SUSTAINABLE MANURE MANAGEMENT IN AGRICULTURE.

MASTER THESIS

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Abstract

Nitrogen compounds, particularly from livestock manure, pose significant environmental challenges. Livestock manure generates ammonia (NH_3) emissions, contributing to nitrogen surplus, pollution, and climate-related problems. Nowadays, the intensification of livestock farming is increasing the problem; for instance, in the Netherlands, agriculture is responsible for 43% of nitrogen (N) emissions. Livestock manure is exceeding the absorptive capacity of agricultural land, leading to nutritional imbalances. As a result, Dutch farmers are facing a lot of pressure to reduce N emissions, so they have to adopt innovative manure management practices. This research investigates various manure management practices, including anaerobic digestion, manure acidification, composting, biochar, and the Lely Sphere method, by reviewing their technical, environmental, and economic implications. First, the study conducted a literature review to understand the implications of each practice, followed by a SWOT analysis to identify each practice's strengths, weaknesses, opportunities, and threats. This methodology helped to provide a comparative evaluation to solve the main research question: How do different manure management practices compare in their operational, environmental, and economic implications? The results contribute to understanding and determining how different manure management practices are suited to distinct environmental objectives and economic needs, enabling stakeholders to make more informed decisions regarding manure management based on their specific characteristics, demands, and needs.

Glossary

- **AD**- Anaerobic Digestion
- **CBS**- Central Bureau of Statistics
- **C**-Carbon
- **CH_4**- Methane
- **CO_2**- Carbon dioxide
- **GHG**- Greenhouse gas
- **H_2S**- Hydrogen sulfide
- **K**-Potassium
- **N_2O**- Nitrous oxide
- **NH_2**- Radical amino
- **NH_3**- Ammonia: Chemical compound of nitrogen and hydrogen.
- **N**-Nitrogen
- **NO_x**- Nitrogen oxides
- **RO**- Reverse Osmosis

1 Introduction

1.1 Problem context

One of the most abundant chemical elements in the Earth's atmosphere and an essential component of all living matter is nitrogen (N). However, the persistent presence of excess anthropogenic nitrogen compounds in the atmosphere is an environmental concern (Krupa, 2002). Nitrogen compounds are emitted into the environment in the form of nitrogen oxides (NOx), ammonia (NH_3), and nitrous oxide (N_2O). These emissions mostly come from human activities such as burning fossil fuels, using mineral fertilizers, and managing livestock waste (Erisman J. W., 2008). These nitrogen forms go from the atmosphere to the soil surface by the processes of dry and wet deposition. Wet deposition occurs when gas or particular matter is dissolved in precipitation and brought to the surface. Dry deposition is when compounds settle on the surfaces without water dissolution (Zhang L. T., 2020). At present, the amount of nitrogen in the Earth's atmosphere is three to four times greater than what Rockstrom's planetary boundaries suggest (Wassen, 2013). The surplus of nitrogen that manure generates especially in regions with high livestock density, mostly in the form of nitrous oxide and ammonia, can lead to adverse environmental consequences, including soil acidification and nitrate-contaminated groundwater. These impacts contribute to climate change because they can generate global warming, eutrophication, and loss of biodiversity. The preceding consequences demonstrate the relationship between nitrogen emissions and environmental impacts, stressing the significance of implementing solutions to mitigate emissions (Piwowar, 2020).

The ongoing existence of surplus anthropogenic nitrogen compounds in the environment is a cause of concern, as different activities emit various forms of nitrogen into the atmosphere. Livestock management particularly because of the excess animal manure, is one of the primary sources of NH_3 emission (Rotz, 2011). The intensification of livestock production represents a big challenge to manure management, as the manure generated exceeds the absorptive capacity of agricultural land, leading to a nutrient surplus in manure (Melse, 2020). The Central Bureau of Statistics in the Netherlands describes nutrient surplus in manure agriculture as an estimate of subtracting nitrogen inputs from outputs, surplus indicates nitrogen loss, both into the soil and into the atmosphere.

It is critical to consider the environmental and economic challenges that result from animal manure, especially in the Netherlands a high livestock country where around 43% of the total nitrogen emissions come from agriculture with 58% of these emissions being in the form of ammonia (Jade, 2021). These challenges have led to a nitrogen crisis, causing distress among farmers and the government. Consequently, this is increasing environmental, economic, and political concerns, such as excessive pollution, reduced competitiveness of Dutch agriculture, and polarization (Kumar I. , 2021) (Stokstad, 2019). Cattle, the most widely raised livestock in the Netherlands, occupy an estimated 3.7 million hectares of agricultural land as of December 2020, according to CBS. In response to the N excess, Dutch farmers must either reduce their cattle numbers or adopt new technologies and methods to lower greenhouse gas emissions, in line with increasing regulations to control emissions. (Beyers, 2022). Hence, the implementation of cow manure management solutions presents an opportunity for farmers, companies, and governments to adopt innovative approaches and technologies for mitigating nitrogen compounds originating from the agricultural sector in the country.

Research highlights the need to comprehend existing methods to efficiently utilize dairy cow manure because of its environmental impacts and associated waste management challenges (Petersen B. M., 2013) (Hou Y. V., 2017). The current status of cow manure management in the Netherlands shows an active approach towards sustainability and environmental responsibility because there have been continuous attempts to enhance effective methods, adopt new technologies, and promote cooperation within the agricultural industry (Gonzalez-Martinez,2021).

1.2 Research Gap

Manure management can be defined as a planned system with components to manage and control slurry from animals in agriculture in a way that tries to minimize damage to the air, water, and soil (Malomo, 2018). Strategies for sustainable manure management aim to reduce nutrient waste, increase the use efficiency of manure nutrients, improve energy efficiency, and reduce the application of synthetic fertilizers (Richard, 1999). Improving manure management through sustainable approaches may significantly impact global environmental issues by decreasing GHG emissions (Wang Y. D., 2017).

There is a need for a comparative analysis that enables an understanding of the potential drivers or influences for farmers to adopt different manure management practices (Niles, 2019). Current research focuses on economic and environmental factors separately, so an integrated approach to analyze the trade-offs between various manure management systems is required (Gebrezgabher S. A., 2012). Since farms are typically individualized, the best manure management system will usually be specific to each farm. While there is not a single practice that can be used as a universal solution, a systematical analysis can help address some specific environmental goals while balancing the economic welfare of farmers (Burton, 2003).

Therefore, the use of an integrated approach to analyzing manure management practices could help decision-makers understand the possible advantages and disadvantages suitable to their own needs including how these practices comply with sustainable requirements (Gebrezgabher S. A., 2014). This information should be conveyed to livestock farmers and other users regarding the different aspects of specific manure management systems, for example, financial viability, optimal operation conditions, regulations and incentives, and environmental performance (Hou Y. V., 2017).

1.3 Research aim

The primary objective of this study is to assess the present state of various manure management systems. The problem of livestock manure management is a complex issue that requires a comprehensive analysis across several stages of the chain. The aim is to raise awareness about the possible benefits of alternative manure management strategies by systematically comparing internal and external elements, as well as analyzing their environmental and economic implications.

Main question:

- *How do different manure management practices compare in their operational, environmental, and economic implications?*

Sub-question

- *What is the current state of different manure management practices?*
- *What are the main challenges and opportunities associated with the adoption of different manure management systems in Dutch agriculture?*

These questions focus on understanding and comparing various practices, reviewing both environmental and economic aspects that align with the broader goal of enhancing sustainable manure management in agriculture. Solving these questions would help to identify the internal and external factors that could influence the successful adoption of each practice and systematically explore the different dimensions of manure management practices, ensuring that these solutions can be applied in the local context. In addition, the practical challenges are considered, including issues related to integration, understanding, and acceptance among farmers and other stakeholders.

2 Theoretical background

2.1 Animal agriculture

Agriculture, encompassing the cultivation of crops and domesticated animals, has evolved beyond mere productivity and profitability goals. Today, it also emphasizes social and environmental enhancements (Bos, 2018). Livestock production, a pivotal aspect of the global food system and economy has surged, notably impacting the ecosystem, landscape, and biodiversity (Malomo, 2018). In animal agricultural process is shown with the combination of livestock and farmland. The cycle of nutrients between livestock and croplands has been disrupted, by the need for synthetic fertilizers. A significant quantity of pollutants are released into the environment, resulting in the contamination of air and water, the depletion of biodiversity, the acidification of soil, and the exacerbation of global warming (Jin, 2021).

Projections suggest that animal production will double in the next century to meet the needs of the growing population (Petersen B. M., 2013). If these assumptions prove true, environmental degradation from NH_3 and GHG emissions from livestock farming may increase. In agriculture, animal livestock is the largest contributor to NH_3 emissions and an important contributor to GHG emissions. The increasing demand for solutions to reduce NH_3 emissions resulting from the growth of livestock production is driving the development of various manure management solutions at different stages of the manure management process (Emmerling, 2020).

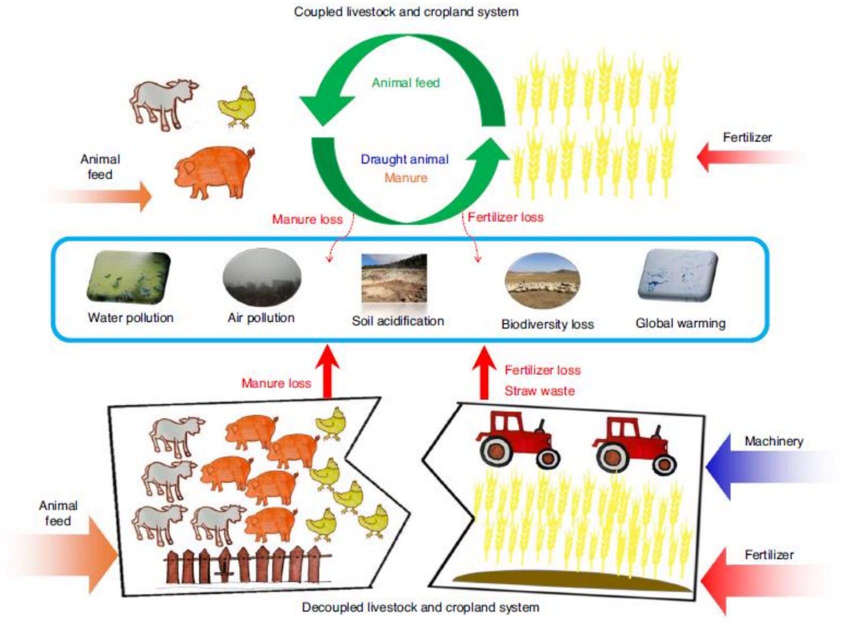


Figure 1: Conventional animal agriculture system (Jin, 2021)

The Netherlands has some of the highest livestock densities in the world, consequently, this has impacted the ecosystem, landscape, and biodiversity (Bobbink, 1998). According to the Food and Agriculture Organization of the United Nations, farms in the Netherlands are characterized by their small to medium size and limited number of staff, as they primarily operate as family-run businesses with an average size of 54 hectares. In this context, manure and slurries have been used as nutrients for soils to recycle them and restore fertility. In general, the nutrients present in manure and slurry can be divided into two categories: (1) nutrients that are in a dissolved mineral form in the liquid fraction and can be easily absorbed by plants, and (2) nutrients that are enclosed within the organic structure and are not readily accessible for plant absorption (Fangueiro D. M., 2023). However, the excess release of N from manure that is not accessible for plant uptake could lead to negative environmental effects and diminish its usefulness as a fertilizer.

Therefore, it is important to remember that, according to CBS, in the Netherlands, manure from dairy farms is mainly spread on the same land where production takes place. As a result, several areas of the country exceeded the natural environment's ability to absorb nutrients. The high costs associated with manure disposal represent a significant obstacle to proper manure disposal affecting the competitiveness of Dutch agriculture. While agricultural livestock production plays a vital role in the Netherlands, it is relevant to consider diverse viewpoints on the challenges to solving the excess emissions.

2.1.1 Manure

Livestock manure, a potential environmental concern, comes in three forms: liquid, mixed (solid and liquid), and solid. Its emissions, containing toxic metals and pathogens, pose risks to ecosystems, soil, and water (Kumar R. R., 2013). Besides releasing NH_3, manure emits other gases like methane CH_4, nitrous oxide N_2O , hydrogen sulfide H2S, and carbon dioxide CO_2 , contributing to ozone layer damage and global warming (Webb, 2012). The sources of NH_3 and GHG emissions in agricultural manure can be categorized into three stages: animal housing, manure storage, and manure application on fields (Seidel, 2017). In animal housing, when urine and feces are deposited on the barn floor, urea is rapidly converted into NH_3 by the enzyme urease, which is present in feces. This releases NH_3 into the air, creating emissions in the stable and barn areas. During storage, organic N compounds are further broken down by microbial activity, resulting in the formation of NH_3. The longer the manure is stored, especially in open systems, the more NH_3 is released. When manure is applied to the field, NH_3 is released as the manure dries and interacts with the soil and air. If manure is left on the surface without being incorporated into the soil, NH_3 losses tend to be higher, especially in warm and windy conditions. Consequently, by incorporating manure into the soil after application emissions can be reduced (Ghaly, 2015). Figure 1 illustrates the release of NH_3 emissions in these three stages where the gases and particles are deposited on land or water bodies through atmospheric deposition processes. This leads to environmental issues contaminating the atmosphere and groundwater. Consequently, it is crucial to understand manure management techniques aimed at reducing emissions during these stages.

