Horse Stall Waste: Amounts, Management, Bioenergy Generation

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Abstract—**The contemporary equine sector is market-driven, highly diverse, and of significant economic importance in the EU and elsewhere. Considerable distance to traditional agriculture is one of its main characteristics. Nevertheless, horse manure is a valuable resource for application as organic soil amendment and for renewable energy generation. Due to utilization of different bedding materials and different management, horse manure varies widely with view to generated quantities and contents. This study aims to evaluate the challenges related to valorization of horse manure and to identify the most promising options for increased utilization especially for bioenergy generation. Anaerobic digestion and thermal treatment are currently the two key options that hold potential for more widespread implementation in practice.**

Keywords- horse manure; horse dung; equine residues; bioenergy

I. INTRODUCTION

Today, in industrialized countries horses are widely domesticated, and are now mainly used in sport and leisure activities. A large number of people are highly engaged in the equine industry around the world, and especially in industrialized countries. For example, in the USA about 4.6 million people are directly involved in the equine industry [1], and the horse industry had a direct economic impact of 39 thousand million $ on the economy in the year 2005, based on a horse population of 9.2 million [2]. In Germany, assessments indicate a horse population of around 1.2 million, which means an increase of a factor 4 in the past 40 years, and which provides labor for around 300,000 people generating a turnover of more than 5 thousand million EUR in the year 2012 [3]. In Sweden, the industry provides full-time employment to over 30,000 people, with increasing importance [1] [4]. The worldwide horse population has been estimated with 60 million animals in the year 2012 [3]. When taking the example of Germany as a reference, in which 3 to 4 horses generate one full-time employment [3] (for UK, US, Sweden, Austria data, see e.g. [5]), it can be estimated, that the global equine sector contributes to 15 to 20 million full-time employments. In Europe (EU27) alone, the horse population amounts to around 5 to 6 million, with the highest total numbers in Germany, UK and France, then followed by Spain, the Netherlands and Poland, while Sweden, Belgium and Denmark have the highest per capita numbers [4] [5]. According to studies from the Netherlands, UK and Sweden, the equestrian sector generates a direct turnover of 1,100 to 2,800 EUR per year per horse [6].

The equine sector has undergone a huge transformation mainly in the second half of the last century. Key tasks of horses in the 1950s have today been taken over by tractors and machinery, but despite this, the total number of horses has increased instead of decreased, while animals have been kept more and more for recreation and sports. Equine activities are among the few growing and most promising industries in rural areas of the EU today. In contrast to main agricultural sectors which are heavily subsidized, the current equine sector is market-driven with very little or no government intervention, and, among others, engages a peculiarly high number of women entrepreneurs and employees [6].

Based on EU data, higher density of horse population occurs in regions with higher consumption level, higher level of education and low unemployment rates [5]. There is often and with an increasing trend a close relationship between horse keeping and proximity to urban population, which reflects that today's equine sector is mainly the result of urban consumer interest [6] [7] [8] [9]. At the same time, equine operation can be in conflict with acceptance by the local inhabitants and with environmentally acceptable practices, in which the following reasons are relevant: surface run-off waters from paddocks and manure storage, aesthetic questions, smells and attraction of insects and rodents [8]. Unlike to other animal manures, it is quite common that at the place of generation of horse manure there is not sufficient capacity or a lack of infrastructure for its treatment. Furthermore, unlike to other animal keeping, closing material loops on site has been and is less in focus. This results into a disposal problem and in necessary transports, and can entail considerable costs. In this, management of horse manure resembles to the challenges of other organic residues generated in urban contexts, such as sewage sludge or urban biowaste.

The activities of the modern equine sector have resulted in the fact that the majority of horses are now being housed, and mainly in box stalls. Over 90% of all horses in northern and central Germany are stabled in boxes, with an average surface area of approximately 12 m² per horse [10] (referring to literature and studies). Many horses spend the majority of their time in their stall, which can easily be up to 23 hours per day. Leisure riding horses generally spend more time outside e.g. grazing, while racing horses spend most of their life in the stall [11]. The time in the stall also varies between different regions and can be significantly dependent of the season. In northern European countries such as Sweden, horses spend considerably more time in the stable during autumn and winter [12].

