Environmental impacts of manure management based on life cycle assessment approach

Havukainen Jouni, Väisänen Sanni, Rantala Tero, Saunila Minna, Ukko Juhani

This is a Post-print version of a publication

published by Elsevier

in Journal of Cleaner Production

DOI: 10.1016/j.jclepro.2020.121576

Copyright of the original publication: © 2020 Elsevier

Please cite the publication as follows:

Havukainen, J., Väisänen, S., Rantala, T., Saunila, M., Ukko, J. (2020). Environmental impacts of manure management based on life cycle assessment approach. Journal of Cleaner Production, vol. 264. DOI: 10.1016/j.jclepro.2020.121576

This is a parallel published version of an original publication. This version can differ from the original published article.

Environmental impacts of manure management based on life cycle assessment approach

Jouni Havukainen[a,] *, Sanni Väisänen[a], Tero Rantala[b], Minna Saunila[b], Juhani Ukko[b]

[a] Department of Sustainability Science, School of Energy Systems, LUT University, Lappeenranta, Finland

[b] Department of Industrial Engineering and Management, School of Engineering Science, LUT University, Lahti, Finland

*Corresponding author: Jouni Havukainen, Sustainability Science, LUT University, P.O. Box 20, 53851 Lappeenranta, Finland Email: jouni.havukainen@lut.fi

Abstract

Horse manure is often a cost for horse owners, and in most cases, it is underutilized when its status as biodegradable waste means that it could potentially be used in renewable energy production and serve as a source of nutrient recycling. The selection of treatment methods requires information on possible environmental impacts; however, much readily available information on this aspect remains lacking. Therefore, in this study, the environmental impacts of horse manure management chains utilizing either saw dust or peat as bedding material are investigated using life cycle assessment, and global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP) serve as impact categories. Selected manure management chains include different composting processes, anaerobic digestion, and combustion. The results reveal that combustion is the most favorable option for saw dust manure for all the studied impact categories, whereas anaerobic digestion is the most favorable for GWP reduction, and combustion is the best option for EP and AP reduction for peat manure. However, it should be considered that the selection of bedding material and treatment options for horse manure is restricted by the availability of bedding material and treatment options and by stable size and location.

Keywords: Horse manure; Life cycle assessment; Composting; Combustion

1 Introduction

The economic importance of the horse industry is increasing in the European Union, and it plays a crucial role in the agriculture and leisure industry (Liljenstolpe, 2009). Urbanization has also affected the horse industry and the location of horse ranches, and this may have increased the importance of sustainable management and solving environmental challenges related to horse keeping (Rantala et al., 2018). Urbanization has caused challenges regarding hygiene and manure handling, and this has resulted in the need to find new types of technologies to solve these problems and increased the interest in investments on green technologies (Saunila et al., 2019; Ukko et al., 2019).

Horse manure is a form of organic waste that can be used for nutrient recycling purposes and renewable energy generation. The increased interest in these two topics are driven on the one hand by concerns raised on the overuse of mineral fertilizer (Kahiluoto et al., 2014) and on the other hand, by increased renewable energy production goals to mitigate climate change. To a limited degree, horse manure could help solve both issues. Horse manure contains energy, valuable plant nutrients, and humus-forming substances that can be used for soil enrichment purposes (Parvage et al., 2013).

In cold northern climates, horses are commonly kept indoors during winter (Keskinen et al., 2017). Horse manure is formed in stables when dung and urine are mixed with bedding material. One horse produces approximately 25 kg of waste per day in the form of feces and urine in addition to 10 kg of bedding material (Westendorf and Krogmann, 2013), which commonly consist of peat, straw, pelletized straw, and wood shavings (Oksala et al., 2017b). Proper manure handling reduces risk to local watercourses, especially from the leaching of P (Keskinen et al., 2017; Närvänen et al., 2008).

In Finland, ca. 73400 horses produce approximately 18 t of manure per year, which equals to 700000–800000 m^3 of manure. Manure is commonly seen as waste and not as a resource or sellable product with an existing market (Oksala et al., 2017a). Most manure is used in agricultural fields as fertilizer. Another traditional option for manure treatment is composting; however, incineration of manure is gaining ground in Finland due to regulation changes. The Finnish Government has prioritized the facilitation of horse manure combustion as a key project of the 2015 bioeconomy initiative and supported the 2017/1262 EU Commission regulation, which stripped animal manure incineration of the requirement of a waste incineration permit with certain preconditions. Manure of farmed animals may present a sustainable fuel when taking into considerations the requirements to reduce adverse effects of its use as fuel. According to the EU 2017/1262 the emission limits for horse manure combustion are equivalent to poultry manure combustion regulated in EU 592/2014 (summarized in the supplementary material Table S3), when thermal input is not exceeding 50MW.

Horse industry operators in Finland are mainly small businesses that struggle to make their operation profitable. Currently, horse manure disposal is a cost for horse owners (Mönch-Tegeder et al., 2013). Use of this material for energy production has potential to bring in revenues and thus compensate for these costs (Wartell et al., 2012). Limited financial resources on the one hand and raised environmental consciousness on the other hand serve as motivating forces to find economical and sustainable horse manure treatment methods (Rantala et al., 2018). Various possibilities for nutrient recycling exist, such as different composting technologies and anaerobic digestion; however, renewable energy is primarily produced in smaller or larger scale incineration plants. Information on environmental impacts of various treatment methods are needed to facilitate the selection of environmentally friendly treatment options.

Environmental impact evaluations for the livestock sector have been previously conducted using life cycle assessment (LCA) methodology (Weiss and Leip, 2012), and this method has also been used more specifically for manure management assessment. These include assessing different livestock manure management options (Sandars et al., 2003), assessing anaerobic digestion of pig, poultry, and cattle manure (Esteves et al., 2019), comparing pig manure land application to biological treatment of pig manure (Corbala-Robles et al., 2018), and thermal gasification of pig manure (Sharara et al., 2019). LCA has been adopted to a much lesser extent for assessing horse manure management systems. To the best of the knowledge of the authors, only Eriksson et al. (2016) have conducted LCA on different horse manure management options and concluded that from a global warming perspective, anaerobic treatment was the most favorable option. The study focused on horse manure management chains utilizing wood chips as the only bedding material option, and the influence of bedding production on the environmental impacts of horse manure management system was omitted (Eriksson et al., 2016). In addition, Hennessy and Eriksson (2015) collected life cycle inventory data for horse manure management with a focus on anaerobic digestion in a region of Gävleborg, Sweden.

The aim of this paper is to compare the three different potential environmental impacts—global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP)—of various horse manure management systems. In this study, the horse manure management system also considers the impact of bedding material selection to increase knowledge on the overall environmental impact of horse manure management.

2 Materials and methods

This study focuses on environmental impact assessments of horse manure treatment using seven different methods, including spreading manure on arable land, three different composting methods, anaerobic digestion, and combustion either in a centralized manner or on a farm scale. Even though, the bedding selection and transport distances are related to the Finnish circumstances these technologies are applicable in other countries for managing horse manure. Environmental impacts were assessed using LCA methodology, a systematic method for assessing potential environmental impacts of products and services that is based on the detailed guidelines and standards in ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006). In LCA, a functional unit describes the quantified performance of a product system for use as a reference unit. In a comparative LCA, all systems under comparison must have the same functional unit. In the present study, the functional unit is 1 t of utilized horse feces (stable manure without added bedding material). This meant that the treatment options are compared to each other using the same quantity of horse feces, and the required amount of bedding material depends on the bedding material selection. Horse manure then includes both the feces and the used bedding.

The LCA results are calculated using GaBi 8 software (Thinkstep, 2018), and CML 2001-Jan 2016 methodology (CML-Department of Industrial Ecology, 2016) was used for life cycle impact assessment (LCIA). The selected environmental impact categories include GWP, AP, and EP. GWP provides information regarding the impact on global climate change, whereas AP and EP consider the more regional environmental impacts of emissions on surface soils and waters in terms of deposited acids or overfertilization (Pacheco-Torgal et al., 2016) that are caused by the horse manure treatment. Both direct emissions from the processes as well as indirect emissions from energy and material provisions are included in calculations.