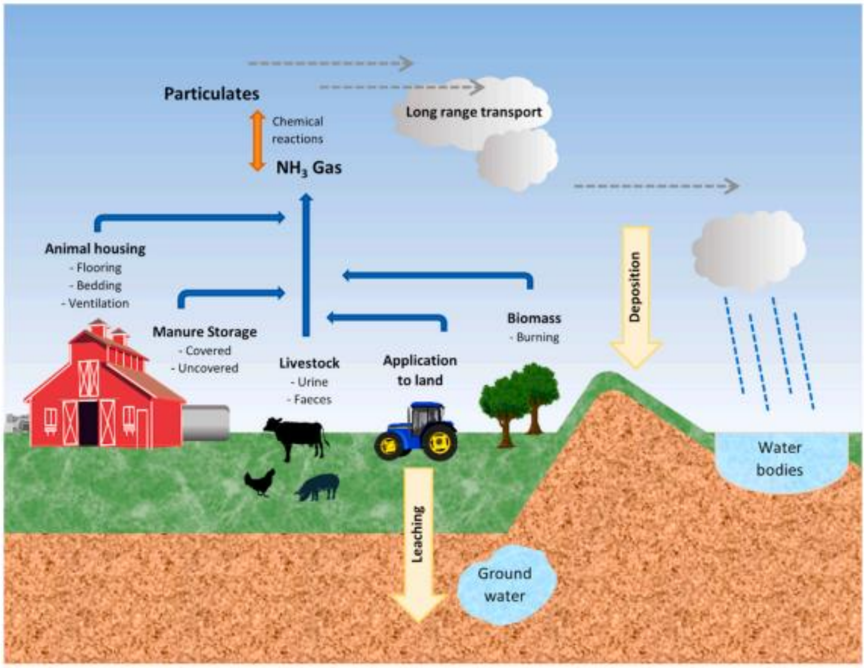


Figure 1 : Sources of NH$_3$ from Livestock Manure in agriculture (Wyer, 2022).

Different scientists and environmental organizations recommended that the Netherlands transition to circular agriculture. This means that farms produce just the amount of manure that can be utilized to fertilize neighboring areas, resulting in a 50% reduction in animal population. However, this might potentially give rise to economic and political challenges because it will require several decades and billions of euros (Stokstad, 2019). Current manure management techniques may help in the transition to sustainable agriculture but, the implementation of field innovations, farm system innovations, new regulations, market innovations, and scientific knowledge is required (Puente-Rodríguez, 2022). It is critical to examine methods that might improve manure management within the agricultural industry, as a mere reduction in animal population is not enough to address all issues and could cause further problems.

Various manure management strategies are implemented to mitigate the environmental effects of emissions in agriculture, while others focus on alleviating economic constraints (Awasthi, 2019). However, these solutions cause different alterations in manure's and soil's physical, chemical, and biological characteristics, which can subsequently affect the release of NH$_3$ and GHG in the management process (Hou Y. V., 2015). Therefore, manure management can be improved by comprehending and analyzing different solutions that could benefit society by reducing emissions resulting in less pollution, and creating economic opportunities.

2.2 Sustainability in manure management

Sustainable manure management aims to enhance agricultural productivity by efficiently utilizing nutrients, considering economic feasibility, and minimizing environmental impact (Gebrezgabher S. A., 2014). Achieving sustainability in agriculture requires a balance between economic prosperity, environmental conservation, and societal well-being (Latruffe, 2016). The choice of an appropriate treatment is based on economic considerations, unique product requirements, and sociocultural factors. Successfully adapting these treatments requires a combination of suitable technology, viable economics, policy support, and favorable environmental circumstances.

Awasthi et al. (2019) conclude that the following parts are critical for sustainable manure management: Increasing scientific knowledge on the ecological consequences of treating manure, establishing a viable cooperative framework, developing a market for goods derived from manure recycling products, and examining the influence of policy in supporting both innovators and consumers. This highlights the need for an integrated approach that addresses both environmental and economic aspects, as many of their elements have to work simultaneously to ensure sustainable manure management.

- **Environmental:**
  Practices that take care of the environment are compatible with the maintenance of natural resources such as water, energy, and biodiversity (Van Cauwenbergh, 2007). So, environmentally friendly manure management should try to recycle most of the manure nutrients that are useful for the soil while minimizing the negative effects on the environment regarding NH_3 and GHG emissions. At the same time, it should set up a waste management system that meets the needs of plants and soil. Additionally, well-used livestock manure is an organic substitute for chemical fertilizers and contains a variety of valuable elements that improve agricultural crop production (Khoshnevisan, 2021). Sustainable manure management techniques can reduce emissions while lowering the need for chemical fertilizer and energy, resulting in more efficient use of resources in a circular manner.
- **Economic:**
  The economic side refers to the ability to generate prosperity for the farming community through revenue or financial capital (Van Cauwenbergh, 2007). Agriculture should be profitable and processes viable, but not at the expense of the environment (Smith, 1998). There are some challenges, for instance, the expenses related to the storage and disposal of manure might contribute to unsustainable methods of managing manure when the alternatives to sustainable management are considered more expensive. Trade and commerce are other potential factors that could influence future manure management practices from an economic perspective. The possibility of selling or using high-quality manure products, which have the potential to be beneficial for agricultural purposes, could encourage actors to take action to implement sustainable manure management

practices. Therefore, an approach that views the use of manure as a problem to an opportunity to become a resource has the potential to benefit both the economic and environmental side (Sefeedpari, 2019).

Although some manure management techniques offer sustainable benefits, they also encounter various challenges. The implementation of proper sustainable solutions is slowed down by operational challenges, lack of knowledge, and managerial issues. Furthermore, financial viability, infrastructure demand, and market uncertainty add to the difficulty of implementing sustainable solutions (Rodriguez, 2009). As a result, sustainable manure management must focus on finding a balance between environmental impacts and economic feasibility because environmental and economic goals can have different priorities. For example, farmers aim to reduce costs associated with manure disposal, whereas environmental groups emphasize reducing environmental harm. To effectively address different decision-makers requirements, it is necessary to adopt an integrated strategy that reflects a comprehensive approach that balances both environmental goals and economic incentives (Gebrezgabher S. A., 2012).

3 Methodology

The research objective is to improve the understanding of the technical, environmental, and economic impacts of manure management through the analysis of various practices. This work aims to compare different available manure management practices. The selected manure management methods included anaerobic digestion, composting, manure acidification, biochar, and the Lely Sphere method. These manure management practices were selected based on the following factors: Anaerobic digestion and composting were chosen due to their wide recognition and extensive research supporting their applicability in current agricultural systems, while manure acidification has gained significant popularity in recent years as one of the most effective technologies for manure treatment (Thiermann, 2022). For biochar, recent research has shown that it can mitigate odor and gas emissions, proving it suitable for manure management (Dougherty B. G., 2017). The Lely Sphere, developed in the Netherlands, has become widely known for its innovative and modern manure separation and emission reduction method. These manure management methods offer a variety of well-established, trendy, and emerging practices that could be analyzed to provide a deeper understanding of their implications in livestock agriculture. Their proper implementation could address the environmental, economic, and regulatory challenges in Dutch agriculture, as they provide solutions to reduce emissions, improve nutrient and soil management, and produce renewable fertilizers and energy which are necessary for achieving the country's sustainability goals in agriculture (Gonzalez-Martinez, 2021).

3.1 Research design

The methodology in this research is divided into four subsequential parts, as shown in Figure 3. The first part of the research involved gathering information on each selected manure management practice through a literature review. The second step was to summarize the information collected during the literature review. The main features of each manure management practice in a description, along with their environmental and economic implications. The purpose of this summary was to determine the potential effects of implementing each practice based on field and laboratory experiments found in the literature. For the third step, after all information was collected and summarized, a SWOT analysis was performed for each practice to provide a clear overview of each technique and to identify the barriers and advantages of its adoption. Finally, a comparison was conducted, utilizing the results from the SWOT analyses to explain which practice is best suited for each specific context. Consequently, this comparison presents an explanation that can help stakeholders involved in manure management to identify the most suitable approach for their specific needs.

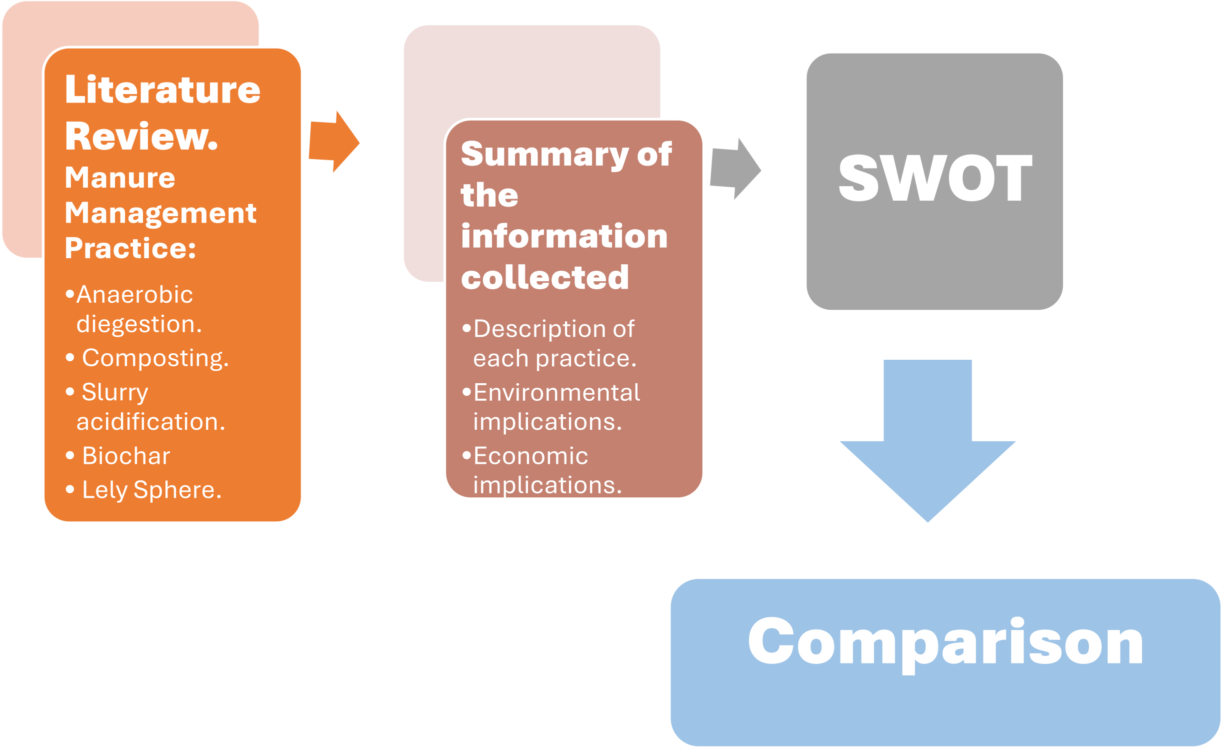


Figure 2: Steps in the methodology. Starting from a literature review to summarizing findings, and then using those findings for a SWOT analysis.

3.2 Data collection

The building block method was used to conduct an extensive literature review as the first step in the data collection. According to Vrije Universiteit Amsterdam, this approach combined multiple search terms in a single query to identify relevant academic sources. For this research, the goal was to compile as much relevant literature as possible. Therefore, search engines such as Google Scholar and SCOPUS were used to obtain data by combining different keywords and terms related to each manure management practice. In addition, the MSc thesis repository at Wageningen University was used to acquire information from previous research on manure management. For the general description, the following terms were searched: "name of the practice" AND “manure management ” AND “description” or "analysis." I scanned the paper's titles and abstracts to see if they were relevant to the research question and sub-questions. Papers were considered appropriate if they provided information that contributed to addressing these questions. For the environmental implications, the following terms were searched: “name of the practice” AND “cattle manure or animal manure” AND “GHG emission” AND “NH_3 emissions". Both laboratory and field experiments were considered, including data from trials that had reference treatments. This was done to enable direct comparisons to determine the variation between emissions for each manure management technique. For the economic implications, the following terms were searched: "name of the practice" AND "cattle manure or animal manure" AND "economic implications" or "economic analysis" or "cost-benefit".

