The amount of manure produced by horses varies between 9 and 29 m3/horse/year (Lundgren and Petterson, 2004), which corresponds to an average of 8-14 tons/horse/year of collectable wet manure (Cui et al., 2011). According to some researchers, horses produce 17 to 25 kg of feces and 8 to 10 kg of bedding materials per day, depending on their feed, bedding and cleaning systems (Böske et al., 2014; Wartell et al., 2012).

Horse manure can also be reused as a sustainable feedstock for pyrolysis, aimed to both waste treatment and useful end products derivation. The operating parameters, such as carrier gas flow rate (Ng et al., 2017), temperature (Cantrell et al., 2012), and microwave receptor proportion (Yerrayya et al., 2018) followed by process optimisation are main factors of pyrolysis process in the maximum yield (Mushtaq et al., 2015).

When horse manure is examined in terms of energy, it is more effective to be dry, which requires approximately 1.4 MJ of energy to completely dry 1 kg of wet manure. In the 6.1 MJ energy content provided by dry manure, the effectively useful part decreases to 4.7 MJ/kg. In addition, horse manure can provide 4.7 MJ/kg of energy production (Da Lio et al., 2021). The management of horse manure causes environmental problems when emissions occur during the decomposition of organic material, in addition to the non-recycling of nutrients (Eriksson et al., 2016).

The composition of the manure is diverse and depends on the type of animal and its feed (Orlando and Borja, 2020). Some researchers who have conducted research on horse manure have shown the analysis results in Table 1.

Table 1 - Some analysis values of horse manure

Proximate analysis	Ash (%)		Volatile matter (%)		Fixed carbon (%)		Nanda et al. (2016)
	16.70		64.80		10.10		
Ultimate analysis	C (%)	H (%)	O (%)	N (%)	S (%)	C/N (%)	Lee et al. (2021)
	43.00	5.70	49.50	1.00	0.80	43.00	
High Heating Value (HHV)	HHV (MJ/kg)						Da lio et al. (2021)
	17.50						
Chemical analysis	Cellulose (%)		Lignin (%)		Hemicellulose (%)		
	42.40		7.20		9.20		Lee et al. (2021)
	6.30		56.00		23.80		Chong et al. (2018)
	19.20		0.30		12.00		Juntupally et al. (2022)

Compost production

Due to its rich nutrient composition (potassium, nitrogen and phosphorus), manure has historically been utilized as a natural fertilizer and soil conditioner (Oenema et al., 2007). Managing a compost pile requires consideration of the carbon-nitrogen ratio, oxygen, moisture, and temperature. The C:N ratio of horse manure is typically 40:1 due to the large amount of bedding mixed into it, but it generally does not require additional nitrogen as long as it has sufficient moisture and oxygen. Typical horse stable waste tends to be dry. Since approximately 50% moisture content is required to create ideal conditions for compost microbes, horse manure may need to be soaked. It is also desirable to maintain a constant temperature of 130° to 150°F in the interior of the compost pile (Smith and Swanson, 2009). When considering the use of horse manure on agricultural land, it can be spread directly on agricultural land or spread after composting (Swinker et al., 1997). When the effects of spreading are examined, it provides nutrients, increases soil organic matter, improves water holding capacity and soil structure. However, ammonia and nitrates in horse manure can change soil-related ecosystems and pollute surface runoff waters and pose a risk to aquatic life. These disadvantages can be significantly reduced by composting horse manure before spreading on fields (Da Lio et al., 2021).

The physicochemical properties and energy content of various fertilizers are presented as; cow ≈ horse > sheep > poultry > pig manure, but this situation is still debated for different reasons (Hoyos-Seba et al., 2024). It is recommended to use horse manure as a biofertilizer on farms (Lundgren and Petterson, 2009). Because this manure has a lignocellulosic structure, it is suitable for composting (Rodhe et al., 2015; Airaksinen et al., 2001). Due to the high content of bedding material in horse manure, its spontaneous decomposition time is slow (Malgeryd and Persson, 2013). Horse manure without bedding material can be composted in a month, but the content of the bedding material slows down the composting process (Airaksinen et al., 2001). In addition, aeration and mixing should be done to accelerate the composting process in composting (Sindhöj and Rodhe, 2013). In general, the use of horse manure as a soil fertilizer after composting is considered beneficial in terms of improving soil quality. However, some metallic contents and especially nitrogen and phosphorus ratios may exceed those required for crop growth and may cause water pollution due to surface runoff (Eriksson et al., 2016). In addition, there are researchers who question the use of composted horse manure as fertilizer both economically and agriculturally (Lundgren and Petterson, 2009). It has also been reported that some grain farmers are reluctant to spread manure due to the potential for the formation of an undesirable weed (such as oats) in addition to the crop they plant when they spread horse manure on their fields (Da Lio et al., 2021).

