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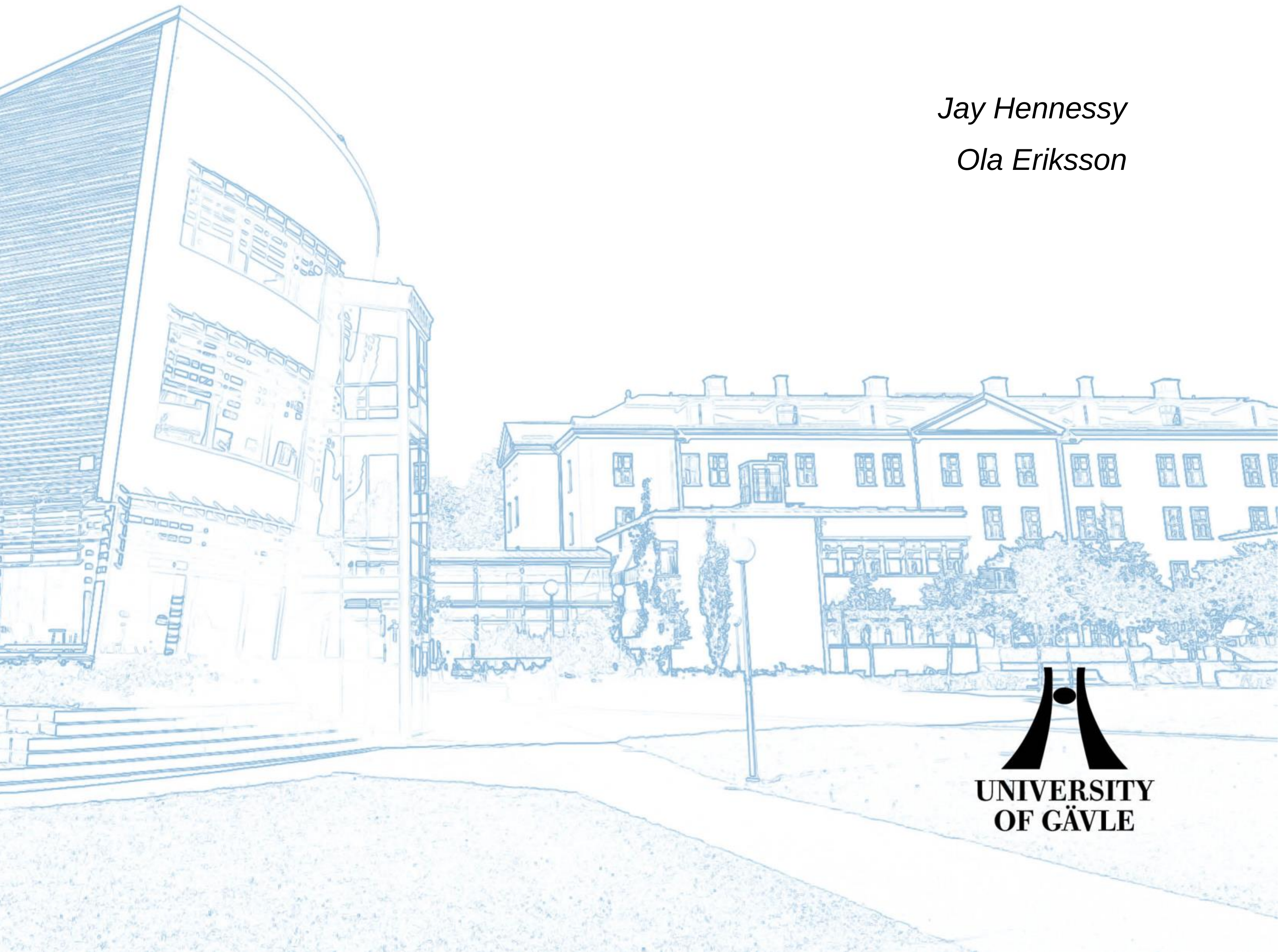

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Energy and nutrients from horse manure

Life-cycle data inventory of horse manure management systems in Gävleborg, Sweden

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Department of Building, Energy and Environmental Engineering

Interim report 2 from the project
Hästkrafter och hästnäring -
hållbara systemlösningar för biogas och biogödsel

UNIVERSITY OF GÄVLE

Region Gävleborg

Abstract

Management of horse manure is seldom subject to energy recovery. In the current project solutions for energy recovery of horse manure, with a focus on biogas production as the process not only recovers energy but also closes nutrient cycles, are identified and assessed from an environmental point of view. The number of horses in society is increasing. Today, according to Statistics Sweden, there are more than 360,000 horses in Sweden, of which three-quarters are situated in urban or near-urban environments. With a dry matter content of 40 %, this equates to a quantity of 1,360 tonnes of horse manure per annum and corresponds to an annual biogas production of 641 GWh, which corresponds to almost 40 % of all biogas produced in Sweden in 2013. Although there are some practical limitations on how much of that potential can be exploited, this is still a significant potential for increased use of renewable energy. Collecting manure and anaerobically digesting it achieves three environmental benefits:

1. Emissions from conventional management, where the manure is piled and stored, or spontaneously composted or decomposed, are avoided.
2. Anaerobic digestion of manure produces biogas that can be utilised to generate electricity and/or heat or, after upgrading (purification and pressure increase), as vehicle fuel; thereby emissions from fossil fuels are reduced.
3. Following the process, the resulting digestate can be used in agriculture, thereby replacing chemical fertiliser and providing additional environmental benefits.

The aim of this project is to find a greater breadth of system solutions than previously, solutions that are proven to function technically and be economically feasible. If these systems are translated into practical reality, environmental gains are made, for example, through reduced environmental impact such as reduced eutrophication and reduced use of finite resources.

This report documents a data inventory made for the life-cycle assessment (LCA) of horse manure management systems in the Gävleborg region, Sweden. The overall result is that data are scarce for all parts of the system, from feedstock characteristics to waste treatment methods as well as utilisation of biofertiliser. There are few plants for solid state anaerobic digestion, at least using horse manure as substrate, and little is known about emissions from current manure practise. Moreover, as the number and location of horses are hard to estimate, the forthcoming systems analysis has to be made for a hypothetical amount of horse manure and emissions etc. have to be expressed per ton VS. Given these uncertainties the systems analysis will just give indicative results.

Sammanfattning

Hantering av hästgödsel är sällan föremål för energiåtervinning. I det aktuella projektet ska lösningar för energiåtervinning av hästgödsel, med fokus på biogasproduktion eftersom processen inte bara återvinner energi utan också sluter näringsämnenas kretslopp, identifieras och bedömmas ur ett miljöperspektiv. Antalet hästar i samhället ökar. Idag finns det enligt SCB mer än 360 000 hästar i Sverige, varav tre fjärdedelar återfinns i städer eller stadsnära miljöer. Med en torrsubstanshalt på 40 %, motsvarar detta 1 360 ton hästgödsel per år vilket motsvarar en årlig biogasproduktion om 641 GWh, vilket utgör nästan 40 % av all biogas som producerades i Sverige under 2013. Även om det finns vissa praktiska begränsningar för hur stor del av denna potential som kan utnyttjas så är detta fortfarande en betydande potential för ökad användning av förnybar energi. Genom att samla in hästgödsel och röta det uppnås tre miljömässiga fördelar:

1. Utsläpp från konventionell hantering, där gödseln läggs på hög och lagras, eller genomgår spontan kompostering och bryts ned, undviks.
2. Rötning av gödsel producerar biogas som kan användas för (1) att generera elektricitet och/eller värme eller (2) efter uppgradering (rening och tryckökning) användas som fordonsbränsle. Därigenom kan utsläppen från fossila bränslen minskas.
3. Efter processen kan den biogödseln användas i jordbruket, och därmed ersätta konstgödsel vilket kan ge ytterligare miljöfördelar.

Syftet med detta projekt är att hitta en större bredd av systemlösningar än tidigare, lösningar som visat sig fungera tekniskt och ekonomiskt genomförbara. Om dessa system omsätts i praktisk verklighet kan miljövinster göras, till exempel genom minskad miljöpåverkan såsom minskad övergödning och minskad användning av ändliga resurser.

Denna rapport dokumenterar en datainventering inför en avslutande livscykelanalys (LCA) av hästgödselhanteringssystem i Gävleborgsregionen i Sverige. Det övergripande resultatet är att data är knappa för alla delar av systemet, från råmaterialets egenskaper till behandlingsmetoder samt utnyttjande av biogödsel. Det finns få anläggningar för torrrötning, åtminstone som använder hästgödsel som substrat, och lite är känt om utsläpp från nuvarande gödselhantering. Dessutom, eftersom antalet och placeringen av hästarna är svårt att uppskatta, så kommer den avslutande systemanalysen göras för en hypotetisk mängd hästgödsel och utsläpp etc. måste uttryckas per ton VS. Med tanke på dessa osäkerheter kommer systemanalysen endast ge vägledande resultat.