Because the equine respiratory tract is very sensitive, inappropriate housing can cause severe diseases. Keeping the stall dry and clean is a prerequisite for animal health and well-being. Among others, type and application of bedding material is crucial to maintain the necessary air quality and hygiene. Choice of bedding material depends on several factors:

- It should be easily and continuously available.
- It should be low in cost.
- It should be easy to use and allow for rapid and resource efficient cleaning.
- It should ensure a healthy environment, which includes that material is dust free, offers a high water binding capacity, and limits formation of gaseous ammonia.
- Resulting manure should be fit for easy and economically viable management.

Straw (e.g. wheat or rye) is the most frequently used bedding material in the world, either in direct use or as pellets. Numerous types of alternative bedding materials are in use, such as wood shavings, sawdust, recycled and chopped paper, peat, flax, hemp and linen shives (residues of lignified plant parts produced during hemp/linen fiber preparation). Conditioned materials such as straw pellets, hemp, linen, wood shavings are in general more expensive than straw, and in addition the disposal of the residue might be more problematic, in particular in urban areas [10]. Dedusted materials are therefore often used for specifically sensitive horses or specific fields of the equine sector. In some regions (e.g. northern Sweden), utilization of wood shavings is most common due to great accessibility, whereas straw is less easily available [4].

Used bedding material in mixture with horse manure needs to be removed regularly in order to maintain a hygienic environment for people working in the stable and for animals. Handling of spent horse stall bedding in mixture with solid manure is an issue of increasing concern for equine facilities due to associated costs and environmental attention. At the same time, horse manure has potential to be used for energy generation or for other valuable products. This requires a precise understanding of the characteristics of the material, knowledge about available amounts, and an assessment of suitable treatment technology. This study provides an overview on challenges related to horse manure handling and highlights the most suitable renewable energy generation technologies.

II. Amounts of Horse Manure

Removal of stall waste generates significant amounts of organic material, which depends on stall management and on chosen bedding material. Practicing complete daily mucking-out generates a much higher quantity of spent material compared e.g. to a 14-day deep litter practice, in which new bedding material is added each day without removing the existent one. In practice, the feces are often removed daily in order to reduce odors nuisance and noxious gasses [13].

It is difficult to obtain detailed data on generation of horse stall waste. One horse itself (à 454 kg) produces on average 17 kg feces and 9 L urine per day (see [14], citing literature). The following figures provide an idea of the horse manure amounts (including bedding material) collected in selected countries:

- USA: $27.6*10^6$ Mg/a [15] (which however is not fully in agreement with below mentioned average figure)
- Germany: $8*10^6$ Mg/a collected from stables (year 2008, see [13], based on data provided by the German Equestrian Association)

On average, one horse produces 8 to 14 Mg of collectable wet manure including bedding material [2] [9]. From previously mentioned data it can therefore be deducted that global annual horse manure production is between $500*10^6$ and $800*10^6$ Mg/a. It can further be deducted that in Europe alone, annual horse stall waste generation can be assumed to amount to a total of 40 to 70 million Mg/a.

Around a quarter to a third of the total wet weight of final manure stems from the bedding material [2] [14]. When looking at the volumes, these relations are different, since the bedding materials typically show low density and therefore have decisive influence on the generated volumes.

On average, manure including bedding from one horse typically accumulates to a volumetric rate of around 0.06 m³ per day [9]. However, horse manure based on straw was noticed to result in up to about twice as much volume as manure with other bedding materials (see Table 1), when stall cleaning was processed in the same way [16] (focus was put on avoiding all removal of clean bedding). Below data provide an indication of minimum to expected amounts, but it needs to be kept in mind that amounts will be higher if clean bedding material will be removed during the cleaning of box stalls.

TABLE I. Amount of Horse Manure when Different Bedding Materials were used in Box Stalls (Daily Removal of Feces and Bedding with Urine, while all Clean Bedding left in Place) [16]

Bedding material	Annual amount of manure [m³/(horse*a)]	Dry matter [%]	Total content weight [kg/m³]
Long straw (cut to 10 cm strips)	19.5	36.8	170
Wood chips	12.4	27.0	480
Peat with sawdust (mixture 3:1)	12.4	26.4	440
Shredded newspaper	11.7	32.5	410
Peat with straw (mixture 3:1)	11.7	28.9	410
Peat	9.8	23.7	600
Peat with wood chips (mixture 3:1)	9.1	28.8	440
Hemp	9.1	35.3	340

Storage of removed manure influences the characteristics of the material, and depending on conditions and duration, this can significantly alter dry matter content and weight content, while contents of nutrients such as phosphorus and potassium might undergo fewer changes [16]. Due to associated costs and environmental concerns, storage time should be as short as possible, but many sites practice considerable storage. In Nordic climates (e.g. Sweden), the storage of manure must be done for up to nine months of the year in order to sustain the chain of manure to agricultural field [16].