2.1 System boundary

The system boundary of the study with the selected treatment chains are presented in

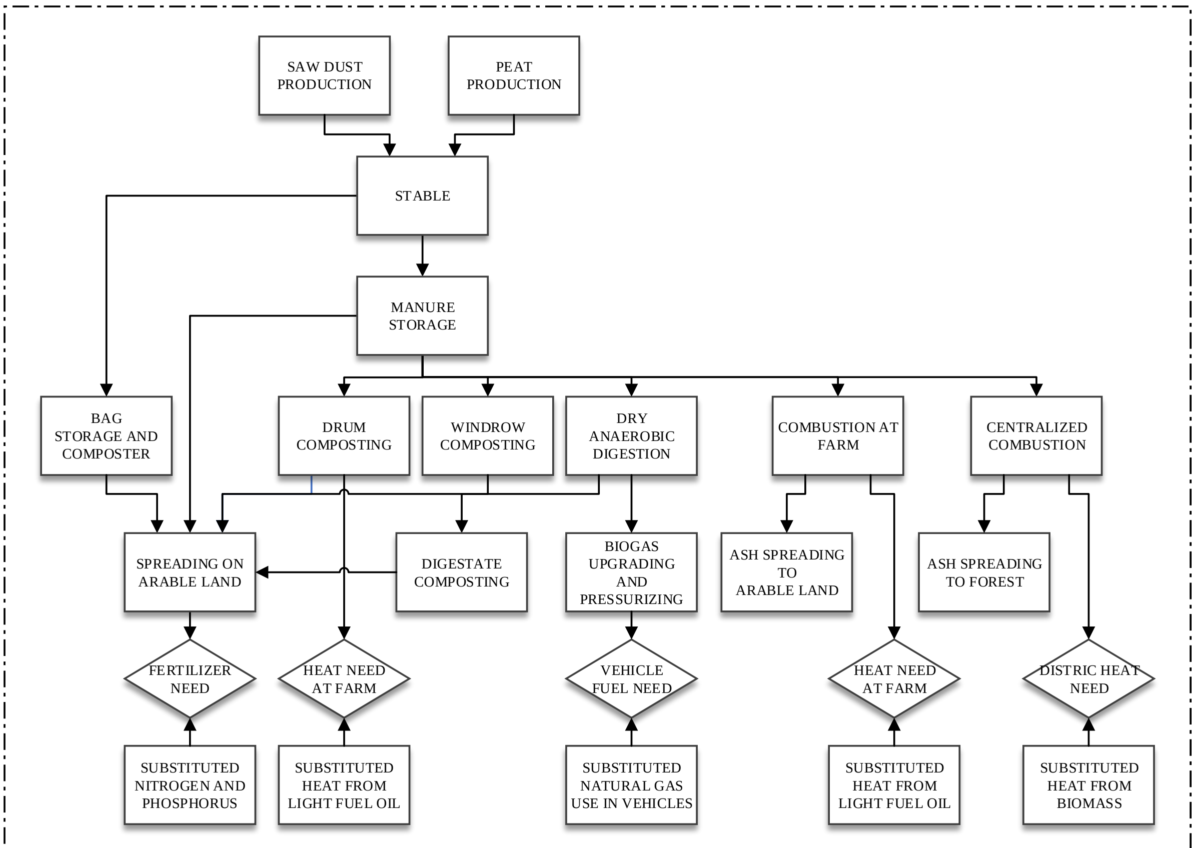

Figure 1. It starts with the production of the used bedding material and ends with the utilization of the end products. The selected bedding materials include saw dust and peat, the main bedding materials used in Finland (Oksala et al., 2017b). The production emissions of these bedding materials are also included in the study.

In the treatment process of horse manure, several recycling products, such as fertilizers, electricity, and heat are produced, depending on the selected treatment method. The environmental impacts of the products are included in the study by utilizing the system expansion approach. The aim of utilizing this approach is to avoid allocation of emissions from the treatment process to different products as recommended by standards in ISO 14044: 2006. Instead of allocation, reduced emissions due to substitution of corresponding products from other production systems are included in the results.

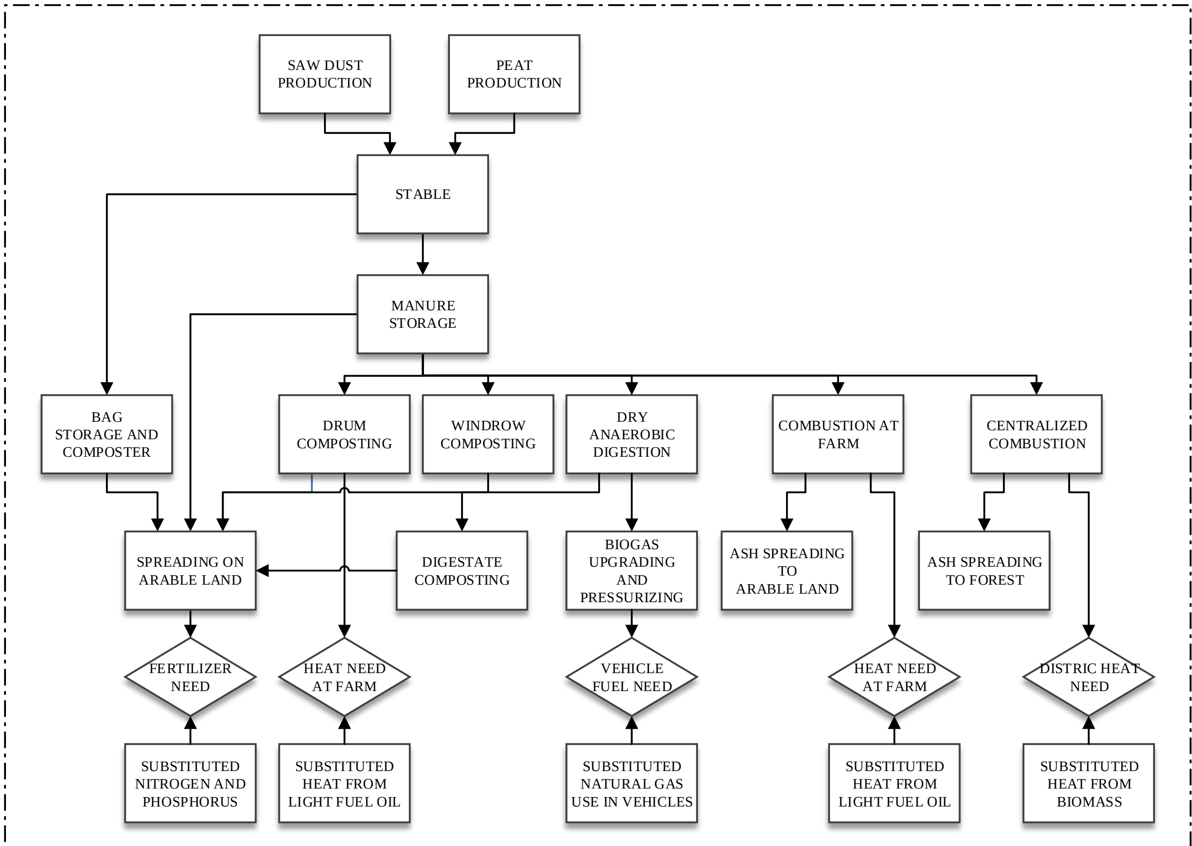

Figure 1. System boundary of horse manure management options.

2.2 Life cycle inventory

2.2.1 Properties of manure and bedding

The properties of manure were calculated, including the properties of horse feces (Table 1) and the demand and properties of bedding (Table 2). One horse produces approximately 6.3 t of feces annually (Manninen et al., 2016), and bedding material is needed to provide hygienic conditions for horses by absorbing the produced urine. Saw dust demand as bedding material is greater than that of peat because it has lower water retention properties (Airaksinen et al., 2001). The lower retention potential means that saw dust manure has lower water content and therefore lower heating value, as the received basis (LHV_{ar}) is higher for saw dust manure compared to peat manure. The annual horse manure production of one horse (bedding included) is 13.5 t when saw dust is used as bedding material, and it is 9.6 t when peat is used.

Table 1. Properties of horse feces, bedding material and horse manure.

		Horse	Bedding material		Saw dust	Peat	Reference
		feces	Saw dust	Peat	manure	manure	
TS	kg / kg	0.17	0.50	0.43	0.34	0.26	Manninen et al., 2016; Hennessy and Eriksson, 2015
VS	kg / kg TS	0.78	0.47	0.68	0.54	0.72	Alakangas, 2000; Manninen et al., 2016
C	kg / kg TS	0.44	0.52	0.27	0.50	0.34	Alakangas, 2000; Manninen et al., 2016

N tot	kg / kg TS	0.033	0.0032	0.0079	0.009	0.019	Manninen et al., 2016
P tot	kg / kg TS	0.0062	0.00040	0.00023	0.0015	0.0027	Manninen et al., 2016
LHV_{ar}	MJ/kg				5.9	4.2	Edström et al., 2011; Baky et al., 2012; Tanskanen ed., 2016
Ash	kg / kg TS				0.070	0.16	Edström et al., 2011; Baky et al., 2012; Tanskanen., 2016

TS = total solid, VS = volatile solid

Table 2. Demand and production emissions of peat and saw dust bedding.