Preface

This is the second report out of three from a project funded jointly by Region Gävleborg and the University of Gävle. Previous report in Swedish (Hadin et al., 2015) explains details on the background of the project and qualitatively discusses various issues and aspects of horse manure management and considerations relating to the different technologies available to transform the manure.

The work documented in this report has been carried out during February-June 2015. Expertise was provided by Åsa Hadin. The report has been peer-reviewed by members of the project reference group and finally by the assessor of the entire project. The third, and last, report from the project (Eriksson et al., 2015) shows results from an environmental assessment of different horse manure treatments based on data documented in this report.

The authors like to thank all people contributing to this report.

Gävle 2015-07-05

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Glossary, prefixes and chemical symbols

-	In tables, '-' means the data was not specified/available
AD	anaerobic digestion
C	carbon
CH_4	methane
CHP	combined heat and power
DM	dry matter; see also TS
dung	fresh faeces from the animal
FM	fresh matter
IVL	IVL Swedish Environmental Research Institute (IVL Svenska Miljö-institutet)
JTI	Swedish Institute of Agricultural and Environmental Engineering (Institutet för jordbruks- och miljöteknik)
KTH	Royal Institute of Technology (Kungliga Tekniska högskolan)
LCA	Life-cycle assessment
manure	faeces, urine and bedding material collected from animal stall; fresh or after storage
N	nitrogen
N/A	'not applicable' (data in tables)
NMMO	n-methylmorpholine oxide
N_2O	nitrous oxide
NH_3	ammonia
NH_4-N	ammonium nitrogen
NO_X-N	oxidised nitrogen
NO_3-N	nitrate nitrogen
ORWARE	an LCA computational model developed in Matlab
P	phosphorous
SLU	Swedish University of Agricultural Sciences (Sveriges lantbruks-universitet)
SS-AD	solid-state anaerobic digestion
TS	total solids
VFA	volatile fatty acid
VS	volatile solids

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1 Introduction

This report details a data inventory made for the life cycle assessment (LCA) of horse manure management systems in the Gävleborg region, Sweden. Details of the aims of the project and the results of the initial literature study can be found in the preceding report, Hadin et al. (2015). The horse manure management systems that have been considered, and for which data have been gathered, are:

1. Discarded piles (unmanaged composting) which should reflect current management practise
2. Managed composting and subsequent spreading of digestate on fields
3. Incineration with energy recovery (large scale and small scale)
4. Anaerobic digestion, both wet and solid state (single substrate and co-digestion of multiple substrates) and subsequent spreading of digestate on fields

The LCA approach uses a number of potential scenarios that include these systems as well as associated logistical systems such as transportation; the LCA system boundaries are described in more detail in Eriksson et al. (2015).

The model chosen for this task is ORWARE, which is an LCA tool for evaluating environmental impacts of waste management and has been in development since the early 1990s (Bisaillon et al., 2000). The model is described in more detail in section 2.1. LCA tools model material flows and, as such, require input data on the composition of materials and the material transformation processes involved in the waste management systems being considered.

The first step in building an LCA model is to make a data inventory of quality data sources. Where reliable data cannot be established it is also necessary to make assumptions. As an example, accurate data on the number and location of horses in the Gävleborg region does not exist, but can be estimated from national statistics and qualitative data and surveys. Such assumptions are discussed in later sections. The ORWARE model itself includes a number of previous assumptions already documented in related literature and will not be included in this report. Once this data is established, scenarios may be proposed to consider the various waste management options. This process, along with the results of the modelling, is described in Eriksson et al., 2015.

1.1. Data sources

The data was collected from peer-reviewed journal papers, technical reports, questionnaires, personal communication, and in some cases relies on pre-existing values in the LCA model, ORWARE. These data sources are referenced further below and the resultant data is listed in the main text or in Appendix A.

1.2. Management systems considered

Hadin et al. (2015) discussed the various horse manure management options, both in use today and as potential options that could be available in the short term. In Figure 1, a system view of possible horse manure management option/treatments is presented.

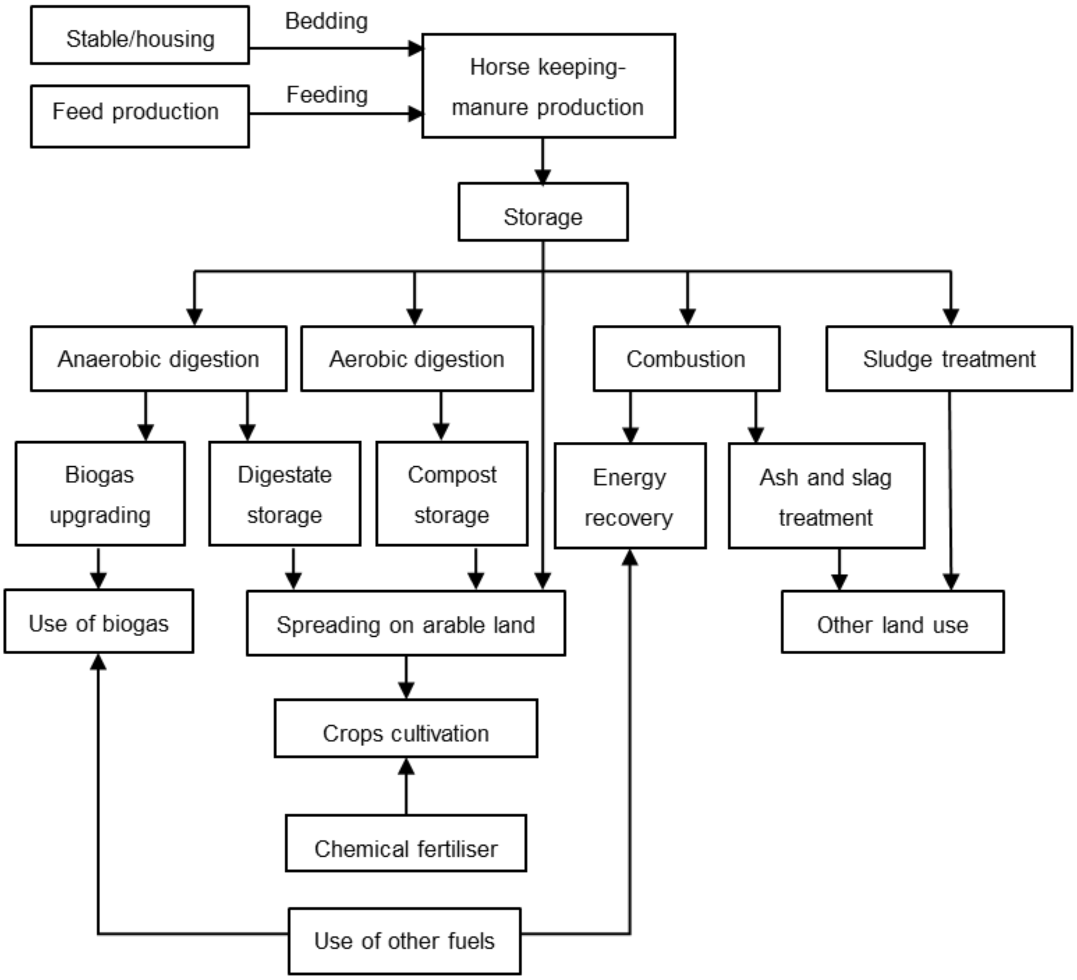

Figure 1. A system view of treatment options for horse manure and biogas generation.

In summary, the following systems are considered:

- Anaerobic ('liquid-state') digestion – the production of biogas with subsequent upgrading to vehicle gas and the resultant digestate, which can be used as fertiliser.
- Solid-state anaerobic digestion (SS-AD) – producing biogas (upgraded) and digestate as above.
- Aerobic digestion (composting) – transforming the manure into fertiliser through either:
  - Piling and storage, leading to passive decomposition (this includes 'unmanaged' composting), or
  - Through active mixing, aeration and turning.
- Combustion (incineration) – for heat and electricity production in either
  - Large scale combined heat and power (CHP) plant. Includes landfill treatment of the resultant ash & slag.
  - Small scale heat boiler at eg. a farm
- Sludge treatment – mixing with sewage sludge and composted before use as top soil cover on a landfill. This option have for long time been the current practise in Gävle but will not be modelled due to a lack of data and also as this is not a future option as the landfill will be finalised within a couple of years.