In order to strengthen the literature review, the snowball backward methodology was applied. This technique focuses on tracing earlier cited and referenced publications that an author consulted, providing a deeper understanding of foundational and complementary studies that allow other significant research to be reviewed. This method helps to expand the scope of the review, ensuring that key, influential research is not overlooked (Wohlin, 2014). Important articles and references mentioned in the most relevant papers were reviewed, enabling the discovery of more sources and providing an extensive collection of data for each manure management practice. Also, grey literature has been used to find additional and supplementary data. Grey literature was useful in reducing data gaps and provided more information for the research. Documents published by governmental and educational entities, agricultural and sustainability magazines, and case studies were utilized.

3.3 Data analysis

The information and data collected from the literature review was organized and compiled into a summary that provides a clear overview of the technical and possible environmental and economic implications of the selected manure management practices. Then, with all the data review, a SWOT analysis was conducted for each practice to categorize key information into internal and external elements that impact any manure management strategy. First, the internal elements of each manure management technology refer to the strengths and weaknesses that exclusively affect the performance of anaerobic digestion, manure acidification, composting, biochar, and Lely Sphere. Second, external elements include opportunities and threats arising from the external environment, as well as potential trends and developments for these manure management technologies (Paschalidou, 2018). By identifying strengths, weaknesses, opportunities, and threats, the study gained deep and practical insights into each manure management practice. Finally, a comparison between the five practices was performed based on the SWOT results, taking into account several aspects such as applicability, environmental impact, economic viability, and individual factors. Examining these factors helped to highlight the most suitable manure management strategies for different contexts, where specific practices could become a better option than others, providing valuable insights.

4 Results

Manure management technologies are crucial for sustainable livestock operations in areas with high animal density. These technologies could improve the use of manure and minimize its environmental effects. Manure management technologies have undergone extensive study and some are now fully developed for practical use, but their utilization has been limited (Gebrezgabher S. A., 2014). Adopting different manure management systems is still restricted by many environmental and economic challenges (Hou Y. V., 2018). Thus, in this results section a systematic comparison that carefully examines them might facilitate a more comprehensive understanding of those challenges. Therefore, the results section presents the most relevant literature review findings, providing a comprehensive review of the current state of knowledge for each practice and highlighting the challenges and opportunities for its implementation.

4.1 Anaerobic digestion

4.1.1 Description

Anaerobic digestion (AD) is a biological process where microorganisms break down organic matter without oxygen. AD consists of four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Font-Palma, 2019). For animal manure, AD converts organic residues into valuable products such as biogas and digestate. Biogas, a renewable fuel, can produce green electricity, heat, or vehicle fuel, while digestate is used as fertilizer in agriculture (Al Seadi, 2006). This process takes place in a reactor that works in one or two stages and is usually designed and built in a way that suits the particular farm and feedstock. The different types of reactor designs often used for AD of animal manure include batch reactors, continuous one-stage reactors, continuous two-stage reactors (CSTR), anaerobic sequencing batch reactors (ASBR), anaerobic filters (AF), and plug flow reactors (PFR) (Nasir I. M., 2012). In a one-stage AD, all four essential processes, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, are carried out within a single reactor or digester. In the case of two-stage AD, the initial three steps hydrolysis, acidogenesis, and acetogenesis are conducted together in a single bioreactor as the first stage. The last step, methanogenesis is performed in a separate reactor as the second stage to form CH_4 and CO_2 (Hans, 2019). The CSTR is commonly used for cattle manure because it manages high-solid content and maintains stable operation in different conditions. The flexibility and efficiency of CSTRs make them suitable for digestion, leading to significant biogas production and waste treatment (Nasir I. M., 2014).

AD may be implemented at various scales, ranging from small-scale digesters that generate sufficient biogas for a single family to large centralized biogas facilities with a digester capacity of several thousand cubic meters (Angelidaki, 2003). At the forefront of AD technology, Europe primarily employs two types of operating digesters: centralized systems and farm-scale digesters (Vasco-Correa, 2018). A centralized or collaborative system co-digests animal manure from many farms and other organic materials, such as food waste and agricultural residues. Denmark is at the forefront of developing a centralized AD system. This system returns a portion of the digestate to farmers as fertilizer, while the surplus is sold to other farms for economic gain (Holm-Nielsen, 2009). On a farm-sized scale, AD facilities are often constructed on large dairy or swine farms. They digest the animal manure from 1 to 3 farms with agricultural wastes and other organic materials, including crops cultivated on the same farm. Germany is the country with more farm-scale facilities (Wilkinson, 2011).

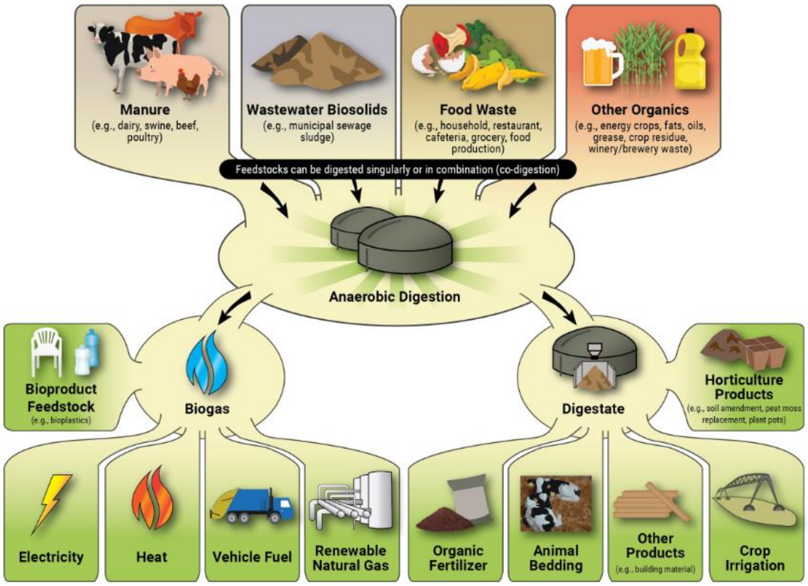


Figure 3: The image shows the process of feedstocks inside the anaerobic digestion (AD) system to generate biogas and digestate (EPA,2024).

Figure 3 illustrates the process of anaerobic digestion, a technological method employed to transform diverse organic feedstocks. The feedstocks consist of animal manure, wastewater biosolids, food waste, and other organic wastes. In the absence of oxygen, the feedstocks undergo decomposition, leading to the generation of two primary products: biogas and digestate. Biogas may be utilized for the production of energy and heat, while the digestate can be transformed into an organic fertilizer. The illustration demonstrates AD's ability to function as a sustainable solution by transforming waste into valuable resources. Converting manure into biogas through AD recovers energy without adding new carbon to the environment (Holm-Nielsen, 2009). Digestate is used as a fertilizer to retrieve nutrients and reduce organic matter depletion in soils due to agricultural activities (Gebrezgabher S. A., 2010).

4.1.2 Environmental Implications

The literature presents diverse findings on the impact of AD on NH_3 emissions. Some studies indicate increased emissions from digested manure, while others see reduced emissions compared to untreated manure (Lemes Y. M., 2023). This can be attributed to the emission measurements applied, generally, changing due to the effects of environmental conditions (Miranda, 2015). By implementing AD for manure management, the release of methane CH_4 and nitrous oxide (N_2O) gases is minimized during storage, reducing the overall emissions of GHGs. AD generates renewable energy and a digestate that works as a fertilizer, reducing the reliance on fossil fuels and artificial fertilizers in farming while contributing to agricultural sustainability and financial benefits (Börjesson, 2006).

Research indicates that approximately small-scale plants have a GHG reduction of 67–75 kg CO_2-eq per ton of manure, while large-scale plants have a GHG reduction of 111–120 kg CO_2-eq per ton. The majority of this decrease was attributed to the avoided use of fossil fuels in energy generation and the prevention of CH_4 emissions during biomass storage (Møller, 2022). The integration of AD with solid-liquid separation systems has the potential to decrease up to 60% in GHG emissions. In the case of NH_3, due to the elevated pH values in the digestate, the emissions are higher than those of untreated manure. In addition, NH_3 emissions may rise as a result of AD due to the elevated levels of Total Ammoniacal Nitrogen (TAN) found in the digestate, especially when no cover is employed during storage (Aguirre-Villegas, 2019). Furthermore, the elevated levels of NH_3 and pH in the digested slurry lead to greater NH_3 losses after spreading, but these losses can be mitigated by the application of manure under optimal conditions, such as cold and humid weather with no wind, and by acidification (Pedersen J. &., 2023). Consequently, implementing efficient management techniques that complement AD, such as manure storage covers, acidification, and appropriate soil application, is essential for emissions reduction.

4.1.3 Economic Implications

A study made by Gebrezgabher in 2010, analyzed an anaerobic digestor plant in the Netherlands, where the facility was established in 2007 by 50 swine producers with an annual input capacity of 70,000 tons. The project utilizes pig manure with various co-digestion resources, including poultry manure, energy maize, food waste, and flower bulbs. A combined heat and power (CHP) plant combusts biogas to produce electricity and heat. The generated electricity is supplied to the local grid at a market price of D 0.06 per kWh, accompanied by an MEP (Environmental quality of electricity production) subsidy of D 0.097 per kWh for a period of 10 years. The facility also produces digestate, which is then pressed into solid and liquid fractions. Reverse osmosis (RO), often known as green fertilizer, has an NPK composition of 6.8, 0.6, and 11.5 kg ton1, respectively. RO is classified as animal manure for their use with an application limit of 170 kg; nevertheless, it can be utilized in trial projects as a substitute for synthetic fertilizers (Gebrezgabher S. A., 2010). The project's longevity was unknown because of the limited long-term experience with digesters in the Netherlands. However, it was presumed that a well-constructed and maintained digester would possess a lifespan of 20 years.

The study's results were categorized into two groups of scenarios: one in which the plant receives an MEP subsidy for electricity generation and another in which it does not receive any subsidy, with RO regarded as either animal manure or artificial fertilizer. All scenarios, excluding the no-subsidy scenario, provide a positive net present value (NPV). The maximum NPV was seen in the RO as a green fertilizer scenario, attributed to augmented income from the sale of RO as a green fertilizer and diminished transportation costs of concentrates. The absence of subsidies gave a negative NPV, indicating that subsidies significantly influence the profitability of the plant (Gebrezgabher S. A., 2010).

De Dobbelaere et al 2015 analyzed several cases to figure out the practical and economical effects for setting up and maintaining anaerobic digesters in farming facilities. This research provided important insights into the capital and operational expenses associated with the installation and maintenance of anaerobic digesters in agricultural contexts. The following two particular cases are relevant to this research.

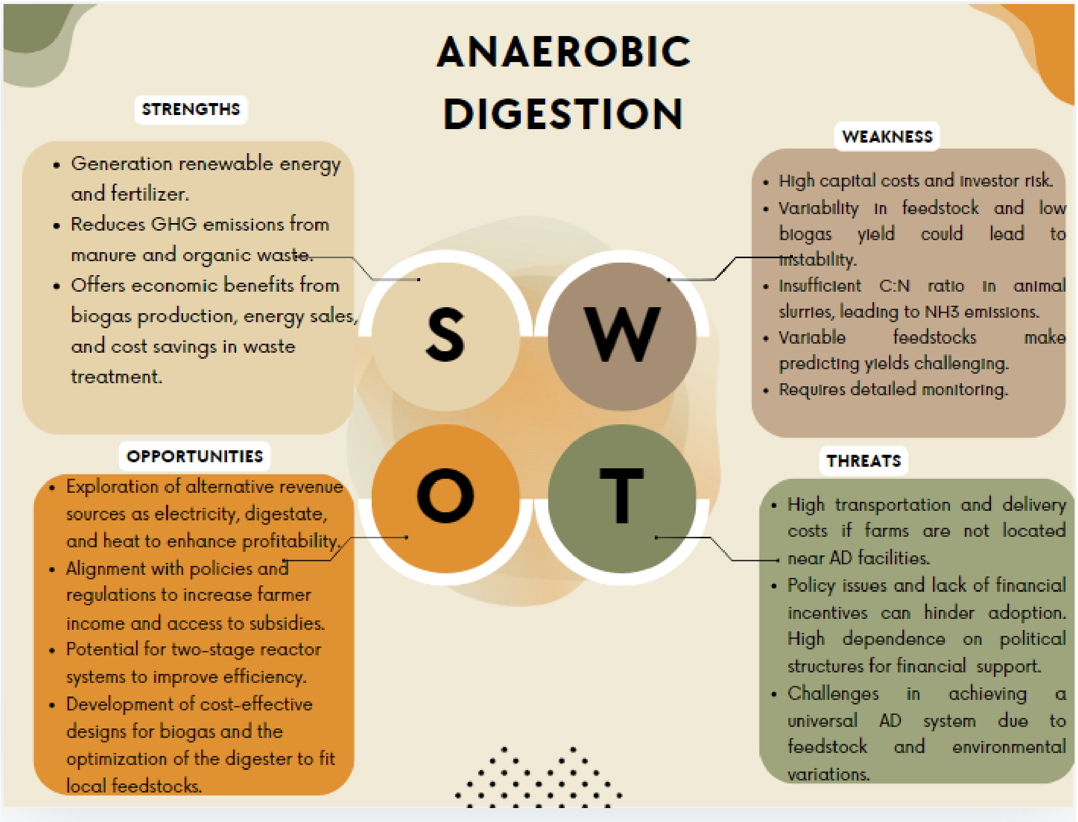
The first case study is in Belgium on a dairy farm in Dendauw examines the implementation and operation of a micro-digester on a small cattle farm with 70 cows. The digester has been exclusively dedicated to processing cow manure since September 2014. Although the cows grazed outside for two months, no manure supply problems occurred because enough reserves were established in the previous months. The installation procedure was simple, with the digester constructed in two days and the entire system operating within three days. The project had an initial investment of €95,000 for the installation of a combined heat and power (CHP) unit, with an additional allocation of €5,000 to €10,000 for infrastructure adjustments in the farm. The digester's operational expenses include a maintenance contract costing €3,500 per year and administrative oversight expenses costing €1,000 per year, with a labor demand of 0.5 hours daily. The projected revenues result from replacing 56,000 KWh of power use on this farm, amounting to an average of €7,500 to €11,000. Additionally, through the production of green power and heat certificates. The calculated payback period is between 5 and 7 years (De Dobbelaere, 2015).

