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Prospects for Increased Energy Recovery from Horse Manure—A Case Study of Management Practices, Environmental Impact and Costs

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Abstract: A transition to renewable energy sources and a circular economy has increased interest in renewable resources not usually considered as energy sources or plant nutrient resources. Horse manure exemplifies this, as it is sometimes recycled but not often used for energy purposes. The purpose of this study was to explore horse manure management in a Swedish municipality and prospects for energy recovery. The case study includes a survey of horse manure practices, environmental assessment of horse manure treatment in a biogas plant, including associated transport, compared to on-site unmanaged composting, and finally a simplified economic analysis. It was found that horse manure management was characterized by indoor collection of manure most of the year and storage on concrete slabs or in containers, followed by direct application on arable land. Softwood was predominantly used as bedding, and bedding accounted for a relatively small proportion (13%) of the total mix. Anaerobic digestion was indicated to reduce potential environmental impact in comparison to unmanaged composting, mainly due to biogas substituting use of fossil fuels. The relative environmental impact from transport of manure from horse facilities to anaerobic digestion plant was small. Results also indicate a relatively high cost for horse keepers to change from composting on site to anaerobic digestion in a centralized plant.

Keywords: horse manure; horse keeping; bioenergy; anaerobic digestion; nutrient recycling; systems perspective; Life Cycle Assessment (LCA); ORWARE; global warming potential (GWP); cumulative energy demand (CED); costs; bedding

1. Introduction

Lower energy use and reduced emissions of carbon dioxide are included in circular economy strategies (CES), as is re-use of raw materials currently handled as waste [1]. Anaerobic digestion is a waste-to-energy (WTE) technology supporting CES, where biological waste is converted to bioenergy and biofertilizer [2]. Nutrient recycling through organic fertilizers represents one step towards a circular economy as it turns waste management problems into economic opportunities. This also reduces dependence on imported phosphates [1]. Natural phosphorous and nitrogen cycles are identified in the planetary boundary framework, with thresholds society needs to manage in a global sustainable approach [3].

Environmental impact, and energy and nutrient recovery from horse manure, depends on collection practices, use of bedding material, manure storage and present manure usage [4].

Horses are to a great extent kept in peri-urban areas, the transition zone between urban and rural areas, where horse activities, like riding schools, are accessible to users situated in urban areas. In these areas horse activities are perceived as being in conflict with existing agriculture and new residential

areas [5,6]. High horse density (a large number of horses per hectare), in combination with horse manure stored and left in paddocks, increases the risk for contaminated surface run-off water [7], and dung removal practices are recommended but reported to be lacking in some studies [8,9].

Horse manure is a mixture consisting of horse dung, used bedding and urine soaked in the bedding. In Sweden horse keepers mainly use softwood shavings as bedding material [10]. Other studies mention straw, peat, hemp, and wood and straw pellets among bedding materials [11–13]. Added bedding material can increase the amount of nutrients in collected and treated horse manure, indicated for both composted horse manure, where peat increased nitrogen and straw increased potassium [12,14], and in anaerobic digestion simulations [15].

In general horse keepers in Sweden store horse manure on concrete slabs but approximately 25% of the horse keepers store horse manure on ground other than arable land [10]. Storing of horse manure with softwood bedding involves minor leakage of nitrogen to water in a managed, fast-composting process [16], while phosphorous has been found in run-off water to a greater extent from turned and static uncovered horse manure piles than from covered piles [14].

In Sweden horse manure is used as a soil improver or fertilizer to a great extent [10], but it is not commonly used for energy recovery, even if incineration and anaerobic digestion are mentioned in some studies [17–19]. Anaerobic digestion can potentially reduce the net environmental impact of horse manure management if the produced biogas replaces fossil fuels in vehicles [20]. Even if fossil fuels are used for transport and in the production process, a decrease of about 75% of greenhouse gases can be reached [21,22].

To enable energy recovery from horse manure by anaerobic digestion, transport of feedstock to a biogas plant is necessary. Transport is generally increasing and the EU aims to increase energy efficiency and use of renewables, and decarbonize the sector [23]. How environmental impact from transport could be reduced is presented in a White Paper [24] focusing on sustainable fuels and propulsion systems, and multimodal logistics using energy-efficient modes and systems. The expected net effect in the present case is that a limited use of transport can help achieve such goals through the production of renewable vehicle fuel from horse manure. Operational decisions like the type of truck used for transport, use of fuel, energy-efficient engines and strategic decisions about size and amount of shipments are among the logistical decisions linked to environmental impact [25].

Potential factors of importance for horse manure as a biogas feedstock are feeding, indoor housing, outdoor keeping, manure storage, fertilization and transport. These factors, identified in a previous study, influence horse manure amounts and characteristics [4]. Horse manure's methane potential is lower than that of food waste, for example, especially when softwood is used as bedding material [13]. A literature review by Hadin and Eriksson [15] indicates a wide range for horse manure methane potential: 56 L CH₄/kg VS for pure horse manure with no bedding material and 277 L CH₄/kg VS for horse manure and straw bedding [11,26]. Many digesters use food waste as a substrate, where the methane potential can range between 178 and 531 m³ CH₄/tonne VS [27,28]. Concerns about the moderate methane potential motivate this case study of anaerobic digestion, including the environmental and economic aspects of transport of horse manure. This study is based on site-specific data and adds a systems perspective on environmental and economic impact from collection of horse manure at horse keepers' sites, not previously studied [20]. This is also complementary to previously published research that discusses parts of the system, e.g., horse manure management, or biogas from horse manure, or transport systems [13,26,29–31]. In a systems perspective it is important that the benefits of anaerobic digestion are greater than the additional burden related to collection and transport.

The aim of the present case study was to describe a specific case of horse manure management practices and compare unmanaged composting with anaerobic digestion from an environmental and economic perspective. The objectives were to:

1. Describe horse keepers' current horse manure management practices (on site collection, storage and utilization) in a Swedish municipality and provide quantitative and qualitative data for a combined assessment.
2. Calculate the potential environmental impact of combined energy recovery and nutrient recycling through anaerobic digestion in a centralized plant, replacing unmanaged composting.
3. Explore economic consequences for horse keepers from a changed treatment.
4. Discuss how current manure management practice influence an altered treatment in relation to environmental impact and associated costs.

2. Materials and Methods

This study was inspired by an embedded single case study design where multiple units of analysis create the context of the case [32]. The case municipality has about 100,000 inhabitants and is located in the southeastern part of northern Sweden. Research activities used in the study differed between which part of the system was studied and the phase of the study (Table 1). A telephone questionnaire was used to explore horse manure amounts, characteristics and practices. The questionnaire was supported with study visits and field observations at three riding schools and one trotting race track. Distances for, and emissions from, manure transport and data for horse manure treatment were also part of the inventory (Table 1). Compilation and calculations of horse manure data were performed in MS Excel, while the horse manure treatment methods were simulated in ORWARE [33].

Table 1. Data collection structure and methods for the study.

Activities	Horse Keeping	Transport	Treatment
Inventory	Questionnaire Field observations	NTM emission data [34] Distances [35]	Data from [20]
Calculation	Compilation in Excel	Calculations in Excel	Simulations in ORWARE

2.1. Horse Keeping

Horse keepers chartered by the County Administrative Board and the municipal board were contacted by telephone and asked to answer questions about their horse manure management, e.g., generated amount of horse manure, type and amount of bedding, collection of horse manure outdoors, storage type and spreading of horse manure or other usage/handling (Figure A1 in Appendix A). Collected data were used to explore horse manure management in the case municipality and partly also to provide data (such as total amount of horse manure, content of bedding material and utilization of horse manure) for calculation/simulation of environmental impact from horse manure transport and treatment in the ORWARE model.