Biogas production

Biogas is a colorless and flammable gas mixture formed as a result of the fermentation of organic substances such as animal and plant waste in airless environments, containing 60-70% methane, 30-40% carbon dioxide and small amounts of hydrogen sulfide, hydrogen, carbon monoxide and nitrogen (Gülen and Çeşmeli, 2012). Efforts to dispose of animal waste products have led people to research the use of these products in different areas. This section of this research addresses the use of manure obtained from horses in biogas production.

The European Union has adopted decisions to encourage waste-to-energy conversion in order to maximize its contribution to decarbonization and reduce waste production (European Commission, 2019). It has also enacted laws that force farmers to transport or treat excess manure obtained from animals (170 kg N/hectare/year) (European Commission, 1991). The interest in anaerobic digestion of horse manure and thus producing biogas has increased with the increasing interest in biogas as a renewable fuel (Eriksson et al., 2016). In studies conducted on horse manure, some researchers (Weiland et al., 2023) reported the obtained biogas and methane values as 185-115 (Day 16-LN kgVS−1) and 207-135 (Day 40-LN kgVS−1), respectively, while others reported 164 (LN kgVS−1) biogas and 277 (LN kgVS−1) methane (Kusch et al., 2008). These values are lower than the biogas energy values obtained from wheat straw (Bauer et al., 2009) (219-484 LN kgVS−1) but similar to the biogas energy values obtained from manure obtained from cows (De Bere, 2000; MarañóN et al., 2001; Saev et al., 2009) (103-184 LN kgVS−1). Ignition tests have shown that the only major limitation in manure combustion is the high moisture content (approximately 60%), and therefore research is being conducted to overcome the detrimental effect of high moisture content and, in particular, its removal efficiency (Da Lio et al., 2021). The economic viability of using horse manure as a substrate for biogas production depends on the availability of manure, the cost of transportation to the biogas plant and the amount of biogas obtained from the substrate, which is affected by the variability of the bedding materials used (Hadin and Eriksson, 2016). Using horse manure for biogas production instead of improper composting reduces its undesirable impact on the environment (Hadin et al., 2017).

ANAEROBIC DIGESTION AND CO-DIGESTION

Anaerobic digestion is an effective method of converting bio wastes like dairy and horse manure into useful forms, and the most common ways of renewable energy recovery (Mata-Alvarez et al., 2014; Mao et al., 2015), which can produce nutrient-rich digestate (bio-fertilizer), biogas and bio-energy simultaneously. There are wide substrates of municipal, agricultural, horticultural and industrial wastes available for anaerobic digestion (Li et al., 2015).

Although food waste with a high methane production potential can be an attractive feedstock for anaerobic digestion (Zhang et al., 2011), but often faces with some disadvantages like low pH, lack of certain nutrients and suboptimal carbon to nitrogen (C/N) ratio (Mata-Alvarez et al., 2014). Solutions were adopted to overcome the deficiencies of mono-digestion and improve the operational stability and economic viability of this method, for example anaerobic co-digestion or simultaneous anaerobic digestion of food waste plus other organic wastes (Hartmann and Ahring, 2005; Banks et al., 2011; Fang et al., 2011), like co-digesting food waste with cattle manure (Zhang et al., 2013) to provide good buffering capacity and favorably alter anaerobic digestion systems using the nutrient profile of manure (Mata-Alvarez et al., 2014).