The next example analyzes the construction of an anaerobic digestion facility in a company called Den Eelder that intends to treat 7,500 m³ of cow slurry in the Netherlands. The facility generates almost 50% of the power needed by the linked dairy processing farm, producing 480,000 kWh per year. Besides power, the plant generates heat, which is employed to sustain the reactor's temperature. Biogas is produced but is not anticipated for use in a combined heat and power (CHP) unit; rather, it is routed to a boiler for application in the dairy processing plant. The digestate generated from the anaerobic digestion process is partially applied to the farm's farmland and grassland, while the surplus is directed to a composting plant for pasteurization. The project's investment comprised an initial capital outlay of €300,000 for the anaerobic digestion facility and a further €150,000 for the combined heat and power unit. Operational expenses are projected to range from €15,000 to €20,000 annually. The plant's revenue sources include around €40,000 yearly from energy generated for on-site use, in addition to subsidies from the Dutch government under the SDE (Stimulering Duurzame Energieproductie) program. The anticipated payback period ranges from 6 to 7 (De Dobbelaere, 2015).

4.1.4 SWOT

From an economic perspective, AD could offer benefits from biogas production, energy sales, and cost savings associated with organic waste treatment and fertilizer (Hjorth, 2008). It also reduces GHG emissions from both manure and organic waste. This practice facilitates sustainable agriculture by generating renewable energy and fertilizer promoting the circular utilization of resources (Rekleitis, 2020). However, researchers have conducted several investigations on biogas production through anaerobic co-digestion of manure and agricultural wastes, and still no cost-effective methods exist for upgrading and refining the produced biogas (Lemes Y. M., 2023). A major prerequisite for this technology to be cost-effective is to locate the livestock and agricultural farms as close as possible to the AD so that huge amounts of residue and animal manure are available (Neshat, 2017). Otherwise, the cost of collecting massive quantities of biomass residues, their transportation, and delivery at the plant gate would not be justified. According to the Environmental Protection Agency (EPA), the main barriers to widespread digester use include high capital costs, investor risk, variability in feedstock and byproduct markets, and policy issues. Problems such as low biogas yield and process instability are often encountered in decentralized anaerobic digestion biogas production, preventing this technique from being widely adopted (Chen Y. C., 2018). There are many challenges to having a universal AD and optimizing parameters due to the variation of feedstocks and environmental conditions. The main barriers that hinder the universal development of this technology are animal slurries that frequently have a low concentration of C, which is insufficient for achieving commercial CH_4 production. In addition, the amount of N provided by slurry often passes the amount needed for microbial development in the anaerobic digestion process, resulting in an insufficient C:N ratio leading to NH_3 emissions (Hamelin, 2011). Consequently, predicting possible gas and fertilizer yields is challenging due to the complex and variable characteristics of the various manures and residues. Therefore, to solve these problems a digester needs to be adjusted and calibrated to fit the local feedstocks and climate. Furthermore, operators need to know the specific parameters for monitoring and control, such as alkalinity, volatile acids, pH, feed rate, and temperature, making it more challenging (Wang J. , 2014). Also, it is essential to have detailed and recent inventory data on the composition of manure before and after AD operation to accurately quantify the trade-offs and net impacts. Evaluating manure composition before and after facilitates the identification of whether or not the intended objectives and efficiencies for producing biogas and reducing emissions are being accomplished (Aguirre-Villegas, 2019). Additionally, dividing the CSTR into a two-stage reactor, with the first stage being a thermophilic reactor and the second stage being a mesophilic reactor, emerges as a superior and effective technology for AD (Nasir I. M., 2014).

AD addresses multiple issues in the Netherlands, such as excess manure and pollution, by recycling organic waste into biogas for electricity and biofertilizers (Tiwary, 2015). The successful adoption of this sustainable method relies heavily on a political structure that establishes and offers a financially appealing motivation for operating anaerobic digestion facilities (Van Rooijen, 2006). To ensure the profitability of biogas plants in the Netherlands without relying on subsidies, it is recommended to explore alternate sources of revenue, such as digestate and heat, as well as reducing feedstock prices by establishing contracts with arable farms for supply (Gebrezgabher S. A., 2010). Further, AD is attractive when it is aligned with policies, regulations, and the generation of external products that can increase the income of the farmers who are willing to install it.



ANAEROBIC DIGESTION

STRENGTHS

- Generation renewable energy and fertilizer.
- Reduces GHG emissions from manure and organic waste.
- Offers economic benefits from biogas production, energy sales, and cost savings in waste treatment.

WEAKNESS

- High capital costs and investor risk.
- Variability in feedstock and low biogas yield could lead to instability.
- Insufficient C:N ratio in animal slurries, leading to NH3 emissions.
- Variable feedstocks make predicting yields challenging.
- Requires detailed monitoring.

OPPORTUNITIES

- Exploration of alternative revenue sources as electricity, digestate, and heat to enhance profitability.
- Alignment with policies and regulations to increase farmer income and access to subsidies.
- Potential for two-stage reactor systems to improve efficiency.
- Development of cost-effective designs for biogas and the optimization of the digester to fit local feedstocks.

THREATS

- High transportation and delivery costs if farms are not located near AD facilities.
- Policy issues and lack of financial incentives can hinder adoption. High dependence on political structures for financial support.
- Challenges in achieving a universal AD system due to feedstock and environmental variations.

Figure 4: SWOT Analysis Anaerobic Digestor

4.2 Composting

4.2.1 Description

Composting is an aerobic biological process that involves the breakdown and stabilization of organic matter. Microorganisms break down organic material to make it stable and rich in nutrients. However, special moisture and oxygen conditions are often required (Viaene, 2016). The advantage of composting is that the nutrients contained in manure are recycled, creating a stabilized product that can be used as fertilizer and has the potential to reduce greenhouse gas emissions and improve soil health (Pardo, 2015) . This process effectively reduces N_2O and CH_4 emissions compared to static solid waste storage. To achieve efficient animal manure composting that yields a high-quality product, it is necessary to effectively manage various factors that may be limited by certain chemical properties of animal manure, such as moisture, porosity, and nitrogen content (Maheshwari, 2014). The composting process reduces the amount and volume of organic matter by approximately 50%, resulting in lower transportation and application costs as nutrients become more concentrated and the fertilizer value of the material increases (Malley, 2005).

4.2.2 Environmental Implications

Composting involves several factors that influence the emissions produced, including the type of waste, temperature, treatment method, and duration (Pardo, 2015). Consequently, it is challenging to accurately predict the quantity of emissions that may be avoided by implementing this solution. Composting manure could also have some drawbacks, such as GHG generation during production (Viaene, 2016). Under ideal conditions, it is possible to compost animal manures with a low C/N ratio without substantial releases of NH_3 and N_2O (Varga, 2024). However, the loss of nitrogen throughout the composting process is unavoidable, so researchers must incorporate NH_3 and N_2O results to develop a comprehensive knowledge of the potential tradeoffs between different forms of N emissions (Chadwick D. S., 2011).

Using research by Pardo (2015) and Hou (2015) it was found that, on average, NH_3 emissions from composting were 52% higher than emissions from traditional storage. On the other hand, CH_4 and N_2O emissions were lower, going down by 71% and 49%, respectively. In addition, composting has the potential to reduce GHG emissions when applied to land, as opposed to not treating manure and simply putting it in the soil (Hou Y. V., 2015). A study performed in Canada by Pattey 2005 on composting cattle manure revealed a favorable correlation between CH_4 emissions and temperatures. As the temperature increased, all forms of manure storage had greater rates of CH_4 production. As temperatures decreased and organic material decomposed, the manure became more porous, causing CH_4 emissions to decline. Also, CO_2 emissions from composting manure and slurry were high at the beginning (50–200 lg) but decreased with time (Pattey, 2005). These findings highlight the importance of controlling temperature conditions in manure storage composting procedures to reduce GHG, including CH_4. Therefore, effective temperature control may play a critical role in reducing the environmental consequences of composting.

4.2.3 Economic Implications

Composting operations can generally be categorized into two types: off-site and on-site. A key consideration in off-site composting is the transportation cost associated with collecting agricultural waste, which contributes to increased overall waste disposal costs. Estimating the cost of composting is challenging due to the significant variability in factors such as the type of raw materials used, the scale of investment in equipment, and the overall economies of scale (Hsu, 2021). Additionally, the economic benefits of composting are closely tied to the amount of chemical fertilizer that can be replaced by the compost produced, further influencing the overall cost-effectiveness of the process.

A case study conducted in Italy examined manure composting on two farms. The first composting plant in the province of Caserta processes about 600 tons of manure per year and is managed by

CERMANU, a research institution of the University of Naples. This facility serves as a prototype for on-farm compost production with refined windrows. The second plant mentioned is located on a private farm in Matera province and processes around 500 tons of manure annually. The compost produced at the ST plant is reused as organic fertilizer on the farm's arable land. Production costs at the Caserta plant vary between 10 and 30 euros per tonne, depending on the type of residue mixed with the manure, with wood chips being the most expensive and corn stalks being the cheapest. Likewise, the costs at the Matera factory are between 14 and 31.5 euros per ton. In contrast, on the Italian market, a ton of commercially produced compost, including transport to the final destination, can cost up to €250 per ton (Pergola, 2018).

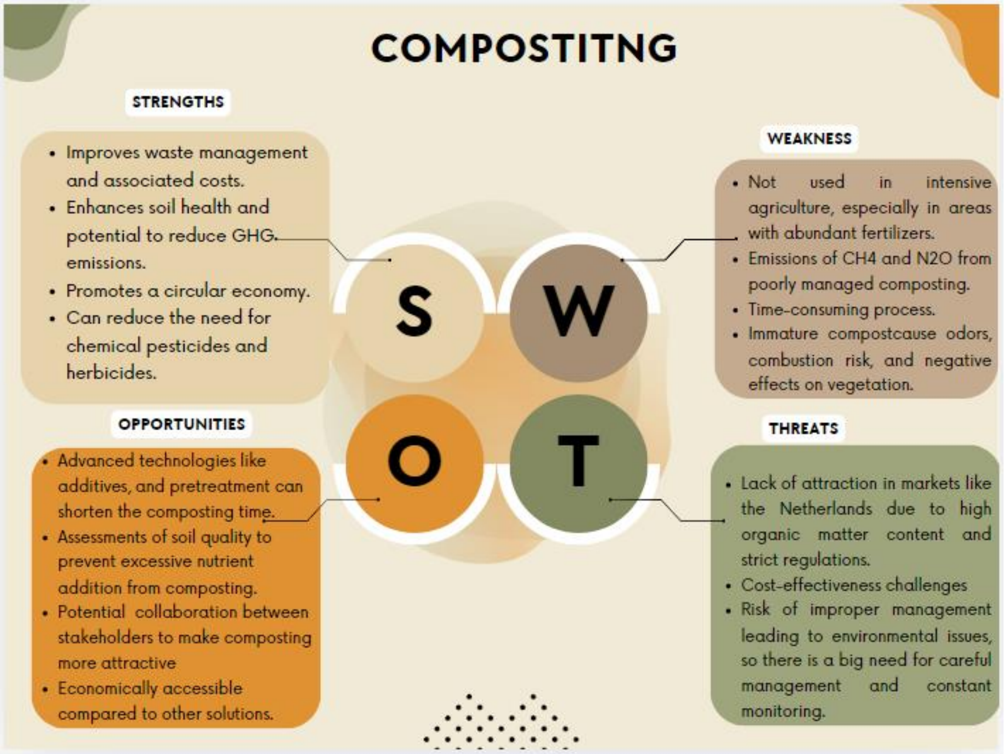
Another case study from Juncosa, Les Garrigues, Spain, focuses on a central composting plant that processes cattle manure from 66 farms, processing approximately 15,000 m^3 per year. The facility uses a twisted windrow composting technique with a manure to bulk material ratio of 9:1. The need for swelling material depends largely on the moisture content of the raw manure, which is between 65% and 80%. This composting process results in a significant reduction in the amount of manure and produces high-quality compost with an annual yield of between 4,000 and 5,600 tons. The compost is sold outside the region at an average price of €27 per ton. The operating and investment costs for the facility are approximately €6 per tonne of manure, with each farmer making additional contributions to cover transport costs to the composting facility (Bonmatí Blasi, 2010).