Peat			Reference
Demand	0.53	kg/kg feces	Tenhunen, 2014; Envitecpolis, 2019; Myllymäki et al., 2014
CO_2,eq.	0.62	kg /kg peat	Tenhunen, 2014; Envitecpolis, 2019; Myllymäki et al., 2014
SO_2,eq.	22	mg /kg peat	Ecoinvent, 2019
PO_4^{3-},eq.	8.2	mg /kg peat	Ecoinvent, 2019
Saw dust			
Demand	1.1	kg/kg feces	Hennessy and Eriksson, 2015; Tenhunen, 2014; Manninen et al., 2016
CO_2	0.045	kg/kg saw dust	Havukainen et al., 2018a; Manninen et al., 2016
N_2O	1	mg/kg saw dust	Manninen et al., 2016
CH_4	87	mg/kg saw dust	Manninen et al., 2016

2.2.2 Stable and manure storage

Horse manure starts producing gaseous emissions from the stable and manure storage, as summarized in Table 3. Manure is directed to storage in all other treatment methods, except bag composting. Bag composting allows bags to be used in a small and stable farm as a storage and treatment unit, avoiding the need for building more expensive manure storage facilities. In stables, emissions are assumed to be caused mainly by horse fecal decomposition while in storage and also by the degradation of bedding material.

Table 3. Emissions of horse manure in stable and storage.

	Stable	Manure storage		Reference
NH_3	17	19	% of tot N	Baky et al., 2012; Karlsson and Rodhe, 2002; Hadin, 2016
N_2O	1.6	0.92	% of tot N	Maljanen et al., 2016; Baky et al., 2012
NO		0.43	% of tot N	Manninen et al., 2016
N_2		5.9	% of tot N	Manninen et al., 2016
CH_4		0.17	% of tot C	Baky et al., 2012; Rodhe et al., 2015

2.2.3 Transport and spreading on field

Emissions from the transport of bedding material as well as manure and ash are included in the study. For the transport distance of bedding materials, published average transport distances in Finland are used (Table 4). Consumption, capacities, and emissions of vehicles used for transportation are summarized in

Table 5. Diesel production emissions contributing to GWP, AP, and EP used in the study are 508 $g_{CO2,eq.}$/kg diesel, 2.2 $g_{SO2,eq.}$/kg diesel, and 0.44 $g_{phosphate,eq.}$/kg diesel, respectively (Thinkstep, 2018). The initial data for the transportation of manure for treatment processes are included from studies related to horse manure management in Finland (Table 4). Currently, horse manure is not much used in the anaerobic digestion process in Finland; therefore, transport distance is estimated for locations of existing biogas plants. Forest tractors are used to spread ash from centralized combustion centers to forests, and agricultural tractors are used to transport manure to treatment centers located on farms and to spread manure, compost, or digestate on fields. The initial data used for the modelling, considering mass spread per hectare, tractor diesel usage, distance driven by the tractor per hectare, and gaseous emissions from spreading are summarized in Table 6.

Table 4. Transport vehicles and one-way distances.

	Vehicle	One-way distance (km)	Reference
Peat bedding	Semi-trailer truck	50	Statistics Finland, 2018
Saw dust bedding	Semi-trailer truck	95	Statistics Finland, 2018
Manure to field	Tractor	14	Ahonen and Koivistoinen, 2014
Manure to drum composting at farm	Tractor	1	Oksala et al., 2017b
Manure to centralized combustion	Truck	64	Oksala et al., 2017b
Manure to windrow composting	Truck	87	Oksala et al., 2017b
Manure to anaerobic digestion	Truck	13	Estimated
Manure to bag storage and composting at farm	Tractor	1	Oksala et al., 2017b
Manure to combustion at farm	Tractor	1	Oksala et al., 2017b
Ash from centralized combustion	Full-trailer truck	40	Manninen et al., 2016

Table 5. Consumption, capacity and emissions of selected vehicles (VTT, 2017).

		Semi-trailer truck	Truck	Agricultural tractor	Full-trailer truck	Forest tractor	Front end loader
Consumption	l/100 km	34	19	29	42	-	-
Capacity	t	25	28	6.0	40	-	-
Emissions							
CO	g/l	0.99	1.1	0.99	1.0	7.9	7.8
HC	g/l	0.21	0.19	0.21	0.22	0.94	2.5
NO_x	g/l	14	15	14	13	6.0	22
PM	g/l	0.13	0.14	0.13	0.12	0.20	1.1
CH_4	g/l	0.013	0.015	0.013	0.013	0.15	0.15
N_2O	g/l	0.086	0.10	0.086	0.068	0.042	0.071
SO_2	g/l	0.0079	0.0077	0.0079	0.0078	0.0081	0.017
CO_2	g/l	2300	2300	2300	2300	2700	2607

Table 6. Energy use, mass of manure spread per hectare, distance covered and emissions from spreading manure.

			Reference
Diesel use	275	l / 100 km	Ahokas, 2013

Mass	37	t/ha	Tontti et al., 2015
Distance	1.8	km/ha	Tontti et al., 2015
N_2O	0.33	% of tot N	Hennessy and Eriksson, 2015; Manninen et al., 2016
NH_3	10	% of tot N	Hennessy and Eriksson, 2015; Manninen et al., 2016
CH_4	2.0	% of tot C	Hennessy and Eriksson, 2015; Manninen et al., 2016
N_2	0.30	% of tot N	Hennessy and Eriksson, 2015; Manninen et al., 2016

2.2.4 Composting: windrow composting, bag composting, and drum composting

Three different composting processes for horse manure management are modelled in this study; namely, bag composting, drum composting, and windrow composting (Table 7). Out of these, bag composting and drum composting are considered as occurring at the farm, whereas windrow composting is considered as occurring in a centralized manner. The bag composting process does not require separate manure storage since it can provide storage as well as treatment for a limited amount of horse manure.

Table 7. Windrow, bag, and drum composting energy use, production, and emissions.

		Bag composting	Drum composting	Windrow composting	Reference
Electricity use	MJ/kg waste		0.1		Myllymaa et al., 2008
Diesel use	l/kg waste			0.0020	Hupponen et al., 2012
Heat recovery	MJ/kg		0.14		Mäihäniemi, 2017
Peat manure TS loss	% of TS	31	31	31	Keskinen et al., 2017
Saw dust manure TS loss	% of TS	18	18	18	Keskinen et al., 2017
C loss	% greater than TS loss	28	28	28	Tiquia et al., 2002
Compost TS	%	32	32	32	Humuspehtoori, 2019
Compost soluble N	% of tot N	6.9	6.9	6.9	Humuspehtoori, 2019
Gaseous emission					Hennessy and Eriksson, 2015; Rodhe et al., 2015; Baky et al., 2012
NH_3	% of tot N	19	2.3	10	
N_2O	% of tot N	0.92	0.26	0.33	
CH_4	% of tot C	2.0	0.06	2.0	
N_2	% of tot N	5.9	0.0	0.30	
Emissions to water					Eriksson et al., 2016

N_2	% of tot N	0.3	0	0.3
NH_4	% of tot N	0.004	0.01	0.004
NO_3	% of tot N	0.033	0	0.033
P	% of tot N	0.07	0	0.07

The difference between peat and saw dust manure lies in the assumption that total solid (TS) loss in the composting process is higher with peat manure since peat is more readily compostable than saw dust. Drum composting causes less direct emissions because the process includes more agitation of the compostable mass compared to windrow and bag composting processes. In addition, the drum composting process includes heat recovery (Mäihäniemi, 2017), whereas windrow composting includes diesel use by front end loaders. Emission levels are presented in Table 4. The emissions of average grid mix electricity production in Finland contributing to GWP, AP, and EP used in the study are 67 $g_{CO2,eq.}$/MJ, 0.16 $g_{SO2,eq.}$/MJ, and 0.021 $g_{phosphate,eq.}$/MJ, respectively (Thinkstep, 2018)

2.2.5 Dry anaerobic digestion

Dry anaerobic digestion was selected as an option for biogas production from horse manure instead of wet digestion since horse manure is relatively dry. Data on existing facilities, including dry mesophilic anaerobic digestion and subsequent tunnel composting of digestate collected by Havukainen et al. (2018b) are used in this study. The electricity used at facilities includes electricity used for anaerobic digestion and for tunnel composting. The electricity demand includes electricity needed for heat pumps, which provide the necessary heat for anaerobic digestion by recovering it from gases exiting the composting. Data relating to anaerobic digestion and subsequent composting are summarized in Table 8. Diesel is used at the facility by the front end loader, and emissions are presented in Table 4. The emissions associated with tunnel composting of digestate are assumed to be similar to that of drum composting presented in Table 7. The compost is applied on arable land, and the methane emission from this application is considered negligible because it is assumed that biologically degradable carbon is consumed in anaerobic digestion and in the subsequent composting process. The produced biogas is upgraded to biomethane using water wash, which is pressurized and injected into the grid and then used as a substitute for natural gas in cars.