2.2. Transport

Transport of manure from horse facilities to a treatment plant was calculated based on the distribution of manure suppliers identified through the survey, and the corresponding amounts to be transported from each address. Transport distances were calculated based on the respondents' locations and the location of the expected anaerobic treatment facility. Transport energy and emissions to air were based on data from NTMCalc 4.0 [34], using Euro 5 vehicles and European diesel B5. The cargo load factor was set to 40% to incorporate one way almost full (80%) transport and one way empty transport of containers. A transport system consisting of trucks with cargo carrier capacity from 7.5 to 34 tonnes was theoretically constructed (Table 2).

Table 2. Constructed transport system in the systems analysis.

Vehicle Type Characteristics	Rigid Truck 7.5–12 t	Rigid Truck 14–20 t	Truck with Trailer 28–34 t
Average load (tonnes)	5	10	20
Cargo carrier capacity (tonnes)	6	12	22
Fuel consumption (L/km)	0.17	0.21	0.29
Distribution (%)	15	62	23

2.3. Treatment

The treatment of horse manure by composting and liquid anaerobic digestion has been examined using ORWARE [33], which is a computer model for simulation of different waste management strategies calculating environmental impact using an LCA (Life Cycle Assessment) approach based on material flow analysis (MFA). The model has been used repeatedly for evaluation of waste management policy and strategies [20,36–39]. In the anaerobic digestion submodel, the amount of biogas generated is dependent on the composition of different organic compounds such as fat, proteins, cellulose, hemicellulose, lignin and rapidly degradable carbohydrates, and the retention time (HRT). The digester temperature affects the degradation rate, i.e., mesophilic conditions produce less gas than thermophilic conditions for a given HRT. Part of the methane in the raw biogas (a mix of CH₄ and CO₂) is set exogenously for each organic compound and has been adjusted to meet the methane potential of horse manure, as found in the literature. Carbon that is not degraded to CH₄ or CO₂ is left in the biofertilizer. All nitrogen in the feedstock is found in the digestate and later separated into liquid and solid fractions. Both are used in agriculture. A more detailed description of the model can be found in [40]. With a few exceptions, the data on manure and process parameters in the simulations are consistent with the data presented in Eriksson et al. [20]. The model was adjusted to this specific case study with respect to actual manure amount, blending of bedding materials, share of digestate being utilized in field cultivation and choice of upgrading and utilization of biogas, thus omitting the general assumptions made in the previous study. The case was structured from horse keeper data reporting a specified amount of horse manure in combination with amount and type of bedding, cf. Table 3.

Table 3. Distribution of horse manure respondents across calculated distance to an expected liquid anaerobic digestion plant (L-AD).

Distance to Plant (km)	1–10	11–20	21–30	31–40	41–50	Sum
Number of horse keepers	5	11	17	13	14	60
Number of horses	91	71	231	56	38	487
Amount of manure (tonnes)	603	285	2751	315	225	4179

Two scenarios have been compared in the economic and environmental assessment (Figure 1). Scenario 1 refers to handling the horse manure according to business as usual (BAU), where unmanaged composting on or close to the site was chosen as the waste management method, presumably consistent with current practice. In the model simulations 74% of the compost from horse manure was applied to arable land, based on horse keeper responses. In Scenario 2 horse manure was transported from horse facilities to a central liquid anaerobic digestion plant using a container system. All biofertilizer and biogas from the plant was utilized. Considering the compensatory system, biogas from the plant was upgraded and used as fuel in Euro VI buses replacing fossil diesel buses [41]. The biofertilizer was subject to land application, substituting chemical fertilizer.

The environmental impact assessment, based on the life cycle inventory (LCI) from MS Excel (transport; Figure 1) and ORWARE (all processes except manure transport; Figure 1) was restricted to use of primary energy (cumulative energy demand, CED) and associated environmental impact categories; global warming potential (GWP), eutrophication potential (EP) and acidification potential

(AP), using the CML 2001 Baseline scenario [42]. CED is the summarized primary energy demand; i.e., all energy input recalculated as the energy content in natural resources such as oil, coal, biomass, etc. in the examined system, and constitutes an analysis of energy resource usage within the performed systems analysis. In the environmental impact assessment, emissions in the system are transferred and assigned to specific impact categories [43]. GWP represents the global warming potential from different greenhouse gases presented in the unit tonnes CO₂ equivalent. EP is the eutrophying emissions to air, soil and water in tonnes PO₄³ equivalent, and AP is the acidifying emissions to air with the unit tonnes SO₂ equivalent [42]. The base scenario was followed up by a sensitivity analysis of potentially important parameters including some with high uncertainty: amount of horse manure, bedding type, transport distances, vehicle type and fuel type. Based on the case data, the environmental impact was calculated for the highest and lowest amounts of horse manure, one bedding type at a time, and transport was changed in terms of different distances, use of larger or smaller trucks solely, or use of biodiesel Hydrotreated Vegetable Oil (HVO) instead of fossil diesel. As a last step, a simplistic economic analysis was performed including inventory and calculation of horse keeper costs for the storage, transport and treatment of horse manure.

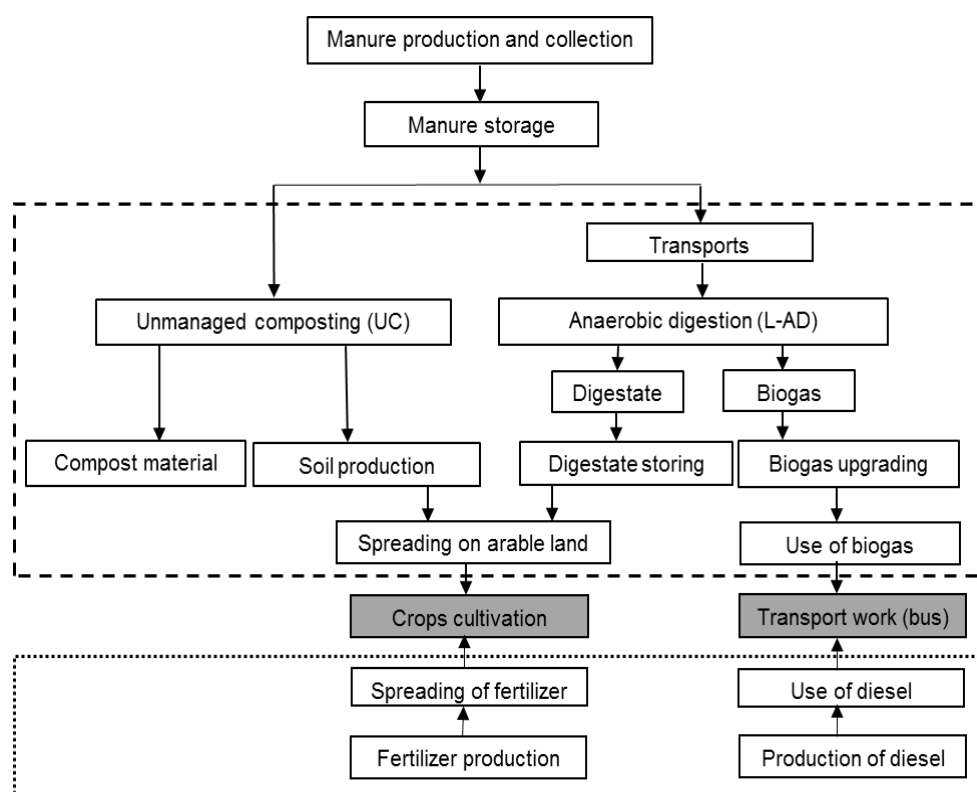


Figure 1. System description. The core system is represented by the dashed line and the compensatory system by a dotted line.