With the exception of passive decomposition, the management systems above can not only prevent emissions from untreated horse manure, they can also potentially offset emissions from other energy uses, for example incineration can generate heat and electricity, and biogas can replace fossil fuels and possibly heat. Such offsetting can be considered in the LCA model, described below. Even if there are many plausible options, not all will be investigated in this project. For biogas baseline scenarios comprise upgrading to vehicle gas and using biogas in a CHP may be considered in sensitivity analysis. Pre-treatment options for the management systems under study are also considered or included in the model, along with transportation and post-treatment such as sorting facilities. The model represents the current state of the systems being considered. As such, possible future changes in the market and policy measures are not considered.

The inventory in this report covers the main processes as described above. Further work related to the systems analysis including final definitions of system boundaries etc. is further described in Eriksson et al. (2015).

2. The LCA method and model

In this chapter, the technical systems covered by the model are discussed on a general level. A life-cycle assessment (LCA) model is used to study and compare the management options mentioned above. The systems modelled were identified through literature reviews, interviews with horse keepers and personal communication with technology experts.

2.1. The ORWARE model

The model chosen for this task is ORWARE, a computational LCA model for evaluating environmental impacts of waste management (Bisaillon et al., 2000). The ORWARE model has been under development since the early 1990s. It started as collaboration between KTH, SLU, JTI and IVL, and has led to a vast number of research papers, theses and major studies (detailed references are found in Eriksson et al., 2015). The model is currently used and developed mainly by the University of Gävle, Profu, SLU and JTI.

The basis for modelling waste management in ORWARE is that the handling of different wastes can be described at an elemental level, i.e., their composition of nutrients, carbon, water and contaminants such as heavy metals, etc. It can handle solid and liquid organic and inorganic waste from different sources. ORWARE is built from a number of modules that describe a process or treatment. To describe the elements that make up waste management requires a large amount of input data. Each project must decide how much information must be gathered for the case being studied. Once the composition of waste is established, the waste flows through the model from the point of collection, via transportation, to processing plants followed finally by consumption, new products or disposal. A major part of the model used here is built on previous work in a project within Waste refinery (Holmström et al., 2013).

2.2. Environmental impact assessment

Life-cycle assessment generally describes categories of possible (potential) impacts on the environment as opposed to actual environmental impacts, which would require a more site-specific assessment of the impacts of emissions. Different emissions contribute to the different impact categories to varying degrees. Characterisation factors are therefore used to determine the effects of different emissions on each impact category. Each emission is multiplied by these characterisation factors so that its contribution can be summarised. Impact categories may include the following:

- Emissions that can lead to acidification (from sulphur dioxide, nitrogen oxides and ammonia), and eutrophication (nitrogen oxides and ammonia).
- Emissions including greenhouse gases, which contribute to global warming: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).
- Heavy metals and toxic levels of various compounds.

Besides the emissions from the core (in this case manure management) system, offsetting emissions from conventional production of products provided by the manure treatment (eg. electricity, district heating, vehicle transport and nutrients) is also included. More details on LCA methodology are presented in Eriksson et al. (2015).

2.3. General assumptions for modelling

The amount of manure produced by horses varies considerably (see section 3.2). In addition, due to a lack of data regarding the exact number and location of horses (cf. Hadin, Eriksson and Jonsson, 2015), the model calculates all impacts per tonne of horse manure treated. Thus, the model is based on the assumption that there is a fixed amount of horse manure, for example 10 000 tonnes, which includes a number of pre-set percentages of bedding material. The model is run using this fixed amount. In this way, it is possible to compare the effects of different management systems (anaerobic digestion, composting, etc.) for a given amount of manure and bedding material. Once the results have been established it can be estimated how many horses 10 000 tonnes may represent. Also because of a lack of data, costs are not included in the model. System-specific assumptions are discussed throughout this report.

3. Data inventory

Summaries of the data are included in this section. The raw data is collected in an Excel file that is available as a separate electronic appendix to this report.

3.1. Validation

The validity of the ORWARE model and its input data has been tested in numerous prior papers, theses and studies (cf. section 2.1). For this study, the ORWARE values for horse manure are brought up-to-date using the latest data collected (see also section 3.2). Having chosen values for the amounts and composition of horse manure, the outputs of the ORWARE model are validated against results from the literature, which may include production-scale plants (‘Plant’ data), laboratory results (‘Lab’ data) and computational/LCA models (‘Model’ data). Therefore, although some data are only used for validation of the model, it is included in this document.

3.2. Horse manure

Pure horse manure (i.e. without bedding) is referred to as ‘horse dung’ in some literature (Mönch-Tegeder et al., 2013), meaning horse faeces (and sometimes urine). The term ‘horse dung’ will be used in this report to differentiate it from ‘horse manure’, which will denote horse dung and urine mixed with bedding material and subsequently removed from stalls.

A study made during 2002-2003 of horse keepers in the county of Gävleborg, who responded to a survey, showed that 81 % use wood shavings, 19 % use straw and 15 % use peat as a bedding material (Femling, 2003). This agrees with Lundgren and Pettersson (2009) who state that “wood shavings” (assumed to mean sawdust) are generally used in northern Sweden, due to their accessibility and therefore lower cost.

The bedding materials that are modelled in this study are:

- Sawdust/woodchips (of similar chemical composition and hence “equal” in model terms)
- Straw
- Peat
- Waste paper pellet (manufactured by e.g. Laxå Bruk)

Other beddings such as hay, straw pellets, reed and different mixes of different bedding materials are not included due to low biogas production (straw pellets) or lack of data (hay, reed).

3.2.1. Physical properties/chemical composition

The ORWARE model uses a dataset for each material being investigated, known as a ‘vector’. Vectors are created for each of the bedding materials above and for pure horse dung. By combining the horse dung vector with a bedding material vector, the model is able to approximate the combination of horse dung and bedding material.

However, it should be noted that Cui, Shi and Li (2011) have demonstrated that anaerobic digestion of bedding material in its raw form gives different results compared to anaerobic digestion of the same material that was used as bedding. For example, in the case of wheat straw, the latter is more easily digested and can produce up to 56 % greater methane yield kg^{-1} volatile solids (VS). The amount of nitrogen, phosphorous and potassium in the horse waste will depend partly on whether the horse is sedentary or exercising (Westendorf and Krogmann, 2006). It is also unclear from the literature what amount of urine is included, if any.

The ORWARE vectors for horse dung and bedding materials (except waste paper pellet where a previous vector for waste paper have been applied) are included in Appendix A, including justifications for the values used and any associated references. From the ORWARE perspective the composition of sawdust and woodchips is the same, since both are sourced from wood. From a horse keeping perspective however, it should be noted that these materials have different properties, and absorb different amounts of urine. This is not accounted for in the model.

3.2.2. Amounts of horse manure generated

The data below (Table 1) shows that total waste per horse is in the range 9-29 m^3 $horse^{-1}$ $annum^{-1}$. The Swedish statutory requirement for storage of deep litter manure is 9.9 m^3 $horse^{-1}$ $annum^{-1}$ according to Swedish Board of Agriculture, where standard values include faeces and urine, bedding material, decomposition losses, cleaning water, water spillage and precipitation. However not all manure will be collected, since horses are not always in the stall.

The values of horse waste production that are assumed for the model, based on the 'mean' values in the Table 1: 15 kg faeces $horse^{-1}$ day^{-1} and 9 kg urine[1] $horse^{-1}$ day^{-1} (Westendorf and Krogmann, 2006; Wheeler and Zajaczkowski, 2009; Wartell et al., 2012), totalling 24 kg waste $horse^{-1}$ day^{-1}, equivalent to 8.7 tonnes waste $horse^{-1}$ $annum^{-1}$.

From Table 1, values for bedding material used per horse per day are: straw 9.9 kg, sawdust 5.3 kg, and woodchips 16.3 kg (Airaksinen, Heinonen-Tanski and Heiskanen, 2001; Häußermann, Beck and Jungbluth, 2002), which would therefore correspond to 29 %, 18 % and 40 % of the total waste by weight, respectively[2]. A horse using sawdust for bedding would thus[3] produce approximately 10.7 tonnes $annum^{-1}$ of manure, assuming it is in the stall all year. There is a large difference between sawdust and woodchips due to the different absorption properties. However, no consistent data on the relationship between type of bedding material, urine and faeces have been found, which in turn means that sawdust and wood chips are treated equally in modelling.