Table 8. Properties of anaerobic digestion and subsequent tunnel composting.

Anaerobic digestion and tunnel composting			Reference
Saw dust manure, CH_4 yield	0. 1	m^3 CH_4 / kg VS	Mäihäniemi, 2017
Peat manure, CH_4 yield	0.09	m^3 CH_4 / kg VS	Mäihäniemi, 2017
Biogas CH_4 content	60	%	Havukainen et al., 2018b
Electricity use	0.76	MJ/kg	Havukainen et al., 2018b
Diesel use	0.0027	l / kg	Havukainen et al., 2018b
Upgrading electricity use	1.1	MJ/m^3 raw gas	Kuisma et al., 2013; Uusitalo et al., 2014
Upgrading methane slip	1.8	%	Kuisma et al., 2013; Uusitalo et al., 2014
Biomethane CH_4 content	98	%	Uusitalo et al., 2014
Pressurizing electricity use	0.71	MJ/m^3 gas	Uusitalo et al., 2014

2.2.6 Combustion

Horse manure is assumed to be directed either to centralized combustion in a heating plant or to small-scale combustion at a farm. The used LHV_{ar} and ash content are summarized in Table 1, and the combustion emissions of both of these cases are included in Table 9. The ash from centralized combustion is assumed to be transported with a full-trailer truck (Table 4) and then spread in the forest by a forest tractor which consumes 5 l diesel/t ash (Wihersaari and Palosuo, 2000). Forest tractor emissions are presented in

Table 5. It is assumed that ash from small-scale combustion at farms is transported to the field and that the amount spread is 7.5 t ash/ha. Diesel use and distance covered in spreading ash in the field are presented in Table 6.

Table 9. The combustion emissions of horse manure at farms and in centralized combustion in relation to fuel energy.

	Combustion on farm	Centralized combustion	
CO	34	-	mg/MJ fuel
SO_2	5	0.78	mg/MJ fuel
NO_x	129	84	mg/MJ fuel
Dust	0.70	0.019	mg/MJ fuel
CO_2*	105	105	g/MJ fuel
Reference	Swebo Bioenergy, 2016;	Manninen et al., 2016	

* In peat manure combustion (Kirkinen et al., 2007; Lapveteläinen et al., 2007)

2.2.7 Substituted material and energy products

The different horse manure management chains result in material and energy products that are accounted for by including the avoided emissions from producing them. The emission factors of substituted energy and material products are summarized in Table 10. The nitrogen and phosphorus in compost and digestate that are directed to arable land substitute mineral fertilizers (triple superphosphate and ammonium nitrate), and the upgraded biogas substitutes natural gas used as vehicle fuel, including for car emissions and for obtaining natural gas. It is assumed that the emissions of gas-fueled cars are the same for natural gas and biomethane, except for CO_2 emissions, because biomethane CO_2 is assumed to be biogenic in origin.

In cases where horse manure is directed to centralized combustion, it is assumed that it substitutes wood chips, half of which are made from forest residue and the other half from sawmill by-product (Manninen et al., 2016). The emissions avoided from obtaining and combusting wood chips are presented in Table 10. In the case of the small-scale combustion at the farm, the produced heat is assumed to substitute heat production from light fuel oil (Table 10). In substitution at the farm, it is assumed that not all produced heat is utilized due to the seasonal variation in heat demand; thus, approximately 50% of the produced heat can be utilized, corresponding to 6 months of heat demand in the region (Väisänen et al., 2016). A similar heat utilization rate was assumed for Swedish conditions by Baky (2013).

Table 10. The GWP, AP, and EP emission factors of substituted energy and material products (Thinkstep, 2018).

	GWP $kg_{CO2,eq.}$	AP $g_{SO2,eq.}$	EP $g_{phosphate,eq.}$	per
Ammonium nitrate	3.5	3.5	1.5	kg N
Triple superphosphate	2.2	82	82	kg P
Light fuel oil heat	0.096	0.11	0.011	MJ
Natural gas use in car	0.57	0.82	0.11	kg
Wood chip combustion	0.001	0.059	0.015	MJ fuel

2.3 Uncertainty analysis

The life cycle inventory collection phase includes collection of data from various sources, and there are uncertainties in the selection of used values in the study. To evaluate the impact that the uncertainty of the initial data has on scenario results, a range of values were used for the major selected parameters (Table 11).

Table 11. The parameters and values used for calculating the range of results.

	Low	High	Used	Unit	Reference
Bedding use					
Peat use	0.38	0.65	0.53	kg/kg feces	Envitecpolis, 2019; Manninen et al., 2016; Myllymäki et al., 2014; Tenhunen, 2014
Saw dust use	0.8	1.6	1.17	kg/kg feces	Envitecpolis, 2019; Manninen et al., 2016; Tenhunen, 2014; Vesiaho, 2015
Peat production	0.3	0.72	0.52	$kg_{CO2,eq.}$/kg	Ecoinvent, 2019; Manninen et al., 2016; Pohjala, 2014; Väisänen et al., 2013
Manure storage emissions					
NH_3	6.3	25	19	% of tot N	Baky et al., 2012; Karlsson and Rodhe, 2002; Manninen et al., 2016
N_2O	0.22	2.0	0.82	% of tot N	Baky et al., 2012; Maljanen et al., 2016; Manninen et al., 2016
LHVar					
Peat manure	3.2	5.9	4.2	MJ/kg	Baky et al., 2012; Hennessy and Eriksson, 2015; Tanskanen (ed.), 2016
Saw dust manure	3.2	7.0	5.9	MJ/kg	Edström et al., 2011; Hennessy and Eriksson, 2015; Tanskanen (ed.), 2016
Incineration					
Peat CO_2	102	106	105	g/MJ	Kirkinen et al., 2007; Lapveteläinen et al., 2007; Statistics Finland, 2019
Biogas yield					
Peat manure	0.079	0.10	0.09	m^3CH4/kgVS	Hadin, 2016; Hadin and Eriksson, 2016; Mäihäniemi, 2017
Saw dust manure	0.071	0.15	0.10	m^3CH4/kgVS	Böske et al., 2014; Nitsche et al., 2017; Wartell et al., 2012

The beginning of the horse manure management chain (viz., bedding usage) already includes uncertainties, since bedding usage is greatly affected by bedding usage practices at the stable. The change in bedding usage material affects all scenarios. Manure storage emissions are difficult to evaluate, and therefore, there is uncertainty involved. The subsequent treatment phases also contain process-related uncertainties. The heating value of horse manure and emissions from peat incineration impact combustion process emissions, whereas biogas yield impacts anaerobic digestion scenario results.

3 Results and discussion

Results for the selected environmental impacts with uncertainty depicted with error bars are summarized in Figure 2 for GWP, in Figure 3 for AP, and in Figure 4 for EP, and Table S1 and Table S2 of the supplementary material provide a more detailed look at results. The GWP results in Figure 2 clearly indicate that the inclusion of bedding material has notable implications for the environmental impacts of horse manure management. Selecting saw dust as a bedding material leads to lower net GWP impacts in all other treatment options, except bag composting and drum composting options.

The difference in the net GWP is most notable in farm scale and centralized combustion options. The net emissions from saw dust manure management are 1.5 times lower in farm scale combustion and 0.9 times lower in centralized combustion than from peat manure management. The main contributing factor for this difference is the carbon dioxide equivalent emissions from peat combustion, whereas carbon dioxide emissions from saw dust manure combustion are assumed to be biogenic and therefore not accounted for. In addition, the substituted emissions from energy production are higher for saw dust manure. This result is related to the higher bedding demand when utilizing saw dust, which means that a larger amount of manure with bedding is produced per functional unit. Since saw dust manure also has a higher LHV_{ar} than peat manure, more energy can be produced per functional unit when saw dust is utilized as bedding material, and the emissions avoided from energy substitution are two times higher for saw dust manure than for peat manure. Avoided emissions do not cause such an impact on net GWP in the case of centralized combustion because in this case, biomass energy is substituted. However, when light fuel oil is substituted in farm scale combustion, the substituted emissions from energy production are four times the produced emissions for saw dust manure and 0.3 times the produced emissions in the case of peat manure.