3. Results

The case consists of information from 81 horse-keeping sites (also referred to as horse facilities) located in the Swedish case municipality. These represent 623 horses in total, where 84% of keepers were in possession of ≤ 10 horses (Table 4). Statistics for Sweden (with high standard errors) estimate the number of horses in the actual county of 10 municipalities to be 11,700, with 51% located in urban areas and adjoining rural areas. In Sweden the average number of horses per site is 4.6 [44]. The total number of horses in the case municipality is hard to estimate based on available statistics, but is probably several times larger than the number covered in this study.

Table 4. Descriptive information about the survey.

Number of Horses	1–2	3–5	6–10	11–90	Sum
Number of horse keepers	29	34	5	13	81
Response (%)	36	42	6	16	100
Number of horses	57	117	36	410	623

Data from the questionnaire, related to manure management practices, were compiled in four groups based on the number of horses per respondent (1–2, 3–5, 6–10, and 11–90 horses). The groups' setup, i.e., the intervals for the number of horses kept at the sites, show similarities with the Swedish legislation about manure storage—Swedish Ordinance (1998:915) on environmental considerations in agriculture [45]—estimated statistics in Sweden [10] and groups in a case study performed in New Jersey [46].

3.1. Horse Manure Management Practices

3.1.1. On-Site Manure Collection

The type of housing affects the possibility of collecting horse manure and the amount of bedding. Most horse keepers in this study (69%) keep horses in stables, 15% use loose housing in combination with stables, and 15% use loose housing exclusively. One horse keeper (1%) uses paddocks to a great extent. The amount of manure collected was derived from the estimated (by the horse keepers) amount and calculated (by the authors); the range was between 2 tonnes per horse and year for loose housing, while for horses held in stables the estimated output is an average of 11 tonnes per horse and year. This difference is explained by (1) interpretation of horse keepers' information on collected manure amount and (2) the fact that manure collection is easier and more often performed when horses are kept stabled. Results on mucking regime are displayed in Figure 2.

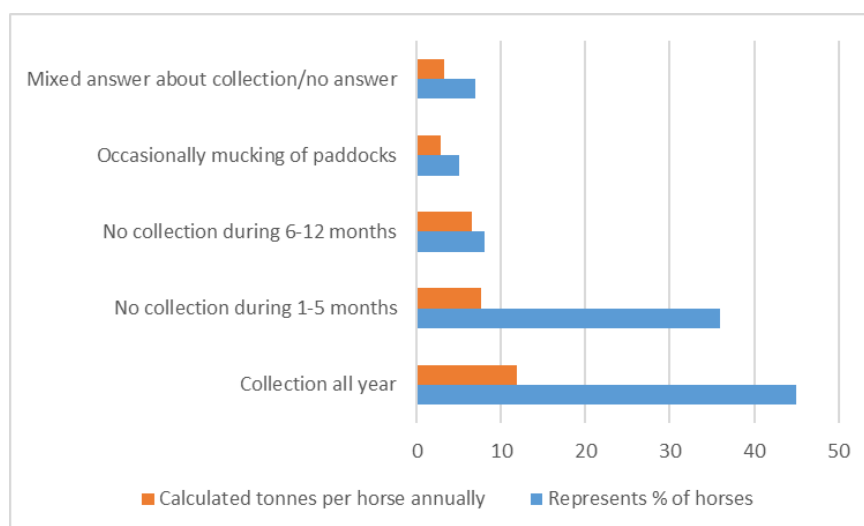
**Figure 2.** Mucking regime.

Figure 2 shows the percentage of horses in the case grouped into various time periods where horses are kept outside grazing/in pastures without collection of horse manure and calculations of corresponding total horse manure amount per horse and year. The results are compiled from 67 horse keepers with 502 horses. The annual amount of collected horse manure from the respondents was calculated to 3–12 tonnes per horse and year. Results indicate that most horse manure is collected year-round or most of the year, representing 74% of the total horse manure amount (Figure 2).

Occasional mucking outdoors is performed for 6% of the horses, while 7% of the horses are kept by horse keepers that do not muck outdoors for 6–12 months. A mix of collection/no answer represent four of these horse keepers and 51 horses.

3.1.2. Bedding Material

Table 5 depicts the use of different bedding materials in the case study. Calculated amounts of bedding indicate softwood to be the most common bedding, closely followed by peat and mixed bedding types. Different types of pellets are rarely used (called “other” in Table 5).

Table 5. Use of bedding materials.

Bedding	Horse Keepers	Horses	Horses (%)	kg Bedding/Horse, Year	Tonnes of Horse Manure/Horse, Year
Peat	19	64	10	892	8
Softwood	37	373	60	1228	11
Straw	3	7	1	1309	6
Other ⁽¹⁾	5	31	5	422	7
Bedding mix ⁽²⁾	16	143	23	750	3
No answer	1	3	1	-	-
Sum	81	623	100	-	-

⁽¹⁾ Straw pellets, wood pellets (stable pellets), paper cuttings, paper pellets. ⁽²⁾ Different mixes mentioned, for example peat and softwood bedding, straw and softwood bedding, peat and straw and wood or straw pellets.

Horse manure with softwood bedding adds up to 11 tonnes per horse and year, in comparison to 3 tonnes for a bedding mix (Table 5). The results should be interpreted to reflect the collected amount of horse manure (manure and used bedding), as opposed to the generated amount. The difference is related to the mucking regime and the separation ability of used bedding, fresh bedding and manure.

3.1.3. Manure Storage

Horse manure storage is characterized by facility designs for stockpiling on impervious surfaces like concrete storage slabs, containers or, for one respondent, storage in sacks. These storing facilities represent 78% of the horses and 73% of the horse keepers in the case (Table 6). There are 13 horse keepers in the case assigning manure stockpiling on site on ground, representing 16% of the horse keepers. Horse keepers with few horses most frequently use stockpiling on the ground, while only one horse keeper with 25 horses stores manure directly on the ground (Table 6).

Table 6. Different manure storage types distributed by groups of horses.

Horse Manure Storage Facility	1–2	3–5	6–10	11–90	Horses (%)	Keepers (%)
Stockpiling on ground	16	13	0	25	8.7	16
Concrete slab	24	48	21	275	59.1	46
Container	11	34	15	54	18.3	26
Other	4	22	0	56	13.2	10
Sack	2	0	0	0	0.3	1
No answer	0	3	0	0	0.5	1
Sum	57	120	36	410	100.0	100

3.1.4. Disposal of Composted Manure

About 40% of horse keepers responded that the composted manure is subject to soil application on other people’s agricultural land (Figure 3). Other management practices are, for example, soil production or unknown destiny. About 20% of the respondents report application on the horse keeper’s own agricultural land (Figure 2). Manure disposal at an off-site disposal plant (hauling to a specific

waste deposit plant) is reported by about 10% of the respondents. One horse keeper did not answer, representing three horses.

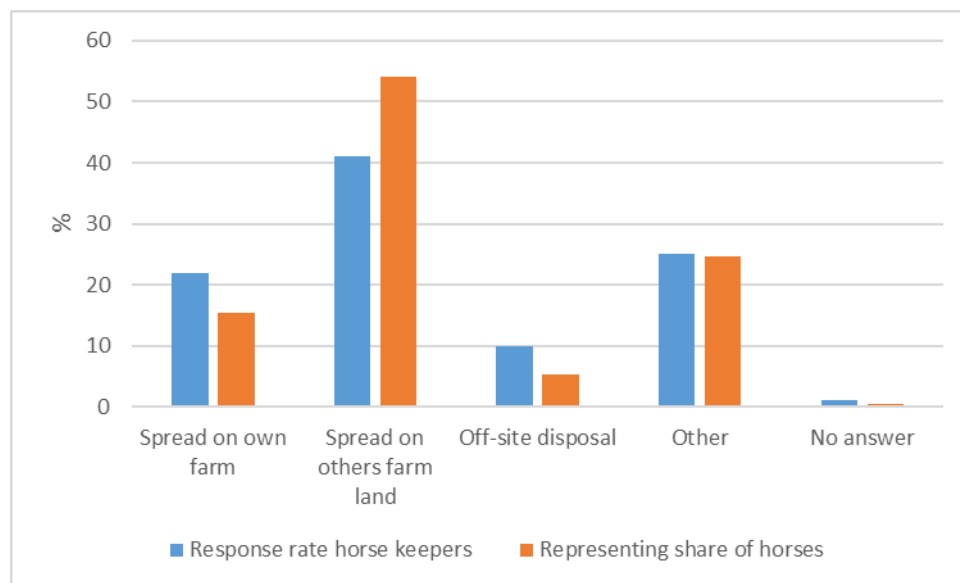


Figure 3. Distribution of respondents' horse manure management practices and the share of horses the practices represent.