III. Waste Management Practices

As highlighted above, huge amounts of horse manure are generated each year. In some regions, generation of horse manure is higher than all other agricultural waste combined (e.g. New Jersey [14] [17]). The following options for handling the manure exist:

- Recycling to agricultural land, either through direct spreading or after composting or anaerobic treatment
- Combustion or other thermal treatment
- Delivery to landfill
- Usages for specific purposes such as delivery to mushroom cultivation sites, soil production for pepper cultivation [18], or soil production for lawns

Treatment on site reduces otherwise necessary transport, which would increase costs and burdens to the environment. However, many horse keepers do neither have the necessary arable land for spreading the manure nor treatment equipment for alternative processing, and many horse owners have significant problems to get rid of the residues to reasonable costs. In Germany for example, most horses are to be found in the regions with the least agricultural land [19].

In many countries, horse manure as organic material has been fully diverted from landfill by legislative restrictions, or high taxes have made this option economically unviable. In Germany, horse manure is mainly used in agriculture on field [13], as well as in the USA, and this is worldwide the most common option. However, this management also means that environmentally relevant substances such as nitrate, nitrite and ammonia in the leachate can pose risks on the ecosystems related to the soil (acidification of soil, water pollution, eutrophication). Especially in the short term following application, nutrients and organic matter are susceptible to transport by runoff, whereas in the longer term leaching of especially nitrate is a key issue [7]. In particular in the last two decades composting has gained high popularity as effect of growing environmental concerns within the equine sector and legislative restrictions with view to landfill disposal.

In some regions, it is still common that many private horse owners and stable managers place the manure in dumpsters or stockpile it to allow decomposition on its own, while others prefer to spread the manure directly onto their fields without composting [9] [17]. Direct spreading of horse manure without further treatment has a series of advantages such as killing pathogens by exposure to direct sunlight and drying, but it has distinct negative effects such as increasing the loss of nitrogen through volatilization, leaching and runoff, and limited blending with the soil (see [9]). Application of horse manure to agricultural land is beneficial for the soil (e.g. for crop production) [20] [21] [22]. In addition to supplying nutrients, the organic matter input improves physical soil conditions, replenishes soil organic matter and stops degradation of favorable soil aggregation structures, improves water holding capacity, and stimulates microbial activity. Compared to other animal manures, untreated horse manure (straw-based) has been shown to have a smaller fraction of easily decomposable organic carbon, a smaller amount of nitrogen and a high amount of fibers [20], which limits short-term losses, but does not eliminate possible burdens to the environment.

Composting reduces the negative environmental effects and (if properly done) transforms the material into a very useful, stable, odorless and pathogen-free product, while at the same time achieves mass or bulk reduction [9] [23]. Composting has now become a well-known and accepted method to treat horse manure, and is especially viable if arable land is available in the vicinity or if market-demand for compost is high. Mono composting, and co-composting with other organic substrates, and in particular with other wastes from urban areas (such as pruning waste from maintaining parks and gardens, biowaste), have been demonstrated to be well feasible and advantageous processes [23] [24] [25] [26] [27] [28]. However, in some cases problems can arise depending mainly on the nature of the bedding material contained in the manure, and in particular related to the existent C:N ratio [9]. The ideal C:N ratio for composting is around 25:1 to 30:1. Horse manure itself has an excellent carbon to nitrogen ratio exactly at this level [8] [9], but the bedding material is deficient in nitrogen (e.g. C:N ratio paper 772:1, sawdust 442:1, wheat straw 127:1 [9]).

Management practices might therefore have a decisive influence on compostability of the stall waste. Complete daily cleaning results in a high bedding to manure ratio and therefore a high C:N ratio, therefore it is advisable to e.g. selectively collect the manure and soiled bedding and, if available, to also add manure from outdoor areas [9]. Addition of nitrogen-rich substrates such as grass or poultry waste might be beneficial during the composting process as well. With view to necessary structure, addition of pruning/ yard waste has been recommended in order to avoid excessive compaction [9].