The impact of bedding material selection on GWP is noticeable in addition to combustion options, also with other treatment options. This result is explained by the fact that peat bedding production emissions are significantly higher than those of saw dust bedding (Table 2), which means that even though the bedding demand of saw dust is higher, selecting peat as bedding material causes four times higher emissions from bedding material production than selecting saw dust. When peat is used as bedding material, obtainment of bedding material is responsible for the majority of emissions in all treatment chains, except in combustion chains, varying from 52% in windrow composting to 71% in drum composting. In combustion chains, the main source of emissions is the combustion process (65%), which is followed by bedding material obtainment (29%).

Higher GWP from saw dust manure compared to peat manure in composting treatment and spreading on field chains are caused by the higher demand for saw dust bedding. The higher demand results in a higher carbon mass in saw dust manure. The carbon input of horse manure is 0.37 kg C/kg feces when using saw dust bedding material and only 0.13 kg C/kg feces when using peat bedding material. This then leads to higher methane emissions from composting and spreading on fields, which is responsible for 60%–70% of the emissions contributing to GWP.

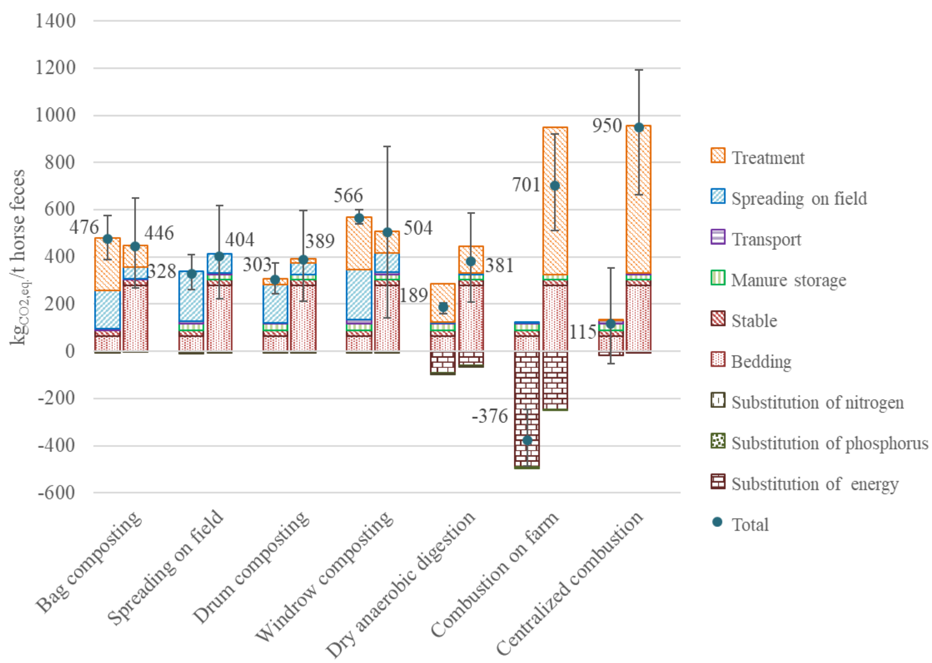

Figure 2. Global warming impact of horse manure management options (left bars saw dust bedding; right bars peat bedding).

The results of the EP and AP impacts of horse manure management chains that are summarized in Figure 3 for EP and Figure 4 for AP do not vary nearly as much as those of GWP. The lowest GWP value is 1.7 times lower than the highest, whereas for EP and AP, the difference is 0.3 and 0.4, respectively. The main reason is that the stable and manure storage processes are significantly more important from the EP and AP results than for the GWP results. The stable and storage processes together are responsible for approximately 70%–90% of the emissions accounting for EP and AP, and these emissions are independent of the selected treatment method for the manure. The highest EP for saw dust manure management is from the windrow composing chain, and the highest AP is from dry anaerobic digestion. Furthermore, for peat manure management, anaerobic digestion has both the highest AP and EP. However, it should be noted that the EP and AP of windrow composting and dry anaerobic digestion chains are almost the same for both peat and saw dust manure.

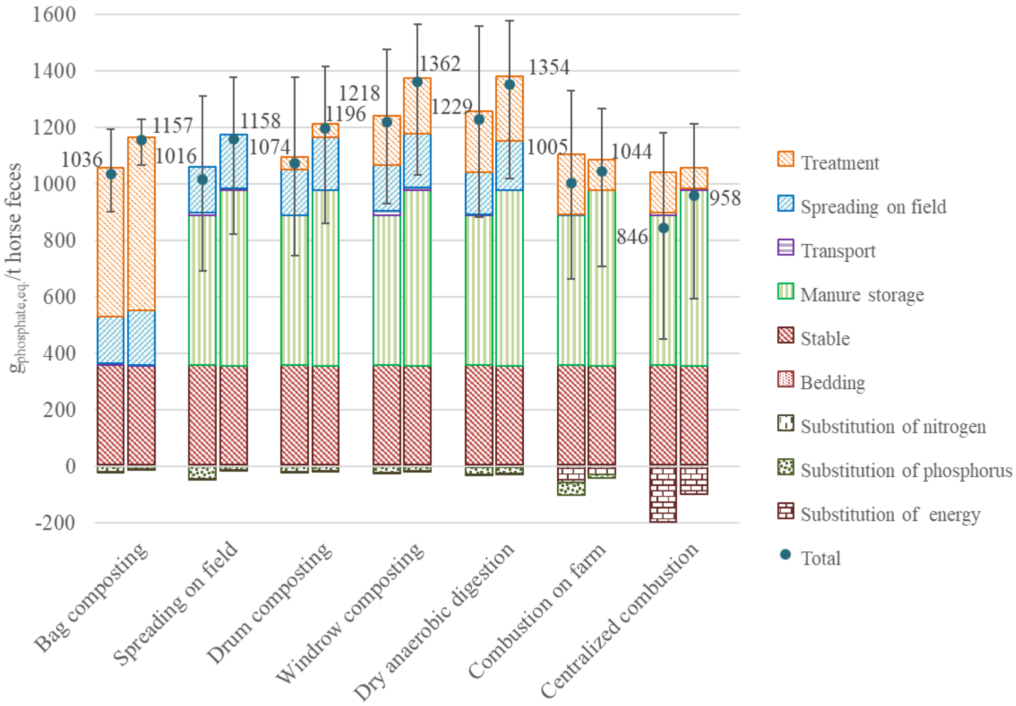

Figure 3. Eutrophication potential of horse manure management options (left bars saw dust bedding; right bars peat bedding).

The main contributor to both EP and AP impact in manure management chains is ammonia gas, which means that manure nitrogen content is important. Both saw dust manure and peat manure, including bedding and feces, contain 7.3 kg N/t feces because the majority of nitrogen comes with feces. In addition, nitrogen levels from bedding are similar for both types of bedding materials because even though bedding demand is higher for saw dust, peat bedding contains more nitrogen.

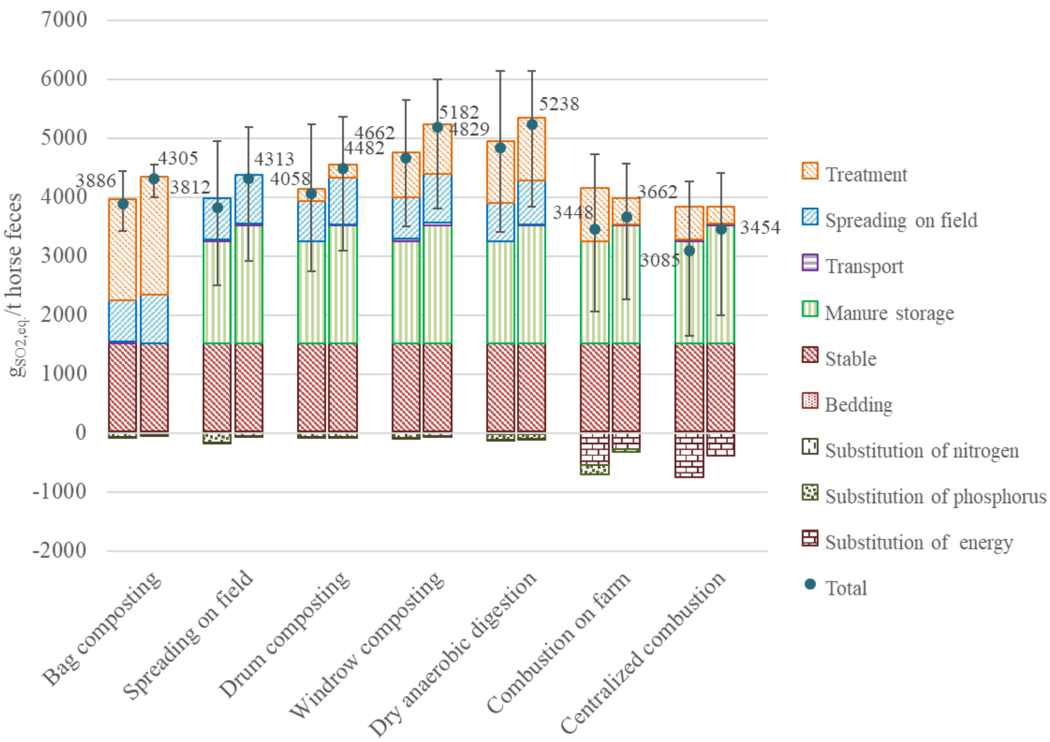

Figure 4. Acidification potential of horse manure management options (left bars saw dust bedding; right bars peat bedding).