The results in Figure 3 have also been analyzed in relation to the size of the horse facility, i.e., intervals of the number of horses held, cf. Table 7. Soil application on other people's agricultural land is frequent for all intervals (Table 7). One exception occurs in the horse keeper group with 6–10 horses, where other use (soil production and unknown use) is more common (60%). In the group with 1–2 horses, soil application is as common on own arable land as on other people's arable land.

Table 7. Distribution of use of horse manure within horse groups.

Spreading Practice (%)	1–2	3–5	6–10	11–90
Applied to own arable land	36	16	-	19
Applied to others' arable land	36	44	40	54
Off-site disposal	14	12	-	8
Other	14	25	60	19
No answer	0	3	0	0
Sum	100	100	100	100

3.2. Environmental Impact

The material flow analysis shows the inflow and outflow of resources in the systems analysis, as amounts of used and produced resources (Table 8), followed by environmental impact assessment in Sections 3.2.1, 3.2.2 and 3.3.1–3.3.3

Table 8. Major material and energy flows in the scenarios.

Material/Energy Flow	Scenario 1 (Unmanaged Composting)	Scenario 2 (Anaerobic Digestion)
Horse manure (tonnes)	4179	4179
Transport (tonne-km)	-	179,505
Compost (tonnes)	501	-
Biofertilizer (tonnes)	-	8033
Biogas (GJ)	-	5952

3.2.1. Relative Impact from Transport

The relative impact from transport of horse manure to and biofertilizer from the biogas plant is shown in Table 9.

Table 9. Transport's contribution to environmental impact in Scenario 2.

Environmental Impact Category	Total	Transport	%
CED (MWh)	788	264	34
GWP (tonnes CO ₂ -eq.)	56	67	120
AP (tonnes SO ₂ -eq.)	2.17	0.07	3
EP (tonnes PO ₄ ³⁻ -eq.)	1.56	0.05	3

Transport's relative contribution to acidification and eutrophication potential was minor, while transport's contribution to CED was considerable. For GWP the relative impact exceeds 100% due to the system total accounting of arable land as a sink for carbon in digestate not being degraded after a 100-year period (Table 9).

3.2.2. Overall Results

The environmental impacts for the two scenarios are summarized in Figure 4. Compared to unmanaged composting, anaerobic digestion results in lower environmental impact for all impact categories considered. In particular, GWP and CED are significantly lower for anaerobic digestion, resulting in net negative impact mainly due to avoided emissions when biogas substitutes for diesel in buses. In unmanaged composting horse manure decomposes in piles and is partly utilized as biofertilizer, and plant nutrients can to a higher degree be lost by surface run-off and as emissions to air, indicated a higher potential environmental impact from the compost process compared to the anaerobic digestion process.

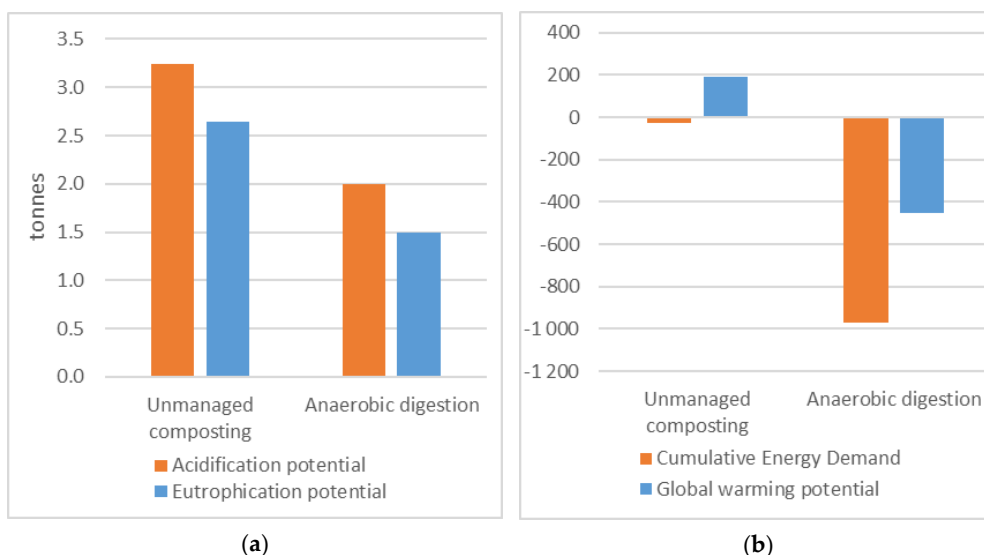


Figure 4. (a) Net acidification (tonnes SO₂-eq.) and eutrophication potential (tonnes PO₄³⁻-eq.) from manure treatment in unmanaged composting and anaerobic digestion; (b) net cumulative energy demand (MWh) and global warming potential (tonnes CO₂-eq.) from manure treatment in unmanaged composting and anaerobic digestion.

The subsequent figures have been included to understand the underlying explanations of the results. In Figures 5–8 the core system (waste management) is comprised of manure collection

(present in Scenario 2), treatment (composting or anaerobic digestion including field application of organic fertilizer) and transport (vehicle gas from upgrading facility to filling station, digestate from anaerobic digestion plant (AD) to spreading area). The compensatory system consists of the avoided conventional production of chemical fertilizer and diesel fuel.

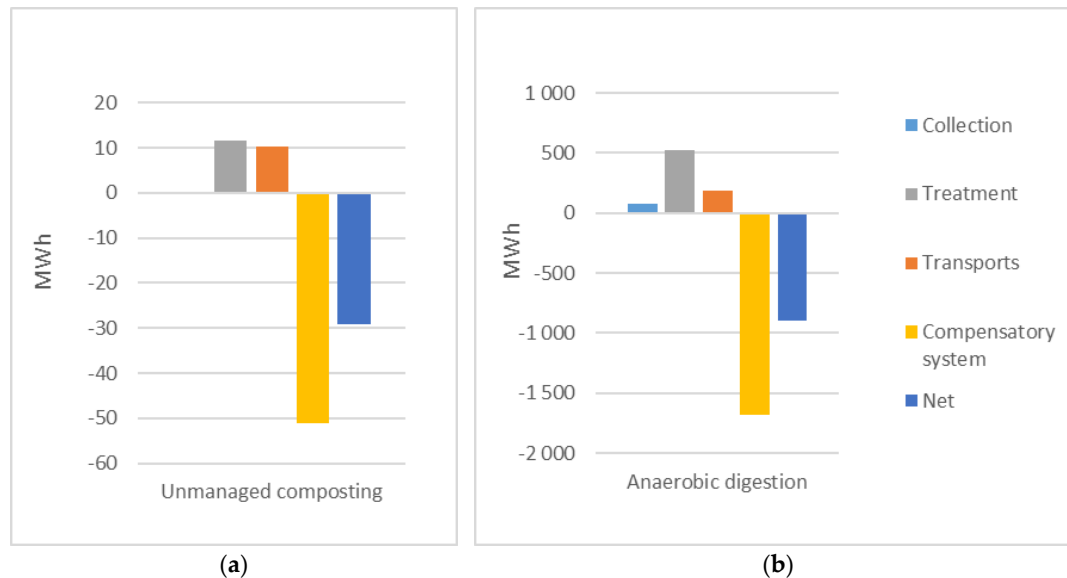


Figure 5. (a) Cumulative energy demand for Scenario 1 (unmanaged composting on site (no transport to treatment)); (b) cumulative energy demand for Scenario 2 (manure transport and anaerobic digestion).

