bedding was decomposed in one month (Airaksinen et al., 2001), phonebook paper was still readable after a period of 65 days of composting and softwood was more decomposed than paper and straw (Swinker, Tanner, Johnson, & Benner, 1998). In dry and compact manure composting starts after some time of storing. Paper or straw as bedding leads to dry manure, and wood shavings or peat result in compact manure with lack of air (Steineck, Svensson, Jakobsson, Karlsson, & Tersmeden, 2000). Less bedding and more manure and urine is positive for the decomposition rate, as it decreases the carbon-nitrogen ratio (bedding-carbon and manure-nitrogen) (Swinker et al., 1998). In Paper I it was stated that covered, and periodically turned, compost treatment of horse manure showed the lowest nutrient runoff of phosphorous and suspended solids, compared to static compost treatment and turned compost treatment. If uncovered, the static piles showed similar or less runoff compared to turned piles (Komar et al., 2010).

Keskinen et al., (2017) reported that the end product was desirable for spreading on arable land, due to its carbon content and beneficial effects on soil structure, but had low values of nitrogen. Composted horse manure is spread as solid manure due to high total solids. In a Swedish study composted horse manure showed as much nitrogen, phosphorous and potassium as solid manure from dairy cows, and produced higher crop yields than cattle manure in field trials (Steineck, Svensson, Tersmeden, Åkerhielm, & Karlsson, 2001). Horse manure has a low content of easily available nitrogen, in comparison to mineral fertilizers, but mineralization add to yields in coming years (Steineck et al., 2001). After seven months of composting, Keskinen et al. (2017) reported composted manure with pelleted straw to have the highest nutrient concentrations (NPK) per dry matter compared to peat and wood shavings. Losses of P (mostly inorganic PO_4-P) was highest from fresh and composted peat manure. A decrease of soluble N during composting reduced the risk for N leaching from wood shavings manure (Keskinen et al., 2017).

3.3 Suitability for incineration

The Paper V literature review concluded that moisture content, pollutants, nutrients, slag formation and ash content are fuel characteristics of importance for solid biomass fuels. Horse manure is a heterogeneous fuel and differs even within the same horse facility, depending on e.g. bedding material. It should be incinerated without time delay to avoid losses from spontaneous composting (Edström et al., 2011). Moisture content was implied to be one of the most important horse manure fuel characteristics, and the heating value differs vastly between wet and dried horse manure (Figure 6). Horse manure for incineration purposes needs to be dried to at least 50% TS or mixed with a fuel with higher heating value, such as peat or wood (Edström et al., 2011). Lower than 50% water content in the wet weight resulted in a good combustion process and low emissions from horse manure and wood chip incineration in a biomass district heating plant (Lundgren & Pettersson, 2009). Pre-drying was reported to increase the possibility to combust horse manure in a farm-scale incineration plant. High emissions to air was reported due to surplus of combustion air added in the incineration process where horse manure was co-incinerated with wood pellets (Baky, Karlsson, Norberg, Tersmeden, & Yngvesson, 2012). Compared to combustion of wood chips, incineration of horse manure caused higher emissions of NO_x, CO, TOC and dust (Baky et al., 2012). Compared to wood chips, horse manure has higher ash content, and content of ash-forming elements, e.g. Si, Mg and K (Baky et al., 2012; Lundgren & Pettersson, 2009).

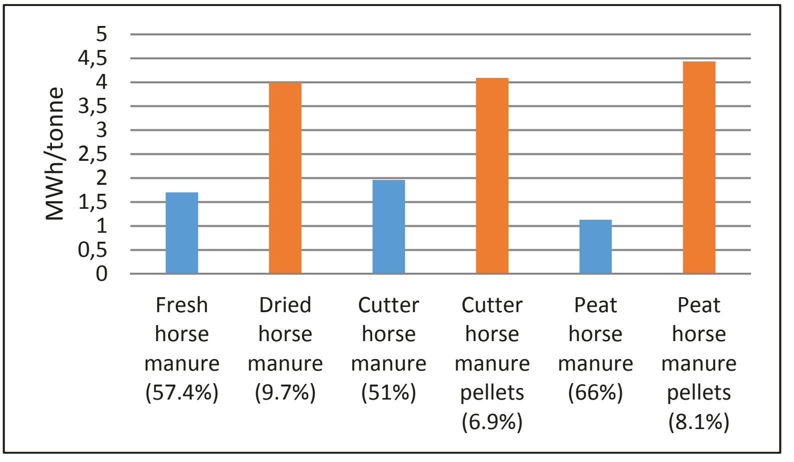

Figure 6. Differences between wet and dried horse manure heating value. Moisture content in brackets (Edström et al., 2011; Baky et al., 2012; Tanskanen et al., 2017).

Incineration, in contrast to other horse manure treatment alternatives, excludes recycling of nitrogen and organic matter (Airaksinen et al., 2001; Heinonen-Tanski et al., 2006). Nitrogen is emitted to air in the combustion process (Lundgren & Pettersson, 2009) while phosphorous and potassium remain in the ash (Edström et al., 2011; Lundgren & Pettersson, 2009). Higher concentrations of nickel, chromium and zinc in horse manure ash, compared to requirements for ash products to be recycled to forests, were explained by reported stainless steel contamination (Lundgren & Pettersson, 2009).

Odor was detected in the processing and storage of horse manure pellets, especially from the drying process, when horse manure was manufactured to pellets. Odor was also detected, but not ensured, from a combustion test (Tanskanen, Soininen, & Lemponen, 2017).

4. Resource recovery and environmental impact from treatment

Paper I stated that horse manure amount and characteristics (nutrient content and biodegradability) are decided by the horse keeping factors of feeding, indoor housing, outdoor keeping, manure storage, fertilization and transports (see Chapter 3 above). Besides characteristics of the feedstock, operating conditions and operational factors were identified in Paper II as affecting biogas and biofertilizer quality and quantity in anaerobic digestion of horse manure (Table 3).

Table 3. Factors affecting biogas and biofertilizer quality and quantity in anaerobic digestion (Hadin & Eriksson, 2016)

Horse manure characteristics	**Operating conditions**	**Operational factors**
Bedding material – type and mixing ratio	Pretreatment	Organic loading rate (OLR)
Horse dung – type and amount of feed	Liquid/solid anaerobic digestion – single/two-stage	Retention time (HRT/SRT)
	Batch/continuous process design	Temperature
	Substrate mixing – co-/mono-digestion	

Pre-treatment had positive effect on horse manure degradability which increased methane yields (Paper II). Horse manure as subject to co-digestion in liquid anaerobic digestion plants (TS 15% or lower), was mentioned in Ruile et al. (2015) (continuously stirred tank reactor, CSTR), in a family-size anaerobic digester in Kalia & Singh (1998) and co-digestion in a farm-based liquid anaerobic digestion plant (Olsson et al., 2014). Horse manure as a fibrous material with high content of lignocellulosic material and solid impurities could cause e.g. scum layers, sedimentation, and wear and tear, observed in experimental batch digestion and in a farm-based L-AD plant (Kalia & Singh, 1998; Olsson et al., 2014). Olsson et al. (2014) reported that despite challenges, primarily in mixing, horse manure gave fewer disturbances than the regular feedstock of deep litter manure.

Solid state anaerobic digestion (SS-AD) is suitable when TS content in the feedstock is above 15%, which is the case with solid organic material such as municipal organic waste and horse manure (Paper II). A single-stage thermophilic continuously fed digestion processes (UASS, upflow anaerobic solid-state) process was reported as promising for horse manure. Other solid anaerobic digester configurations described in literature are batch digestion (garage type), sometimes followed by an UASB (upflow anaerobic solid bed) in a two-stage process design, and plug-flow principles (Böske et al., 2014; Kothari, Pandey, Kumar, Tyagi, & Tyagi, 2014; Xu, Li, & Wang, 2015). Plug-flow processes are single-stage high solids processes. The high viscosity feedstock is continuously fed and moved by screws, or agitators, from inlet to outlet of a often horizontal reactor (Kothari et al., 2014).

Operational factors in anaerobic digestion are organic loading rate (OLR), retention time (HRT/SRT) and temperature in the digester. OLR is the amount of volatile solids loaded into the digester per day. HRT (hydraulic retention time) refers to the time microorganisms have to degrade the substrate and SRT (solids retention time) is the quantity of solids in the digester divided by the quantity of solids in the outflow. Higher OLR decreases the average time in the digester (HRT/SRT), while lower temperature slows down the process and thus requires longer HRT/SRT for the same methane yield. The balance between these determines the digestion efficiency. Higher temperature (thermophilic) could give positive effects in degradation of cellulose, but could also give a decrease in biogas production, described in Böske et al. (2014, 2015).

4.1 Energy performance

Energy performance was expressed in Paper II as energy balance (MJ/tonne wet material) and methane yield (L CH_4 per kg VS). Methane yield is the produced methane per added volatile solids (VS) (Banks & Heaven, 2013). Energy balance is one of a number of energy use indicators, considering the usable and used energy in the life cycle of products and byproducts. If the gained energy from the fuel is greater than energy use in the life cycle, this suggests a benefit of producing the fuel (Arvidsson & Svanström, 2016). Energy balance in Paper II was based on the energy value of the produced biogas, minus heating and electricity for biogas plant operation. Energy used for heating was used for sanitization and maintaining temperature in the digester, and electricity was used for pumping and agitation.

In Paper II, simulations were performed to test the effect of horse manure characteristics on methane yield and energy balance for the chosen scenario (Table 2). This was done with added bedding amount of 25% and 90% (Cui et al., 2011; Malgeryd & Persson, 2013), which resulted in 20% and 47% bedding in the mix. Retention time was 30 days and temperature 37°C. In Table 4 the maximum and minimum results from the simulations are presented. The results (Paper II) indicated waste paper as a favorable bedding in terms of both energy balance and methane potential (Table 4). Simulations on type and rate of bedding (paper II) suggested a contribution to the energy balance if either paper, straw or wood were added. Peat, on the other hand, had negative impact on the results. This could be explained by the chemical composition with a high proportion of carbon-lignin in peat (Hadin & Eriksson, 2016) and slow degradation of lignocelluloses (Yang et al., 2015).

Table 4. Maximum and minimum results of energy performance of biogas production based on model simulations (HRT 30 days and temperature 37°C).

Results	Min	Max	Bedding	Part bedding
Methane yield (L CH_4/kg VS)		151	Paper	20%
Energy Balance (MJ/tonne)		3597	Paper	47%
Methane yield (L CH_4/kg VS)	-7		Peat	47%
Energy Balance (MJ/tonne)	-582		Peat	47%

Increased amount of feedstock had a positive effect on energy balance although methane yield decreases with added bedding (Table 4, Figure 8). Mesophilic temperature and shorter retention time improved the energy balance (Figure 7), due to less need for input energy (heating). Simulations of hydraulic retention time (HRT) and temperature, indicated a high temperature and long retention time as positive for methane yield, but to a very small extent (Figure 8).