According to the results of the present study, using peat as bedding material leads to lower GWP, AP, and EP in the majority of the manure management chains investigated. Furthermore, combustion appears to be the most favorable option for saw dust manure management, with farm combustion demonstrating the lowest impact for GWP and centralized combustion demonstrating the lowest impact for AP and EP. For peat manure management, it appears that there is a tradeoff between GWP, AP, and EP because combustion, which demonstrates the lowest impact for GWP leads to highest impact for EP and AP.

Comparing these results to other studies is difficult since a limited number of studies related to the environmental impact of horse manure management exist. Eriksson et al. (2016) reveal that for GWP, anaerobic digestion of manure with wood chip bedding was the most favorable option, followed by incineration, results similar to this study in which incineration is the most favorable option followed by anaerobic digestion. This is most likely related to the differences in biogas yields. For AP and EP, both the present study and the study by Eriksson et al. (2016) demonstrate that centralized combustion is the most favorable option. Comparing results in greater detail is unreasonable since in the study by Eriksson et al. (2016), neither bedding production emissions nor manure storage prior to treatment are included. Similar to the study by Manninen et al. (2016), the combustion of manure utilizing saw dust results in lower GWP and AP than the reference case of composting feces, even though the reference case in Manninen et al. (2016) had a mixture of bedding materials. The results of this study suggest higher GWP from combustion; namely, 115 $kg_{CO2,eq.}$/t feces compared to the 59 $kg_{CO2,eq.}$/t feces obtained by Manninen et al (2016), whereas the results for AP are identical for both studies; namely, 3 $kg_{SO2,eq.}$/t. The difference in GWP between the two studies are mainly due to the difference in stable and storage emissions, 70% of the difference, since in the study by Manninen et al. (2016) the storage time is assumed to be short and thus resulting to low emissions. Similarly, windrow composting emissions in this study is higher; namely, 535 $kg_{CO2,eq.}$/t feces, compared to 308 $kg_{CO2,eq.}$/t feces in Manninen et al. (2016), which is mainly due to emissions from field application since Manninen et al. (2016) does not account for methane emissions from field application. AP results in the two studies were closer to each other, with 5 $kg_{SO2,eq.}$/t feces in the present study and 7 $kg_{SO2,eq.}$/t feces in Manninen et al. (2016).

The limitations of the study included the limited availability of information on emissions from horse manure treatment, the varying properties of feces, and the varying usage of bedding, which can change from stable to stable. It was also difficult to precisely define the changes in material properties in a longer treatment chain. For example, in the case of anaerobic digestion and subsequent digestate composting processes followed by the spreading of compost on arable land, precisely calculating properties, such as the compounds that compose total nitrogen, was not possible. The anaerobic digestion process can increase soluble nitrogen share, which in turn increases ammonia emissions from subsequent processes, such as spreading manure on fields. This means that emission factors for ammonia calculated from total nitrogen content does not necessarily provide precise results and may reduce result accuracy.

Bedding has visible impact on the results; however, bedding selection at horse stables is affected by bedding material availability, bedding material price, and utilization methods available for the treatment of manure. The location of horse stables further away from agricultural regions limits possibilities for spreading manure on fields and promotes the use of centralized treatment options. In addition, farmers receiving horse manure may prefer peat manure since peat has faster biodegradability, higher water retention properties, and greater ability to hold more ammonia compared to saw dust. The faster biodegradability also makes peat manure attractive for composting and anerobic digestion, whereas higher heating and lower moisture content make saw dust manure more appealing for combustion. The availability of peat bedding might be reduced when energy production from peat is reduced since it might not be economical to extract peat only for bedding purposes.

It should be borne in mind that the results did not take into consideration horse stable size, which has an impact on the feasibility of treatment method and on the utilization method for manure. The bag composting process is most suitable for smaller stables that have only few horses and which do not want to invest in larger manure storage systems. The bag composting process acts as a small-scale storage and treatment option. The drum composting process is already a more significant investment (Oksala et al., 2017a) and suitable for larger stables with 10 horses or more (Oksala et al., 2018). Drum composting also provides opportunities for heat recovery, so it is more suitable for larger stables that have possibilities to utilize the recovered heat (Mäihäniemi, 2017). The produced compost could be utilized as a fertilizer product to be sold outside farms. Combustion at farm scale can be more suitable when horse numbers are 50 or more. Benefiting from the energy content of the manure requires suitable heat sinks for the produced heat since the stable might not be able to utilize all the produced heat. Windrow composting, anaerobic digestion, and large-scale combustion processes arranged in a centralized manner are suitable for stables of various sizes, providing that they are within reasonable distance from treatment plants.

4 Conclusions

Environmental impacts, including GWP, AP, and EP of different horse manure management chains, including bag composting, spreading manure on arable land, various composting processes, anaerobic digestion, and combustion were assessed using LCA. According to the results, the selected bedding and emissions from treatment processes are the most significant contributors to GWP, whereas stable and storage processes have the most impact on AP and EP emissions. The results indicate that when selecting saw dust as a bedding material, the most favorable option is combustion considering all the investigated impact categories. However, in cases where peat is used as bedding material, the results favor anaerobic digestion to reduce GWP and combustion to reduce AP and EP. It has to be borne in mind that the use of bedding material and selected waste management options are affected by the availability of the bedding, treatment options, and by stable location and size, which reduces possibilities for selecting favorable options from an environmental perspective. Furthermore, the results should be interpreted with some caution since there is insufficient primary data available on emissions from the different processes related to horse manure management, and more research on the topic is required to arrive at a more thorough estimation of environmental impacts and to validate the results obtained in this study.

References

Ahokas (ed.), J., 2013. Fuel consumption in field work (in Finnish). Helsinki University, Helsinki.

Ahonen, J., Koivistoinen, P., 2014. Manure logistics and remote storing (in Finnish). Savonia University of Applied Sciences, Mikkeli.

Airaksinen, S., Heinonen-Tanski, H., Heiskanen, M.L., 2001. Quality of different bedding materials and their influence on the compostability of horse manure. J. Equine Vet. Sci. 21. 125–130. https://doi.org/10.1016/S0737-0806(01)70108-6

Alakangas, E., 2000. Properties of fuels used in Finland (in Finnish). VTT Technology 258. VTT Technical Research Centre of Finland Ltd., Espoo.

Baky, A., 2013. Life Cycle Inventory & Assessment Report: Combustion of Horse Manure with Heat Utilisation, Sweden. Swedish Institute of Agricultural and Environmental Engineering, Uppsala

Baky, A., Karlsson, E., Norberg, I., Tersmeden, M., Yngvesson, J., 2012. Combustion of dried horse manure on farm scale level—Evaluation of dryer performance and combustion properties (in Swedish). Swedish Institute of Agricultural and Environmental Engineering, Uppsala.

Böske, J., Wirth, B., Garlipp, F., Mumme, J., Van den Weghe, H., 2014. Anaerobic digestion of horse dung mixed with different bedding materials in an upflow solid-state (UASS) reactor at mesophilic conditions. Bioresource Technol. 158, 111–118. https://doi.org/10.1016/j.biortech.2014.02.034

CML-Department of Industrial Ecology, 2016. CML-IA Characterisation Factors. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed 12 November, 2016).

Corbala-Robles, L., Sastafiana, W.N.D., Van linden, V., Volcke, E.I.P., Schaubroeck, T., 2018. Life cycle assessment of biological pig manure treatment versus direct land application—a trade-off story. Resour. Conserv. Recy. 131, 86–98. https://doi.org/10.1016/j.resconrec.2017.12.010

Ecoinvent, 2019. Ecoinvent 3.6 database.

Edström, M., Schüßler, I., Luostarinen, S., 2011. Combustion of Manure: Manure as Fuel in a Heating Plant. Swedish Institute of Agricultural and Environmental Engineering, Uppsala.

Envitecpolis, 2019. Horse manure composting (in Finnish). http://envitecpolis.fi/helmet/tietopankki/kompostointi/ (accessed 29 March, 2019).