Horse manure, is one of the major sources of animal manure in Türkiye. Although Kafle and Chen, (2016) reported that the biochemical methane potential of horse manure are the lowest in most cases compared to other livestock manures because of bedding materials (straw, woodchips, etc.) which have a high content of refractory organic compositions such as lignin and cellulose, but Yerrayya et al. (2018) and Mong et al. (2020) stated that the lower ash content and higher lignin compositions in horse manure makes it a potential feedstock to produce solid fuel and phenol-rich bio-oil with high phenolic content. Chong et al., (2019) also reported that the high volatile and low ash content in horse manure indicates the potential for bioenergy recovery. Miron et al. (2000) stated that lignin is one of factors limiting anaerobic digestion of lignocellulosic biomass due to surrounding the cellulose by lignin and preventing the accessibility of cellulose.

Therefore, the efficiency of co-digestion of food waste when mixtured with horse manure is limited because of the higher content of lignin. There are some physico-chemical pretreatment methods to destroy the structure of lignin and increase the digestibility of lignocellulose, improve the biochemical methane potential of lignocellulosic biomass, and reduce operating costs and energy of anaerobic digestion systems (Shahriari et al. 2013; Ma et al. 2011, Chekani-Azar et al. 2008). A cost-effective separate biological dissolution process has also been suggested for treating bio waste as a pre-treatment step, so that particles are microbiologically hydrolyzed and their size is reduced prior to anaerobic digestion (Gonzales et al., 2005). Zhang et al. (2017) anticipated that the overall performance of anaerobic digestion could be improved if the hydrolyzing and fermenting process of horse manure and food waste were conducted before methanogenesis within the same anaerobic digester.

The digestion and transport of large fibrous particles in manure or solid manures or other residues can cause pumps and pipes to choke and are limited in conventional anaerobic digesters. On the other hand, the transfer and digestion of large fibrous particles in manures are liable to cause technological issues like choking of pumps and pipes18, 19. For this reason, only liquid manures are commonly used in practical AD plants while the utilization of most of solid manures or other residues with fibrous materials is limited in conventional anaerobic digesters (Mönch-Tegeder et al., 2014).

Anaerobic co-digestion of food waste with livestock manure and sustainable development goals

The anaerobic digestion system is one of the important economies of bio wastes which connect the circular economy and bio-economy to sustainable development goals (SDGs) (Fagerström et al., 2018, Netherlands Enterprise Agency, 2021).

Anaerobic digestion convert disposable waste material into high-end outcomes such as biogas (60% methane and 40% carbon dioxide), and nutrient-rich digestate as bio-fertilizer (Holm-Nielsen et al., 2009 Appels et al., 2011 Lohani et al., 2015) which could be the sustainable future replacement for fossil fuels and is an excellent solution for the reduction of the toxic emissions and contamination of soil and water (Miller et al., 2020; Haltas et al., 2017; Labatut and Pronto, 2018). In addition, anaerobic digestion of biowastes contributes towards the achievement of sustainable development goals (SDGs) 2 (zero hunger), 3 (good health and well-being), 5 (gender equality), 6 (clean water and sanitation), 7 (affordable and clean energy), 9 (industries, innovation and infrastructure), 12 (responsible consumption and production),13 (climate action) and 15 (life on land) (Sarika, 2021; World Biogas Association, 2021).

Converting animal manure sources to biogas as renewable energy, which can be successfully done at domestic and industrial scales, can also positively impact sustainable development goals like 7, 9, 12, and 13 SDGs, especially SDGs 9 (innovation) and 13 (climate action) that require urgent implementation for protecting the global health. Shaibur et al. (2021) and Lohani et al. (2021) reported that small-scale biogas systems would contribute to SDGs 1, 3, 5, 7, 13, and 15. The SDGs 3, 4, 5 and 7 are highlighted by Rahman et al. (2019) for biogas implementation, while agriculture residue biogas was considered to SDG 6 by Orner et al. (2020). New method or guidelines are suggested by Obaideen et al. (2022) to enhance the contribution to the SDGs.

Livestock manure as a major issue for sustainable agricultural development can be contributed greatly to the development of some SDGs. Three main categories (reducing emissions to protect the environment, adapting to change, and financing adjustments) which are suggested by the treaties to achieve a zero greenhouse gas emissions (Subbarao et al., 2023) are achievable through the application of the technologies mentioned in Figure 1. The figure shows different processes and technologies of manure treatment using aerobic, anaerobic, and thermochemical pathways so that this optimizasion in the use of materials and energy is in line with SDGs (Hoyos-Seba et al., 2024).