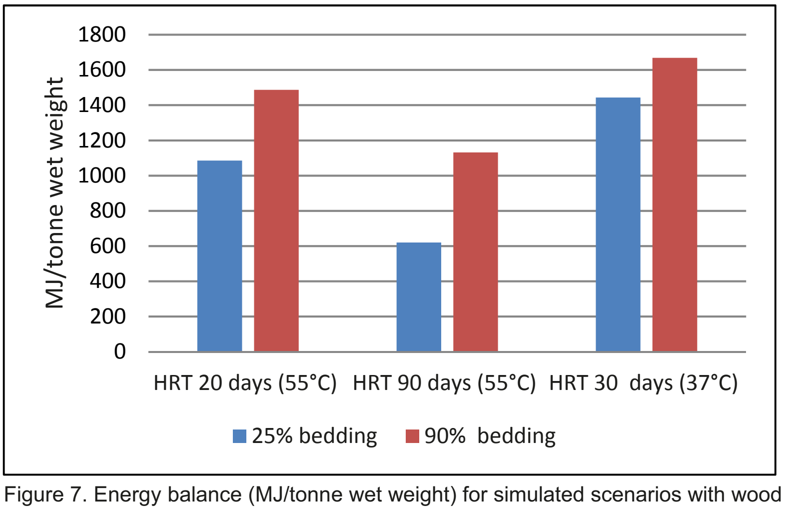

Figure 7. Energy balance (MJ/tonne wet weight) for simulated scenarios with wood bedding at 55°C and highest energy balance at HRT 30 days and 37°C.

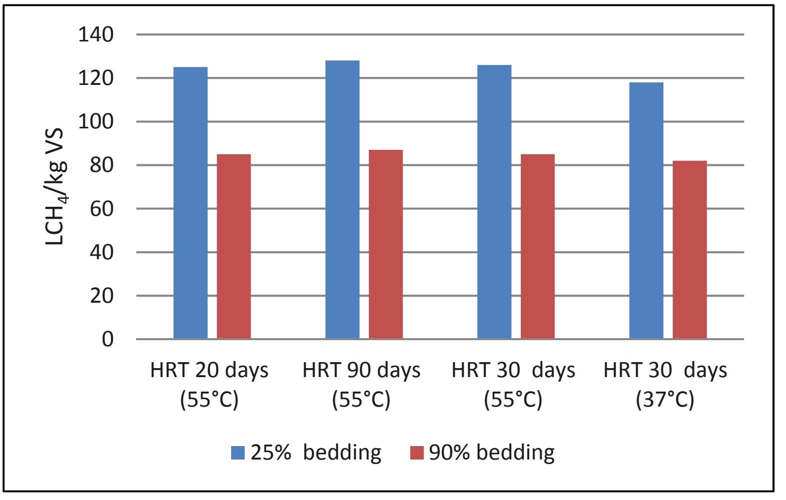

Figure 8. Methane yield (L CH_4/kg VS) for simulated scenarios with wood bedding at 55°C compared to methane yield at HRT 30 days and 37°C.

4.2 Nutrient content in biofertilizer

Besides energy rich methane, anaerobic digestion also produces a digestate, biofertilizer. Recycling of plant nutrients in the biofertilizer requires quality management of the feedstock due to heavy metals and other contaminants (Holm-Nielsen et al., 2009). Anaerobic digestion does not change the quantities of nutrients in the feedstock (Lukehurst, Frost, & Seadi, 2010; Teglia, Tremier, & Martel, 2011), but plant availability is improved as part of the organic nitrogen is converted to ammonium (NH_4-N). The content of ammonium could be about 20% higher in digestate than in undigested cattle manure and dairy manure (Al Seadi, Janssen, & Drosg, 2013; Lukehurst et al., 2010).

This study shows that horse manure fertilizing characteristics are affected by the type and amount of bedding material used for horses. Physical properties and chemical composition of horse manure and bedding material used for simulations in Paper II-IV, presented in Paper II, showed peat to have the highest ratio of nitrogen (N), while straw had higher ratio of potassium (K) and somewhat higher ratio of phosphorous (P) (Table 5).

Table 5. Physical properties and chemical composition of horse manure and bedding material used for simulations in Paper II-IV (Hadin & Eriksson, 2016).

Property (%TS)	Horse dung	Peat	Straw	Sawdust/ wood-chips	Paper
Total nitrogen, N-tot	1.48	2.20	0.6	0.8	0.10
Phosphorous, P	0.12	0.05	0.08	0.03	0
Potassium, K	0.19	0.04	0.28	0.21	0.07

In simulations of process parameters in Paper II high ratio of peat contributed to N-tot and straw to the K-tot and P-tot content in the biofertilizer (Table 6). Compared to slaughterhouse waste and source-separated household waste, the content of plant nutrients was lower in this study, or in the lower range. Abubaker et al. (2012) N-tot ranged between 2.6–7.9 kg per tonne digestate, tot-P ranged between 0.2-0.9 kg per tonne digestate, and K-tot between 1.1-1.6 per tonne digestate. Silage from ley and source-separated household waste had the highest yield of K-tot with 3.7 kg per tonne digestate (Abubaker et al., 2012).

Table 6. Effects on biofertilizer by choice and rate of bedding material (HRT 30 days and temperature 37°C) (Hadin, 2016).

Results (kg/tonne digestate)	Max	Min	Bedding	Part bedding in the mix
N-tot	4.00		Peat	47%
		0.31	Paper	47%
P-tot	0.21		Straw	20%
		0.02	Paper	47%
K-tot	0.55		Straw	47%
		0.08	Peat	47%

4.3 Environmental impact from horse manure treatment

Environmental impact from unmanaged composting, managed composting, small-scale incineration, large-scale incineration, and anaerobic digestion was simulated in Paper III. The scenarios and parameters are described in section 2.5.1 and Table 2. Unmanaged composting was assumed to be business as usual (BAU) and its potential environmental impact is visualized as "1" in Figure 9. Environmental impact from the other treatment methods is compared to this level. When the other treatment methods resulted in higher potential environmental impact this is illustrated by bars above "1" and when potential environmental impact is lower it is illustrated by lower bars, below "1" (Figure 9). Managed composting reduced acidification potential and global warming potential, but increased cumulative energy demand and eutrophication potential compared to unmanaged composting (Figure 9). The reduction was mainly a result of a compost filter decreasing methane and ammonia emissions in compost gas from the managed composting process. Large-scale incineration generated heat and electricity from horse manure and reduced all category indicator results compared to unmanaged composting (Figure 9). This was a result of the studied expanded system with compensatory supplies of electricity, heat, vehicle fuel and fertilizer. The studied systems of composting and anaerobic digestion were expanded with heat produced from biomass and electricity from fossil fuels. This resulted in high category indicator results from the compensatory systems for composting and anaerobic digestion. Use of compensatory mineral fertilizer in the system of large-scale incineration had no eutrophication potential to water while other treatment methods had rather high results on eutrophication to water from use of biofertilizer (Paper III).

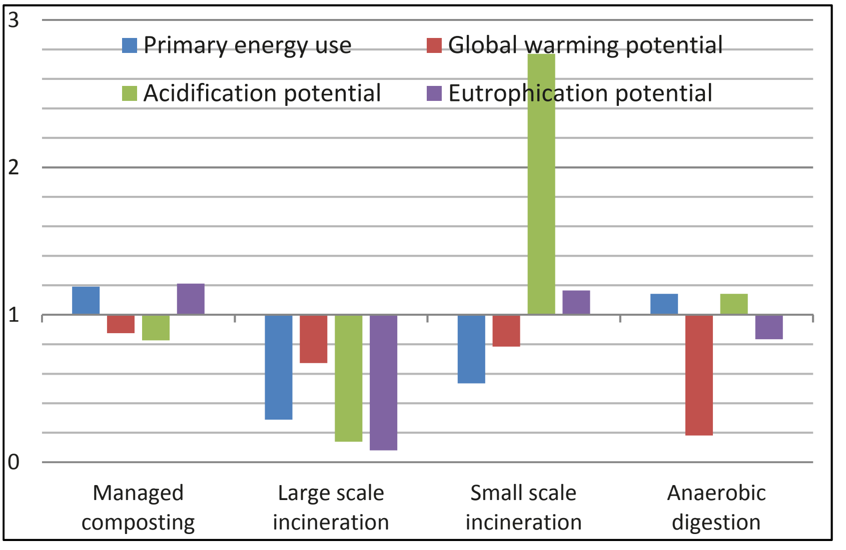

Figure 9. Comparative potential environmental impact for treatment options in relation to unmanaged composting (Paper III).

Small-scale incineration resulted in higher acidification potential and eutrophication potential compared to unmanaged composting. High emissions from the incineration process are the main reason. Energy recovery in the anaerobic digestion process reduced eutrophication potential compared to unmanaged composting (Figure 9) due to lower emissions to air and the assumption that all biofertilizer was used in agricultural land, while 50% of the compost was not used but left unmanaged. Anaerobic digestion reduced global warming potential due to use of biogas and the biofertilizer carbon sink function in the studied system (Paper III).

Results from simulations (Paper III) of co-incineration with municipal solid waste registered the lowest cumulative energy demand (CED) for large-scale incineration of the treatment methods in the study (Figure 9). Produced heat and electricity resulted in a high energy benefit for the incineration process, as well as low energy demand for the core system incineration process. Low energy demand for compensatory vehicle fuel and use of mineral fertilizers affected incineration CED moderately negatively (Figure 10). Co-incineration is positive for a substrate such as horse manure, with total solids around 30-50%. Respondents in interviews (Paper V) also mentioned this.