Steineck et al. (2000 cited in Baky et al., 2012), agree that generated faeces and urine is 8-10 tonnes $horse^{-1}$ $annum^{-1}$, and that bedding material adds from a few tonnes up to 7 tonnes $horse^{-1}$ $annum^{-1}$, depending on the size of the horse[4] (Jordbruksverket, 2006 cited in Baky et al., 2012). However Jordbruksverket (2013) claims that the straw content of horse manure can be up to 90 percent. Cui, Shi and Li (2011) state that bedding make up 25 % of the wet weight of manure.

[1] Assuming 1 L urine equals 1 kg.
[2] For example, for straw, 9.9 kg straw is 29 % of 15 kg faeces + 9 kg urine + 9.9 kg straw.
[3] (24 kg waste + 5.3 kg sawdust) × 365 days = 10 695 kg.
[4] They assume an average horse weighs 500 kg.

Table 1. Average properties of horses and horse manure generated per day or per annum

Reference	Wartell et al. (2012)	Westendorf and Krogmann (2006)	Lundgren and Pettersson (2009)	Airaksinen, Heinonen-Tanski and Heiskanen (2001)	Häußermann, Beck and Jungbluth (2002)	Wheeler and Zajaczkowski (2009)	Mean
Weight of horse [kg]	454	454				454	
Feces [kg/day]	17	14				14	15
Urine [litre/day]	9	9				9	9
Total waste incl. bedding [kg/day]	27				49.7	33	
Total waste incl. bedding [m³/annum]							
a) Woodchips				12.4			
b) Wood granules					65.0		
c) Straw				19.5	130.0		
d) Rough wood shavings					83.7		
e) Sawdust / fine wood shavings			9–29		62.4		
f) Peat and sawdust (3:1)				12.4			
Bedding (*excluding urine)/bedding manure [kg/day]							
a) Unspecified	9*	4-7*					
b) Woodchips				16.3			16.3
c) Wood granules					9.0		9.0
d) Straw				9.1	10.8		9.9
e) Rough wood shavings					10.6		10.6
f) Sawdust / fine wood shavings					5.3		5.3
g) Peat and sawdust (3:1)				14.9			14.9

Notes regarding the data in Table 1 can be found in Appendix A.

The values for bedding should therefore be considered uncertain and liable to variation depending on the horse-keeping practices and bedding materials in use. To account for this, the systems analysis will investigate the importance of different proportions of bedding in separate scenarios. This is being discussed further in Eriksson et al. (2015).

3.3. Transport

Transport modelling includes site specific data on distances between stables and treatment plants and type of vehicle being used as well as data related to each vehicle type such as energy efficiency, fuel type and related emission factors. No new data or specific modelling of transports is made in this study. Transport distances between waste source (stable) and waste treatment plant are set to 15, 50 or 80 km, thereby testing the importance of transport distance. The distance between treatment plants are set to 15 km. For biogas transported to a gas station and digestate and compost going to arable land, an average distance of 50 km is used. All these figures are assumptions used in the national study of a future biogas market (Holmström et al., 2013). Most vehicles are truck and trailer transport. For details on fuel and emissions, see Eriksson et al. (2015).

4. Horse manure management systems

The sections below describe in more detail the various treatments/management systems considered. See Table A-1 (Appendix A) for a system view of the different treatment methods under consideration.

4.1. Unmanaged manure – natural decomposition

For the comparison of management systems, unmanaged horse manure represents the base case. This is manure that is left in piles or dumped in nature and left to decompose naturally. In this situation natural composting can occur, but often under sub-optimal conditions; uncontrolled emissions of gases can be higher and contamination occurs due to leaching of nutrients into water systems (Rodhe et al., 2015). Alternatively the manure does not compost, due to a lack of nitrogen or water, and is leached of nutrients.

Few data were found on average emissions from unmanaged horse manure. The IPCC (2006) estimates the methane emission factor for horse manure in cool climates[5] to be 1.56 kg CH_4 horse^{-1} year^{-1}.

However, there is an overlap between emissions from unmanaged manure and those from composting (cf. section 4.2), since unmanaged manure can still compost naturally. Rodhe et al. (2015) measured methane emissions from a manure mix – 90 % horse manure and bedding[6] and 10 % food waste – before, during and after drum composting[7]. The pre-drum-composting manure (stored in a pile indoors) produced 72-85 % of the CO_2 emissions of all three stages combined, even though it was stored for only 3 days.

Their results also showed that for the manure stored prior to drum composting, methane emissions (CH_4) averaged 0.8 % of the total carbon (C) content, compared with an average 3.5 % from a literature review of cattle, prig and poultry manure (Webb et al., 2011 cited in Rodhe et al., 2015, p. 46). For a horse producing 24 kg waste day^{-1} (see section 3.2), and assuming 22 % C (see Table A-2 in Appendix A), 0.8 % of C is 15.4 kg CH_4 horse^{-1} annum^{-1}.[8]

Rodhe et al. (2015) also provide measurements of emissions of nitrous oxide (N_2O) from the manure mix, ranging from zero to 0.23 % of total nitrogen (N), depending on the stage of decomposition, compared with a standard IPCC value of 0.5 % (Rodhe et al., 2015, p. 46). Ammonia (NH_3) emissions were under 3 % of N content during all composting stages (Rodhe et al., 2015, p. 47).

Steineck et al. (2001 cited in Rodhe et al., 2015) state that windrow composting over about 1.5 months released ammonia emissions of 11.2 % of the total nitrogen (N) for horse manure with straw bedding and 0.2 % of the total N from horse manure with peat as bedding. Karlsson and Torstensson (2003) also tested emissions from windrow compost-

[5] Cool climates are defined by the IPCC as those with an average annual temperature below 15 °C, whereas the average annual temperature for the Gävleborg region is around 5 °C (SMHI, 2015), so emissions may be lower.
[6] With bedding material of 50% sawdust, 35% straw, 10% peat, and 5% straw pellets.
[7] Figures taken from Rodhe et al. (2015, tables 7, 10, 24) Wiggeby study: averages of values for food combinations 1, 2, 3 and 4 (‘compost A’ and ‘compost B’).
[8] Although the 0.8 % methane emissions include emissions from the 10 % proportion of food and the bedding material, and the indoor conditions meant there was a limited air flow.

ing, finding 0.3 % of N and 0.7 % of phosphorous (P) were lost during composting (6-8 weeks) and 2 % and 3 %, respectively, during storage (4.5-5 months). 6-8 % of total N was lost through NH_3 emissions during composting.

The values chosen to represent unmanaged manure are based on a number of data sources, including those mentioned above. The data is summarised in the Table 2, which shows results from Rodhe et al. (2015) for two situations: 1) emissions for all three composting stages (pre-composting, drum composting and post-composting) and 2) values specific to the 3.5-day pre-composting stage; Garlipp, Hessel and van den Weghe (2011) for deep bedding manure during 19 days; and miscellaneous values from other sources.

Values for the following emissions are chosen for these reasons:

- Nitrous oxide (N_2O) gas: value chosen to be between Rodhe et al. (2015) and IPCC (2006).
- Ammonia (NH_3) gas: value[9] chosen between Steineck et al. (2001 cited in Rodhe et al., 2015) and Karlsson & Torstensson (2003).
- Methane (CH_4) gas: Rodhe et al. (2015) showed reduced methane production due to forced aerobic drum composting. The value is also chosen to be lower than emissions reported in Webb et al. (2012 cited in Rodhe et al., 2015, p. 46).
- Total nitrogen in leachate: value[10] chosen from Karlsson & Torstensson (2003) since it is the closest to unmanaged manure.
- Ammonium nitrogen (NH_4-N) in leachate: average of source values used.
- Nitrite nitrogen (NO_2-N) in leachate: value of zero used since the values reported are considered insignificant.
- Nitrate nitrogen (NO_3-N) in leachate: value known for wheat straw and woodchip used, since it is assumed they are the most prevalent bedding materials.
- Phosphorous (P) in leachate: value from Karlsson & Torstensson (2003) is the only known data.

4.2. Aerobic digestion – composting

The C/N ratio also affects composting (Karlsson & Torstensson, 2003). Similar to anaerobic digestion, aerobic digestion (composting) requires a C/N ratio (weight ratio) of 30:1 at start-up to be optimal (Poincelot, 1975 cited in Rodhe et al., 2015). Similar to AD, the mix of horse dung and bedding material chosen for use in the model is pre-validated in Excel as having a C/N ratio in the range 20-30.

4.2.1. Windrow composting

Windrow composting is assumed to have similar emissions to unmanaged manure and is therefore not compared in the model.