An analysis of dairy manure compost pelletization in the United States showed great potential for profitability, with an estimated production cost of $77 per ton and a market value of approximately $110 per ton per year. A sensitivity analysis conducted as part of this study also shows that the costs of personnel, raw materials, and equipment have the greatest influence on production costs. Therefore, implementing cost reduction strategies in these areas could increase the profitability of the process (Alege, 2021).

4.2.4 SWOT

When used correctly, this practice improves waste management and associated costs, improves soil health, reduces greenhouse gas emissions, and promotes a circular economy, making it relevant to sustainable agriculture (De Corato, 2020). However, composting is rarely used in intensive agriculture, especially in areas with abundant fertilizers (Viaene, 2016). Composting management can lead to difficulties that deteriorate soil quality, which can have negative environmental consequences such as air pollution from greenhouse gases, acidification, and contamination of surface and groundwater (Goldan, 2023). Inadequate management practices can lead to the formation of compost heaps that emit CH_4 and N_2O, contributing to global warming (Lim et al., 2016). In addition, high temperatures during composting lead to the loss of C and N in the form of CO_2 and NH_3 (Walling, 2020). Since composting is a time-consuming process, N_2O emissions could increase due to the mineralization process in the nitrogen cycle. Although advanced technologies such as additives and pretreatment processes can shorten composting time, they often lack cost-effectiveness (Chen L. C., 2023). Finally, using immature compost can cause various problems such as the generation of odors and the risk of combustion during storage, and the addition of immature compost to the soil has negative effects on vegetation (Ji, 2023).

An effective approach to deal with these difficulties is to use compost in moderation and regularly assess soil quality to prevent excessive nutrient addition. Therefore, the use of compost on the soil surface should depend on its maturity and stability level, which can be evaluated by analyzing its physicochemical properties and phytotoxicity (Huang, 2017). Additionally, well-applied compost can reduce the need for chemical pesticides and herbicides by creating robust and balanced soil (Goldan, 2023). The Dutch market is not attracted to composting, although it is more economically accessible than AD and RO due to the low initial investment. This is due to the high organic matter content in the soil and strict regulations on land erosion (Hou Y. V., 2018). Finally, it is important to emphasize that effective composting systems require careful management and constant monitoring to ensure that all materials are properly optimized. Governments, scientists, composting companies, and farmers need to work together to make this technology cost-effective and efficient.



COMPOSTITNG

STRENGTHS

- Improves waste management and associated costs.
- Enhances soil health and potential to reduce GHG emissions.
- Promotes a circular economy.
- Can reduce the need for chemical pesticides and herbicides.

WEAKNESS

- Not used in intensive agriculture, especially in areas with abundant fertilizers.
- Emissions of CH4 and N2O from poorly managed composting.
- Time-consuming process.
- Immature compostcause odors, combustion risk, and negative effects on vegetation.

OPPORTUNITIES

- Advanced technologies like additives, and pretreatment can shorten the composting time.
- Assessments of soil quality to prevent excessive nutrient addition from composting.
- Potential collaboration between stakeholders to make composting more attractive
- Economically accessible compared to other solutions.

THREATS

- Lack of attraction in markets like the Netherlands due to high organic matter content and strict regulations.
- Cost-effectiveness challenges
- Risk of improper management leading to environmental issues, so there is a big need for careful management and constant monitoring.

Figure 5: SWOT Analysis Composting.

4.3 Slurry Acidification

4.3.1 Description

Slurry acidification is the process of treating manure with an acid to reduce NH_3 and GHG levels while improving the fertilizer properties of the manure (Sørensen, 2009). This manure treatment technique lowers the pH of the manure. This reduces the release of NH_3 gases as well as microbial activity, thereby reducing CH_4 and $N_2$0 emissions during storage (Fangueiro D. H., 2015). The effectiveness of acidification depends on the specific acid additive, the method of administration, the manure, and the time of its administration (Borgonovo, 2019). Sulfuric acid is the most used acid due to its cost-effectiveness and ability to efficiently lower manure pH (Ma, 2022). However, excessive use of sulfur beyond the required amount can result in sulfate leaching. The acidification process can take place in-house, in storage tanks, or during field application, as shown in Figure 6. On a daily or weekly basis, in-house acidification refers to the process of adding acid to the slurry in storage facilities, such as slatted floors. Acidification in storage tanks is performed before the slurry is removed from the tank. Finally, field application occurs when the slurry is applied to the soil (Ten Hoeve, 2016). Field application reduces NH_3 emissions in the field but has no impact on emissions from animal housing and slurry storage (Nyord, 2013). Therefore, treating slurry with acid before field application often leads to a higher decrease in NH_3 emissions (Lemes Y. M., 2022).

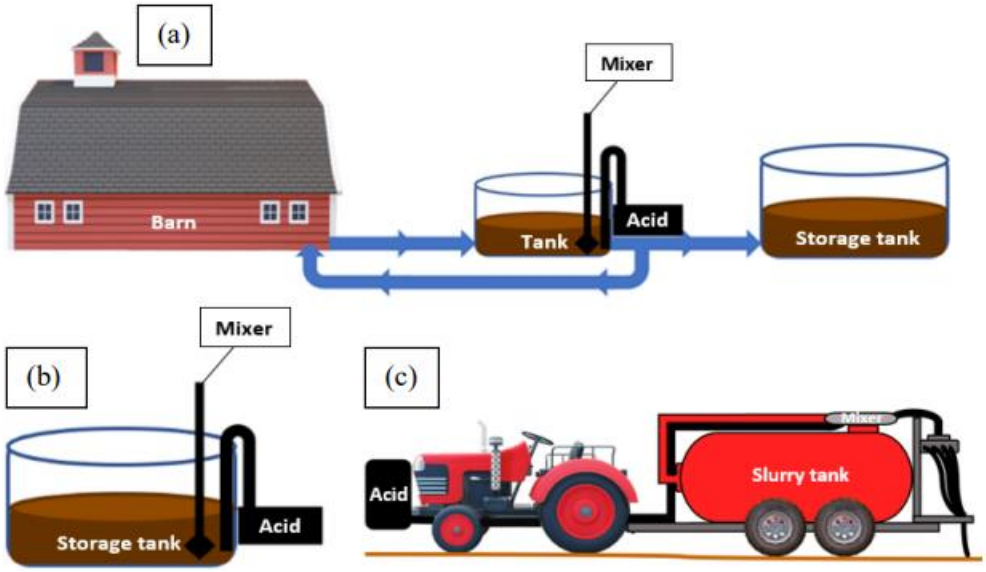


Figure 6: Ways for acidifying animal slurry as shown in the image. A) In-house where the feedstock. B) In a storage facility C) Acidification in the field (Larsson, 2018).

4.3.2 Environmental Implications

On-farm acidified slurry shows higher net nitrogen mineralization and immobilization in soil due to increased decomposable organic matter. Untreated slurry resulted in lower soil mineral nitrogen content, potentially due to increased nitrogen immobilization or gaseous losses. Acidified cattle slurry has higher dry matter and nutrient content, with a similar ammonium-to-total nitrogen ratio and N/S ratio of about 1.3. Acidification significantly reduces NH_3 emissions, with higher pH reduction leading to lower emissions. For example, acidified slurry to pH 5.5 reduces NH_3 emissions to 26.6%, and at pH 4.8 to 2.5%. Laboratory results show a 46% reduction in total N loss and a 68% reduction in total NH4-N applied within 14 days of application (Langley-Randall, 2024). Another study reported 61% reduction in CH_4 and 75% reduction in NH_3 emissions across acidification in storage periods (Misselbrook, 2016). Acidification improves the fertilizer value of slurry by increasing soil NH4-N concentrations without raising soil solution NO3-N levels (Langley, 2022). The implementation of this technique has the potential to improve sustainability in livestock agriculture. The previous results promote the adoption of slurry acidification for farmers who have the knowledge and resources as a method for reducing NH_3 and GHG emissions while enhancing proper nutrient management for the soil. It is relevant to know that acidification can lead to the over-application of sulfur, therefore, it requires careful management to avoid soil nutrient imbalances (Pedersen J. &., 2023). Long-term impacts of acidification on N leaching and environmental nitrogen losses need a systematic analysis, continuous monitoring, and dynamic management practices to maintain low pH during storage and maximize emission reduction benefits (Malique, 2021).

4.3.3 Economic Implications

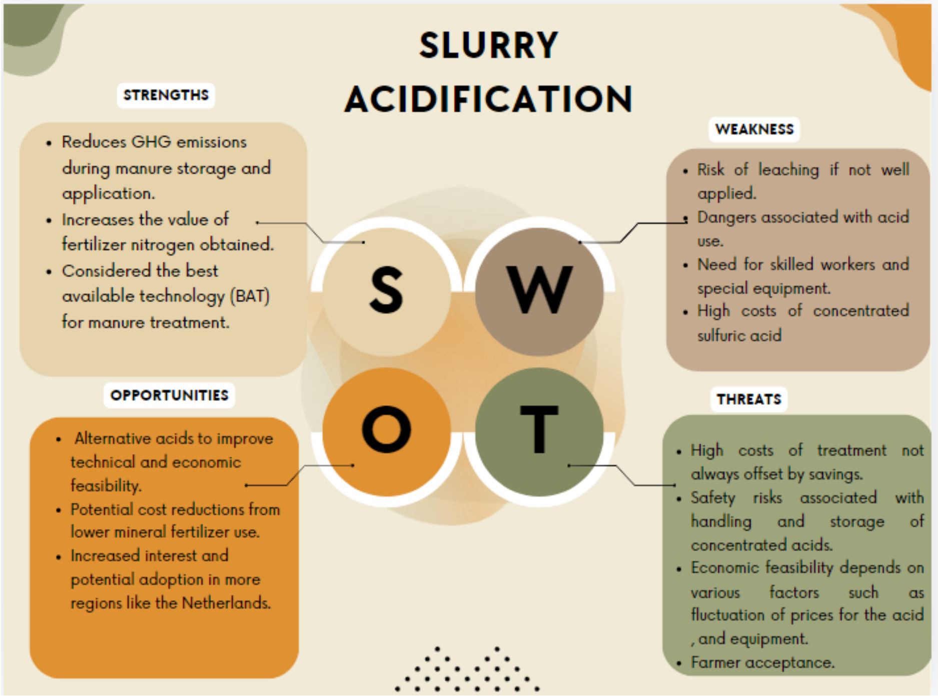
The application of acidification will incur additional financial expenditures for the farms; however, these costs can be mitigated by increasing the nitrogen and sulfur fertilizer value of slurry (Langley, 2022). The cost per cubic meter of treated slurry ranged from 2.64 euros for alum to 0.38 euros for sulfuric acid. Therefore, sulphuric acid was shown to be more economically viable (Kavanagh, 2019). The acidification in both the field and the slurry tank is significant. At equivalent pH levels, both kinds of acidification incur similar costs of 1-2 euros per ton of acidified slurry (Birkmose T. &., 2013).

Acidification in the tank has been shown to reduce ammonia volatilization from the barn by 65% compared to untreated slurry with an approximate cost of 60 euros per livestock unit (Kai, 2008). Acidification in the stable is the most expensive approach due to high investment costs and low capacity. In swine production, the initial investment is minimal, with a calculated cost of 3-3.5 euros per ton of acidified slurry. However, the cost for in-house cattle acidification is only implemented from an environmental perspective due to high costs and the difficulty of recovering the initial investment (Birkmose T. &., 2013). The primary constraint of this approach is the management of concentrated acid, which must be executed by specialized personnel, resulting in rising costs. Furthermore, the lack of specialized equipment for acidifying solid manures and separating the solid portion limits the potential field applications of the treatment (Fangueiro D. H., 2015).