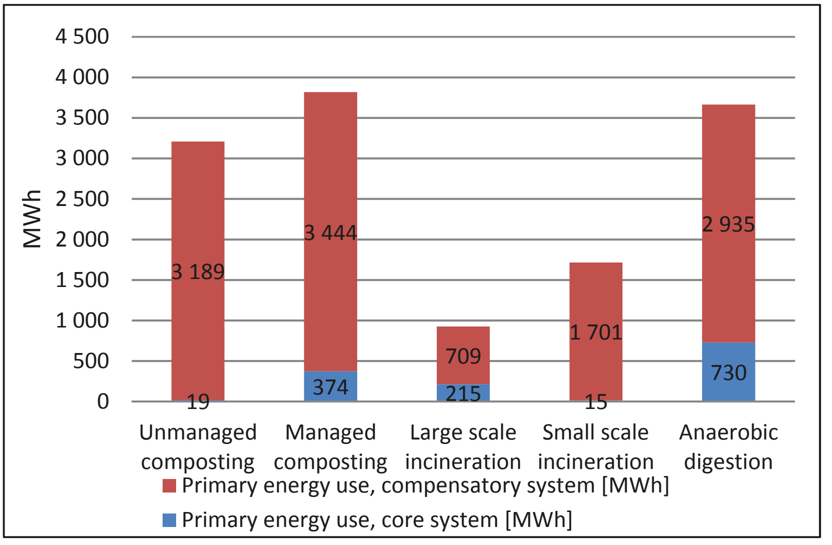

Figure 10. Use of primary energy (CED) in simulated scenarios (Paper III).

In Paper IV, when combined energy recovery and nutrient recycling through anaerobic digestion in a centralized plant replaced unmanaged composting, AP, EP, CED and GWP were reduced, also when environmental impact from horse manure transports to the anaerobic digestion plant was added. The biogas was assumed to be used for buses, replacing fossil fuels and thereby compensating for environmental impact from other parts of the studied system (Paper IV).

Biofertilizer land application and digestate transport resulted in higher potential environmental impact from anaerobic digestion in comparison to unmanaged composting (Paper IV). The spreading process of liquid digestate with nitrogen converted to ammonia, and a larger amount of biofertilizer due to higher water content in biofertilizer from L-AD created higher demand for transport energy and higher emissions to air in the scenario with anaerobic digestion. Cumulative energy demand (CED) from anaerobic digestion was higher in the core system but, as stated above, in a systems perspective the potential environmental impact from reduced use of fossil fuels in the compensatory system resulted in avoided CED (Figure 11), as well as reduced potential environmental impact for all chosen environmental impact categories (Figure 12).

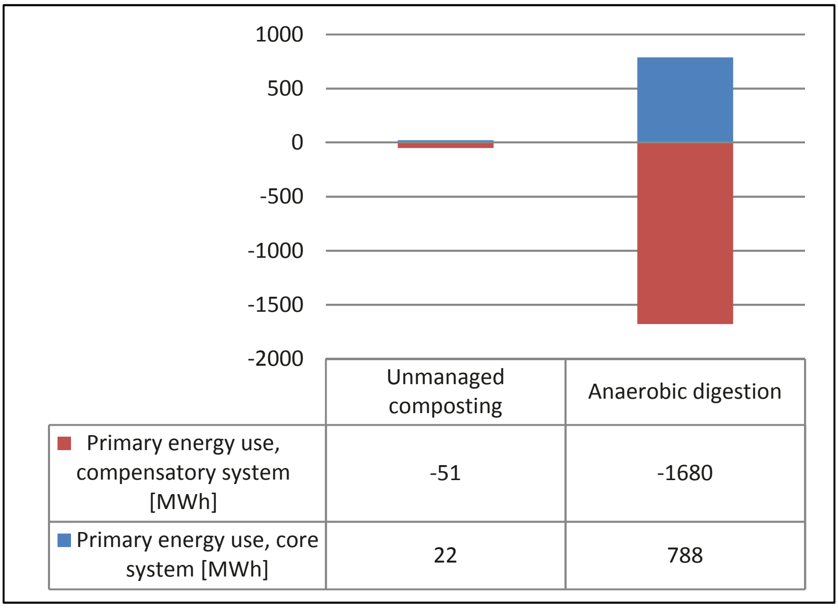

Figure 11. Primary energy use from unmanaged composting (UC) and liquid anaerobic digestion (L-AD) (Paper IV).

Results from Papers III and IV cannot be directly compared as the studied systems are different. In the system with produced heat, electricity, transport work and crops cultivation (Paper III) CED was lower for the system with unmanaged composting than anaerobic digestion (Figure 10). Results in Paper IV point at larger CED savings in anaerobic digestion (about -900 MWh) compared to unmanaged composting (about -30 MWh) in a system including transport and crops cultivation (Figure 11).

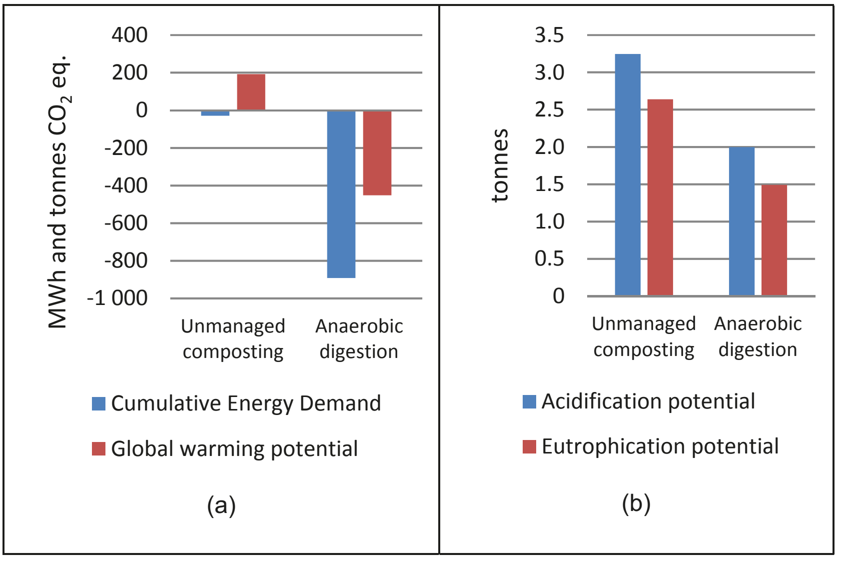

Figure 12. (a) Net cumulative energy demand (MWh) and global warming potential (tonnes CO_2-eq.) from manure treatment in unmanaged composting and anaerobic digestion; (b) Net acidification (tonnes SO_2-eq.) and eutrophication potential (tonnes PO_4^{3-} eq.) from manure treatment in unmanaged composting and anaerobic digestion (Hadin et al., 2017).

4.3.1 Environmental impact from associated transports

Environmental impacts from transport of horse manure to an AD plant were calculated for the amount of horse manure and transport distances in the case. This resulted in transport adding a minor part of the total environmental impact to the core system regarding AP and EP, while contribution to CED and GWP was considerable (Figure 13).

The transport distance (1679 km) was sensitivity tested and varied by ±10%. This resulted in increased and decreased cumulative energy demand by 1%, global warming potential by 0.4%, eutrophication potential with 0.1% and acidification potential by 0.2%. This means environmental impact is not sensitive to transport distance.

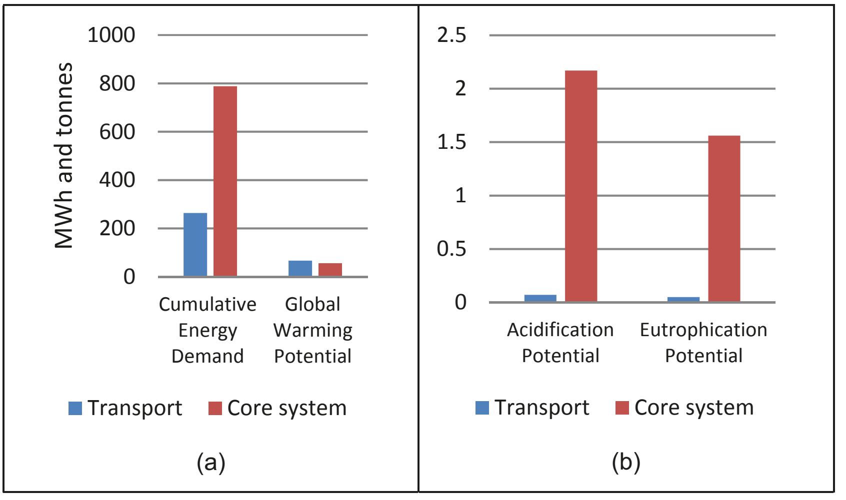

Figure 13. Contribution of transports to core system (Paper IV). CED in MWh, GWP in tonnes CO_2-eq., AP and EP in tonnes SO_2-eq.and PO_4^{3-} eq. respectively.

Paper IV made a statement that transport distance could increase 40 times before the unmanaged composting level of GWP was reached for the AD plant. Recalculations of this showed that the actual number was 34 times regarding global warming potential. Cumulative energy demand (CED) is the lowest common denominator, most sensitive for increased transport distances by a figure of eleven times (Table 7). The total transports could thereby increase eleven times in the case before there is no gained energy from the anaerobic digestion process compared to composting.

Table 7. Additional analysis of results of transport environmental impact in the case (Paper IV).

Environmental impact categories	Compost	Anaerobic digestion	Transport (collection)	Possible added transport (times)
CED (MWh)	-29	-892	78	11
GWP (tonnes CO_2-eq.)	192	-452	19	34
AP (kg SO_2-eq.)	3245	1996	44	28
EP (kg PO_4^{3-} eq.)	2639	1492	9	127

Simulations were sensitivity tested with regard to amount of horse manure. This was made by calculations of environmental impact in the system according to the calculated largest and smallest amount of manure per horse annually for the case (Paper IV). GWP and CED decrease linearly with increasing amounts of horse manure (Figure 14a) due to the positive effects from biogas produced and used for transport work in buses, replacing fossil fuels. Correspondingly, the local/regional environmental impact AP and EP increased linearly with increased amount of horse manure (Figure 14b).

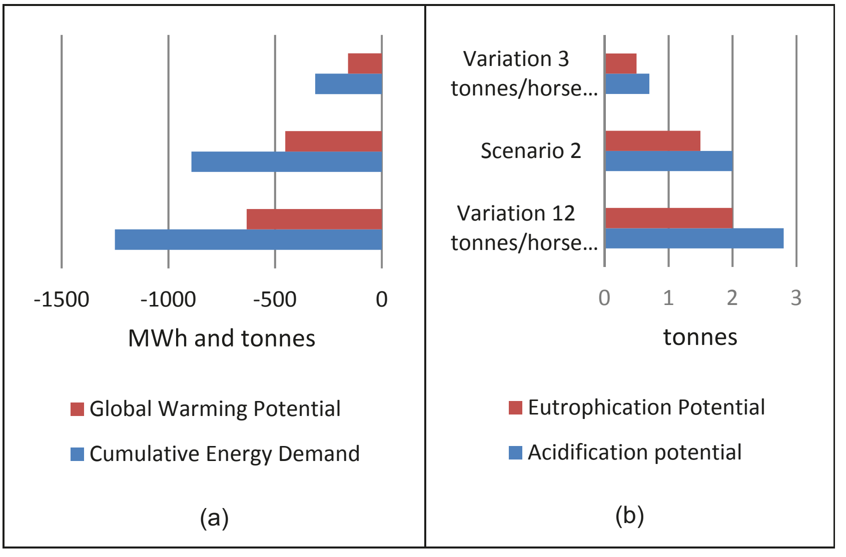

Figure 14 (a). Global warming potential (tonnes CO_2 -eq.) and Cumulative Energy Demand (MWh) decreases in the studied system with increased horse manure amounts; (b) Eutrophication potential (tonnes PO_4^{3-} eq.) and acidification potential (tonnes SO_2-eq.) increase.