The trend in CED (Figure 5) is similar for the two scenarios, but the magnitudes are much higher for anaerobic digestion. The sum of collection and transport in Scenario 2 vastly exceeds the total values for the composting scenario, but as savings from using fertilizer and vehicle fuel are even higher, the anaerobic digestion scenario indicates the largest savings (a factor of 30).

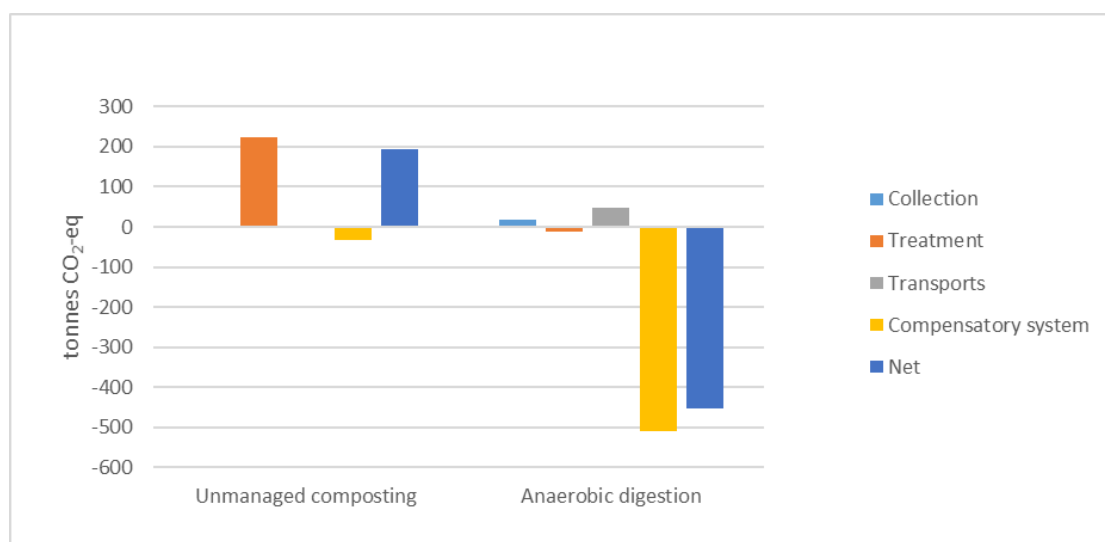


Figure 6. Global warming potential (tonnes CO₂-eq) of unmanaged composting (no transport to treatment) and anaerobic digestion with transport of the manure to the expected digestion plant.

In terms of global warming potential (Figure 6), unmanaged composting results in a net contribution to global warming potential from the composting process, mainly from methane formation in

the compost process [40]. Some minor savings are accounted for due to the carbon sink in arable land (organic/biogenic carbon is sequestered in the soil after a period of at least 100 years). For the anaerobic digestion scenario, emissions from collection and transport are minor and treatment actually adds to the negative contribution due to the carbon sink. Savings when biogas replaces diesel are extremely high, indicating AD as the best option.

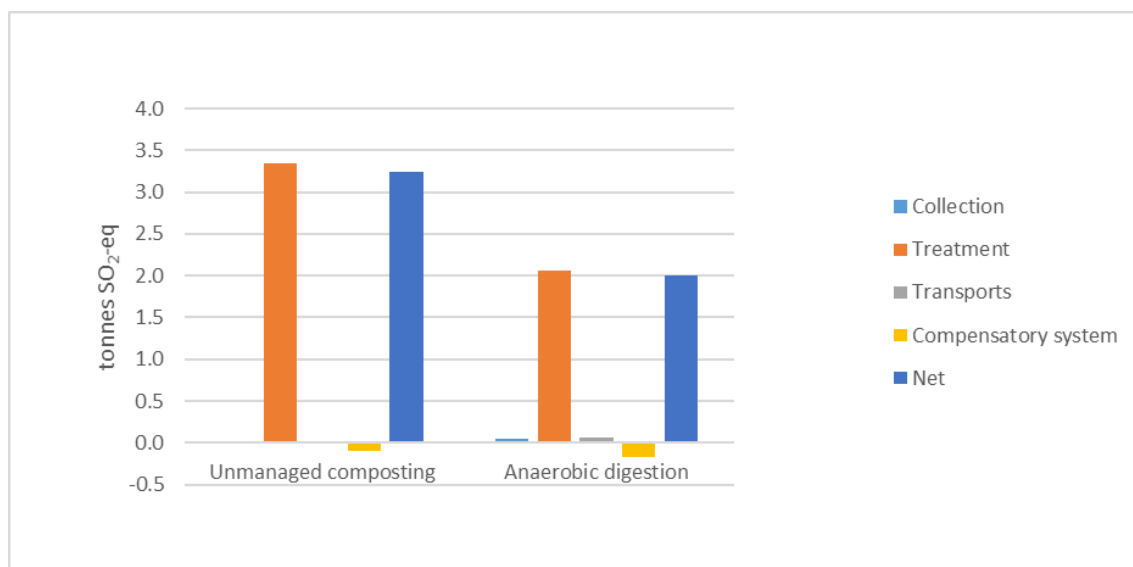


Figure 7. Acidification potential for unmanaged composting and anaerobic digestion divided into the processes and the net potential environmental impact.

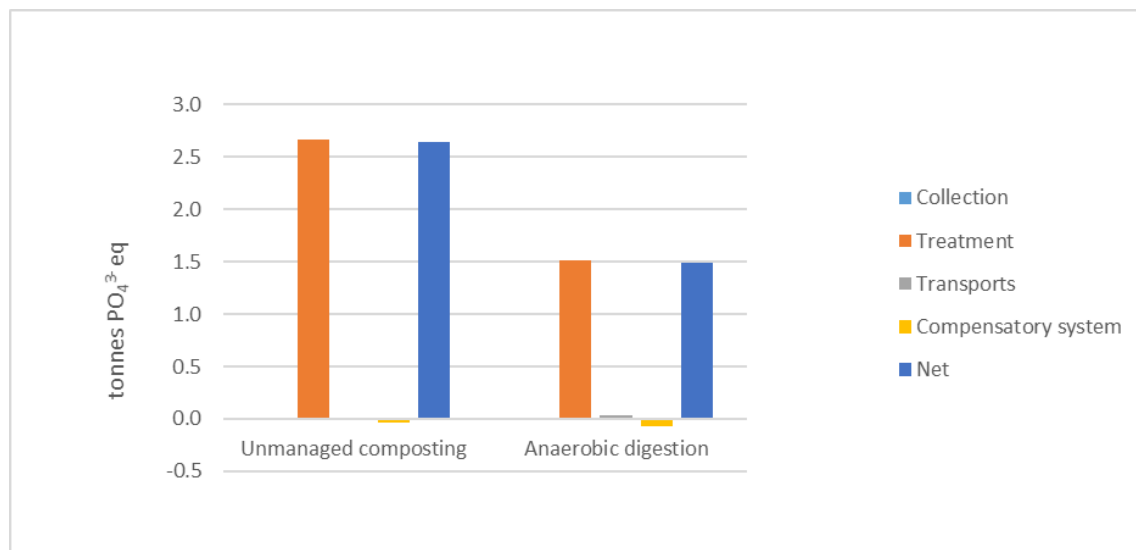


Figure 8. Eutrophication potential for unmanaged composting and anaerobic digestion divided into the processes and the net potential environmental impact.