4.3.4 SWOT

The main benefits of manure acidification are reduced GHG emissions during manure storage and application and the value of fertilizer nitrogen obtained (Wierzchowski, 2021). However, acidifying the manure can result in losses due to leaching as mineral components are dissolved. Advances in technology have been unsuccessful due to foaming and the likely dangers associated with the use of acids (Björs, 2023). Currently, the main limitation of this technology is the handling of highly concentrated acids, a task that requires the expertise of highly skilled workers. This is due to the need for precise handling and safe storage of acids to minimize risk, which in turn increases costs. Additionally, concentrated sulfuric acid is used, and the costs associated with the acid often exceed the savings achieved by purchasing fertilizer (Borusiewicz, 2017). The lack of specialized equipment for acidifying solid manure limits the scope of this treatment. Options are available to replace concentrated acids, but further research is required to improve their technical and economic feasibility. The economic feasibility of manure acidification depends on factors such as the costs associated with the type of acid, equipment, application method, and the potential cost reductions from lower mineral fertilizer use (Stokstad, 2019).

Slurry acidification has attracted great interest in Denmark as it is considered the best available technology (BAT) for manure treatment and some encouraging results have been achieved in reducing emissions from pig manure acidification (Petersen S. O., 2016). Acidifying manure is an expensive treatment and sometimes the costs resulting from this treatment are not offset by the savings achieved. Large-scale studies are needed to assess the reproducibility of this approach in the Netherlands, taking into account factors such as long-term soil impacts and farmer acceptance (Fangueiro D. H., 2015).



SLURRY ACIDIFICATION

S W O T

STRENGTHS

- Reduces GHG emissions during manure storage and application.
- Increases the value of fertilizer nitrogen obtained.
- Considered the best available technology (BAT) for manure treatment.

WEAKNESS

- Risk of leaching if not well applied.
- Dangers associated with acid use.
- Need for skilled workers and special equipment.
- High costs of concentrated sulfuric acid

OPPORTUNITIES

- Alternative acids to improve technical and economic feasibility.
- Potential cost reductions from lower mineral fertilizer use.
- Increased interest and potential adoption in more regions like the Netherlands.

THREATS

- High costs of treatment not always offset by savings.
- Safety risks associated with handling and storage of concentrated acids.
- Economic feasibility depends on various factors such as fluctuation of prices for the acid , and equipment.
- Farmer acceptance.

Figure 7: SWOT Analysis Slurry Acidification.

4.4 Biochar

4.4.1 Description

Biochar is a carbon-rich substance produced through a process called pyrolysis. Pyrolysis involves heating biomass such as wood or agricultural waste to high temperatures with limited oxygen (Weldon, 2022). This material is derived from organic materials and has the potential to be used in agriculture due to the beneficial effects of reducing NH_3 emissions when applied as a cover to manure (Baral, 2023). Biochar has high porosity, slow decomposition, low density, and high nutrient retention properties. Unlike other organic materials used as manure covers, biochar can serve as a physical barrier for an extended time (Holly & Larson, 2017). As shown in Figure 8, the process of pyrolysis is critical for producing biochar. This process works by converting biomass inside a pyrolysis reactor with high temperatures and limited amounts of oxygen. As a result, products such as synthetic gas, bio-oil, and biochar are produced at high temperatures with limited oxygen.

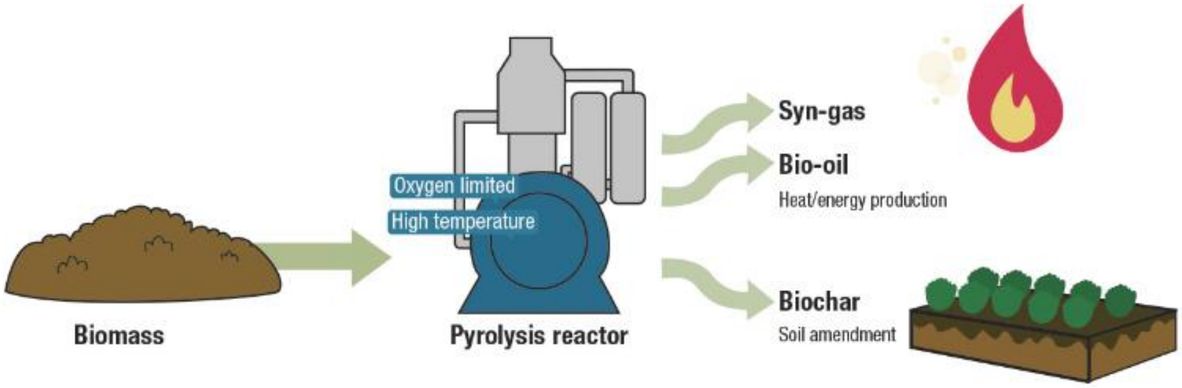


Figure 8: The image shows the production process of biochar that can be utilized as a floating cover to mitigate ammonia emissions in manure in agricultural soils while addressing issues around manure storage (Sanford, 2019).

The use of biochar as a biocover in manure storage structures has the potential to provide a range of environmental benefits such as the absorption of valuable nutrients and a reduction in gas emissions and odor (Dougherty B. , 2016). In general, biochar covers can help extract nutrients, eliminating the need for compressors or additional manure tanks. Soils in which biochar is mixed with dairy manure produce fewer greenhouse gas emissions and store more carbon and nitrogen (Sarkhot, 20212). Another advantage is that it absorbs additional nutrients from wastewater and creates a loop for recycling (Ghezzehei, 2014).

4.4.2 Environmental Implications

According to Di Petra E.S., 2021 findings in a study to evaluate biochar covers, the thickness of a biochar cover influences the reduction of NH_3 levels. Increasing the thickness can improve the effectiveness of reducing NH_3 emissions. For example, using a 2-cm layer of biochar to cover digestate significantly reduces 58% in NH_3 emissions. A laboratory experiment was conducted in a controlled environment to examine NH_3 from two sets of slurry samples—one with a cover and one without. The study replicated the process of storing slurry and then applying it to the soil. The control group, which was not covered with slurry, had an average ammonia content of 24.2 mg/m3. The experimental group that was provided with a cover reduced the average NH_3 content to 6.14 mg/m3 (Berg, 2006).

In a separate trial made by Di Petra., 2020, biochar was produced using pyrolysis at a temperature of 550 °C using a combination of wood chips as feedstock. The manure was stored in a climate-controlled room using six 5-liter cylindrical glass containers, and the average temperature of the room was 18.6 °C. The control group, which did not have a biochar cover, had cumulative NH_3 emissions of 35.61 g m2, and the manure covered with biochar NH_3 emissions decreased to 7.78 g m2, resulting in a reduction of 78%. Furthermore, the bio-cover's effectiveness in reducing emissions decreases over time as the storage period increases. The study found that by the 29th day, the emission rates of the control manure and the biochar-covered manure were close, at 12.5 mg m2/h and 7.6 mg m2/h, respectively. In the case of CH_4 emissions, the control had a measurement of 413.2 g/m2, whereas the manure cover with biochar had a measurement of

275.5 g/m2, indicating a 33% decrease in methane emissions. However, another lab-scale experiment study found that CH_4 generation increased with the duration of most of the trials that use biochar. This lab-scale experiment showed that treatments of biochars with different properties result in different mitigation or generation effects for the targeted gases over the duration of trials.The greatest decrease in emissions occurred right after the application of biochar, as biochar functioned as a physical barrier to restrict the release of NH_3 from the slurry surface to the atmosphere (Holly & Larson, 2017). Also, the total N content dropped 1.5 times with biochar covers compared to the control groups mainly due to the high biochar porosity that might adsorb N (Meiirkhanuly, 2020). These studies suggest deeply analyzing the relationship between emissions released and biocovers to understand their overall environmental impact better.

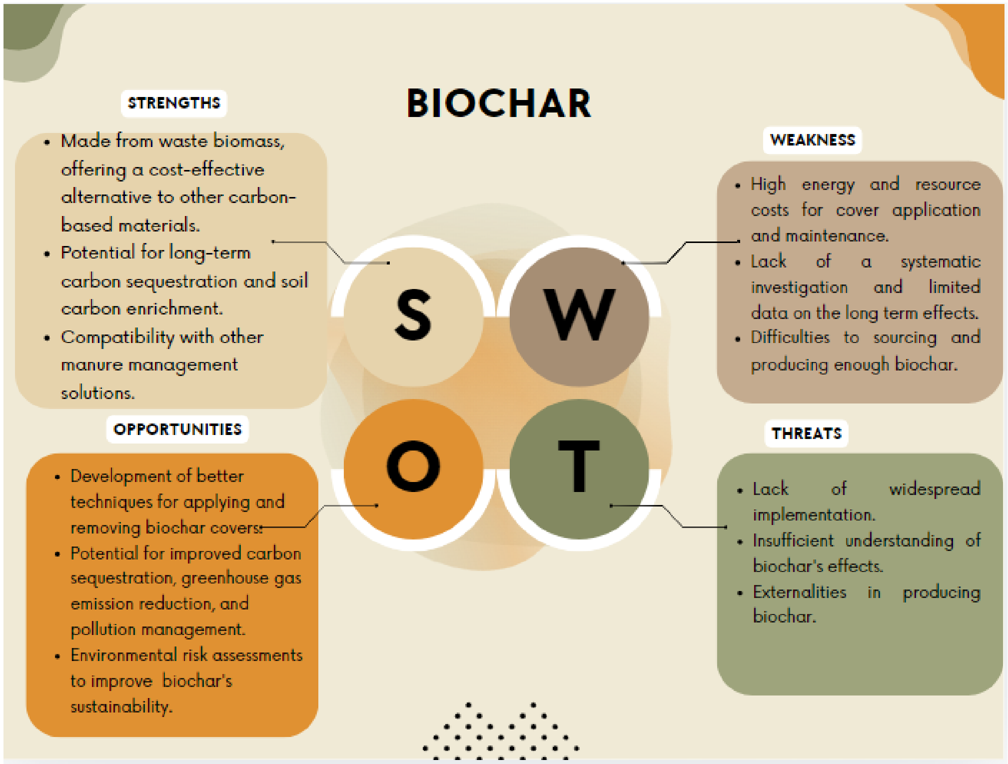
4.4.3 Economic Implications

Similar to composting, cost estimation for biochar production is significantly different and dependent on several aspects, including the type of agricultural waste or crop residues used as feedstock and the pyrolysis process applied, whether fast or slow. These variables have a significant impact on production costs, as feedstock availability, processing conditions, equipment requirements, scale of production, and local market conditions play a critical role (Campion, 2023). Despite significant interest in biochar production as a carbon sequestration method, the infrastructure for its production remains developing. Furthermore, producers contemplating the use of biochar as a cover must consider supplementary management factors (Sanford, J. R. 2019). Biochar, therefore, offers a potentially advantageous option for manure treatment, particularly in consideration of its environmental benefits, including carbon sequestration and waste reduction.

However, the scarcity of biochar and its inflated price of 300–500 € t−1 have resulted in most findings being derived from lab experiments and mathematical calculations. Despite the enthusiasm of academics and extensive publication efforts, the adoption of biochar farming is progressing so slowly that it could hinder the total transition of the technology into the commercial sector (Vochozka, 2016). There are no studies that review the profitability of applying biochar as a cover of manure to reduce emissions because most of the experiments performed in the past are laboratory. Clovery a platform for scaling climate action solutions, estimates that the average price of biochar in 2023 was $131 per metric ton. However, there are limited studies that assess the economic profitability of using biochar as a manure cover specifically to reduce emissions. Most of the existing research on this application has been confined to laboratory experiments, which provide valuable insights into its effectiveness in controlled settings but do not fully capture the operational costs or economic benefits at the farm scale.

4.4.4 SWOT

Despite their benefits in reducing gas emissions, biochar covers have not been widely implemented. Their use is sometimes unjustified due to energy and resource costs as well as application and maintenance problems of the coverage. If it is not managed sustainably, these factors can negate some of its environmental benefits and make it less attractive to farmers (Dougherty B. , 2016) . To this date, there has been no systematic investigation of the effect of biochar on organic matter quality and carbon speciation. However, these properties are critical in determining the long-term stability and soil carbon sequestration potential when using biochar-enriched composts. There is a need for an environmental risk assessment that considers biochar's impacts on long-term carbon sequestration, pollutant releases, and soil changes to determine its sustainability (Zhang C. Z., 2019). Although soil organisms, including bacteria, fungi and fauna, are important players (Marks, 2014), there is little data to assess their response to biochar in the field (Biederman, 2017). This is due to a lack of understanding of the long-term effects of changes that biochar has at the field level. Because biochar is made from waste biomass, it offers a more cost-effective alternative to other carbon-based materials (Baral, 2023). However, further studies should focus on determining the most favorable pH and particle size distribution to improve cover longevity and nutrient absorption, as well as the techniques for applying and removing biochar covers (Dougherty B. G., 2017), to provide more accurate information on carbon sequestration, greenhouse gas emissions, and pollution management.