4.3.2 Economic impact of changed horse manure management

Utilization of horse manure for energy conversion and nutrient recovery requires collection and transport to energy conversion plants. This is both an environmental and economic issue, because of the energy use and cost for the activities. Reflections about economic consequences for horse keepers from a changed horse manure management accounted for a minor part of the study performed in Paper IV. An assumed zero cost for business as usual (unmanaged composting) was compared to an assumed cost for rent of container, transport cost and gate fee for horse manure treatment in anaerobic digestion. Cost per horse increased by about 6,000 SEK per horse and year for a horse keeper with seven horses, irrespective of size of container, and by about 7,000-10,000 SEK per horse annually for a horse keeper with two horses, the lower cost representing a container size of 10 m^3 and the higher cost a 22 m^3 container (Table 8). This cost represents 580-1040 EUR per horse annually and is higher than in a supply-chain analysis in Svanberg et al. (2016) where costs ranged between 100-400 EUR/horse annually. Horse manure to energy conversion included container rent, transport cost and reception fee in both studies. The study in Paper IV differed from Svanberg et al. (2016) with higher costs for container rent, which could represent regional differences. Value of plant nutrients, N and P (Table 9) represent about one and five assumed gate fees respectively, to a biogas plant. A price of biogas as vehicle fuel of 19 SEK/kg results in a biogas value representing 21 and 74 assumed gate fees of 350 SEK/tonne material, respectively.

Table 8. Differences in cost related to value on biogas and biofertilizer (Paper IV).

Number of horses	Increased cost container 10 m^3 (SEK)	Increased cost container 22 m^3 (SEK)	Value biogas (SEK)	Value biofertilizer (N and P) (SEK)
2 horses	7,000	10,000	7,400	500
7 horses	6,000	6,000	26,000	1,800

Table 9. Plant nutrient content in case horse manure amount (Paper IV).

Plant nutrients	Compost	Biofertilizer	Per horse in the case	Per tonne in the case
N-tot (kg)	16,760	18,400	27	4.0
P-tot (kg)	1,200	1,200	2	0.3
K-tot (kg)	1,740	1,700	3	0.4

4.4 Energy actors' experience with horse manure as an energy resource

Paper V explored energy actors' experience with energy conversion of horse manure. The respondents had either practical experience, research experience, or experience from consulting. They shared experience from single tests or current work in the field. Five actors within the field of incineration, and eight actors in the biogas area, answered a questionnaire by e-mail or were interviewed by telephone. The aim was to let the respondents tell about their experiences in their own words, but questions were also directed in the areas of technical, economic and ecological aspects. Results from the data collection were categorized into practical/technical aspects, economic aspects and environmental aspects. Results are presented according to these categories, and according to the process to which they refer.

4.4.1 Experience with anaerobic digestion

Horse manure as an energy feedstock in L-AD processes was found to give a high methane rate in co-digestion with poultry manure, but the high TS was not optimal for the process. Use of straw pellets as bedding was reported by respondents to reduce amount of horse manure, and straw pellets were regarded as performing best in most aspects: methane yield, ease of handling and degradability. Operational problems in a farm-based L-AD plant (in co-digestion with cattle manure) were described as crust, overflow, pump stops and sedimentation. Adding horse manure to the process resulted in a thickened digestate and added more plant nutrients to the digestate, which reduced transport cost per hectare of fertilized land. Plant nutrient content and value depended on which other feedstock horse manure was co-digested with. In co-digestion with cattle manure, horse manure contributed to biogas production in periods of low availability of cattle manure. In SS-AD (a high-TS stirred process), horse manure was regarded as difficult to handle with technical issues occurring before digestion and at digestate separation. Required biogas plant adaptations to horse manure included a larger fermenter, an ability to handle higher TS, stirrers to cope with higher viscosity, and greater wear and tear from sand. These adaptations make biogas plants more expensive, and made the respondent perceive that the biogas plant could not pay anything for horse manure. The solid digestate was sold as fertilizer after further processing.

One respondent considered horse manure as a suitable feedstock in a plug-flow process, in co-digestion with food waste. Instead of adding shredded wood material to the process, the respondent suggested horse manure. Its content of carbon, high TS, wood shavings, pellets, and small quantities of long straw was regarded as suitable for the process. Furthermore, solid impurities were not regarded as a major problem, and swimming layers and sedimentation could be handled in the process. Remaining lignin in the biofertilizer was regarded as usable in the composting process, which converted the digestate to a compost fertilizing material.

The importance of horse manure collection, i.e., collection infrastructure, was mentioned. This was described as a system where horse keepers do not dispose solid waste in horse manure and with frequent deliveries of horse manure according to biogas plant requirements, not allowing the gas-producing process to start. Respondents diverged between requesting deliveries of horse manure several times a week, storage for two weeks, and collection once a month. The supply chain, the flow of horse manure with the right quality feasible for the biogas plant process, was suggested to be solved by a system where a company provides a container and collection system and delivers manure to anaerobic digestion plants. It was mentioned that suppliers of horse manure should be horse keepers with more than ten horses, to enable enough feedstock in co-digestion with food waste. Trucks for wood chips (140 m^3) were described as economically preferable for transport.

4.4.2 Experience with incineration

In the farm-scale incineration plant horse manure was experienced to call for co-incineration with pellets and a high need for maintenance and monitoring due to the moisture content. Wood bedding replaced the former use of peat because wood suited the incineration process better. The farm incineration plant was a large investment, but incineration (of half of the produced amount of manure) reduced the horse facility´s costs for disposal. The plant had no requirements on filters for reduction of air emissions, and ash, in a mix with manure, was spread on agricultural land.

In larger-scale co-incineration (waste incineration plant, CHP plants and sawmill combustion plant), air emissions were reduced with existing filter strategies. Ash, mentioned by some respondents, was disposed to landfills or used as construction material. Commonly NO_x emissions are reduced in flue gases by adding purchased ammonia or urea to reduce NO to N_2. Trials with horse manure resulted in NO_x reduction in one CHP plant, but odor put an end to the tests. In the sawmill the configuration of the plant stopped the trials. Moisture content was regarded to have minor importance in large-scale co-incineration, as long as feedstock was solid. It was stated that transport of wet material leads to smaller loading capacity due to high weight. Regarding bedding material, wood shavings and straw were part of the used mixtures. Straw was mentioned to be harder to burn, and hemp as getting stuck in the process. Grate furnaces were suggested to be more suitable for horse manure than the fluid bed incineration process. A positive impact on plant economy was that energy companies got paid to incinerate horse manure, while they have to buy other types of feedstock.

4.4.3 Horse manure as an energy feedstock

The respondents' information showed the importance of adaptation of technology and substrate characteristics, transports and economic aspects. Regarding substrate characteristics, a dry feedstock was said to facilitate loading and transport. Additionally, low moisture content was important for the combustion process in the farm-scale incineration process. Horse manure was reported to have a stabilizing effect on the C/N ratio and to add carbon to the anaerobic digestion process. The concentration of nutrients increases with added horse manure in co-digestion. Impurities like sand, gravel and big particles of bedding material, e.g. long straw, are a natural part of the manure. The extent of these impurities can be reduced by not adding horse manure from outside areas to manure delivered to biogas plants, and by choice of bedding. Respondents stressed the importance of teaching horse keepers to sort out solid waste, to avoid waste fractions in the manure. There was otherwise a risk that horseshoes, concrete, crowbars, and horse rugs occurred as solid waste in horse manure. Impurities were not mentioned related to incineration and its possible importance in the incineration process was not visualized in this study. Furthermore, this study showed that bedding material must be selected in relation to treatment method. Respondents from farm-scale incineration and plug-flow anaerobic digestion preferred wood shavings, while L-AD preferred, and SS-AD required, straw pellets. Incineration experiences showed economic advantages with horse manure through gained gate fees compared to other biomass that needs to be bought. Experiences from anaerobic digestion plants showed more variety regarding economic aspects. It was mentioned that treatment cost should be connected to gate fees, and that biogas plants could not pay for horse manure due to high costs for treatment. One respondent visualized the importance of providing a feedstock of suitable quality at the right time for energy recovery. A collection infrastructure was suggested that should encompass a recycling system for horse manure where bedding producers co-ordinated and provided bedding, and recycled horse manure. Another respondent described a system that included rental of containers, collection, transportation and selling horse manure to biogas plants.

5. Discussion

Applying a systems perspective, this study detected flows of energy and materials from horse manure, indicating it to be a potential bioenergy resource. In the ongoing transition to more renewables in the energy system, horse manure could add to the mix of wind, hydro, solar, and bioenergy. The transition of energy systems to higher share of renewable energy, and increased energy efficiency, does not depend on one, or a few, specific energy sources but on several – both existing and new – renewables and technologies. There is not one solution to the environmental problems, e.g. with rising carbon dioxide emissions from transport. Mixes and adaptions can increase the benefits from existing facilities for energy recovery, while it can also increase costs and technical challenges in other cases. Altogether, contributions from new bioenergy resources, efficiency measures and energy savings, as well as adaptations to local and regional situations are necessary when fossil fuels are decreased and replaced. Regarding energy savings, Mathiesen et al. (2015) stated it as equally important to reduce the use of bioenergy as to limit the use of fossil fuels, because biomass cannot replace the present use of fossil fuels on a global level.

How much horse manure could contribute to a renewable energy system is a relevant question. This study shows a potential for increased utilization and resource recovery from horse manure, but for several reasons it is hard to state an amount of available energy and nutrients. It was not feasible to identify the number of horses in a specific area, which corresponds with literature reporting problems estimating the size of horse populations (Bratt, 2001; Femling, 2003; Hammer, Bonow, & Petersson, 2017; World Horse Welfare and Eurogroup for Animals, 2015). In addition, the amount of horse manure produced depends on horse size, age, and workload, bedding material, mucking and feed resulting in unique conditions at horse keepers regarding amount and characteristics of horse manure. Even if technology for delivering bioenergy exists, it continues to develop to increase efficiency, often with specific feedstock in mind. With the approach that horse manure could be regarded as a resource, energy actors' experiences and perceptions, presented in Paper V, can guide technology development and planned energy conversion plants to add this not fully used resource to potential feedstock for energy purposes.