4.2.2 Drum composting

A drum composter accelerates the composting process by physically turning the manure and providing a constant flow of air. In the commercially available *Quantor XL®*, it takes about 24 hours for the substrate to pass through the drum composting process and reaches a compost temperature of 52 °C during at least 13 hours (Ecsab, 2015), fulfilling Swedish regulations on hygienisation[11].

[9] Does not apply to peat.
[10] May not apply to peat.
[11] Discussed in more detail in Hadin et al. (2015).

Table 2. Data sources to determine unmanaged horse manure emissions

Reference	Rodhe et al. (2015)	IPCC, 2006 cited in Rodhe et al. (2015, p. 46)	Webb et al. (2012 cited in Rodhe et al., 2015, p. 46)	Rodhe et al. (2015)	Garlipp, Hessel and van den Weghe (2011)			Steineck et al. (2001 cited in Rodhe et al., 2015)		Karlsson & Torstensson (2003)	Chosen value for model
Comments	All composting stages combined: pre-, drum- and post-compost		Emissions from chicken, pig and cow manure	Pre-compost during 3.5 days	Deep bedding manure during 19 days			Windrow composting during 1.5 months		Windrow 6-8 weeks plus storage 4-5.5 months	
Manure mix	90 % horse manure & 10% organic food waste	-	-	90 % horse manure & 10% organic food waste	Horse manure: 60% horse faeces, 60 L urea, 25 kg bedding						
Bedding	50% sawdust, 35% straw, 10% peat, 5% straw pellets	-	-	50% sawdust, 35% straw, 10% peat, 5% straw pellets	Wheat straw	Rye straw	Sawdust	Straw	Peat	Mostly straw, some sawdust	
Air emissions											
- N_2O, Nitrous oxide [% of total N]	0-0.23%	0.5%		0.01%							0.25%
- NH_3, Ammonia [% of total N]	3%			0.5%				11.2%	0.2%	6-8%	10.0%
- CH_4, methane [% of total C]	0.86%		3.5%	0.8%							2.0%
- Leachate											
- Nt, total nitrogen [% of total N]					0.10%	0.06%	0.10%			0.3%	0.30%
- NH_4-N, ammonium nitrogen [% total N]	0.01175% (drum only)				0.004%	0.005%	0.004%				0.004%
- NO_2-N, nitrite nitrogen [% of total N]					0.00015%	0.00017%	0%				0%
- NO_3-N, nitrate nitrogen [% of total N]					0.033%	0.010%	0.034%				0.033%
- P, phosphorous [% of total P]										0.7%	0.7%

Work by Rodhe et al. (2015) provided measurements of emissions from the three stages in the *Quantor XL*® drum composting process: storage prior to drum composting (‘pre-compost’), mechanical drum composting (‘drum’), and finally post-composting (‘post-compost’). The following data (Table 3), from the Wiggeby farm experiment (Rodhe et al., 2015), are used in the model:

Table 3. Emissions from drum composting including pre-compost and post-compost stages

Reference	Rodhe et al. (2015)			
Manure mix	Horse manure (90%) & organic food waste (10%) - Wiggeby farm			
Bedding	50% sawdust, 35% straw, 10% peat, 5% straw pellets			
Stage	Pre-compost (in)	Drum (in)	Post-compost (in)	Post-compost (out)
Duration	3.5 days	26 hours	4-6 weeks	N/A
Total solids (TS) [% FM]	31.10%	32.30%	33.10%	38.80%
Total nitrogen [% TS]	1.32%	1.33%	1.12%	1.49%
C/N ratio	35	33	37	21
Emission factor gas CH_4, methane [% of C]	0.80%	0.02%	0.04%	
Emission factor gas N_2O, nitrous oxide [% of N]	0.01%	0.00%	0.26%	
Emission factor gas NH_3, ammonia [% of N]	0.50%	0.52%	1.77%	
Emission factor leachate NH_4, ammonium [% of N]	-	0.01%	-	

4.3. Incineration

The Fuel Handbook (Strömberg & Svärd, 2012) does not recommend the use of horse manure in its pure form in biofuel plants, due to a risk of both sintering and corrosion caused by high moisture content and high levels of sulphur and chlorine. Baky (2012) describes sintering when the bedding material used was peat or straw, but not from manure with bedding consisting of sawdust and only a little straw.

Incineration of pure horse manure has been tested in small-scale plants (Pettersson et al., 2006; Lundgren & Pettersson, 2009; Edström et al., 2011), and incineration of horse manure mixed with other biofuels and wastes has been tested in both small- and large-scale plants (Puustinen, 2009 cited in Edström et al., 2011; Baky, 2012; Henriksson et al., 2015).

The ORWARE model includes a sub-model for large-scale incineration, which is used in this study. The large scale incineration uses emission factors for the most relevant emissions based on environmental reporting from the Sävenäs waste CHP in Gothenburg (Holmström et al., 2013). Data on degree of efficiency, power-to-heat ratio and use of electricity is based on national averages. Ash and slag is subject to landfill disposal using appropriate landfill submodels.

However, for small-scale incineration, data is taken from experiments by Baky (Baky et al., 2012; Baky, 2013b). Pre-drying horse manure has been shown in tests to increase the lower heating value (LHV) and produce a net gain in energy of 1.9 MWh/tonne of dried manure, after deducting the energy used for drying (Baky, 2012). Therefore manure is dried prior to combustion, decreasing water percentage from 57.4 to 9.7 %. Drying equipment uses 0.40 MWh heat/ton wet manure for evaporating water. Due to aeration of the manure a slight composting takes place, leading to some losses of C and N. The furnace has a degree of efficiency of 80 %. All energy is released as heat and utilised (just 50 % utilisation in the report). The simplified model does not handle combustion residues. For further details, please see references above. In Table 4 some data on incineration collected from literature is displayed.

4.4. Anaerobic digestion (AD)

The mono-feedstock anaerobic digestion (AD) of horse dung and of horse manure has been tested in numerous lab-based and pilot plant trials, but so far there are no known large-scale implementations. From these trials the results of measuring carbon, nitrogen and nutrient content and other chemical compounds in the substrate are shown to vary considerably due, in part, to the manure's freshness (Mattsson, Karlsson and Nilsson, 2015) and the bedding material used (Olsson et al., 2014).

Measurements of methane production from the digestion process of horse dung (i.e. without bedding material) are also very inconsistent, production is strongly influenced by feeding intensity and feed composition (Mönch-Tegeder, 2013, p.166 citing Møller et al., 2004 and Amon et al., 2007).

The age of the manure can also have a strong influence on methane production. According to Mattsson, Karlsson and Nilsson (2015), fresh horse manure produced more methane when peat had been used as a bedding material, whereas for one-month-old horse manure, straw bedding produced more methane. After two months of storage, methane production was worse in both cases compared to fresher manure. Even a late harvest due to weather conditions can affect straw feed quality and in turn methane production (Mönch-Tegeder, 2014). See also section 4.4.1.

Therefore, although the model has modules for AD, it can only provide an approximate calculation of biogas production and emissions. It is still possible to validate those values as being within the range collected in the inventory data. This data is summarised in section 4.4.5.

4.4.1. Storage

Garlipp, Hessel, and van den Weghe (2011) showed that deep litter horse manure, placed in mostly anaerobic conditions, gave different results according to the bedding material, with wheat straw producing significantly higher NH_3, N_2O, CO_2, CH_4 and H_2O concentrations over 19 days compared to rye straw, indicating faster degradation. Both types of straw generated significantly higher concentrations of N_2O, CO_2, and CH_4 compared to wood shavings over 19 days.