BIOCHAR

STRENGTHS

- Made from waste biomass, offering a cost-effective alternative to other carbon-based materials.
- Potential for long-term carbon sequestration and soil carbon enrichment.
- Compatibility with other manure management solutions.

WEAKNESS

- High energy and resource costs for cover application and maintenance.
- Lack of a systematic investigation and limited data on the long term effects.
- Difficulties to sourcing and producing enough biochar.

OPPORTUNITIES

- Development of better techniques for applying and removing biochar covers.
- Potential for improved carbon sequestration, greenhouse gas emission reduction, and pollution management.
- Environmental risk assessments to improve biochar's sustainability.

THREATS

- Lack of widespread implementation.
- Insufficient understanding of biochar's effects.
- Externalities in producing biochar.

Figure 9: SWOT Analysis Biochar.

4.5 Lely Sphere

4.5.1 Description

The Lely Sphere system separates urine and feces on the floor of the animal stalls. This method uses stainless steel dividers on the slatted floor to direct urine to the lower level while manure remains on the upper level. The system works with robots and is therefore an attractive option for manure processing as it effectively absorbs a larger amount of nutrients with less effort. This separation process of feces and urine, combined with the removal of manure gases, improves safety by limiting gas accumulation in the pits. In this process, there is a filter in the mixing pit outside the stable that captures the NH_3 in the air and converts it into nitrogen fertilizer from three mineral products for agricultural use. Then, the process has a collector that transports the solid manure to the disposal site (Kestem, 2024). The liquid nitrogen fertilizer produced, which can be either ammonium nitrate or sulfate depending on the acid used in production, is stored and can be applied to the fields as needed. This is a closed-loop system of circular farming where nutrients are efficiently recycled within the farm, minimizing waste and promoting sustainable use of manure.

Figure 10 illustrates how the Lely Sphere system works, the barn where cows stay, is equipped with ventilation systems for air circulation with autonomous vehicles collecting cow manure and directing it, along with urine, to specific areas located beneath the barn. The collected manure is subsequently converted into nitrogen fertilizer, which is stored in large tanks located outside. A tractor is then transporting this processed fertilizer to be applied back onto fields facilitating the recycling of nutrients and closing the mineral cycle.

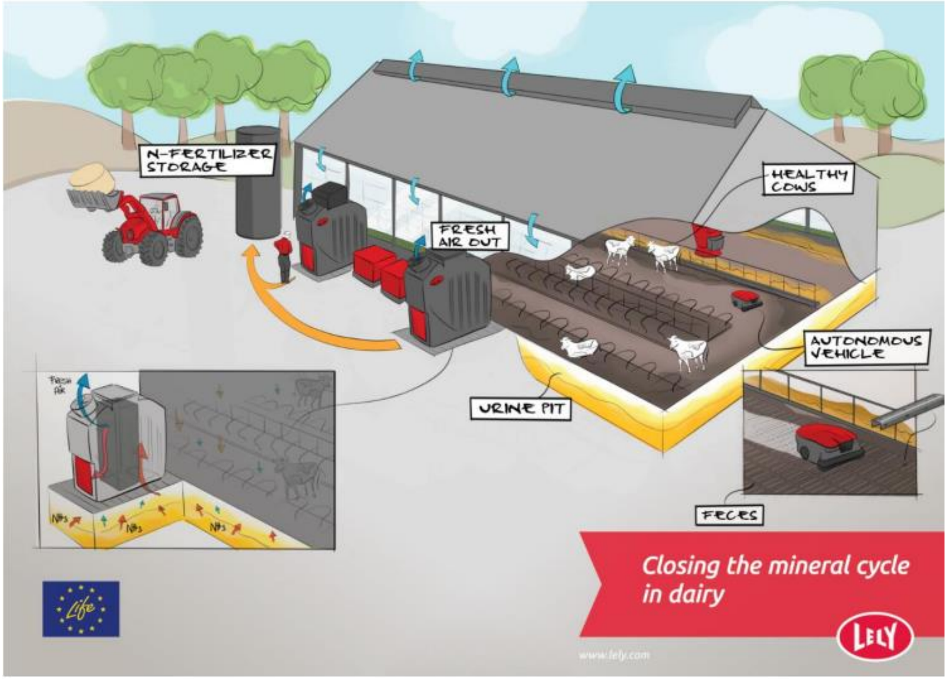


Figure 10: Lely Sphere integrates many technologies, including a customized barn floor, a robotic system for managing manure, an air extraction machine that transforms ammonia from manure fertilizer, and a container for storing the produced fertilizer. LIFE Public Database.

4.5.2 Environmental Implications

The Lely Sphere system was analyzed to ascertain its emissions. According to Kenniscentrum InfoMil, 2023, this circular housing system has an emission factor of 5 kg of ammonia per cow per year, while traditional housing systems have an emission factor of 13 kg per cow per year. This process reduces NH_3 production and prevents evaporation. This significantly decreases the open slurry surface, lowering emissions (De Bruin, 2024). In comparison to a normal slatted floor, the Lely Sphere cuts down on emissions by 77%, resulting in 3 kg of separated NH_3 per animal year (PBL VVM, 2019).

The Ministry of Infrastructure and Water Management has officially released the exact emission factor for the Lely Sphere circular barn system. This information may be found on the RAV list, which is the Ammonia Livestock Farming Regulation. Implementing the Lely Sphere concept can effectively decrease N emissions from livestock by almost 77%, compared to the standard slatted floor barn's per year. The primary objective of this system is to reduce NH_3 emissions from dairy farms while simultaneously repurposing N in NH_3 as a fertilizer for crops.

4.5.3 Economic Implications

According to the Nieuwe Oogst portal, the estimated cost of the Lely Sphere system for a farm with 120 cows and a slatted area of approximately 600 square meters is between 150,000 and 180,000 euros. This price includes delivery of stainless steel belts, a manure robot, two N-Capture units, and a silo for flushing water storage. However, depending on the barn layout and basement aisle configuration, additional manure robots and N-Capture units may be required, which would increase the overall cost. According to Lely, the system offers an annual return of around €5,000 through savings on chemical fertilizer and manure disposal, improved nutrient utilization, and improved barn conditions that promote a healthier environment for the cows. However, a more important motivation for adopting the Lely Sphere system may be the need to comply with environmental regulations.

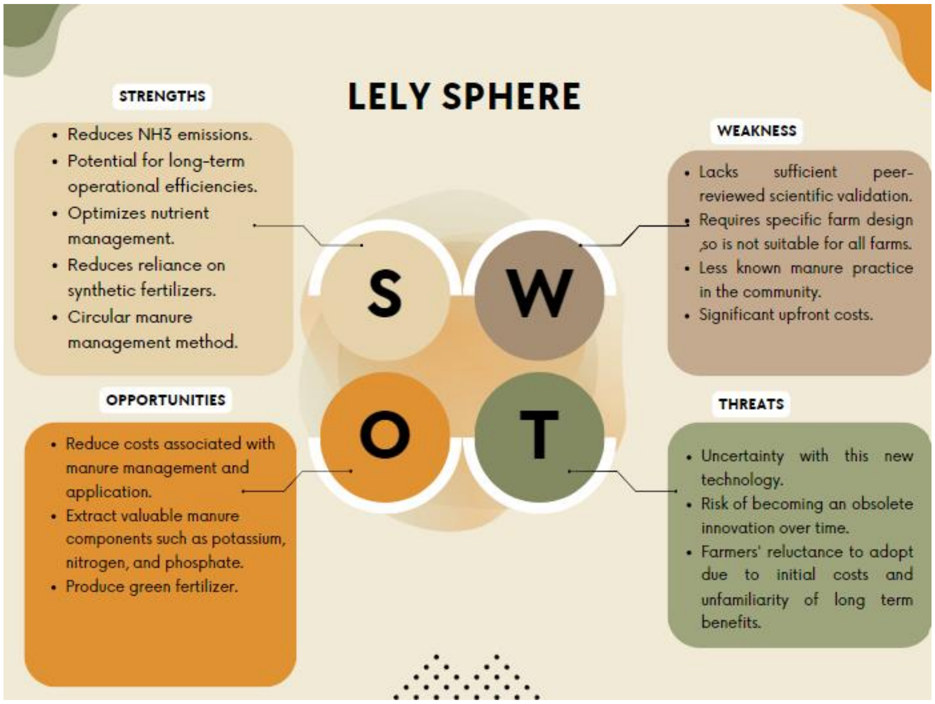
Currently, the Dutch government is providing subsidies aimed at promoting the reduction of nitrogen deposition on livestock farms and increasing sustainability, with the Lely Sphere system being a possible option that could be considered. To qualify for Sbv (Subsidie brongerichte verduurzaming) funding, nitrogen deposition in a congested Natura 2000 area must exceed the peak load threshold of 2,500 moles and farmers must commit to reducing the number of animals on the farm for five years upon receipt not to increase the subsidy. The program offers animal owners a subsidy of up to 80% of the investment costs, with the maximum funding limit being €600,000 per animal location. This initiative is part of broader efforts to support sustainable agricultural practices in the Netherlands.

4.5.4 SWOT

The environmental implications indicate that the Lely Sphere can reduce NH_3 emissions, but further scientific validation and a comprehensive understanding of the suitability of the Lely

Sphere for the agricultural market in the Netherlands are required as not enough valid peer-review data was found. Another important aspect is to determine farmers' willingness to adopt a less popular manure management method as dairy barns are mostly open systems and air handling systems, therefore, the method requires a specific design for farms. However, using this manure separation technology with their floors and robots could lead to long-term operational efficiencies for farmers reducing the effort and time needed to manage manure.

This technique increases economic benefits by optimizing nutrient management, thereby reducing reliance on synthetic fertilizers. It also helps farmers reduce costs associated with manure management and application. This is a circular manure management method as farmers would extract valuable manure components such as potassium from the urine stored under the separation floor, organic nitrogen and phosphate from the stored feces, and fertilizers from ammonium nitrate or sulfate (Lely, 2023). However, the significant upfront costs and uncertainty associated with this new technology pose a risk for farmers to integrate it into their manure management process with additional solutions. Also, as is often the case with innovations that have not been implemented at scale, they risk becoming obsolete over time.



LELY SPHERE

STRENGTHS

- Reduces NH3 emissions.
- Potential for long-term operational efficiencies.
- Optimizes nutrient management.
- Reduces reliance on synthetic fertilizers.
- Circular manure management method.

WEAKNESS

- Lacks sufficient peer-reviewed scientific validation.
- Requires specific farm design ,so is not suitable for all farms.
- Less known manure practice in the community.
- Significant upfront costs.

OPPORTUNITIES

- Reduce costs associated with manure management and application.
- Extract valuable manure components such as potassium, nitrogen, and phosphate.
- Produce green fertilizer.

THREATS

- Uncertainty with this new technology.
- Risk of becoming an obsolete innovation over time.
- Farmers' reluctance to adopt due to initial costs and unfamiliarity of long term benefits.

Figure 11: SWOT analysis Lely Sphere

4.6 Comparison

The following comparison was performed, using the findings of the SWOT assessments to explain which practice could be the most appropriate for each particular circumstance. Thus, this comparison offers a brief explanation that might assist stakeholders involved in manure management in determining the most appropriate strategy for their particular requirements. When prioritizing emissions reduction, slurry acidification offers an available and established option, particularly in regions where emission reduction is a short-term priority. This practice lowers emissions from manure storage and land application. However, its implementation is suitable for operations that have the appropriate resources and knowledge for managing acid safely and effectively (Kavanagh, 2019). Moreover, slurry acidification has the advantage of not requiring extensive infrastructural development or significant changes to existing farm operations (Beyers, 2022).

For farms with access to large amounts of capital, whether through private equity or government subsidies, AD and the Lely Sphere could be an attractive long-term solution for managing manure. In the case of AD, an initial investment in infrastructure is required, but it offers the potential for significant economic returns through biogas production, heat production, and digestate that could be used as fertilizer. Large-scale operations with consistent access to feedstock and manure are well-suited for this practice, especially if there is a supportive policy framework (O'Connor, 2021). Finally, AD contributes to reducing GHG emissions in energy production and fertilizer products. While the Lely Sphere also requires significant investment, it provides long-term economic advantages by effectively managing manure, requiring less human effort, disposal expenses, and synthetic fertilizers. Also, the system helps to reduce NH_3 emissions, which is beneficial for the environment (De Bruin, 2024). Both technologies represent promising options for sustainable manure management, but their economic viability is dependent on access to substantial amounts of capital and supportive policies.