As a bioenergy resource, horse manure needs processing, while current treatment most often consists of composting, followed by plant nutrient recovery but also other uses. Focus in this thesis was on processing horse manure by anaerobic digestion, in a biogas energy system. With anaerobic digestion it is possible to treat horse manure and produce renewable energy for energy recovery, biogas, and a digestate with plant nutrients, biofertilizer, suitable as fertilizer, closing natural cycles. Depending on current manure management, the change to a biogas system may produce several energy and environmental benefits, called multiple revenue in the interviews, consisting of reduced emissions from storing and treatment of manure, production of renewable energy to replace fossil fuels, and a biofertilizer to replace mineral fertilizer. Results from simulations agree with this: anaerobic digestion of horse manure reduced global warming potential compared to unmanaged composting in Paper III. In Paper IV anaerobic digestion also resulted in reduced AP, EP and CED compared to unmanaged composting.

5.1. Availability and characteristics – influence on energy performance

The amount of horse manure available for active resource recovery is a product of produced, collected and utilized horse manure. It is dependent on horse keepers' individual choices of bedding, to keep a healthy indoor environment for horses, and dry and clean sleeping areas in loose housing. Empirical information from study visits and interviews revealed a great variety regarding number of horses at horse keeping sites, feeding practises, use of bedding, storage of horse manure, utilization of horse manure, and transport distance to final treatment on or off site. The results from energy actors' experiences in Paper V diverge somewhat with respect to the necessity for horse keepers to adapt choice of bedding to a specific treatment, or if the treatment facility needs to be adjusted to the heterogeneous horse manure. Some claim that horse keepers should adapt, while others think that treatment plants should be adapted to different bedding materials that will inevitably come to the plant. With communication of requirements and expectations from treatment plants, and conditional delivery, respondents believed that horse keepers would adapt to conditions for a secure supply of horse manure of the right quality for energy and plant nutrient recovery. During field observations (part of systematic combing) horse keepers described adaptations to end users' requirements, and for reduction of the amount of horse manure. One riding school used peat in a mix with wood shavings, to adapt to farmers' request for peat due to its composting and fertilizing effects. It was also described how riding schools taught their pupils how to muck out to minimize spillage of bedding material. Energy recovery plant owners, transport distributors and horse keepers need to meet and discuss opportunities for energy recovery and each actor's requirements for common understanding. This encompasses development of cooperation and tests of energy recovery in various technology and in both small and large scale.

5.1.1 Bedding and solid impurities

Horse manure is regarded as a heterogeneous substance and a low methane yield feedstock, often due to high content of bedding and solid impurities (Paper II-V). The case study implied that horse keepers used a low-rate bedding material (average 13% of the weight in the mix) compared to suggested rates of bedding from 25–90% in literature. This is positive as literature indicates lower methane potential from bedding than horse dung, with the exception of straw which adds to methane production (Mönch-Tegeder et al., 2013; Olsson et al., 2014; Wartell et al., 2012). On the other hand, if the bedding rates were higher, increased amounts of bedding in this study (Paper II) resulted in more positive energy balances, for straw, wood and paper, even if the methane potential decreased per kg VS. Adding more bedding results in more feedstock that produces more biogas in simulations. High rate of peat, on the other hand, indicated negative figures for both methane yield and energy balance. Possible reasons for negative methane production and negative energy balance can be derived to model constraints, with difficulty in handling slow degradation of lignocellulose and the low energy performance from peat, described in Olsson et al. (2014). Bedding material at interviewed horse keepers was mostly wood shavings. Wood shavings are also high in lignocellulosic material but despite this, wood bedding performed almost as well as straw in methane yield and energy balance simulations. This disagrees with the low methane performance of wood bedding in literature, suggesting wood bedding to have a diluting effect on methane potential in horse dung (Böske et al., 2015; Mönch-Tegeder et al., 2013; Olsson et al., 2014; Wartell et al., 2012). Data used for physical properties and chemical composition of bedding material in simulations could explain the differences in methane potential. Straw and wood have quite similar properties regarding lignin, while peat has almost double (Paper II). Regarding cellulose the rate in wood and peat are almost similar, indicating this property to be of less impact than lignin for energy recovery from wood. This corresponds with the statement by Zheng, Zhao, Xu, & Li (2014) that "lignin is a major barrier to utilization of lignocellulosic biomass in bioconversion processes."

Paper V concluded that small incineration plants need a lot of maintenance because of moisture content in horse manure, and as a biogas feedstock horse manure caused a lot of wear and tear and was not considered suitable for certain plant feeding technology. The adaptations to horse manure with a great variance of bedding material were reported as costly for biogas plants. Sedimentation of sand, gravel and other solid impurities in L-AD digesters caused added work hours. Solid impurities, like gravel, increase with outside collection and this reduces the possibility to use outside horse manure in L-AD and anaerobic digestion at high TS with stirring. This manure needs treatment in processes like plug-flow anaerobic digestion or separate treatment in composting processes, instead of anaerobic digestion. There were no experiences mentioned of problems with solid impurities in incineration, and therefore the result lacks a description of this. In the proposed cooperation between energy recovery plants and horse keepers the issue with solid impurities, as well as other impurities or contaminants, could be discussed and further investigated. To keep the cycle of plant nutrients clean should be an aim for all interested parties about horse manure as an energy feedstock. Co-digestion should exclude feedstock that risks the natural cycle of plant nutrients and humus.

5.1.2 Collection

Current horse keeping and manure practice have implications for increased resource recovery. Results suggest that it is common for horse farms to have few horses. In this study 78% of the interviewees had five horses or less, and in

Westendorf, Joshua, Komar, Williams, & Govindasamy (2010) that rate applied to more than 50% of the interviewed farms. The number of horses reflects the theoretical amount of horse manure produced in a defined area. Transport is a prerequisite for offsite energy recovery of horse manure and exhibits the need to invest energy before renewable energy can be harvested.

It was reported in interviews that biogas plants benefit from continuous deliveries, of newly laid horse manure or after only short storage periods. To accommodate biogas plants' request for frequent deliveries, suppliers need to be rather large horse facilities, or else collection at many smaller facilities is required. A short storage period reduces the risk for the composting process or biogas process to start. This result agrees with Mönch-Tegeder et al. (2013), who stated that short storage periods are critical as stored horse manure resulted in lower methane yields. One respondent (Paper V) with laboratory experience of reduced methane potential of storing peat and straw bedding manure complemented this. How to collect horse manure from scattered horse facilities with a small number of horses at a frequency and volume suitable for energy conversion plants is a logistical challenge. Horse facilities with a larger number of horses were reported as preferable suppliers, to assure enough feedstock. Possibly these suppliers could add a covered storage, on concrete and without mixing to keep the manure pile dry and reduce the moisture and air of importance for composting. Insufficient moisture content will slow down the decomposition or even stop it (Gajalakshmi & Abbasi, 2008). This is important if only natural aeration is provided, as continued microbial activity could turn an aerobic process to equally undesirable anaerobic decomposition. On the other hand forced aeration could lead to desiccation which is also a hindrance for composting (Gajalakshmi & Abbasi, 2008). Both scattered manure collection and collection from horse facilities with large number of horses may result in long transport distances. While storage seems to be negative for biogas production, a long storage time is positive when composting is the treatment method. In composting storage is part of the treatment and required to create a valuable fertilizer.

Most horse keepers in the case study store horse manure on concrete slabs and transport the manure to other people´s farmland, where it is subject to field application. Removal from the horse facilities includes loading e.g. to tractor wagons, in containers or wood chip trucks. This means the same handling as if manure were transported to a biogas plant. Horse manure left in heaps to compost, and not used, brings a greater difference for the horse keeper. Loading, in containers or trucks, and removal would be required. The cost for horse keepers, for horse manure management, transport and rental of containers, is a subject for further studies. The cost for horse keepers to manage the manure could act as motivation for horse keepers to decrease the amounts of horse manure, e.g. by choice of bedding type and mucking regimen.

5.1.3 Economy

In the cases where horse manure is regarded as waste or an animal by-product, it is also categorized as an energy feedstock. The economic value, or cost, for horse manure seems to be a question of whether it is regarded as waste or as a bioenergy resource. A price for treatment seems to be calculated in various ways according to respondents and in literature. The bioenergy price, the value that energy conversion plants put on the manure, the cost for a plant to treat horse manure, the transport cost, or combinations of these aspects are mentioned as parts of economic calculations (Olsson et al., 2014; Tanskanen, Föhr, Soininen, & Ranta, 2017). When horse manure is experienced as waste in need of treatment the gate fee implies a contribution to plant income from produced fertilizer and energy, reducing plant cost. The overall economy of anaerobic digestion is related to several revenues and costs, and whether horse manure is interesting as a feedstock in co-digestion with food waste is suggested to be a matter of supply and demand. Biogas plants have gate fees for waste and generally do not actively seek out other substrates, according to one respondent (Paper V). In co-digestion with cattle manure Olsson et al. (2014) calculated that, depending on bedding, manure treatment could be charge neutral for the horse facilities. Incineration plants in this study (Paper V) seem to be even more positive to horse manure treatment, as they generally pay for other fuel and ammonia or urea for NO_x reduction. The positive view was clouded in some cases due to severe odor problems. If horse facilities adapt to biogas plants' requirements they could be seen as suppliers of bioenergy, in the same way as woody fuels. But if it is viewed as waste it will follow other waste management principles: that the waste producer pays for an environmentally sound treatment. Energy actors with experience from anaerobic digestion prefer straw pellets but it was mentioned that it increased bedding costs for horse keepers and that horse keepers had some quality considerations about pelletized bedding material. On the other hand it was suggested that pelletized bedding material, according to experiences from energy actors, reduced the amount of material to transport, and thereby also transports.

Reduction of horse manure also follows the first stage of the waste hierarchy, to reduce waste (2008/98/EC). If a waste-to-energy concept (horse manure to biogas) results in higher costs for horse keepers, it needs to be followed by extensive communication and education. Waste management (e.g. municipal household waste in Sweden) changed in the 1990s from landfill of mixed solid waste materials to sorting at source. This was a more expensive waste management system than the former landfill treatment and meant a higher cost and higher work load for households, but increased recycling and energy utilization. In the same way as for other waste management, this could be a possible development for horse manure.