Table 4. Heating values, emissions and ash contents from incineration of horse manure, both pure and mixed

Reference		Pettersson, Lundgren, and Hermansson (2006, pp. 396-400); Lundgren & Pettersson (2009); Edström et al. (2011, p. 9).	Edström et al. (2011, p. 8) citing www.swebo.com	Puustinen (2009) cited in Edström et al. (2011, p. 4)	Henriksson et al. (2015). Ash analysis from Strömberg & Herstad Svärd (2012) cited in Henriksson et al. (2015).	Baky et al. (2012)
Fuel		Horse manure	Horse manure	Horse manure (40%) & sawdust	Horse manure (10%) & household waste (90%)	Horse manure (dried)
Bedding material		Woodchip/ sawdust	Sawdust (woodchip)	Sawdust	Straw	Sawdust
Plant size		250 kW(th)	150 kW(th)	40 kW(th)	-	350 kW(th)
Total solids, TS	kg/t FM	43.0%	51.0%	30.1%	37.0%	90.3%
Total Nitrogen	% TS	0.9%	-	-	1.0%	0.7%
Higher heating value (dry fuel, free of ash)	MJ/kg	19.37	-	20.4	18.84	17.29
Lower heating value (dry fuel, free of ash)	MJ/kg	18.14	-	19.1	-	16.08
EMISSIONS						
CO, Carbon monoxide	mg/Nm³	170.6	40	320	-	-
	mg/MJ	-	-	-	15.45	-
NOx, Nitrogen oxide	mg/Nm³	395.6	320	340	-	-
	mg/MJ	-	-	-	75.15	-
Particles (dry gas)	mg/Nm³	425.8	-	120	-	-
ASH (horse manure)						
Ash content	% TS	7.3%	-	-	7.3%	12.3%
Al, Aluminium	% Ash	-	-	-	1.3%	2.5%
Ca, Calcium	% Ash	24.3%	-	-	9.1%	30.1%
Cu, Copper	% Ash	-	-	-	0.0%	-
K, Potassium	% Ash	4.3%	-	-	4.3%	7.2%
Mg, Magnesium	% Ash	3.0%	-	-	3.9%	1.9%
Na, Sodium	% Ash	0.3%	-	-	1.2%	1.0%
Pb, Lead	% Ash	-	-	-	0.0%	-
Si, Silicon	% Ash	7.0%	-	-	11.2%	10.6%
Zn, Zinc	% Ash	-	-	-	0.1%	-

Mattsson, Karlsson and Nilsson (2015) tested the anaerobic digestion of horse manure after different storage times: fresh manure, 5 days old and 14 days old. They found that there was a decrease in methane production in relation to the increase in age, by up to one-third for 14-day-old manure. However they also point out that temperature has a big effect, and losses from storage at 10 °C are smaller (Møller, 2012 cited in Mattsson, Karlsson and Nilsson, 2015).

The emissions from storage are assumed to be the same for all management options, since the manure will always require a period of storage regardless of the final treatment. This is discussed further in Eriksson et al. (2015).

4.4.2. Substrates suitable for anaerobic digestion

The version of the ORWARE model being used includes a module for wet anaerobic digestion. This submodel has been adjusted to also represent dry anaerobic digestion, see section 4.4.4. For the substrate to be suitable for anaerobic digestion, certain conditions must be met. Many authors cite a requirement for the carbon/nitrogen (C/N) ratio to be in the range 20-30 (Karthikeyan, 2013). Mönch-Tegeder (2013, p.164) and Mao et al. (2015) also state the optimum C/N ratio to be 20-30.

The mix of horse dung, manure and bedding material chosen for use in the model is pre-validated in Excel as having a C/N ratio in the range 20-30 to ensure that the results of anaerobic digestion are valid.

Concentrations of compounds like calcium (Karthikeyan, 2013, p. 275-277) and low pH caused by excessive concentrations of volatile fatty acids (VFAs) – which are in turn caused by high organic loading and C/N ratio (Brown et al., 2012) – are also inhibitory to some methanogens. Kusch, Oechsner and Jungbluth (2008, p.1289) state that ammonia concentrations of horse manure are well within acceptable limits, but it is not clear if urine or bedding was included. Baky (2013) removed some ammonia in order to reduce the nitrogen level for AD, whereas Böske et al. (2014) added ammonium carbonate in order to increase it. Mönch-Tegeder (2014, p.166) states "horse manure cannot provide sufficient amounts of trace elements for a stable biogas process." Factors such as these (calcium, pH) are not considered in the anaerobic digestion submodel.

Despite the reservations above, the results of many experiments (Nilsson, 2000 cited in Edström et al., 2011, p. 4; Edström et al., 2005; Pettersson et al., 2006; Kusch, Oechsner and Jungbluth, 2008; Wartell et al., 2012; Baky, 2013b; Mönch-Tegeder et al., 2013; Böske et al., 2014, Smith and Almquist, 2014; Mattsson, Karlsson and Nilsson, 2015) – summarised below in section 4.4.5 and listed in more detail in the electronic appendix 'Manure Composition and Treatments.xlsx' – show examples of successful anaerobic digestion of unadulterated horse manure. It is assumed in the model that the composition of the manure, represented by the vector, is appropriate for AD.

4.4.3. Codigestion

Codigestion provides the flexibility to simultaneously utilise more than one substrate, and also gives the ability to manipulate the C/N ratio to improve the stability of the digestion process (Karthikeyan, 2013, p. 272). In this model, data from a plant-scale study from Olsson et al. (2014) is used to validate the codigestion of horse manure mixed with cow manure.

Table 5. Data sources for anaerobic digestion using codigestion of multiple substrates

Reference	Olsson et al. (2014)	Olsson et al. (2014)
Substrate	Horse manure (69%) & cattle dung (31%)	Horse manure (56%) & cattle dung (44%)
Bedding material	Saw dust	Straw pellets and sawdust
Digestion time [days]	50	30
Total solids (TS) [% FM]	7.5%	7.5%
Specific methane production [m³ CH4/t VS]	125	131
Process temperature [°C]	30-41	29-40
Notes	Manure 'FL1' in reference	Manure 'FL2' in reference

4.4.4. Solid-state anaerobic digestion (SS-AD)

Solid-state anaerobic digestion (SS-AD) of horse dung is possible without the addition of inoculum (Kusch, Oechsner and Jungbluth 2008, p.1288). The model uses the same vectors for manure and bedding materials, only the sub-model representing the anaerobic digestion process is changed for SS-AD.

Initially a mesophilic digestion process is applied as most solid state digestion plants we know of (and they are quite few) has a process temperature representing mesophilic conditions. The percentage of TS in the digester has been set to 30 % which is considerably higher compared to liquid state digestion and corresponds quite well with the TS percentage in the substrate (which depends on how much bedding of which type is mixed with pure manure). The initial retention time is set to 27 days, which corresponds to the plant for food- and garden waste in Mörrum, Sweden. Use of electricity is supposed to be lower due to less pumping and mixing etc, an assumption of 50 % compared to wet anaerobic digestion is made. A gas loss of 1 % is assumed, which is in line with default values in ORWARE with reference to on-site measurements by SP on several biogas plants in Sweden. Biogas production will be used as validation parameter where the model may be fed with food waste to meet a production rate of 85 Nm^3/ton. Finally, the digestate will have a TS percentage of 30 % to ensure dry spreading equipment can be used. The final values for the model after validation are presented in Eriksson et al. (2015).

4.4.5. Validation data for anaerobic digestion

This section shows a summary (Table 6-9) of data collected for the validation of anaerobic digestion of horse manure.

Table 6. Results of anaerobic digestion of horse manure with straw bedding

Reference	Nilsson (2000) cited in Edström et al. (2011, p. 4)	Edström et al. (2005)	Baky (2013b)
Scale	Lab/batch	Plant	Model
Digestion time [days]	-	-	-
Total solids (TS) [% FM]	30.00%	30.00%	23.25%
Volatile solids (VS) [% TS]	84.00%	84.00%	75.53%
Total nitrogen [% TS]	0.35%	2.60%	2.51%
Process temperature [°C]	37	37	-
C/N ratio	-	-	-
Specific methane production [m³ CH4/t VS]	180.0	200.0	146.7
Specific methane yield [m³ CH4/t VS]	-	-	-

Table 7. Results of anaerobic digestion of horse manure with straw pellets

Reference	Mattsson, Karlsson and Nilsson (2015)	Mattsson, Karlsson and Nilsson (2015)	Mattsson, Karlsson and Nilsson (2015)
Scale	Lab	Lab	Lab
Digestion time [days]	35	35	35
Total solids (TS) [% FM]	27.10%	20.20%	25.00%
Volatile solids (VS) [% TS]	-	-	-
Total nitrogen [% TS]	1.85%	3.12%	2.92%
Process temperature [°C]	37	37	37
C/N ratio	22.6	12.5	13.9
Specific methane production [m³ CH4/t VS]	24.0	12.7	14.1
Specific methane yield [m³ CH4/t VS]	-	-	-
Age [days]	0	5	14

NB: the authors claim that some of these results may not be reliable and methane production was derived from total production.

Even if straw pellets are not investigated further Table 8 clearly shows the low methane production from this bedding material.