To be used as complementary strategies for other manure management practices, composting and biochar could be proper options. When integrated with other management practices, composting is an accessible and less capital-intensive option, particularly suitable for smaller-scale farms or as a supplemental strategy for reducing manure volume waste. However, relying only on composting for manure may not be enough, especially within intensive manure management contexts (Viaene, 2016). In my opinion, biochar has not yet been demonstrated to be a complete standalone solution, but it has the potential to be a valuable complement to existing practices. It can be employed as a cover material during manure storage to reduce emissions or integrated with anaerobic digestion to enhance digestate quality. While biochar's potential benefits for soil health and carbon sequestration are promising, further research and development are necessary to know its potential with other manure management strategies (Baral, 2023).

Table 1: An overview of the fundamental components of each manure management practice to facilitate a comparison. All of the information is based on the previous results section.

	Anaerobic digestor	**Composting**	**Slurry Acidification**	**Biochar**	**Lely Sphere**
Applicability	Requires high investment and infrastructure. Complexity to manage, and the need for proximity to feedstock. Challenging to implement without support.	Simpler to implement, requires monitoring and management to ensure effectiveness and prevent negative impacts.	Needs special equipment, expertise, and careful handling of acids.	Application and maintenance are resource-intensive.	Requires specific farm designs, may face adoption barriers due to novelty and integration challenges to current practices.
Environmental	Reduces GHG emissions, and promotes sustainable agriculture by producing renewable energy and green fertilizer.	Improves soil health, and can reduce GHG emissions with proper management.	Effectively reduces GHG and NH_3 emissions during storage and application.	Potential for carbon sequestration and improved soil health.	Reduces NH_3 emissions, and supports circular manure management.
Economic	Revenue from biogas, heat, and fertilizer, but high capital costs and feedstock. Dependent on policy support and market conditions.	Lower initial investment. cost-effective with proper management.	High operational costs due to acid handling and specialized equipment. Savings on possible reduction of synthetic fertilizer.	Cost-effective material waste biomass, but application and maintenance could be high.	Potential long-term savings through optimized nutrient management, but high upfront costs because of the infrastructure
Individual aspects.	Renewable energy generation. Feedstock dependence. Requires proper policies or subsidies.	It may be a suitable option for small operations.	Does not require big changes for farm operations.	In developing technology, further research is needed on long-term impacts and optimization.	Requires further validation and implementation.

After this study, several suggestions can be made to improve the sustainability and attractiveness of various manure management practices as each solution offers distinct advantages and faces unique challenges. For AD, it is important to subsidize the initial investments required to build a plant and promote the use of renewable energy from biogas (Holm-Nielsen, 2009). In the case of composting, efforts should focus on increasing demand for the end product, perhaps by promoting sustainable fertilizers derived from the composting processes. In addition, the establishment of manure co-processing centers in the agricultural sector could improve composting manure's cost efficiency and transportation, which would benefit both on- and off-farm composting operations (Bonmatí Blasi, 2010) (Viaene, 2016). Regarding slurry acidification, further research is needed to assess the long-term effects of acid application on the soil. Additionally, efforts are needed to improve knowledge and training on the proper application of acid to manure. Further research is needed to explore the cost-benefit analysis of biochar with practical case studies outside laboratories that could be practical in agricultural applications and provide useful insights. These studies should consider real-world variables such as transportation, labor, and equipment costs because there is a gap in understanding the potential return on investment of implementing this technology. Overall, these measures would help make manure management practices more efficient and sustainable.

5 Discussion

5.1 Theoretical Implications

This research examined various manure management techniques used in agriculture. The study found that there is no one best solution to be applied. After analyzing these practices, there is enormous potential for improving manure treatment and for combining different solutions depending on the specific conditions of farms to achieve their environmental and economic goals. While the transition to sustainable agriculture through manure management has been widely discussed in academic research, the role of comparative analyses that enable an understanding of the potential drivers or influences for farmers in adopting different manure management practices is crucial.

The results of this research support the theoretical contributions of previous studies, confirming that proper management of manure may lead to substantial environmental and economic advantages. Nevertheless, the effective execution of these strategies encounters multiple challenges. These include the need for validation and integration into existing farming systems, ensuring resource availability and acceptance from stakeholders. Additionally, a deeper understanding of the implications and complexities associated with each solution is crucial for overcoming barriers to adoption. To fully maximize the potential of sustainable manure management strategies, it is crucial to address these concerns as sustainable manure management methods offer numerous direct and indirect advantages to society, such as the reduction of environmental pollution, the preservation of biodiversity, the creation of diverse revenue streams, and the generation of jobs (Malomo, 2018).

In line with existing literature, there is a need for further research into the long-term effects of each manure management method, particularly about their environmental and economic benefits, to determine whether these techniques mitigate the negative impacts of manure or merely shift the burden. Furthermore, it is critical to understand the replicability of these manure management techniques in various settings to ensure their effectiveness in different conditions because different manure management methods and technologies can be applied in many environments and production-sized facilities.

5.2 Limitations

The literature review is a valuable tool for synthesizing existing knowledge; however, it is important to recognize its limitations. The study relies on previously collected and analyzed data, including primary and site-specific data, and the selection of sources has a significant impact on the results. The comparison and synthesis of results are more challenging since different studies employ different methodologies for measuring emissions and calculating costs. Additionally, the periods and locations covered in existing studies limit the study's scope. However, the study literature review comprises articles from peer-reviewed publications and reliable sources, giving priority to research that demonstrates the most up-to-date methodology and technical developments. Consequently, this limitation is acknowledged so readers can understand the boundaries when attempting to generalize findings, as emissions and costs can fluctuate significantly based on factors such as technological advancements, policy changes, climate conditions, geography, and local practices.

The primary goal of this study was to identify patterns and trends in manure management, such as environmental impacts, economic feasibility, and technological advancements, rather than uncover new solutions. Given advances in agricultural technologies and practices, some of the literature review may get outdated. Finally, the literature review in this study is useful for understanding the wider context and current patterns, and future research that addresses this study needs to address its limitations.

5.3 Future Research Areas

Large-scale studies have not systematically analyzed and compared the environmental implications of manure treatment techniques. Researchers have conducted several laboratory and pilot experiments to evaluate NH_3 and GHG emissions from manure. The majority of these experiments have predominantly concentrated on a specific gas or emission source (Hou Y. V., 2015). The results of these experiments differ significantly among farms depending on the stables, storage systems, and application methods they use for each solution. Therefore, as a way to facilitate the development of more informed decisions and effective manure management systems that reduce emissions within the capabilities of each farm, it is essential to conduct an environmental comparison for each manure management technique in similar conditions of various manure management solutions for treating manure (Puente-Rodríguez, 2022).

There is a gap in understanding the financial implications of various manure management systems due to the lack of a large-scale economic analysis of manure treatment techniques. While some studies have evaluated the costs of implementation and operation in specific cases with specific conditions, these findings often vary due to differences in farm size, infrastructure, and regional economic conditions. The variability in initial investment requirements, labor costs, and operational costs can make direct comparisons challenging. To facilitate financial decision-making for farmers and policymakers, it is essential to conduct a comprehensive economic analysis that examines the costs and potential savings of different manure management techniques under standardized conditions. Such analysis should also account for subsidies, and potential revenue from byproducts like biogas or fertilizer, explaining the return on investment and long-term financial viability.

5.4 Key points to consider

Manure treatment is still considered a secondary priority; however, the majority of techniques studied before resulted in reductions in GHG emissions and NH_3 emissions. This emphasizes the importance of applying manure treatment systems to create a more sustainable agricultural system. Manure treatment produces manure products that have a wide range of nutrient ratios (N, P, and K) (Hou Y. V., 2018). This presents an opportunity to optimize the utilization of manure, which could be beneficial to farmers in terms of cost reduction, crop nutrient requirements, and the identification of additional revenue sources, such as green energy. Enhancing the practical application of these manure management system technologies may help achieve the NH_3 and GHG emission targets (Dick A.J. Starmans, 2017). However, it is critical to know that nitrogen losses are unavoidable, but they should be reduced by various measures that require the implementation of coordinated and consistent actions when storing and treating manure that try to promote optimal nutrient recycling that helps to reduce GHG emissions while producing renewable resources such as energy or fertilizers (Marques-dos-Santos, 2023).

Furthermore, adopting sustainable manure management in agriculture presents multiple challenges for farming operations. The variety of manure management systems, each with unique characteristics and processes, has made it difficult for farmers to determine the best approach to treating manure. Many challenges exist in manure management, and no single approach can solve all of them. The primary objective was to carefully evaluate various techniques so stakeholders are better equipped to implement tailored solutions that align with their specific operational needs and sustainability goals. This thesis conducts a comprehensive examination of several techniques that can assist farmers in reducing NH_3 and GHG emissions from manure. Following an overview of this study, stakeholders can determine which practice best suits their capabilities and meets their environmental and economic requirements. Improving manure management could reduce environmental problems and increase economic resilience while creating a more sustainable future that fosters collaboration among everyone involved in the agricultural sector.

6. Conclusion

Manure management methods that aim to be sustainable generally promote optimal nutrient recycling, which helps reduce NH_3 and GHG emissions while also producing renewable resources such as energy or fertilizers. Applying those methods will result in an improvement in sustainable agriculture with additional revenue streams. Technological and scientific innovations are increasing the efficacy of these solutions, which could reduce waste management and storage costs, but there is still a need to improve manure management. This study examined various manure management techniques available today, including their environmental and economic impacts. The manure management systems examined were AD, composting, slurry acidification, biochar, and the Lely sphere system. This research aimed to answer the following research question: How do different manure management practices compare in their operational, environmental, and economic implications? and the following sub-questions: What is the current state of different manure management practices? - What are the main challenges and opportunities associated with the adoption of different manure management systems in Dutch agriculture? The research methodology included an analysis using a literature review to gain technical, environmental, and economic information for a SWOT assessment. This approach offered a clear understanding of each practice's strengths, weaknesses, opportunities, and risks.

The main research question helps to provide a comparison of the implications of various manure management practices by offering valuable insights into their suitability with different conditions. Slurry acidification is effective for emissions reduction, while anaerobic digestion and the Lely Sphere could provide long-term economic and environmental benefits for farms with access to capital. Additionally, composting and biochar can be used as complementary strategies to other practices. This research comparison enables stakeholders to gain a better understanding of these strategies, however, the choice of which manure management practice should be implemented has to be based on the specific context of each farm. To determine the best solution for them, stakeholders must consider the previous factors, as well as available resources and policy frameworks suitable for them. The first research sub-question question addresses the current state of manure management systems by examining their technical, environmental, and economic aspects. The findings illustrate the environmental implications of these methods, especially regarding emissions, while evaluating their economic implications such as costs or initial investments. The research aimed to consolidate the most updated information, reflecting the current status of each manure management practice. The second sub-question focuses on identifying the main barriers and opportunities associated with the implementation of manure management solutions through a SWOT analysis of each studied technique. Consistent with the existing literature, the research discussion highlights the necessity of integrating complementary techniques, enhancing the understanding of each technique's proper use, fostering greater collaboration among various stakeholders in the manure management chain, conducting long-term environmental studies, conducting economic feasibility studies, and implementing policy frameworks such as incentives or subsidies to improve manure management in the Netherlands.

Finally, it can be concluded that manure management techniques have the potential to influence the process of manure management in both environmental and economic terms. Manure management is promising because it can increase the value of manure, increase sales of other products such as energy and fertilizers, and reduce operational costs in Dutch agriculture. This can be crucial for the sustainable future of the agricultural sector and requires a change in the current mindset that views manure as waste and instead recognizes it again as a useful resource (Backus, 2017). However, successfully adopting and implementing existing manure management practices in the Netherlands depends on effectively removing barriers and adapting solutions to the existing agricultural systems. To gain a broader understanding of how to transition to more sustainable manure management systems, future research could make use of a larger sample and take into account more perspectives, such as those from governments and other private actors in the sector. In short, to foster the development of sustainable manure management in dairy farming, policies need to be consistent with the set targets, leave space for dairy farmers to experiment with new practices, and support them with knowledge and resources. To achieve competitive and sustainable agriculture, governments, dairy farmers, and the private sector must align the knowledge gap between operational, environmental, and economic because effective manure management requires the cooperation of several stakeholders and decision-makers, each with divergent perspectives on sustainable development. This research aims to support stakeholders in Dutch agriculture by providing insights into the crucial aspects that impact the effective implementation of manure management techniques.

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