5.2 Horse keeping and manure treatment – effects on plant nutrient recovery

The by-product from horse keeping—horse manure—is a resource for plant nutrients, e.g. N, P and K, but it requires composting for a longer period than six months before field application, with the exception of peat bedding, which decomposes faster (Airaksinen et al., 2001). Photosynthesis and material degradation are part of the natural cycle of materials in ecosystems, where nutrients are captured in living organisms and released for plant growing by degradation of dead organisms by detritivores and by-products from organisms, e.g. manure. Horse keeping that does not include crop cultivation, has no use on site for horse manure content of plant nutrients. In those cases manure management is more of a waste management problem. This study reveals that most horse keepers in the case (Paper IV) spread horse manure on other people's farmland, which requires cooperation with farmers. This is positive due to the challenges with inefficiency in phosphorus (P) use, and is among the strategies to reduce the dependency of rock-derived P suggested by Withers et al. (2015). Horse keepers can contribute to more efficient phosphorus use by balanced feed, removing non-essential P inputs, and by reduced P runoff from storage and paddocks, followed by integration of crop cultivation and horse keeping system and improvements of manure transportability. The performed impact assessment does not include resource impact categories, and thereby the organic fertilizer content of non-fossil phosphorous is not included as an environmental benefit in terms of resource extraction. The fertilizing effect and emissions of plant nutrients vary depending on the respective nutrient. The emissions from phosphorous are assumed to be the same from mineral fertilizer and biofertilizer in the mathematical model, while plants more easily take up mineral fertilizers' nitrogen content, which results in smaller emissions compared to organic fertilizers in the mathematical model (Dalemo et al., 1998). Nitrogen immobilization in the compost process makes horse manure less desirable as fertilizer (Keskinen et al., 2017). On the other hand nitrogen in horse manure is slowly released after application and this favors yearly application of manure to get a nitrogen fertilizing effect (Steineck et al., 2000). Anaerobic digestion and composting of horse manure still enable recycling of plant nutrients, valuable in crop production. Horse manure adds the same fertilizing effect as the corresponding amount of potassium and phosphorous in mineral fertilizers (Steineck et al., 2000). Besides this the content of humus in compost and biofertilizer adds important organic material. This material is beneficial to the soil as it improves the soil structure and C content (Keskinen et al., 2017). The carbon remaining in the soil represents a carbon sink, an assumed benefit from compost material and biofertilizer, in the mathematical model used in simulations. Treatment methods that include landfilling of composted material or ash, indicate a greater carbon sink than recycled compost material or digestate, as landfilled material results in the greatest carbon sink in the model (Eriksson et al., 2015).

5.2.1 Bedding and storing

Horse keepers' reports of type and amount of horse manure resulted in small amounts of mainly wood shavings in the total mix of horse manure (Paper IV). This correlates to the highest plant nutrient content and methane yields for wood bedding in simulations (Paper II). Peat and straw added most plant nutrients to horse manure, but wood shavings in small amounts performed second best after straw and peat. This concurs with Keskinen et al. (2017), who concluded small differences in soluble N and P concentrations in fresh horse manure samples, but the total nutrients content was lowest in wood shavings horse manure compared to pelleted straw and peat bedding.

Despite legislation and rules of consideration, there are diverging interpretations of requirements for horse manure management, e.g. about storage. This stems from diverging Swedish legislation about storing and spreading between areas of special and no special concern (SFS 1998:915), and municipalities' doubts about how to interpret the rules at hobby horse facilities, or regarding small number of horses (personal communication with officials in two different municipalities). Legal requirements about manure management are sometimes not applicable at horse keeping sites and local adjustments and adaptations to risks for emissions to air, soil and water, together with the Swedish general rules of consideration, then govern manure management (Eskilsson, 2013; Malgeryd & Persson, 2013; SFS 1998:808). Overall, manure should always be managed with least possible environmental impact. Most often this includes storing and composting in a paved and, if possible, covered area, and that composted material is used as biofertilizer. Storing increased the total nutrient content (N, P and K) due to loss in dry mass for pelleted straw, wood shavings and peat, except from total N concentration for peat manure (Keskinen et al., 2017). It can be discussed that horse manure not valued as a resource by the horse keeper, i.e., the waste producer, increases the need to control and reduce risk for environmental impact, by rules and control of compliance. Horse manure left in heaps on the ground, not spread on farmland, breaks the natural cycle of plant nutrients when nutrients risk leaching to the surrounding soil and water. On the other hand, if horse manure is viewed as waste by the horse keeper, i.e., not composted and used as biofertilizer, that allows for increased use of horse manure as a biofuel, which fits with the increased interest in organic resources for energy purposes. Used for crop cultivation directly on site, horse manure would not have the same availability for energy actors and energy recovery.

5.3 Potential environmental impact

Potential environmental impact from the studied systems is used to gain more knowledge about the impact from several variants of horse manure management in an energy system. In the following sections, the results are discussed related to each treatment method. Impact categories were chosen with respect to the environmental impact from horse manure management described in Paper I: acidification potential (AP), eutrophication potential (EP) and global warming potential (GWP), and primary energy use (CED) from horse manure treatment.

5.3.1 Composting

Unmanaged composting, where a part of the horse manure was used on farmland and a part was left unutilized, was one alternative of horse manure treatment studied in this thesis (Papers III and IV). This was assumed to describe the current horse manure management. Compost treatment resulted in a low input of energy, but high emissions to air, soil and water, compared to anaerobic digestion (Paper IV). Regarding acidification potential (AP), unmanaged composting had slightly lower potential impact than AD in Paper III, although a higher contribution to AP from the composting process. As mentioned above, composting supports the opportunity to use the compost material as biofertilizer, but horse facilities decide final use. This result in variations in current horse manure treatment between systems with or without plant nutrient recycling, associated transports or no current use of transports. Most often horse keepers used compost material on agricultural land (Paper IV). The higher eutrophication potential from unmanaged and managed composting in comparison to AD in Paper III was a result of higher emissions from the compost process, arable land and landfill. Although managed composting support recycling of humus and plant nutrients it resulted in higher energy use, due to the process's need of energy, and higher eutrophication potential than unmanaged composting in Paper III. In managed composting all compost material was assumed to be used on farmland, resulting in increased emissions from arable land compared to the use of mineral fertilizer in unmanaged composting. Additionally, horse manure left unmanaged (as in a landfill) meant high contribution to carbon sink and low emissions from transports of produced compost material (Paper IV). Paper III had no emissions from transports of produced compost material as it was assumed to be used on site.

5.3.2 Incineration

Large-scale incineration was the most preferable in terms of reduced potential for acidification, eutrophication and cumulative energy demand (Paper III). The use of remaining ashes from incineration as construction material, or on landfill, does not contribute to increased resource recovery regarding plant nutrients or soil structure (Paper V). This inefficient use of plant nutrients increases human interference with planetary boundaries related to N and P cycles (Rockström et al., 2009). The NO_x reducing effect respondents reported from co-incineration of horse manure and biomass is an interesting positive environmental effect (Paper V). NO_x reduction with urea or ammonia in combustion of biomass was described in Nussbaumer (2003) and Goelkhe et al. (2010). A NO_x reducing effect of cattle manure was reported in Otero, Sánchez, & Gómez (2011), referring to co-firing with coal (Annamalai, Thien, & Sweeten, 2003; Carlin, Annamalai, Harman, & Sweeten, 2009), but no literature about co-firing horse manure and biomass has been found to validate, or reject, interview results. Another environmental impact from horse manure incineration, mentioned by respondents, was odor (Paper V). Despite reported NO_x reduction in co-incineration with biomass, odor was a reason for stopping incineration tests, while in co-incineration with waste odor was not mentioned. An explanation for this could be that odor is more accepted in processes already using other fuels with odor (waste).

5.3.3 Anaerobic digestion

Treating horse manure in anaerobic digestion (AD) is a concept that comprises use of biofertilizer for crop cultivation and energy recovery. Anaerobic digestion has benefits from low emissions from the digestion process and upgrading. Furthermore, environmental impact from AD benefits from biogas replacing fossil fuels. Despite the transport of horse manure to an anaerobic digestion plant, AD had the potential to reduce potential environmental impact compared to unmanaged composting (Paper IV). Extended transport distance increased potential environmental impact, and trucks with smaller loading capacity nearly doubled the potential environmental impact from transport in the sensitivity analysis. Still, the total potential environmental impact changed only slightly compared to unmanaged composting (Paper IV). Higher amounts of horse manure were notably favorable for energy balance (Paper II). Due to increasing potential environmental impact per weight unit, increased AP and EP was a consequence of increased horse manure in the AD scenario in Paper IV. On the other hand, CED and GWP decreased with higher amount of manure. Accordingly, more produced biogas, used in the compensatory system, increased environmental benefits (Paper IV). This should not be used to justify high amounts of produced horse manure. Effective horse keeping limits the production of horse manure with horse health in focus, by choice of bedding, efficient feed and mucking principles. To prevent, i.e., reduce waste, as the first waste measure agrees with the waste hierarchy (2008/98/EC). The final waste, not avoidable, should also follow the waste hierarchy's next management steps: recycling of plant nutrients and recovery of energy. This concurs with Djuric Ilic et al. (2018) who conclude that ideally there is no waste in a circular economy. Instead of waste there are by-products from product life cycles, that should be treated by the waste hierarchy's strategies. Djuric Ilic et al. (2018) state that environmental impact from production and use of these by-products (also called secondary resources) should be included in LCAs of waste management to include the problems with waste generation.

In a system with combined production of heat, power, fuel and fertilizer (Paper III), the total use of primary energy (CED) was slightly lower for unmanaged composting than for anaerobic digestion. The AD scenario used more input energy in the system than it gained energy from digestion of horse manure. This was a result of the sum of energy demand in the process, upgrading, manure collection and digestate transport being higher than produced vehicle fuel. The system still delivered a benefit of reduced GWP in Paper III, as well as in Paper IV. This reduction of GWP is an important contribution to energy and environmental policies to increase the share of renewable energy and decrease GWP from energy systems (EC No 1096/2009). In Paper IV, AD reduced all chosen environmental category indicators, compared to unmanaged composting. This included CED, after a lower electricity figure for biogas upgrading was selected.

Paper IV aimed to add the question of environmental impact from the required transport of horse manure to a planned biogas plant. Transport had big impact on GWP in the core system (Figure 13), while the achieved reduced GWP from the AD treatment originated from low GHG emissions in the process and a carbon sink. Transport for collection not only resulted in a contribution to global warming. It also increased potential for acidification, cumulative energy demand and eutrophication, but as visualized in Table 6, this contribution to environmental impact is minor in relation to avoided burden from the studied system. These environmental impacts from collection were not apparent in composting, which was assumed to take place at the horse facility. Unmanaged composting was implied to have lower CED (20 MWh) than AD (788 MWh) in the core system, i.e., collection, treatment and transport after treatment (Paper IV). This visualizes the importance of using produced biogas as compensatory vehicle fuel to gain the reduced CED and GWP. The environmental gain is greater than the effort, as transport for collection of horse manure in a systems perspective has a low contribution to environmental impact categories. Distances for collection could increase eleven times before CED for unmanaged composting was reached, and 34 times for GWP, which indicates a small sensitivity regarding environmental impact of increased transport distances (Paper IV), when the compensatory system is accounted for.