Table 8. Results of anaerobic digestion of soft woodchips

Reference	Wartell et al. (2012)
Scale	Lab
Digestion time [days]	-
Total solids (TS) [% FM]	32.00%
Volatile solids (VS) [% TS]	79.80%
Total nitrogen [% TS]	-
Process temperature [°C]	35 ±1
C/N ratio	-
Specific methane production [m³ CH4/t VS]	111
Specific methane yield [m³ CH4/t VS]	-

Table 9. Results of anaerobic codigestion of horse manure with cow slurry

Reference	Kalia & Singh (1998)	Olsson et al. (2014)	Olsson et al. (2014)	Baky (2013b)
Substrate mix	Horse manure (20%) & cattle dung (80%)	Horse manure (69%) & cattle dung (31%)	Horse manure (56%) & cattle dung (44%)	Horse manure (44%) & cattle slurry (56%)
Bedding material	Unspecified	Saw dust	Straw pellets and sawdust	Straw
Scale	Plant	Plant	Plant	Model
Digestion time [days]	84	50	30	-
Total solids (TS) [% FM]	8-10%	7.5%	7.5%	16.8%
Volatile solids (VS) [% TS]	88.8%	-	-	77.4%
Total nitrogen [% TS]	-	-	-	-
Process temperature [°C]	25-30 ± 1	30-41	29-40	-
C/N ratio	-	-	-	-
Specific methane production [m³ CH4/t VS]	162.5	125.0	131.0	141.2

4.4.6. Pretreatment for AD

Hadin, Eriksson and Jonsson (2015) explained that hygienisation must be used in Sweden when horse manure is collected for treatment from two or more different production locations. The model therefore assumes that hygienisation is used and this is included in the model.

Lignocellulosic material, such as straw in horse manure, can cause low bioavailability or low biodegradability (Carlsson et al., 2012). The results data gathering of horse manure pretreatment methods for AD did not provide sufficient data for modelling, however they suggest that an increase of biogas production and/or rates of generation are possible and the potential methods are briefly discussed below. The model does, however, include a pre-existing sub-model for steam explosion.

Potential pretreatments of horse manure for AD

The chemical treatment of lignocellulosic materials has been investigated in a number of studies, although no studies were found that tested chemical pretreatments of purely horse dung or horse manure. For example, treating straw from cattle and horse manure with N-methylmorpholine oxide (NMMO) for 15 hours was shown to increase the methane yield by 51 %, through a decrease in the structural lignin content (Aslanzadeh et al., 2011). Teghammar (2013) also showed that NMMO pretreatment of spruce woodchips for 15 hours resulted in an increased production of 202 NmL CH_4/g. Lidner et al. (2015) warn that the high cost of chemicals and investment in equipment is an obstacle for chemical pretreatment in full-scale plants.

In contrast to chemical and thermal methods, mechanical pretreatment has no inhibitory or toxic byproducts formed during the disintegration process (Mönch-Tegeder et al., 2014). There is no change to the total solids (TS), volatile solids (VS) or chemical compostition (Mönch-Tegeder et al., 2014, p.142). In addition, mechanical devices for decomposition are available and easy to implement in biogas plants (Mönch-Tegeder et al., 2014, p.139). The main disadvantage of mechanical pretreatment is the high energy consumption (Bruni et al. 2010).

Chopping manure with a compost chopper was shown by Kusch, Oechsner and Jungbluth (2008, p.1288) to increased yield, especially during the initial stages of digestion (up to 42 days), although the final methane yield was the same over long digestion times. However, no data was provided on the energy consumption of the chopping process or the net energy saving.

Mönch-Tegeder et al. (2014), on the other hand, demonstrated that 15 seconds of mechanical grinding of horse manure (with straw bedding) could lead to a positive energy balance of 12.7 kWh $tonne^{-1}$ FM, since methane yields were increased 10 % in comparison to untreated manure.

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Appendix A

An electronic version(Table A-1) of the data below (Table A-2) shows that total waste per horse is in the range 9-29 m³ horse^{-1} annum^{-1}. The Swedish statutory requirement for storage of deep litter manure is 9.9 m³ horse^{-1} annum^{-1} according to Swedish Board of Agriculture, where standard values include faeces and urine, bedding material, decomposition losses, cleaning water, water spillage and precipitation. However not all manure will be collected, since horses are not always in the stall.

Table A-1 is available as an electronic appendix - 'Measurements Per Horse.xlsx'. The values stated for volume per year in Airaksinen, Heinonen-Tanski and Heiskanen (2001) are described as relating to 'bedding manure'. It is assumed this means bedding material that includes urine but is separated from faeces - the bedding material is taken from box stalls via a daily removal of faeces followed by the 'dirty' bedding with urine, while all clean bedding is left in place. Values for bedding [kg/day] are derived from table 3 & 4 in Airaksinen, Heinonen-Tanski and Heiskanen (2001, p. 128f) - this can be seen in cells F16-21 (Table A-1).

Wheeler and Zajaczkowski (2009) value for manure [kg/day] is derived from the annual value for a "full-time" occupant (see cell H6 in Table A-1).

Häußermann, Beck and Jungbluth (2002, table 2, p. 51) show the amount of 'dung' and 'dung volume' but it is inferred from 'density of dung' that these values are for faeces, urine and bedding combined. Figures in red are believed to be incorrect or use a strange measurement system.

ORWARE vectors

The known values of the ORWARE vector for horse dung (i.e. excluding bedding) are detailed below (Table A-2).

Table A-2. ORWARE vector for horse manure, including justifications for choices of values

Vector index	Property	Value	Justification
0	Total solids, TS [fraction of Fresh Matter]	2.35E-01	Fraction of FM. Chosen from Mönch-Tegeder et al. (2013), who made analyses of samples from 10 farms. This is the average of values ranging from 20.67 to 27.3. Contradicts Strömberg & Herstad Svärd (2012, p.244), who state 40.1% TS. Wartell et al. (2012, p. 44) states 37%, however it is not certain that this excludes bedding. Smith & Almquist (2014) states 27.8%.
1	Organic carbon total [fraction of TS]	3.70E-01	Same as original ORWARE vector. Sum of vector indexes 2, 3, 4, 5 and 41 is 21.7%. The difference between this and the ORWARE value may be the insoluable lignin.
2	Carbon-lignin [fraction of TS]	2.23E-02	NOT total lignin: only the soluable part. Average of 10 farms with value range 0.87-1.17% of TS acid detergent lignin in Mönch-Tegeder et al. (2013, p.165)
3	Carbon-starch & sugar [fraction of TS]	0.00E+00	Same as original ORWARE vector
4	Carbon-fat [fraction of TS]	6.71E-03	Average of 10 farms with value range 1.8-4.1% of TS crude fat in Mönch-Tegeder et al. (2013, p.165)

5	Carbon-protein [fraction of TS]	1.93E-02	Average of 10 farms with value range 6.8-11.7% of TS crude protein in Mönch-Tegeder et al. (2013, p.165)
7	Volatile substance, VS [fraction of TS]	8.87E-01	Derived from values of % of FM from Mönch-Tegeder et al. (2013), who made analyses of samples from 10 farms. This is the average of values of VS as % of FM ranging from 18.22 to 24.72.
8	Dry substance	1.00E+00	Same as original ORWARE vector
9	O, Oxygen total [fraction of (ash-free) TS]	3.93E-01	Fraction of ash-free TS. From average value 39.31% in Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.244).
10	H, Hydrogen total [fraction of (ash-free) TS]	6.42E-02	Fraction of ash-free TS. From average value 6.42% in Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.244).
11	N, Nitrogen total [fraction of (ash-free) TS]	1.48E-02	Average of 10 farms with value range for total nitrogen 1.172-1.868% of TS in Mönch-Tegeder (2013, p.165)
12	NH3/NH4+-N	8.09E-04	Missing NH3?? Average of 10 farms with value range for NH4 of 0.037%-0.233% of TS in Mönch-Tegeder (2013, p.165)
13	S, Sulphur [fraction of (ash-free) TS]	3.00E-03	Fraction of ash-free TS. From average value 0.3% in Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.244).
14	P, Phosphorus [fraction of (ash-free) TS]	1.24E-03	Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.244)
15	Cl, Chlorine [fraction of (ash-free) TS]	2.80E-03	Fraction of ash-free TS. From average value 0.28% in Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.244).
16	K, Potassium [fraction of (ash-free) TS]	1.91E-03	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
17	Ca, Calcium [fraction of (ash-free) TS]	1.00E-02	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
18	Pb, Lead [fraction of (ash-free) TS]	1.10E-06	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
19	Cd, Cadmium [fraction of (ash-free) TS]	1.00E-07	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
20	Hg, Mercury [fraction of (ash-free) TS]	1.00E-08	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
21	Cu, Copper [fraction of (ash-free) TS]	1.40E-05	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
22	Cr, Chromium [fraction of (ash-free) TS]	4.70E-06	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
23	Ni, Nickel [fraction of (ash-free) TS]	3.10E-06	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
24	Zn, Zinc [fraction of (ash-free) TS]	5.50E-05	Fraction of ash-free TS. Example from Hermansson et al. (Unknown) cited in Strömberg & Herstad Svärd (2012, p.252)
25	Carbon-cellulose	1.69E-01	Derived from original ORWARE vector by adjusting to new TS fraction

The known values of the ORWARE vector for sawdust/woodchip are detailed in Table A-3.