Therefore, additional efforts are required to overcome the current climate change problem. One of most important efforts is to encourage greater use of existing technologies like those presented in Figure 1 to achieve sustainable development goals through valorization of livestock manure.

Gasification, combustion and pyrolysis of horse manure

The thermochemical biomass conversion process known as gasification offers non-oxidative conversion conditions with very low emissions of pollutants, making it a desirable technique for the production of energy and fuel (Ferdous et al., 2001, Tavasoli et al., 2009). Horse dung is a good candidate for catalytic gasification to produce H2-rich syngas, according to research by Nanda et al. (2016). A win-win-win situation, including the creation of biofuel (H2), waste management (manure remediation), and carbon sequestration (application of biochar), might be addressed by using horse manure in supercritical water gasification. Overall, the findings support the idea that using livestock manure in the waste-to-energy conversion process might yield a variety of renewable products with additional value (Nanda et al., 2016).

Horse manure burning directly could be a desirable alternative for combusting heat. Horse manure is rarely used as fuel for three reasons: (a) it is produced in fragmented, mostly small stables that rarely cooperate; (b) regulations vary from one country to another regarding whether or not manure qualifies as a waste or as a renewable fuel and whether it is eligible for renewable energy subsidies (Kusch, 2014); and (c) designing furnaces fed only horse manure is difficult because it needs to be customised for a very wet, heterogeneous, and potentially sticky feedstock (Da Lio et al., 2021). A research comparing horse manure samples of varied origins, management, and ages discovered that the heating values, ash, and melt temperatures were compatible with combustion, but the manure's relatively high moisture content prohibited it from burning (Da Lio et al., 2021).

Pyrolysis is the heat decomposition of a solid fuel in an inert, oxygen-free atmosphere, yielding a liquid or gaseous fuel and a solid residue known as char, which contains the fuel's ash and fixed carbon content (Soria-Verdugo, 2019). According to some recent studies, horse dung is a carbon-neutral biological waste that can be exploited for bioenergy production by microwave-assisted pyrolysis, with microwave pyrolysis producing up to 73.1 vol% of the syngas component (Mong et al., 2020).

Thermochemical conversion methods such as gasification, combustion, and pyrolysis present great opportunities for using horse dung as a viable feedstock for renewable energy production while also addressing waste management and contributing to carbon sequestration. Despite constraints such as high moisture content and regulatory barriers, novel techniques such as catalytic gasification and microwave-assisted pyrolysis have the potential to unlock a wide range of bioenergy products, thereby facilitating the transition to a more sustainable and circular economy.