5.4 Prospects for increased resource recovery

Out of the previous discussion and results this chapter will discuss advantages and disadvantages of different treatment methods related to increased resource recovery.

5.4.1 Current practise: unmanaged composting

Unmanaged composting is characterized by the ability to be performed at the horse facility, low energy demand and that it enables plant nutrient recycling. On the other hand composting of horse manure is reported to be a slow process, which does not start, or continue, easily (Swinker et al., 1998). Bedding material affects the composting process in various ways. While peat was the only bedding ready for utilization after composting in Airaksinen et al. (2001), sawdust bedding composted more readily than phonebook paper and straw in Swinker et al. (1998). A third result was that pelleted straw composted best, wood shavings second best, and peat had the lowest compostability (Keskinen et al., 2017). On-site composting requires management (work input) to be effective. For example, actions of turning and aeration are preferably added to the treatment (Heinonen-Tanski et al., 2006). Besides this, manure should be stored and covered imperviously, on concrete slabs for example, to reduce potential environmental impact during composting, as described in Komar et al. (2010). Horse manure is dry and precipitation can be an advantage for the compost process but not for leakage of nitrogen and phosphorous to surface and groundwater. Increased resource recovery from composting would incorporate improved storage and management (see above), and closing of natural cycles of plant nutrients, where it does not occur today. Heat recovery from composting described in Smith et al. (2017) could increase resource recovery from composting, by extraction of heat by direct utilization of compost vapour in for example greenhouses, or within-pile heat exchangers, called hydronic heating. In this study, unmanaged composting was modelled as open windrow composts without mixing or heat exchange to comply with horse manure management experienced at field observations. The third system Smith et al. (2017) mentioned uses a heat exchanger to extract heat from compost vapor. These systems are commonly used at commercial composting plants with managed composting processes (Rodhe et al., 2015; Smith et al., 2017).

5.4.3 Increased energy recovery from incineration

Despite the loss of plant nutrients and organic materials that takes place in the incineration process one energy actor reported recycling of ash in a farm-scale incineration plant, while in larger scale recycling ash was put on landfill or used in concrete. The possibility to recycle nutrients remaining in ash, if content of impurities is low, was not further studied in this thesis. Still, in a system with compensatory supplies of heat, vehicle fuel and fertilizer (Paper III), large-scale incineration of horse manure resulted in decreased potential environmental impact. This was related to e.g. produced renewable heat and power, use of mineral fertilizer and efficient air emission measures. Respondents reported no or minor experienced technical problems and no emission problems from larger scale co-incineration. This was because of small amounts of horse manure in the fuel mix, and existing filter strategies (Paper V).

In existing large-scale waste incineration plants there is a possibility to gain environmental, economic and energy benefits, compared to unmanaged composting, while small-scale incineration seems to have more environmental and technical aspects to consider (Paper III and Paper V). Incineration of horse manure in farm-based plants showed lower environmental benefits, compared to large-scale incineration in Paper III. This was related to the missing reduction equipment for air emissions, but the study also suffered from insufficient data availability. The results should therefore be considered as indicative. The respondent with experience from farm-scale plants conveyed that it required a lot of maintenance, wood bedding and a high content of added pelleted wood, due to high moisture content (Paper V).

Energy actors did not mention high ash content of horse manure, which causes high particulate emissions to air, or loss of plant nutrients caused by incineration (Paper V). This could be related to respondents' lack of connection to crop cultivation, existing equipment for air emission control present at large-scale incineration plants, and because respondents provided information about non-existent restrictions on air emissions for farm-scale incineration plants. The reported reduction of NO_x emissions in co-incineration, economic compensation and reduced costs for waste treatment are economic considerations that favor horse manure. On the other hand, Tanskanen et al. (2017) suggested that horse manure was given low value by energy actors because of impurities. Impurities were however not mentioned in interviews regarding incineration.

5.4.2 Increased resource recovery from anaerobic digestion

The prospects for increased resource recovery from horse manure are positively affected by e.g. the increase of feedstock and concentration of plant nutrients, and added carbon and total solids content to which horse manure contributes in AD processes (Paper V). The increased resource recovery and reduced environmental impact from the production and use of renewable energy followed by reduced use of fossil energy was shown in Paper III and IV. Simulation results hint that a large amount of bedding adds to energy balance, except for peat. This is positive due to the often large ratio of bedding material in horse manure. Wood shavings is in Sweden the most used bedding for horses (Enhäll et al., 2012), which complies with this case study (Paper IV). Wood shavings as bedding also technically suit the plug-flow process, but straw pellets were preferred by most respondents. Horse manure characteristics tends to result in technical problems in stirred, liquid processes (L-AD), or high total solids mixed processes (Paper V). The content of semi-degradable substances, problematic in L-AD digestion processes, are valuable in the compost process of the biofertilizer, after the plug-flow process. The technical aspects and characteristics of the substrate create costs and more expensive biogas plants affecting the economy of the plant. Solid impurities are more of a problem in L-AD processes. This requires that manure left outdoors should not be part of the manure delivered to these biogas plants as mucking outdoors increases the risk for sand and gravel.

A change from unmanaged composting to anaerobic digestion is a change from a lower to a higher degree of resource recovery of horse manure. A change like this needs a development of connections between organizations and measures to increase cooperation between organizations. Materials, by-products or wastes from one organization need to be found and utilised by another organization. This suggests a need for organizational structures to create cross-border contacts within organizations and between actors, e.g. energy actors and suppliers of horse manure, and energy actors and users of organic fertilizers. This kind of resource exchange could be initiated for reasons consistent with the cooperation and exchange of resources that take place in industrial symbiosis: reduce cost, enhance revenue and expand business (Chertow, 2007). The transition to a more renewable energy system can be managed through the use of transition management (Kemp, Parto, & Gibson, 2005), by exploring possible paths, configurations, and benefits towards the environmental and energy goals set by society and the European Commission. Change can be approached as a continuous process of adaptions and learning (Todnem By, 2005). Success of change is suggested to be dependent on change readiness and facilitating for change, achieved through understanding, and identification of options.

5.4.1 Implications for stakeholders

Horse keepers

Results suggests that some changes and adaptations in horse keeping could make horse manure more attractive for energy actors. Regardless of treatment method, reduction of the amount of horse manure (waste reduction) is advocated. Choice of bedding, selective mucking and covered storage reduce the amount of horse manure and contribute to more efficient transport. Bedding is often referred to as troublesome in both energy aspects and practical aspects. A change to straw pellets was experienced by energy actors to reduce horse manure amounts (Paper V), also suggested by Fleming et al. (2008). Horse manure for anaerobic digestion requires fewer solid impurities and less bedding. Straw and straw pellets in general show highest methane potential in literature (Paper II). Preferred bedding in high total solid stirred anaerobic digestion is pellets. It is also possible that the bedding material the horse keeper desires to use, because of horse health, economy or other various reasons not further investigated in this thesis, is suitable for a specific energy conversion plant. For example, plug-flow anaerobic digestion processes can handle horse manure and wood shavings, and can manage straw, in smaller amounts and smaller size. Storage under roof and on concrete slabs or in containers both reduces the adding of weight from precipitation, protects the manure storage from surrounding water, and could prevent decomposition. Lower weight is positive for transportability as it improves the loading capacity. Small-scale incineration favors dry feedstock, where covered storage is recommended. Sorting at source should be part of the waste management and solid waste should never be part of horse manure. When solid material (e.g. gravel) is a problem for the energy plant, horse manure from paddocks and pastures should be sorted out and composted separately.

Energy actors

Horse manure is suitable for anaerobic digestion plug-flow processes, in co-digestion with other feedstock and in co-incineration, mainly on a large scale. The experienced challenges regarding horse manure as an energy substrate suggest some anaerobic digestion processes and incineration processes more or less suitable for horse manure. Another point of view was that enough adaptations in substrate and technology may solve these challenges. Both opinions are presented in the results. A cooperation where energy actors provide information to horse keepers about the requests, if such exist, and the connection to energy conversion could facilitate energy recovery of this heterogeneous material. The experience is also that a system for supply of horse manure is needed.

Policy makers

To turn horse manure from a waste problem into a resource in a biogas energy system has the opportunity to contribute to energy policies, energy and environmental targets and sustainability objectives. The results in this thesis act as a complement to policy documents and present options for reduced environmental impact and increased energy recovery from horse manure. Focus in this thesis is the potential for reduced environmental impact, but some other aspects of sustainability, e.g. social sustainability, are closely related, and described in literature. For example, environmental effects of horse keeping, because of changed land use and availability of land in peri-urban areas, are also related to social effects. Improved horse manure management could reduce risks for water quality, and thereby reduce negative effects on the living environment. On the other hand, increased transport for resource recovery will have impact on residents, even if transport enables reduced environmental impact from the studied system in this thesis. The information in this thesis could contribute in planning, advisory and permission matters of horse facilities, as horse-keeping activities always include horse manure management.

5.5 Methods applied and uncertainties

5.5.1 Literature review

Paper II summarizes different results from literature, revealing a span of methane yields depending on specific conditions of experimental design and scale of trials. Results from literature indicate that there could be a difference between measured and calculated methane yield, methane potential, and the methane released from a reactor. Every reference experiment or operational test is unique, and the literature review visualizes this variation and combinations that give some limitations to the comparability between data. The literature reviews resulted in sometimes contradictory results, but summaries of differences are hopefully a benefit for awareness, for example about bedding compostability. Literature has described a wide range of horse keeping activities related to the subject of this thesis, horse manure, which resulted in a challenge to draw conclusions and create a synthesis of collected data from literature.