Figures 7 and 8 show AP and EP for the scenarios, where AD performs better than composting due to lower NH_3 emissions from the main treatment process. Almost all contributing emissions in the AD scenario are found for biofertilizer application, where the model calculates energy consumption and emissions from spreading residues on fields [40].

3.3. Sensitivity Analysis

In the sensitivity analysis the importance of parameters associated with high uncertainty or variation have been investigated: manure amount, bedding type, transport distance, vehicle size and fuel type.

3.3.1. Manure Amount

Based on respondents' estimations, the average horse manure amount was calculated as 8.6 tonnes per horse and year. In the sensitivity analysis, the amount of horse manure produced was set to 3 or 12 tonnes per horse and year, based on reported variation in collected manure amounts at the case facilities. The change corresponded to 65% (2700 tonnes) less and 40% (1700 tonnes) more collected horse manure, respectively, compared to Scenario 2. These changes caused consequences for both transport and biogas production. Considering manure transport, the environmental impact decreased with less horse manure and increased for more. However, when also including treatment and substitution of fossil fuels for a lower amount of manure, EP and AP decreased while CED and GWP increased due to the lower amount of produced biogas to replace fossil fuels. For the higher amount of 12 tonnes per horse and year the results were the opposite, with increased acidification and eutrophication and decreased global warming potential and CED.

3.3.2. Bedding Type

The mix of softwood, straw, peat and other, which is constructed based on respondents' estimations, resulted in 529 tonnes of bedding material. In simulations other bedding material was defined as wood (pellets of wood), straw (pellets of straw) and waste paper (paper pellets or paper cuttings). In a sensitivity analysis, simulations were performed with softwood, straw, peat, and waste paper, one at a time. Results for cumulative energy demand are depicted in Figure 9.

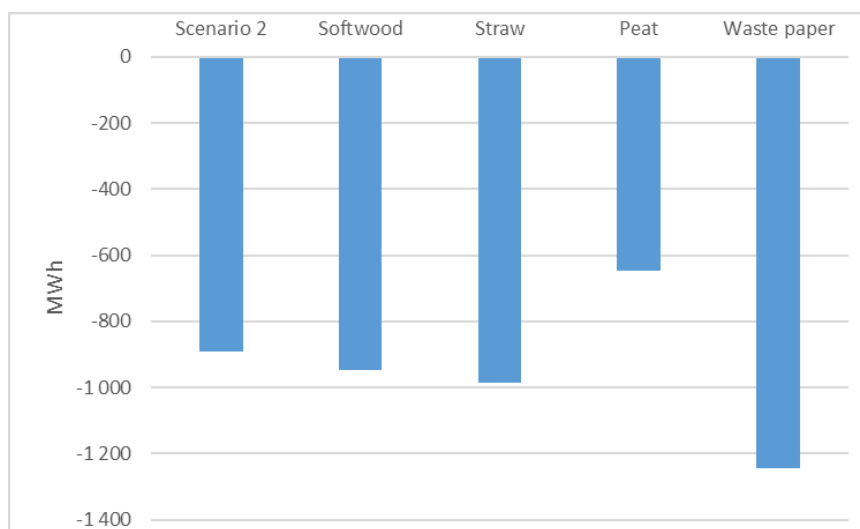


Figure 9. Cumulative energy demand for Scenario 2 and various bedding types.

The CED is negative (i.e., savings of primary energy), independent of bedding material. Softwood bedding is just slightly better than the bedding mix in Scenario 2 due to the high share of softwood in the bedding mix. Using waste paper as bedding leads to the highest savings of energy resources, while peat has poor performance—worse than the baseline scenario but still with net savings. The results confirm the results of a previous study on methane potential [15], where the most positive energy balance was indicated for waste paper, followed by straw, softwood and peat.

Air emissions contributing to AP and EP for various beddings are displayed in Figure 10a. The lowest impact is found when waste paper is used as the sole bedding material, whereas a change in any of the other bedding materials does not change much compared to Scenario 2. The global warming potential (Figure 10b) does not differ much in simulations of the different beddings, with values varying by approximately 10% compared to Scenario 2.

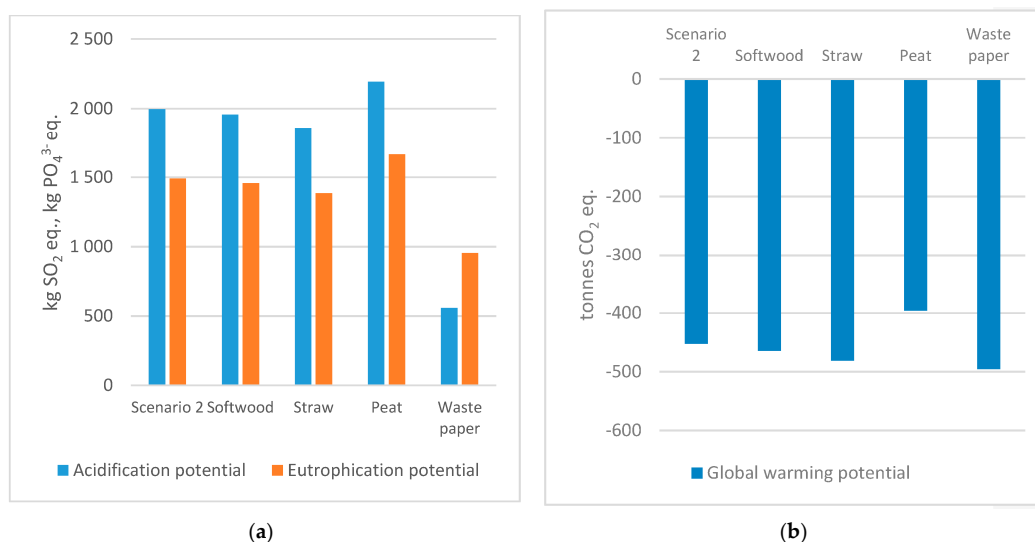


Figure 10. (a) Acidification and eutrophication potential for Scenario 2 and various beddings; (b) global warming potential for Scenario 2 and various beddings.

Simulations with single bedding materials for Scenario 1 (unmanaged composting) indicated a negative cumulative energy demand for all bedding types, ranging between -22 MWh for waste paper and -33 MWh for peat, to be compared with the bedding mix with -29 . Furthermore, simulations indicated that AP and EP increased for unmanaged composting when the bedding material was 100% peat, while waste paper, straw and softwood resulted in a lower potential environmental impact than for the bedding mix. Again, using 100% softwood bedding does not alter the baseline results much as it was a high share of the bedding mix. The composting sensitivity analysis indicated the highest GWP for waste paper, almost no change for softwood and lower for straw and peat, in comparison to the case bedding mix.

3.3.3. Transport Distance, Vehicle Size, and Fuel Type

In Scenario 2, the respondents' locations in relation to an expected anaerobic digestion plant resulted in a total distance of 1679 km. In the sensitivity analysis, the distance changed by $\pm 10\%$. The results then varied by ± 2 tonnes for GWP, ± 1 kg for EP, ± 4 kg for AP, and ± 8 MWh for CED. These are all minor changes. An additional analysis of the results shows that, in the case of anaerobic digestion and adjoining transport, the total transport distance could increase by 40 times before the same level of global warming potential would be reached as for unmanaged composting. This is well beyond the level of uncertainty regarding transport distance.

In the next sensitivity analysis, manure transport was assumed to be performed by smaller trucks (rigid truck, 7.5–12 tonnes). Using smaller trucks should increase transport work and thus environmental impact. When looking just at the potential environmental impact from transport, GWP emissions and CED increased by about 90%, whereas AP and EP emissions increased by 105% compared to Scenario 2 transport. When calculations were based solely on the larger truck type (truck with trailer, 28–34 tonnes), the potential environmental impact instead decreased by 10% for GWP and cumulative energy demand, and 16% and 18% for AP and EP, respectively.