Successful composting of horse manure has been demonstrated to result into a product of high quality [29] [30] [31]. In cases where compost was amended to suppress plant diseases (this potential effect on soil-borne pathogens is known since several decades), horse manure compost failed to be successful [32] [33], hence it might be more suitable for standard applications. Its value is also relevant when assessing economic viability. Although management of residues is in general not the main criteria when deciding in favor of a bedding material, its good compostability is advantageous at this stage, and should be considered. Furthermore, composted material that contains undecomposable bedding material may still absorb soluble nitrogen (which previously had been one of its main functions) from the soil, which could result into very low fertilization effects [16]. Using bedding material that composts readily also reduces the likelihood of dumping used bedding in urban or other dump sites [16].

Although horse manure is a high-energy biomass [4] [34], its utilization for energy production is limited to few examples. In this, horse manure significantly stands behind other manures and other organic wastes. In addition, only few research studies exist on the topic. According to the following chapter, energy generation with horse manure via either biochemical or thermochemical pathways is a challenging field. However, it holds high potential to make a vital contribution towards increasing the share of renewable energy.

IV. Bioenergy Production

For many horse stables, the energy content of the annually generated manure would easily be sufficient to cover the energy demand for space heating and hot water of the buildings and facilities on site [4]. This would decrease energy costs and at the same time reduce the ecological footprint.

One main reason for the current low level of utilization of solid agricultural substrates such as horse manure e.g. as fuel in power plants is attributed to the lack of sufficient information concerning handling and process characteristics of the material [35]. This would not only be essential for the design and operation of the installations, but also for assessment of economic viability during the planning phase. The large variety of horse manure characteristics is especially challenging.

Aside of generation of energy, biochemical and thermochemical processes generate a residue in general in solid form. While compost from horse manure has been studied in various projects, only little is known about the effects of applying the respective digestate from anaerobic digestion or ash from thermal treatment to agricultural land. Aside of the direct effect on the soil, the residue can be of decisive influence when assessing economic viability and achieving profit. From state-of-knowledge in anaerobic digestion it can be deducted that digested horse manure represents an even more valuable organic fertilizer and soil amendment than compost. Analysis of ash from combustion of horse manure indicated appropriate quality to allow recycling to forests and to agricultural land [4]. Compared to biochemical processes, it needs to be considered that with thermal treatment no nitrogen can be recycled, as all nitrogen leaves in gaseous form during treatment.

Knowledge about technologies and their suitability for the given material, about regional and site-specific factors, as well as economic viability under site-specific circumstances (including necessary investment, running costs, and value of energy and solid residues), and adaptability of the management of the equine unit, are central factors when considering bioenergy production with horse manure.

Management of equine waste and its potential valorization is not a new problem, but an ongoing subject of discussions since many years [36] [37]. A Chinese adage says ‘A good message hardly goes beyond the gate, while bad news spreads far and wide’ [38]. Although it is likely that successful results are more often published in scientific literature than results with negative outcomes, any failed bioenergy projects in full scale in practice hold high potential to have significant negative impact on general perception of reliability and economic viability of the technology.

Besides the necessity to generate and make available data by research, it is an objective assessment of both successful and failed full-scale projects which is to be regarded as being essential to advance in the field. The currently poor rate of energetic valorization of horse manure indicates that without specifically targeted programs, adoption of best practices and of promising valorization strategies is not likely to experience significant increase. As mentioned previously, the equine sector is not comparable to other agricultural sectors under many perspectives, which means that application of traditional agricultural programs might not prove sufficiently efficient. In this context, it should in particular be taken into account that the equine sector is highly market-driven, but has often fallen between policy fields in an uneasy way (see e.g. its exclusion from eligibility for the same bonus as agricultural manures in the feed-in tariffs of the German Renewable Energy Law). As pointed out by Häggblom et al. [6], the sector is not sufficiently well organized to efficiently communicate to public authorities or among its own members, is of highly extensive nature, is particularly highly diversified and for many an ambiguous sector, and engages many actors with little knowledge on keeping of other animals as well as of agricultural practices.

A. Thermal Treatment Processes

Comparable to other agricultural solid residues, horse manure is produced locally and has a low density. Due to the resulting high transport costs, it is in general uneconomical to use such agricultural residues as the main fuel in big power stations [35]. Co-firing in coal power plants might be a viable option, if a plant is available in suitable distance. The use of small local power stations reduces transport necessity, but has the disadvantage of higher investment costs, a specific higher need of employees and a lower efficiency degree [35].

The low bulk density complicates processing, transport, storage and firing. Densification by e.g. pelleting increases viability of transport and storage, and combustion properties, but implies additional costs, and therefore needs assessment on individual case basis [35].