Eriksson, O., Hadin, Å., Hennessy, J., Jonsson, D., Eriksson, O., Hadin, Å., Hennessy, J., Jonsson, D., 2016. Life Cycle Assessment of Horse Manure Treatment. Energies 9. 1011. https://doi.org/10.3390/en9121011

Esteves, E.M.M., Herrera, A.M.N., Esteves, V.P.P., Morgado, C. do R.V., 2019. Life cycle assessment of manure biogas production: A review. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2019.02.091

EU 2017/1262, 2017. Commission Regulation 2017/1262 of 12 July 2017 amending Regulation No 142/2011 as regards the use of manure of farmed animals as a fuel in combustion plants.

EU 592/2014, 2014. Comission regulation No 592/2014 of 3 June 2014 amending Regulation (EU) No 142/2011 as regards the use of animal by-products and derived products as a fuel in combustion plants.

EU 2017/1262, 2017. Commission Regulation 2017/1262 of 12 July 2017 amending Regulation

No 142/2011 as regards the use of manure of farmed animals as a fuel in combustion plants.

EU 592/2014, 2014. Comission regulation No 592/2014 of 3 June 2014 amending Regulation (EU) No 142/2011 as regards the use of animal by-products and derived products as a fuel in combustion plants.

Hadin, Å., 2016. Anaerobic digestion of horse manure – renewable energy and plant nutrients in a systems perspective. University of Gävle, Gävle.

Hadin, Å., Eriksson, O., 2016. Horse manure as feedstock for anaerobic digestion. Waste Manage. 56, 506–518. https://doi.org/10.1016/J.WASMAN.2016.06.023

Havukainen, J., Nguyen, M.T., Väisänen, S., Horttanainen, M., 2018a. Life cycle assessment of small-scale combined heat and power plant: Environmental impacts of different forest biofuels and replacing district heat produced from natural gas. J. Clean. Prod. 172, 837–846. https://doi.org/10.1016/j.jclepro.2017.10.241

Havukainen, J., Uusitalo, V., Koistinen, K., Liikanen, M., Horttanainen, M., 2018b. Carbon Footprint evaluation of biofertilizers. Int. J. Sust. Dev. Plan. 13, 1050–1060. https://doi.org/10.2495/SDP-V13-N8-1050-1060

Hennessy, J., Eriksson, O., 2015. Energy and nutrients from horse manure Life-cycle data inventory of horse manure management systems in. University of Gävle. Gävle.

Humuspehtoori, 2019. Humuspehtoori - products (in Finnish). https://www.humuspehtoori.fi/tuotteet (accessed 17 May, 2019).

Hupponen, M., Luoranen, M., Horttanainen, M., 2012. Life Cycle Assessment of Greenhouse Gas Emissions From Biowaste Management : Case Study of Lappeenranta , Finland, in: Proceedings Venice 2012, Fourth International Symposium on Energy from Biomass and Waste San Servolo, Venice, Italy; 12-15 November 2012.

ISO 14040, 2006. Environmental management—Life cycle assessment—Principles and framework.

ISO 14044, 2006. Environmental management — Life cycle assessment — Requirements and guidelines.

Kahiluoto, H., Kuisma, M., Kuokkanen, A., Mikkilä, M., Linnanen, L., 2014. Taking planetary nutrient boundaries seriously: Can we feed the people? Glob. Food Secur. 3, 16–21. https://doi.org/10.1016/j.gfs.2013.11.002

Karlsson, S., Rodhe, L., 2002. Review of Statistics Sweden's calculation of the ammonia discharge in agriculture - emission factors for ammonia when storing and spreading manure (in Swedish). Swedish Institute of Agricultural and Environmental Engineering, Uppsala.

Keskinen, R., Saastamoinen, M., Nikama, J., Särkijärvi, S., Myllymäki, M., Salo, T., Uusi-Kämppä, J., 2017. Recycling nutrients from horse manure : effects of bedding type and its compostability. Agr. Food Sci. 26, 68–79.

Kirkinen, J., Minkkinen, K., Penttilä, T., Kojola, S., Sievänen, R., Alm, J., Saarnio, S., Silvan, N., Laine, J., Savolainen, I., 2007. Greenhouse impact due to different peat fuel utilisation chains in Finland-a life-cycle approach. Boreal Environ. Res. 12, 211–223.

Kuisma, M., Kahiluoto, H., Havukainen, J., Lehtonen, E., Luoranen, M., Myllymaa, T., Grönroos, J., Horttanainen, M., 2013. Understanding biorefining efficiency - The case of agrifood waste. Bioresource Technol. 135, 588–597. https://doi.org/10.1016/j.biortech.2012.11.038

Lapveteläinen, T., Regina, K., Perälä, P., 2007. Peat-based emissions in Finland's national greenhouse gas inventory. Finnish Environment Institute, Helsinki.

Liljenstolpe, C., 2009. Horses in Europe. Swedish University of Agricultural Sciences, Uppsala.

Mäihäniemi, M., 2017. Alternatives for horse manure utilization and assessment of environmental impacts (in Finnish). Aalto University, Helsinki.

Maljanen, M., Gondal, Z., Bhattarai, H.R., 2016. Emissions of nitrous acid (HONO), nitric oxide (NO), and nitrous oxide (N2O) from horse dung. Agr. Food Sci. 25, 225–229.

Manninen, K., Luostarinen, S., Saastamoinen, M., 2016. Environmental impacts of utilizing horse manure in energy recovery (in Finnish). Finnish Environment Institute, Helsinki.

Mönch-Tegeder, M., Lemmer, A., Oechsner, H., Jungbluth, T., 2013. Investigation of the methane potential of horse manure. Agr. Eng. Int. CIGR Journal 15, 161–172.

Myllymaa, T., Moliis, K., Tohka, A., Rantanen, P., Ollikainen, M., Dahlbo, H., 2008. Environmental loads and costs of waste recycling and incineration processes. Inventory report (in Finnish). Finnish Environment Institute, Helsinki.

Myllymäki, M., Särkijärvi, S., Karppinen, T., Kumpula, H., Virkkunen, E., 2014. Increasing the utilization of horse manure, case Kainuu (in Finnish). Agrifood Research Finland, Mikkeli.

Närvänen, A., Jansson, Håkan, Uusi-Kämppä, J., Jansson, Helena, Perälä, P., 2008. Phosphorus load from equine critical source areas and its reduction using ferric sulphate. Boreal Environ. Res. 13, 265–274.

Nitsche, M., Hensgen, F., Wachendorf, M., 2017. Energy Generation from Horse Husbandry Residues by Anaerobic Digestion, Combustion, and an Integrated Approach. Sustainability

9, 358. https://doi.org/10.3390/su9030358

Oksala, J., Havukainen, J., Rantala, T., 2018. From problem to resource Horse manure utilization technology guide for stables (in Finnish).

Oksala, J., Havukainen, J., Rantala, T., 2017a. Sustainable utilization of horse manure - technologies for manure treatment (in Finnish). Lappeenranta University of Tehcnology, Lappeenranta.

Oksala, J., Rantala, T., Havukainen, J., Saunila, M., Ukko, J., 2017b. Sustainable utilization of horse manure: Results from the questionaire to stable owners (in Finnish). Lappeenranta University of Tehcnology, Lappeenranta.

Pacheco-Torgal (eds.), F., Ivanov, V., Karak, N., Jonkers, H., 2016. Biopolymers and Biotech Admixtures for Eco-Efficient Construction Materials. Woodhead Publishing, Cambridge.

Parvage, M.M., Ulén, B., Kirchmann, H., 2013. A survey of soil phosphorus (P) and nitrogen (N) in Swedish horse paddocks. Agr. Ecosyst. Environ. 178, 1–9. https://doi.org/10.1016/j.agee.2013.06.009

Pohjala, M., 2014. What are the climate impacts of different life cycles of energy and horticultural peat? (in Finnish). University of Helsinki, Helsinki.

Rantala, T., Ukko, J., Saunila, M., Havukainen, J., 2018. The effect of sustainability in the adoption of technological, service, and business model innovations. J. Clean. Prod. 172, 46–55. https://doi.org/10.1016/j.jclepro.2017.10.009

Rodhe, L., Niklasson, F., Oostra, H., Gervind, P., Ascue, J., Tersmeden, M., Ringmar, A., 2015. Controlled drum composting with limited climate impact - emissions and heat recovery (in Swedish). Swedish Institute of Agricultural and Environmental Engineering, Uppsala.