In Scenario 2 European diesel B5 was used as the vehicle fuel for transporting manure to the plant (Table 8). In a sensitivity analysis the fuel was changed to HVO made from either waste cooking oil or palm oil, using data from [47]. The sensitivity analysis only comprised CED and GWP due to data scarcity. The analysis indicated that if waste cooking oil HVO is used, GWP from transport is reduced by 90% and CED is reduced by 86%. The use of palm oil HVO reduced GWP by 59% and CED by 4%.

3.4. Economic Assessment

The combined assessment also includes an economic assessment of horse manure treatments, based on the costs for the horse owner. The cost analysis was performed in a very simplistic way through an inventory of costs associated with (1) storage and composting on-site and (2) storage, collection and transport to an anaerobic digester. For the composting scenario, the manure is stored on a concrete plate in the vicinity of where the horses are held, and local farmers or private persons retrieve the compost. It is assumed that there are no associated costs with this baseline option, as the municipality places restrictions on the safe storage of manure and the utilization of compost means no cost for the horse owner. In a systems perspective these omitted costs are “hidden” costs but it is reasonable to exclude these if drivers and barriers for the horse owners are the focus. The biogas scenario comprises costs associated with a container solution for storage and collection/transport of the manure to the treatment facility and the reception fee at the AD plant. As container sizes of 10 or 22 m³ seem to dominate the market, costs are presented for both these options and for the whole case where these sizes have been applied. These containers are loaded with 5 and 10 tonnes of manure, respectively, which in combination with the annual manure amount determines how often manure is being collected. The reception fee is supposed to reflect the costs (investment, running and maintenance costs) of the main process and utilization of biofertilizer and biogas. In a systems perspective, either revenues for biogas and biofertilizer or avoided costs for fossil vehicle fuel and mineral fertilizer should be included. These are excluded using the horse owner perspective but is still indicated to show the societal benefits. The cost inventory is found in Table 10 and the costs for Scenario 2 are found in Table 11.

Table 10. Cost inventory (1 € = 9.71 SEK).

Cost Analysis	Composting	Anaerobic Digestion	Comment/Unit	Refs.
Storing on site	0	371	Rent of a 10 m ³ container, SEK/month	[48]
		1061	Rent of a 22 m ³ container, SEK/month	[48]
		342	Rent of a container, SEK/month	[49]
Transport	0	1219	SEK/container retrieved	[48]
		891	SEK/tonne	[49]
		109	SEK/tonne	[50]
Treatment	379	350	SEK/tonne	[48,51]
	183	−100–550	SEK/tonne	[50,52]
Spreading	-	95	SEK/tonne	[50]

Renting a 22 m³ container is more expensive than a 10 m³ container when calculated per volume and month or per tonne and month (maximum loads are 5 and 10 tonnes, respectively) [48]. The rent presented in [49] probably refers to a 10 m³ container. Costs for collection vary vastly between different references. This may be due to the fact that container services to minor customers/private persons can be considered minor isolated markets with few stakeholders. This also holds for treatment where reception fees vary a lot; in one study the gate fee is calculated to vary from −100 SEK/ton to 500 SEK/ton depending on financial support and sanitation requirements [52].

In Table 11 two examples are shown, 18 and 64 annual metric tonnes, respectively, which—using 8.6 tonnes manure/horse, year (found in the case study)—correspond to two or seven horses.

The lower figure reflects the median amount in the case, whereas the higher figure is the average value. Calculations are made based on data from Table 10 following references in Table 11.

Table 11. Cost analysis for different container sizes and applied to case (1 € = 9.71 SEK).

Cost Analysis	10 m ³ Container	22 m ³ Container	Case	Unit	Ref.
Storing on site	4452	12,732	867,648	SEK/annum	[48]
Transport	-	-	513,077	SEK/annum	[48]
Treatment	-	-	1,562,650	SEK/annum	[51]
Total	-	-	2,843,375	SEK/annum	
	-	-	681	SEK/tonne	
	-	-	5839	SEK/horse	
Transport, 18 tonnes	4388	2194		SEK/annum	
Treatment, 18 tonnes	6300	6300	-	SEK/annum	
Total, 18 tonnes	15,140	21,226	-	SEK/annum	
	841	1179	-	SEK/tonne	
	7234	10,141	-	SEK/horse	
Transport, 64 tonnes	15,603	7802		SEK/annum	
Treatment, 64 tonnes	22,400	22,400	-	SEK/annum	
Total, 64 tonnes	42,455	42,934	-	SEK/annum	
	663	671	-	SEK/tonne	
	5705	5769	-	SEK/horse	

Choosing the 10 m³ alternative means a moderate cost for storing, but with a smaller container the manure has to be collected more often, leading to a higher collection cost. The 22 m³ alternative is the other way round. For small horse facilities with two horses, the total cost varies considerably between the two container solutions. For the seven-horse case, the total cost is independent of container size.

From a horse owner's perspective the cost per horse and year could be seen in relation to the cost for fodder, which is roughly 7000–10,000 SEK/year (own calculations). From a societal perspective, this cost should be seen in relation to the benefit created, i.e., vehicle fuel and plant nutrients. With a vehicle gas price of 19 SEK/kg, the market value of biogas is approximately 2 MSEK. The value of the biofertilizer is somewhat more complicated to determine as some is mixed into plant soil, some is used by farmers for soil improvement where the market value is hard to determine, and some may be sold to private persons. One way to assess the value of biofertilizer is to account for the content of NPK and the avoided cost for mineral fertilizer. According to our estimations, the market value of the nitrogen and phosphorous content is approximately 0.1 MSEK.

Supply chain costs for horse manure in Sweden have been calculated by Svanberg et al. [31]. The case study results in Table 11 have been translated into euros, and compared to Svanberg et al. in Table 12. The costs in the case study are much higher than in Svanberg et al., mainly due to higher costs for container rent.

Table 12. Comparison of results.

Cost Analysis	Svanberg et al. [31]	Case Study	Unit
Container rent	35–60	38–109	€ per month
Transport	60–360	126	€ per transport
Reception fee	25–40	36	€ per tonne
Total	100–400	601	€ per horse, year
	12–47	70	€ per tonne

4. Discussion

4.1. On Site Manure Management

Methane production is different depending on the type of bedding material. Methane potential is crucial as the more methane that is produced, the more fossil fuels can be replaced by biogas. The best material to digest according to the simulations is waste paper, which has the lowest environmental impact; straw is also competitive, having the lowest CED.

Treatment of horse manure away from horse keeping sites requires manure collection both outdoors and indoors and storage in containers, or on concrete slabs followed by loading in containers. In this exploratory case study, most horse keepers collect horse manure left outside all year or for parts of the year, which could coincide with a grazing period or time in paddocks. This mucking regime creates a good opportunity for energy utilization as it already involves collection before transportation to a biogas plant. It should, however, be noted that outdoor collection increases the amount of collected manure without bedding material but also increases the risk of solid impurities. Sensitivity analysis summarizing environmental impact from transport and AD process indicates a reduction of GWP and CED with increased amount of horse manure, while other environmental impact categories (AP and EP) increase with a higher amount of horse manure.

Despite storage on the ground being indicated, mostly by horse keepers with few horses, horse manure was mostly stored on impervious surfaces. Storage in containers and concrete slabs was apparent to a greater extent in the case municipality than in Swedish statistics [10].