Early experiments with combustion of horse manure indicated poor results and process problems [39], but more recent studies using a 250 kW(th) furnace especially designed for wet and inhomogeneous biomass (adapted two-zone furnace) resulted in efficient energy conversion after combustion in good quality [4]. It is now well understood that this type of biomass requires consideration of its specific properties when choosing the basic combustion type system, when designing the firing concept in detail, and when operating the process under giving attention to a range of particularly relevant parameters [35]. A two-stage combustion system with controlled temperature zones and the possibility to easily remove ashes is most suitable for combustion of such agricultural materials with low moisture content due to the following reasons [35]:

- Devolatilization starts at very low temperatures (due to high content of volatile matter) and releases mainly combustible gases (CO, H_2, C_xH_y). There is a tendency for instantaneous ignition and rapid completion of the combustion process, which is most relevant for the feeding system and the combustion itself. E.g. in a one-stage fluidized bed system combustion might be completed in the freeboard with very little heat being transferred to the bed. In addition, incomplete combustion (related to temperature and oxygen profile) may cause smoke formation. A two-stage system allows devolatilization and gasification in the first stage, and complete combustion in the second zone.

- The low ash melting point (related to contained alkali oxides and salts, and mainly to high K_2O content), can cause severe problems with agglomeration, fouling, slagging and corrosion. Low temperatures in the first stage allow removal of a significant part of the ashes (below grate or from gas flow), before combustibles are completely burnt in an environment low in ash (the second stage). The use of additives might be favorable.

Pyrolysis/ syngas production through gasification has been proposed as possible alternative to combustion, and has been studied on research level [34] [40].

B. Anaerobic Digestion for Biogas Production

Anaerobic digestibility of horse dung to produce biogas has been studied already by the end of the 19th century, and is documented in various approaches in literature [41] [42] [43]. However, application to full scale has revealed that horse dung requires detailed knowledge, adapted technology and appropriate management, and that the risk of failure is not be neglected. Horse dung was found unsuitable for co-digestion in higher ratios in conventional slurry-based plants due to its high tendency to float on top of the liquid phase [44]. Stratification and formation of layers of floating material is one typical reason for failure of AD plants run on horse manure. It is further relevant to note that the contained bedding material must be digestible, which is the case for materials such as straw and paper, but not the case for e.g. wood chips and sawdust.

Dry digestion in box type fermenters (with percolation: sprinkling of liquid on top of the stacked solid substrate) has been demonstrated to be a favorable and well suited process for horse manure by Kusch et al. [45], and the process has been further studied by other groups [2] [14]. For German frameworks, dry digestion of horse dung has been assessed to be economically viable, provided that appropriate technology is chosen and that the plant is well operated [46].

A full-scale plant for mono-digestion of flooded horse dung has been in operation in southern Germany [47], but failed to be successful (it is however worth noticing that the reasons for failure were not related to the material itself). In dry digestion with percolation, trials in full-scale showed that the principle is applicable for horse manure, though problems can occur [48]. Dry digestion in a plug-flow digester (co-digestion of horse manure, turkey dung, energy crops) is successfully operated in Schrozberg (Germany). 2-stage digestion and grinding pre-treatment has been implemented at the biogas plant IM Brahm in Essen (Germany) in 2005, digesting cow and horse manure together with kitchen waste. The Bavarian AD plant Kolbermoor digests 80% horse manure in a 2-stage process. Grass silage (+ enzymes) is added to improve hydrolysis, thus improving digestibility and achieving better plant performance [49]. Other easily digestible co-substrates (e.g. glycerol) could have the same positive effect on hydrolysis.

Similar to other lignocellulosic biomass, various forms of pretreatment can increase the biogas yield [50] [51], but need to fit into the whole management concept, and must increase economic viability in order to be suitable.

Digestate is a valuable byproduct in particular in regions with shortage of organic fertilizer. But it has also been reported that digested and dried horse manure (e.g. by using the waste heat of the AD process) is an excellent solid biofuel. While untreated straw and horse dung require specific technology due to the low melting point, a regular industrial boiler could be used for digestate (increased melting point due to reduced mineral content after hydrolysis) [49]. This indicates that a combination of different technologies can be particularly well suited in order to improve overall efficiency and economic viability.

V. CONCLUSIONS

The equine sector generates huge amounts of organic residues. Situations and possible management concepts vary in different regions, depending on demands for horse manure as fertilizer or disposal costs, availability and costs for bedding material, stall management, economic viability of energy generation as well as the relevant general frameworks. Bioenergy production is still poorly adopted by the equine sector and should be encouraged by targeted programs.

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