Sandars, D.L., Audsley, E., Cañete, C., Cumby, T.R., Scotford, I.M., Williams, A.G., 2003. Environmental benefits of livestock manure management practices and technology by life cycle assessment. Biosyst. Eng. 84, 267–281. https://doi.org/10.1016/S1537-5110(02)00278-7

Saunila, M., Rantala, T., Ukko, J., Havukainen, J., 2019. Why invest in green technologies? Sustainability engagement among small businesses. Technol. Anal. Strateg. Manage. 31, 653–666. https://doi.org/10.1080/09537325.2018.1542671

Sharara, M., Kim, D., Sadaka, S.S., Thoma, G.J., 2019. Consequential Life Cycle Assessment of Swine Manure Management within a Thermal Gasification Scenario. Energies 12, 4081. https://doi.org/10.3390/en12214081

Statistics Finland, 2019. Fuel classification 2019. https://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html (accessed 8 January, 2020).

Statistics Finland, 2018. Goods transport by road 2017 (in Finnish). (accessed 5 Dezember, 2019). http://www.stat.fi/til/kttav/index.html

Swebo Bioenergy, 2016. Metlab Miljö Ab report on 499 kW. Biotherm Emission measurements.

Tanskanen, R. (ed.), 2016. Prestudy on utilizing material flows of South Savo horse industry in producing renewable energy (in Finnish). South-Eastern Finland University of Applied Sciences, Kouvola.

Tenhunen, A., 2014. Report on utilization options of horse manure from technical, juridical and stable entrepreneur point of view (in Finnish). University of Oulu, fOulu.

Thinkstep, 2018. GaBi ts - Software-System and Database for the Life Cycle Engineering.

Tiquia, S.M., Richard, T.L., Honeyman, M.S., 2002. Carbon, nutrient, and mass loss during composting. Nutr. Cycl. Agroecosys. 62, 15–24.

Tontti, T., Kapuinen, P., Ojajärvi, J., Joki-Tokola, E., Laurila, M., Ikäläinen, T., Kekkonen, J., Veijalainen, A.-M., 2015. Storing, spreading and dosing of organic fertilizer products (in Finnish). Natural Resources Institute Finland, Helsinki.

Ukko, J., Saunila, M., Rantala, T., Havukainen, J., 2019. Sustainable development: Implications and definition for open sustainability. Sustain. Dev. 27, 321–336.

Uusitalo, V., Havukainen, J., Kapustina, V., Soukka, R., Horttanainen, M., 2014. Greenhouse gas emissions of biomethane for transport: Uncertainties and allocation methods. Energ. Fuel. 28. https://doi.org/10.1021/ef4021685

Väisänen, S., Mikkilä, M., Havukainen, J., Sokka, L., Luoranen, M., Horttanainen, M., 2016. Using a multi-method approach for decision-making about a sustainable local distributed energy system: A case study from Finland. J. Clean. Prod. 137, 1330–1338. https://doi.org/10.1016/j.jclepro.2016.07.173

Väisänen, S.E., Silvan, N.R., Ihalainen, A.V.J., Soukka, R.M., 2013. Peat Production in High-Emission Level Peatlands — A Key to Reducing Climatic Impacts? Energ. Environ. 24, 757–778. https://doi.org/10.1260/0958-305X.24.5.757

Vesiaho, A., 2015. Bedding material in single stables and horse sheds (in Finnish). Jamk University of Applied Sciences, Jyväskylä.

VTT, 2017. LIPASTO Unit emissions database. http://lipasto.vtt.fi/yksikkopaastot/indexe.htm (accessed 6.8.18).

Wartell, B.A., Krumins, V., Alt, J., Kang, K., Schwab, B.J., Fennell, D.E., 2012. Methane production from horse manure and stall waste with softwood bedding. Bioresource Technol, 112, 42–50. https://doi.org/10.1016/J.BIORTECH.2012.02.012

Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agr. Ecosyst. Environ. 149, 124–134. https://doi.org/10.1016/j.agee.2011.12.015

Westendorf, M., Krogmann, U., 2013. Horses and manure. https://njaes.rutgers.edu/fs036/ (accessed 24 April 2019).

Wihersaari, M., Palosuo, T., 2000. Wood energy and greenhouse gases. Part 1: Greenhouse gas emissions of wood chip supply chains from final felling (in Finnish). VTT Technical Research Centre of Finland Ltd. Espoo.

Supplementary material

Table S1. Global warming impact, eutrophication potential and acidification potential when utilizing saw dust bedding.

	Bag composting	Spreading on field	Drum composting	Windrow composting	Dry anaerobic digestion	Combustion on farm	Centralized combustion
Global warming impact ($kg_{CO2,eq.}$/t horse feces)							
Bedding	62	62	62	62	62	62	62
Stable	25	25	25	25	25	25	25
Manure storage	0	31	31	31	31	31	31
Transport	8	9	1	16	2	1	12
Spreading on field	164	211	164	211	4	0	0
Treatment	220	0	24	224	160	0	1
Displacement energy	0	0	0	0	-92	-491	-16
Displacement phosphorus	-2	-4	-2	-2	-2	-4	0
Displacement nitrogen	-1	-6	-1	-1	-1	0	0
Total	476	328	303	566	189	-376	115
Eutrophication potential ($g_{phosphate}$/t horse feces)							
Bedding	7	7	7	7	7	7	7
Stable	351	351	351	351	351	351	351
Manure storage	0	532	532	532	532	532	532
Transport	7	8	1	2	13	1	10
Spreading on field	164	164	160	149	163	0	0
Treatment	527	0	43	215	174	215	142
Displacement energy	0	0	0	-3	0	-57	-196
Displacement phosphorus	-20	-43	-20	-24	-23	-43	0
Displacement nitrogen	0	-3	0	0	0	0	0
Total	1036	1016	1074	1229	1218	1005	846
Acidification potential ($g_{SO2,eq.}$/t horse feces)							
Bedding	28	28	28	28	28	28	28
Stable	1490	1490	1490	1490	1490	1490	1490
Manure storage	0	1726	1726	1726	1726	1726	1726
Transport	28	32	2	8	54	2	39
Spreading on field	706	705	690	643	703	0	0
Treatment	1709	0	197	1048	748	903	557
Displacement energy	0	0	0	-23	0	-538	-757
Displacement phosphorus	-74	-163	-74	-91	-86	-163	0
Displacement nitrogen	-1	-6	-1	-1	-1	0	0
Total	3886	3812	4058	4829	4662	3448	3085

Table S2. Global warming impact, eutrophication potential and acidification potential when utilizing peat bedding.

	Bag composting	Spreading on field	Drum composting	Windrow composting	Dry anaerobic digestion	Combustion on farm	Centralized combustion
Global warming impact ($kg_{CO2,eq.}$/t horse feces)							
Bedding	278	278	278	278	278	278	278
Stable	25	25	25	25	25	25	25
Manure storage	0	22	22	22	22	22	22
Transport	4	7	0	11	2	0	8
Spreading on field	51	81	50	81	4	0	0
Treatment	92	0	16	90	113	623	624
Displacement energy	0	0	0	0	-60	-246	-8
Displacement phosphorus	-1	-1	-2	-1	-2	-1	0
Displacement nitrogen	-1	-7	-1	-1	-1	0	0
Total	446	404	389	504	381	701	950
Eutrophication potential ($g_{phosphate}$/t horse feces)							
Bedding	6	6	6	6	6	6	6
Stable	351	351	351	351	351	351	351
Manure storage	0	621	621	621	621	621	621
Transport	3	6	0	1	9	0	7
Spreading on field	191	191	187	174	191	0	0
Treatment	615	0	48	227	198	108	71
Displacement energy	0	0	0	-2	0	-29	-99
Displacement phosphorus	-9	-13	-16	-23	-14	-13	0
Displacement nitrogen	-1	-3	-1	0	-1	0	0
Total	1157	1158	1196	1354	1362	1044	958
Acidification potential ($g_{SO2,eq.}$/t horse feces)							
Bedding	21	21	21	21	21	21	21
Stable	1490	1490	1490	1490	1490	1490	1490
Manure storage	0	2015	2015	2015	2015	2015	2015
Transport	13	22	2	6	38	2	28
Spreading on field	822	821	804	749	821	0	0
Treatment	1995	0	213	1062	852	453	281
Displacement energy	0	0	0	-15	0	-270	-380
Displacement phosphorus	-34	-49	-61	-88	-52	-49	0
Displacement nitrogen	-1	-7	-1	-1	-1	0	0
Total	4305	4313	4482	5238	5182	3662	3454

Table S3. Emission limits for on-farm combustion plant of chicken manure with total thermal input not exceeding 5MW (EU 592/2014).

Pollutant	Emission limit mg/m^3
Sulphur dioxide	50
Nitrogen oxides (as NO2)	200
Particulate matter	10