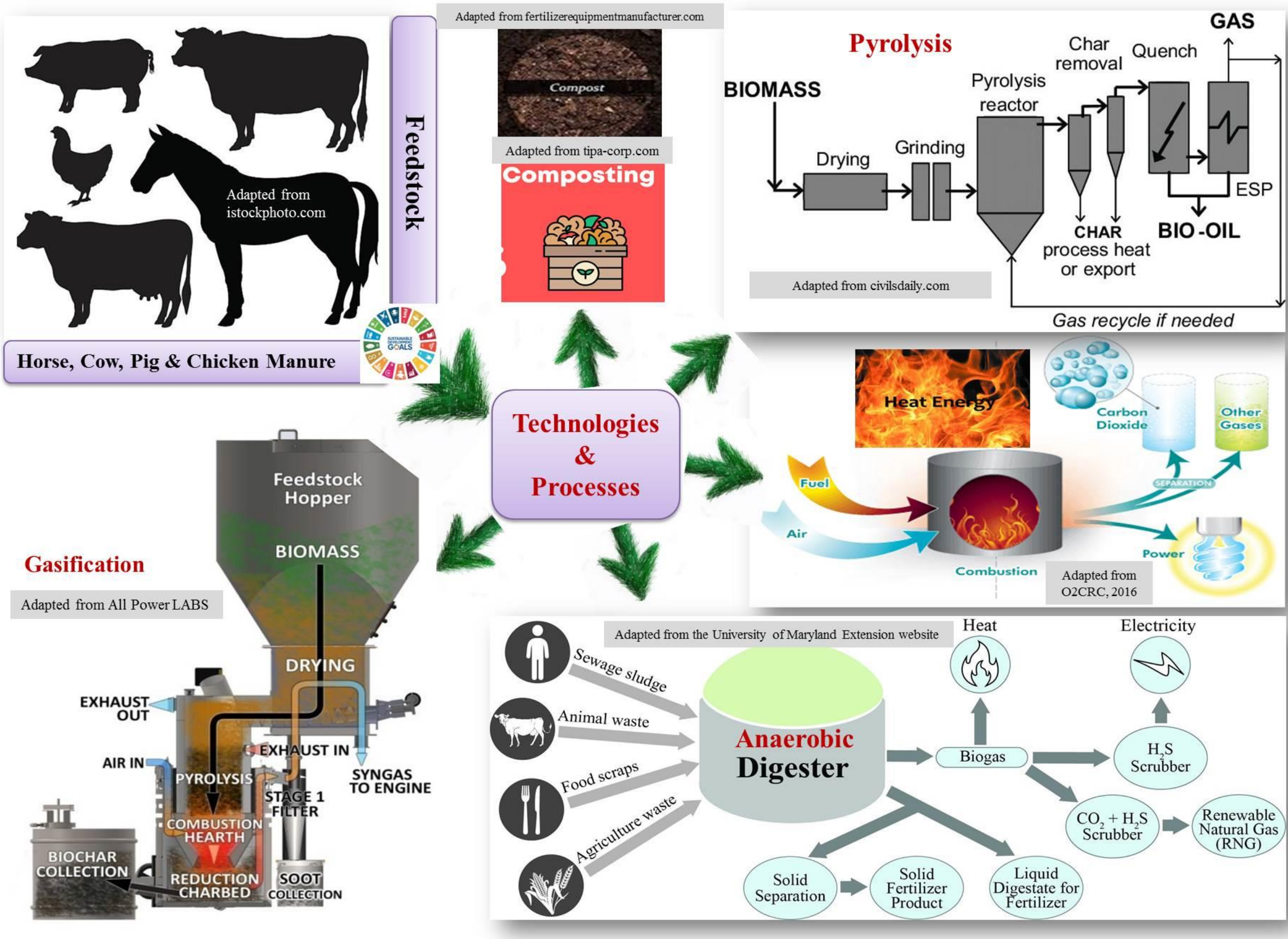

Figure 1 - Products made from various manure treatment technologies and processes.

CONCLUSION AND RECOMMENDATION

In the face of growing environmental challenges and the increasing energy demand, utilizing animal waste—especially horse manure—emerges as a promising solution to address both waste disposal and renewable energy generation. The potential of horse manure as a sustainable feedstock for biogas production, composting, and bioenergy recovery has been extensively explored, demonstrating its value not only as an organic fertilizer but also as a resource for generating clean energy. While its biochemical methane potential may be lower compared to other manures, recent advancements in anaerobic digestion, including co-digestion with food waste and the application of pre-treatment methods, show promise in improving its digestibility and energy yield. Furthermore, adopting biogas technology aligns with the European Union's renewable energy goals and sustainable development objectives, such as climate action, clean energy, and responsible consumption.

Despite the challenges associated with managing horse manure—such as high moisture content and slow decomposition due to bedding materials—innovative technologies offer opportunities to optimize its conversion into valuable byproducts, including biogas and biofertilizers. By enhancing the efficiency of anaerobic digestion systems and promoting horse manure in circular economy models, we can reduce harmful emissions, improve soil quality, and generate renewable energy that supports global sustainability goals. To fully realize the potential of horse manure, further research and technological advancements are needed to overcome existing barriers and scale these solutions. Ultimately, the valorization of animal waste through biogas production and other renewable energy pathways can be crucial in mitigating environmental impacts, fostering energy independence, and contributing to a more sustainable future.

DECLARATIONS

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Authors' contribution

F. Yildirim and Y. Açar contribute to the research, data analysis, and manuscript writing.

Acknowledgements

The authors thank Y. Betül Apaydin for providing the resources in this research.

Competing interests

The authors declare no competing interests in this research and publication.

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