4.2. Manure Transport

Treatment of horse manure in a central anaerobic digestion plant requires manure transport, which is facilitated by a container system. The proposed transport system was already familiar to several horse keepers in the case as manure is either directly collected in containers, or temporarily stored on concrete slabs and then removed. Transport is a prerequisite for anaerobic digestion of manure, which adds environmental impact to the AD system, but also increases the amount of substrate available for biogas production and fertilizer production. In terms of GWP, the emissions avoided when biogas replaces diesel and biofertilizer replaces fertilizer are about 10 times greater than the emissions from transporting the manure to the plant. The AD process, including biofertilizer application on arable land, makes a negative contribution to GWP as it works as a carbon sink. The GWP impact from digestate application is larger than that of spreading composted horse manure due to (1) the higher content of water in the digestate, causing higher emissions from digestate transport and (2) less carbon left in the residue as most of the carbon has been converted to biogas. The sensitivity analyses of manure transport show that the impact from transport can increase significantly before the total impact equals the impact from unmanaged composting. A sensitivity analysis of transport also reflects logistical strategic decisions like use of fuel and what trucks to use for transport [25]. The sensitivity analysis indicated a large decrease of environmental impact from transport if HVO replaced diesel, pointing at improvement potential in choice of fuel for the necessary transport for energy recovery. Furthermore, a lower environmental impact is obtained for transport with larger trucks, due to the higher cargo capacity. A positive effect on environmental impact from less frequent and larger transport is also presented by Aronsson and Brodin [25]. Choice of fuel and type of vehicle are aspects of the efficient collection of horse manure, and decisions about this are part of the planning that would have to take place if a transport system for horse manure was implemented. Choice of trucks comprises not only the loading capacity but also assessment of road viability for heavy trucks and loads, and therefore a mix of lighter and heavier trucks is more probable than sole use of the largest trucks.

4.3. Environmental Impact

Simulations indicated horse manure treatment in AD with associated transport to reduce environmental impact for all categories; while CED and GWP are decreased (net savings) in

the anaerobic system, AP and EP still have a net contribution. In simulations, environmental impact from unmanaged composting was 70% higher for EP and 50% higher for AP. Unmanaged composting is resource-efficient as it only reaches 3% of the CED for AD. For GWP unmanaged composting has a net contribution, while AD leads to double the savings. Anaerobic digestion uses energy in the processes (for example upgrading, heating, and stirring), but contributes to the change from fossil fuels to renewable fuels for transport, thereby reducing the total potential environmental impact from the system according to simulations and calculations.

4.4. Biofertilizer Application and Nutrient Recycling

A change from compost to digestate in terms of application on arable land has some implications as solely solid manure is converted to a liquid digestate when using a liquid anaerobic digestion plant. This may affect where plant nutrients are being spread, depending on machinery and the need for plant nutrients in the area of an expected biogas plant. Most horse keepers use softwood for bedding, which corresponds to estimated Swedish statistics [10]. The use of softwood is also positive for low nitrogen leakage and run-off, which are also affected by turning and cover of compost [14,16]. Whether or not horse keepers turn or cover their manure piles was not investigated in this case, but it was noticed that turning of compost to facilitate degradability was mentioned by a couple of horse keepers. There seems to be a high level of nutrient recycling in the BAU scenario as most horse keepers in the case spread horse manure on others' or their own arable land. There is a strengthened need for cooperation between farmers and horse keepers to close natural cycles of plant nutrients based on the findings in the case. Other recycling systems described in the case were horse manure turned into soil, composted, and collected by households for gardening. Nutrient recycling is beneficial for the business-as-usual scenario as scarce plant nutrients are currently recycled, but also for a future system where horse manure is subject to energy recovery before the biofertilizer is spread on arable land.

4.5. Cost Assessment

The major benefit of the cost assessment is that it puts expected manure management costs for the horse keeper in perspective against the other costs associated with horse keeping, and also in relation to the benefits for society. The major drawback of the present assessment is that it is incomplete; it does not sum up all costs for the life cycle of either unmanaged composting or anaerobic digestion, and it does not include environmental costs. Furthermore, it does not point to cash flow for different stakeholders in the value chain and thus cannot be used to make any predictions on effective policy instruments. Most horse keepers are private people with few horses, and their willingness to pay is uncertain. However, some of the horse facilities with many horses exist on a commercial basis and may have the ability to take on increased costs. Such differences in raw material supply must be addressed when improving the cost assessment. By expansion of the cost assessment, comprising a higher level of detail, different policy measures such as tighter regulations on environmental permits for horse keeping, subsidy for reduction of methane leakage, or producer responsibility on horse manure could be evaluated. Also, other measures would be of interest in order to affect the pricing of horse manure as a renewable resource. For example, increasing the demand for (and the price of) biogas could lead to lower reception fees at the biogas plant, and horse manure can also be made more attractive as a substrate by different measures in horse keeping, such as enhanced medicine control and optimization of bedding practices.

4.6. Uncertainties

Answers in the questionnaire have been the basis for calculations of total amounts of horse manure and collected amounts of horse manure. Interpretations of horse keeper answers were necessary and sometimes assumptions about amounts of bedding and horse manure were made. Even accounting for such uncertainty, the case illustrates horse manure characteristics and aspects of horse manure management of importance for energy recovery.

In a previous paper [4], potential factors of importance in horse manure management were identified. Examples of factors not included in the questionnaire were feeding practices, soil conditions, spreading method, and time of storage. Horse keeper estimations of horse manure amount are assumed to cover the fact that feeding affects the amount and content of produced horse manure. The aspects of spreading method and time of storage are taken into account in the ORWARE simulations as emissions to air and water from unmanaged composting and anaerobic digestion and emissions from application of compost and digestate on arable land.

In Scenario 1 (unmanaged composting) no transport of manure was included, as composting is assumed to be located at the horse keeping site, representing one of the differences between treatment methods identified in earlier studies and visualized in this study. A liquid anaerobic digestion process was used in simulations due to a lack of reliable data on a dry anaerobic process, thus a possible difference in processes is not investigated in this study.

5. Conclusions

The case study contributed with real data on horse manure management practices and related environmental and economic impact. Some of the major findings are:

- Horse manure management in the case is characterized by collection of horse manure most of the year and storage on concrete slabs or in containers followed by spreading on agricultural land;
- Bedding material, most often softwood, is a minor component of the manure mix;
- Anaerobic digestion reduces the potential environmental impact in comparison to unmanaged composting;
- Transport constitutes an increase in potential environmental impact that is lower than the reduced potential environmental impact to which anaerobic digestion contributes;
- Horse keeper costs for manure management will increase for anaerobic digestion as compared to unmanaged composting on site;
- The costs of manure management are of the same magnitude as feeding costs.

Due to the conclusion that environmental impact is reduced if horse manure is transported to an expected biogas plant, further research could address energy companies' willingness to use horse manure as a biogas feedstock. Depending on their answers, continued research might consider horse keepers' willingness to adapt to energy companies' requests to, for example, change bedding or perform thorough sorting at the site to ensure good quality of feedstock.

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Appendix A

Main question and supplementary questions
1 How many horses are held at the property?
2 What kind/which kinds of stabling are used?
<ul style="list-style-type: none"> Do you keep horses in stables, loose housing or other? During which time period are horses stabled or kept in loose housing?
3 For how long are horses kept outdoors, in pasture, grazing without collection of horse manure for storage or use?
4 What kind of bedding do you use?
<ul style="list-style-type: none"> How much bedding of different kinds are used (distribution between different beddings)? Peat, straw, softwood shavings, other (volume/weight amount per year or week)?
5 How much manure do the horses produce annually (volume/weight)? Please estimate if it corresponds to an annual number of
<ul style="list-style-type: none"> Containers Lorries Trailers Tractor buckets Wheelbarrows per day Other, what?
6 How is manure stored?
<ul style="list-style-type: none"> In a pile on the ground On a concrete slab In a container On agricultural land In sacks Other; if so, what ways?
7 How is manure utilised?
<ul style="list-style-type: none"> It is applied on keeper's own agricultural land It is applied on other people's agricultural land It is transported to a specific waste management plant Other way/ways, what?
8 Do you want to provide any other relevant information about horse manure management?
9 Can we contact you again for optional further questions?

Figure A1. Questions in the telephone questionnaire to horse keepers.

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