5.5.2 Interviews

Telephone interviews have the potential to provide quick data collection (Burke Johnson & Onwuegbuzie, 2004). The telephone interviews that provided data for Paper IV were conducted during one week, but careful preparations were made beforehand to prepare the interviews and interviewers. An interview guide was prepared, questions were tried in a test interview with a horse keeper, and interviewers were introduced and informed about the project. Preparations aimed to help interviewers reach the greatest possible number of respondents, reduce potential effects of surprise for respondents, and motivate people to participate. The purpose of the call was explained early in the conversation to counteract rejections because of unprepared respondents. A more suitable time and day was decided for the interview with respondents positive to participate but not available directly. In Paper V, the possibility to answer by e-mail was offered. In Paper IV, respondents' estimations were used for calculations, for example of horse keeping activities and amounts of manure. Telephone interviews provide no possibility for respondents to check data and pressure in the situation could be experienced (Wärneryd, 1990). To prevent this, respondents were given suggestions, if needed, for connecting answers to the daily activity. This was the case in assumptions about amount of horse manure, which could be specified as number of wheelbarrows, tractor wagons and the like. Calculations was made from interpretations of answers and general volumes of respective measurement. This was a way to estimate the horse manure amount at a large number of horse keepers without performing measurements, which could be a method to use in further studies. Measurements could complement and widen the results from Paper IV and continue the attempts to identify and explore horse manure as potential feedstock for energy conversion. Interviews by telephone or e-mail could act as the first contact, followed by more interviews about specific questions of interest. In Paper V respondents in some cases were contacted for clarification or descriptions of details. The telephone interviews with horse keepers revealed many persons that no longer kept horses. Since address lists were not recently updated, this indicates that the respondents participating were horse facilities keeping horses for more than 10 years.

5.5.3 Environmental systems analysis

In environmental systems analysis the reality is simplified to study the effects of an actual, preferred, or future system. This simplification is a prerequisite for studying the connection between technological subsystems and the complicated natural systems. In systems analysis, when models are used, they should be kept simple (Miser, 1981). Due to simplifications and assumptions in models it is important to always interpret results from simulations as general descriptions of real conditions (Winkler & Bilitewski, 2007). The simulation results should be handled with caution as they are derived from the assumptions. This study constitutes a novel area where choices of systems, data and technologies sometimes have big influence on results, while other decisions could be of smaller importance.

The sub-model for anaerobic digestion treatment process in simulations was based on an existing liquid anaerobic digestion plant (L-AD), which represents the most common configuration of AD plants. Treatment in a solid state anaerobic digestion process must be postponed to future studies, when suitable mathematical models are available. The model used accounted for energy resources, and CED was summarized to primary energy demand. Environmental impact from use of resources is included in some categories, but the use of resources is not included as any specific impact category. An environmental impact category for use of resources could take into account potential environmental impact from e.g. virgin rock phosphate in mineral fertilizers or recycled phosphorous in organic material.

Emerging technologies have different conditions for data supply and data certainty. That is the case for different treatment methods in the study. In Paper III this is apparent for small-scale incineration having less data, e.g. about electricity use, ash and slag, while large-scale incineration was well defined. Adaptation of waste descriptors, i.e., the chemical composition of horse manure and bedding materials, was made according to relevant literature. Some of the data used on chemical composition of horse manure was found to have an unknown type and amount of bedding incorporated (Strömberg & Herstad Svärd, 2012). The extent of effect on results because of variance in chemical composition was not sensitivity tested, but as a part of simulations the validity of the anaerobic digestion sub-model was tested. This was done by a comparison of methane potentials in literature, and the model was adjusted to a lower biogas production rate to better match data in literature (Eriksson et al., 2015). The effects of choice of data and system boundaries were experienced when methods and results from Paper III and Paper IV were compared. Consistency of anaerobic digestion reduction of GWP was detected between both simulated systems, but not according to the other environmental impact categories. Differences were found in use of input data, differences in the studied systems and additional system expansion. In Paper III the system consisted of L-AD with heat exchanged pre-treatment compared to potential environmental impact from composting and incineration. Due to system expansion, the studied system comprised production of heat, vehicle fuel and electricity. This resulted in higher potential environmental impact from anaerobic digestion compared to incineration, except for global warming potential.

The L-AD process in Paper IV comprised a high energy-consuming process, with energy demand as high as for the larger amount of horse manure in Paper III. The choice of technology had a big influence on the result, i.e., the change of input data for the biogas upgrading process changed the CED for the AD process from a higher CED to a lower one, compared to unmanaged composting. The change was motivated by updated water scrubbing technology, a process with lower energy demand. System expansion constituted avoided emissions from biogas use for vehicle fuel in Paper IV. Even though different processes, system boundaries and data were revealed to have great influence on results, it is most relevant in systems analysis to interpret the results based on the questions asked and the problems studied.

6. Conclusions

This thesis explored horse manure as a resource, for plant nutrients and for biogas. It investigated horse manure characteristics, and connected these to energy recovery. The main conclusions after analyses of results from systems analysis, interviews, and systematic combining with literature are that horse manure used as an energy feedstock means both challenges for, and contributions to, energy conversion processes. Horse manure for biogas production and a biogas system requires adaptation of energy conversion plants to horse manure characteristics or, when necessary, adaptation of horse manure to energy plants' requirements. Changing treatment methods, from composting to recovery of energy, potentially reduces the environmental impact from horse manure management. The conclusions of this thesis answer the research questions below.

What potentially critical factors in horse keeping affect the amount and characteristics of horse manure?

Identified activities and critical factors for resource recovery from horse manure in Paper I were feeding, bedding, mucking, collection, indoor and outdoor horse keeping, manure storage, fertilization and transport, as they affect the total weight, nutrient content, utilization and biodegradability of horse manure.

How do feedstock characteristics and biogas process parameters affect energy performance and nutrient content in biofertilizer?

Feedstock parameters (type and amount of bedding) were indicated to have more effect on resource recovery, i.e., energy performance and nutrient content, than biogas process parameters (hydraulic retention time and temperature) in Paper II. Higher amount of added bedding had a positive effect on energy balance, while lower amount of bedding implied higher methane potential. Energy performance of bedding material was, in descending order, paper, straw, wood bedding and peat. Regarding nutrient content, straw and peat added plant nutrients, a low amount of wood bedding was positive for nutrient content, and paper lacked plant nutrient content. Hydraulic retention time (HRT) and temperature had no impact on nutrient content in biofertilizer. Mesophilic temperature registered the best energy balance, while long HRT and thermophilic temperature had a limited contribution to methane potential compared to shorter HRT and lower temperature.

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

Simulations in Paper III stated anaerobic digestion to reduce global warming potential (GWP) compared to composting and incineration. Anaerobic digestion resulted in lower eutrophication potential (EP) compared to composting and small-scale incineration. Compared to small-scale incineration, the biogas process had lower acidification potential (AP) as well. Large-scale incineration was registered to have lower environmental impact than anaerobic digestion in AP, EP and cumulative energy demand (CED) when the expanded system comprised production of heat, power, fuel and fertilizer.

Paper IV studied unmanaged composting and anaerobic digestion with input data from horse keepers in a specific area. Horse keepers in the study used wood bedding to the greatest extent. The studied system comprised a compensatory system with avoided burden from vehicle fuel and fertilizer. Despite the environmental impact that transport work added to the system, anaerobic digestion reduced cumulative energy demand (CED), GWP, AP and EP compared to unmanaged composting.

How do potential energy actors view horse manure as an energy resource?

Energy actors in the study conveyed a wide variety of experiences within incineration and anaerobic digestion, related to the type of treatment (Paper V). Both farm-scale and larger scale incineration reported economic advantages to treat horse manure. Co-incineration reported no or minor technological problems, besides farm-scale incineration that had high demand for monitoring, and need for co-incineration with wood pellets to maintain combustion. While existing filter strategies handled air emissions in co-incineration, odor problems excepted, farm-scale incineration had no special requirements for air emissions.

Biogas experiences diverged between views of horse manure as a contribution in anaerobic digestion processes to a perception that horse manure is a problematic feedstock. Contributions in co-digestion plants were added carbon, stabilization of the process and increased methane production. The variety of bedding and solid impurities was reported to cause technical and economic challenges for biogas plants. Energy actors suggested that horse manure kept dry in covered storage is a basis for more efficient transport. Furthermore, horse manure should be newly laid, and frequently delivered to supply the energy plant with feedstock. In anaerobic digestion, most important for wet and stirred processes, a low amount of solid impurities was a request, and straw pellets was preferred as bedding material.

The conclusions in Paper V state that with some adaptations by horse keepers to increase transportability and characteristics positive for energy recovery, horse manure could contribute in co-digestion with other feedstock. Many of these adaptations positively affect nutrient recovery as well. Energy actors have a potential feedstock in horse manure to support and stabilize biogas and biofertilizer production in co-digestion biogas plants. Still, the policy framework does not actively support such development. The results of this thesis show that changing horse manure treatment promotes reduced environmental impact, and contributes to meeting environmental and energy objectives, targets, and legal requirements. This thesis adds to information, communication and practice about resource recovery from horse manure useful for horse keepers, energy actors and policy makers.

7. Further research

Interesting areas for future research are to explore horse keepers' views of horse keeping and how this affects the content and treatment of horse manure. Questions about reasons for choices and the possibility to adapt to make horse manure more preferable for resource recovery would continue and enrich the studies in this thesis. Horse keeper manure collection and sorting at source is an interesting part of this and could constitute a study of horse facilities' possibilities to keep the natural cycle clean, and not add solid waste or contaminants. A study with focus on practical and economic aspects of horse manure and bedding material for energy purposes would complement data from literature and experiences in this study. The horse manure content, amount and cost for use of different bedding material would be interesting to study as well as horse keeper experiences of use of different bedding material. Aspects e.g. regarding smell, mucking and sorting of clean and used material could be added to a study about bedding material with energy focus.

Another area for further research is supply chain structures for horse manure. In interviews, respondents had suggestions for cooperation between container rental, bedding producers and energy actors regarding collection and delivery of horse manure. Other aspects of interest are to follow up the question of storage time and the preferred straw pellets. Field observations and personal contacts revealed that deep litter from cattle is used in co-digestion with food waste and that there is existing cooperation between AD operators, straw pellets producers and farmers to provide AD plants with preferred feedstock. Further contacts to study their experiences of deep litter effects of storage time and cooperation could add relevant information for energy recovery of horse manure.

The simulation method used in this thesis was an L-AD process and in future studies the possibility to use a model adapted to SS-AD would be interesting. A systems analysis that adds environmental impact from different bedding materials could further improve the options for choosing bedding material. How, and if, horse manure is affected/changed as a biofertilizer after anaerobic digestion would be a practical and interesting study as a complement to the performed studies.

The economic aspects of horse manure treatment are a minor part of this thesis. The interesting aspects of how to value a substrate such as horse manure in economic terms is addressed to future studies. The cost to treat a waste or to buy a feedstock and the value of gained energy and biofertilizer could be linked with studies about horse keepers' actual costs for horse manure management. In this thesis it was assumed that horse keepers in the case had no cost for current horse manure treatment, but it would be interesting to add information on the variety of costs for horse keepers. Horse keepers assigning containers for current storage may have a cost for both rental and collection and gate fee for treatment of the horse manure today.

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Papers

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

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