Table A-3. ORWARE vector for sawdust/woodchip, including references for values

Vector index	Property	Value	Reference for value
0	Total solids, TS [fraction of Fresh Matter]	5.58E-01	[1]
1	Organic carbon total [fraction of TS]	5.08E-01	[1]
2	Carbon-lignin [fraction of TS]	2.82E-01	[5]
3	Carbon-starch & sugar [fraction of TS]	0.00E+00	Assumed
4	Carbon-fat [fraction of TS]	0.00E+00	Assumed
5	Carbon-protein [fraction of TS]	0.00E+00	Assumed
7	Volatile substance, VS [fraction of TS]	5.09E-01	[1]
8	Dry substance	1.00E+00	Assumed
20	O, Oxygen total [fraction of (ash-free) TS]	0.00E+00	Assumed
21	H, Hydrogen total [fraction of (ash-free) TS]	6.20E-02	[1]
23	N, Nitrogen total [fraction of (ash-free) TS]	5.00E-04	[1]
24	NH3/NH4+-N	0.00E+00	Assumed
28	S, Sulphur [fraction of (ash-free) TS]	1.00E-04	[1]
30	P, Phosphorus [fraction of (ash-free) TS]	0.00E+00	Assumed
31	Cl, Chlorine [fraction of (ash-free) TS]	0.00E+00	Assumed
32	K, Potassium [fraction of (ash-free) TS]	0.00E+00	Assumed
33	Ca, Calcium [fraction of (ash-free) TS]	0.00E+00	Assumed
34	Pb, Lead [fraction of (ash-free) TS]	0.00E+00	Assumed
35	Cd, Cadmium [fraction of (ash-free) TS]	0.00E+00	Assumed
36	Hg, Mercury [fraction of (ash-free) TS]	0.00E+00	Assumed
37	Cu, Copper [fraction of (ash-free) TS]	0.00E+00	Assumed
38	Cr, Chromium [fraction of (ash-free) TS]	0.00E+00	Assumed
39	Ni, Nickel [fraction of (ash-free) TS]	0.00E+00	Assumed
40	Zn, Zinc [fraction of (ash-free) TS]	0.00E+00	Assumed
41	Carbon-cellulose	0.00E+00	Assumed

References: [1] Strömberg & Herstad Svärd (2012, p.43); [2] Assumed to be wheat in Strömberg & Herstad Svärd (2012, p.121); [3] Strömberg & Herstad Svärd (2012, p. 316); [4] NIST (2015a); [5] NIST (2015b); [6] 'Mean NSC' in Watts (2005, p. 339); [7] Government of Saskatchewan (2008); [8] Preston (2010); [9] Stanton (2014); [10] Nilsson (1994).

The known values of the ORWARE vector wheat straw are detailed in Table A-4. In some references, the type of straw is not specified and wheat is assumed.

Table A-4. ORWARE vector for straw, including references for values

Vector index	Property	Value	Reference for value
0	Total solids, TS [fraction of Fresh Matter]	8.76E-01	[2]
1	Organic carbon total [fraction of TS]	4.83E-01	[2]
2	Carbon-lignin [fraction of TS]	1.81E-01	[4]
3	Carbon-starch & sugar [fraction of TS]	1.17E-01	[6]
4	Carbon-fat [fraction of TS]	1.65E-02	[8,9]
5	Carbon-protein [fraction of TS]	3.63E-02	[7,9,8]
7	Volatile substance, VS [fraction of TS]	8.27E-01	[2]
8	Dry substance	1.00E+00	Assumed
20	O, Oxygen total [fraction of (ash-free) TS]	4.49E-01	[2]
21	H, Hydrogen total [fraction of (ash-free) TS]	5.93E-02	[2]
23	N, Nitrogen total [fraction of (ash-free) TS]	6.00E-03	[2]
24	NH3/NH4+-N	0.00E+00	Assumed
28	S, Sulphur [fraction of (ash-free) TS]	8.00E-04	[2]
30	P, Phosphorus [fraction of (ash-free) TS]	8.21E-04	[2]
31	Cl, Chlorine [fraction of (ash-free) TS]	1.20E-03	[2]
32	K, Potassium [fraction of (ash-free) TS]	2.79E-03	[2]
33	Ca, Calcium [fraction of (ash-free) TS]	3.82E-03	[2]
34	Pb, Lead [fraction of (ash-free) TS]	0.00E+00	Assumed
35	Cd, Cadmium [fraction of (ash-free) TS]	0.00E+00	Assumed
36	Hg, Mercury [fraction of (ash-free) TS]	0.00E+00	Assumed
37	Cu, Copper [fraction of (ash-free) TS]	0.00E+00	Assumed
38	Cr, Chromium [fraction of (ash-free) TS]	0.00E+00	Assumed
39	Ni, Nickel [fraction of (ash-free) TS]	0.00E+00	Assumed
40	Zn, Zinc [fraction of (ash-free) TS]	0.00E+00	Assumed
41	Carbon-cellulose	1.32E-01	Assumed

References: [1] Strömberg & Herstad Svärd (2012, p.43); [2] Assumed to be wheat in Strömberg & Herstad Svärd (2012, p.121); [3] Strömberg & Herstad Svärd (2012, p. 316); [4] NIST (2015a); [5] NIST (2015b); [6] 'Mean NSC' in Watts (2005, p. 339); [7] Government of Saskatchewan (2008); [8] Preston (2010); [9] Stanton (2014); [10] Nilsson (1994).

The known values of the ORWARE vector for surface-layer peat are detailed in Table A-5. In some references, the level of the peat is not specified and it is assumed to be the surface layer.

Table A-5. ORWARE vector for surface-layer peat, including references for values

Vector index	Property	Value	Reference for value
0	Total solids, TS [fraction of Fresh Matter]	5.18E-01	[3]
1	Organic carbon total [fraction of TS]	5.68E-01	[3]
2	Carbon-lignin [fraction of TS]	3.09E-01	[10]
3	Carbon-starch & sugar [fraction of TS]	0.00E+00	Assumed
4	Carbon-fat [fraction of TS]	0.00E+00	Assumed
5	Carbon-protein [fraction of TS]	0.00E+00	Assumed
7	Volatile substance, VS [fraction of TS]	7.22E-01	[3]
8	Dry substance	1.00E+00	Assumed
20	O, Oxygen total [fraction of (ash-free) TS]	3.56E-01	[3]
21	H, Hydrogen total [fraction of (ash-free) TS]	5.80E-02	[3]
23	N, Nitrogen total [fraction of (ash-free) TS]	2.20E-02	[3]
24	NH3/NH4+-N	0.00E+00	Assumed
28	S, Sulphur [fraction of (ash-free) TS]	2.90E-03	[3]
30	P, Phosphorus [fraction of (ash-free) TS]	5.07E-04	[3]
31	Cl, Chlorine [fraction of (ash-free) TS]	5.00E-04	[3]
32	K, Potassium [fraction of (ash-free) TS]	3.64E-04	[3]
33	Ca, Calcium [fraction of (ash-free) TS]	6.70E-03	[3]
34	Pb, Lead [fraction of (ash-free) TS]	5.88E-06	[3]
35	Cd, Cadmium [fraction of (ash-free) TS]	1.86E-07	[3]
36	Hg, Mercury [fraction of (ash-free) TS]	6.36E-08	[3]
37	Cu, Copper [fraction of (ash-free) TS]	2.20E-05	[3]
38	Cr, Chromium [fraction of (ash-free) TS]	3.76E-06	[3]
39	Ni, Nickel [fraction of (ash-free) TS]	5.67E-06	[3]
40	Zn, Zinc [fraction of (ash-free) TS]	1.30E-05	[3]
41	Carbon-cellulose	3.22E-01	[10]

References: [1] Strömberg & Herstad Svärd (2012, p.43); [2] Assumed to be wheat in Strömberg & Herstad Svärd (2012, p.121); [3] Strömberg & Herstad Svärd (2012, p. 316); [4] NIST (2015a); [5] NIST (2015b); [6] 'Mean NSC' in Watts (2005, p. 339); [7] Government of Saskatchewan (2008); [8] Preston (2010); [9] Stanton (2014); [10] Nilsson (1994).

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