To what extent can nitrogen emissions be mitigated on dairy farms: A case study using a symbiotic approach

Sadaf Shoohanizad
EES-2020-400

Master Programme Energy and Environmental Sciences, University of Groningen

university of groningen
faculty of science and engineering
energy and sustainability research institute groningen

Research report of Sadaf Shoohanizad

Report: EES-2020-400

Supervised by:
PhD. Frank Pierie, IVEM
MSc. Tjerk Lap, IVEM

University of Groningen
Energy and Sustainability Research Institute Groningen, ESRIG

Nijenborgh 6
9747 AG Groningen
T: 050 - 363 4760
W: www.rug.nl/research/esrig

TABLE OF CONTENTS

SUMMARY

Nitrogen makes up 79% of atmospheric air, however, the reactive compounds of this element, i.e. ammonia and nitrous oxide adversely affect different forms of life on Earth and have concerned humans in the past few decades. Around 86% of NH_3 and 70% of N_2O emissions in the Netherlands come from agricultural activities. Since the most recent approach of the Netherlands to reduce nitrogen emissions (PAS) has proven to be ineffective, new strategies need to be applied in order to overcome the problem of nitrogen. In this project, initially the processes in a dairy farm that lead to N emissions will be identified, followed by the assessment of mitigation strategies that can be applied in dairy farms and their potential in overcoming the problem of nitrogen. The reference case scenarios in this study include a conventional farm in the Netherlands and a farm with an installed anaerobic digester. The improving technologies to be applied to the farm include solid-liquid separation, coverage, feeding management, acidification, manure corporation and injection. Finally, two of the best performing scenarios, both with a use of artificial cover followed by injection to land and solid-liquid separation are introduced and their environmental impacts and basic financial overviews are explained. The achieved amount of reduction for NH_3 in the enhanced scenario is up to 90% and N_2O emissions are reduced up to 60%. The main drawback of such enhanced scenarios is the increased amount of leachate and consequently a high environmental impact on aquatic environments. Recommendations for future studies are given at the end of this report.

LIST OF ABBREVIATIONS

TAN: total ammoniacal nitrogen Moreover, it refers to all the ammonia forms such as ammonia (NH_3), ammonium (NH_4^+), nitrogen gas (N_2), nitrates (NO_3^-), nitrites (NO_2^-)

IPCC: Intergovernmental Panel on Climate Change

AD: Anaerobic Digestion

FAO: Food and Agricultural Organisation

NI: Nitrification inhibitors

SLS: Solid-liquid separation

1. INTRODUCTION

The Netherlands, a relatively small country in Western Europe and the second largest exporter of agricultural products in the world, has been facing problems caused by excess nitrogen emissions and deposition since 1980 (R. A. Spears, 2003) (Dutch News, 2019). Nitrogen, N_2, makes up 79% of atmospheric air. This gas can be removed from the atmosphere and be transformed into compounds that are necessary for many biological activities on Earth such as plant growth; however, nitrogen's reactive compounds, NH_3, N_2O and NO_2 have concerned scientists and policy makers the past few decades (Dutch News, 2019). The reason of this concern is the adverse effects of the aforementioned compounds on different forms of life on earth. For instance, N_2O has a global warming potential of 300, which means that 1 kg of N_2O is equal to 300 kg of CO_2 emitted to the atmosphere (Ling Ng, Chen, & Edis, 2016); moreover, high amounts of ammonia emission can result in health hazards for humans, acid rains, declination of air and water quality, degradation of ecosystems, etc. (Rotz, Montes, Hafner, Heber, & Grant, 2014). In order to stop further damage by nitrogen emissions, the main sources of nitrogen should be first identified and then mitigated. Agricultural activities are the biggest producers of reactive nitrogen compounds, i.e. NH_3 and N_2O in the Netherlands; around 86% of NH_3 and 70% of N_2O emissions in the Netherlands come from agricultural activities (En Ling Ng, 2019) (H. chaoiui, 2009). Therefore, substantial mitigation efforts need to be taken in order to stop further damage considering the fact that three quarters of the country's land is already affected by excessive nitrogen deposition (Dutch News, 2019).

The most recent approach of the country to reduce nitrogen emissions called the Integrated Approach to Nitrogen (PAS) has recently been declared to be ineffective by The Council of the State (Laurence G. Smith, 2018); this claim has resulted in halting of many economical activities. PAS followed the goal of finding the balance between nitrogen intensive economical activities and reserving of the nature (Ishler, 2016). Despite the goal followed by PAS, this program tolerates emissions rather than reducing them, permission is given to high nitrogen emitting projects if they would be compensated for in the future; this is why the intended goal of the program was not achieved (Rijksoverheid, 2019). The most recent alternative strategy for the reduction of nitrogen emissions includes cutting the number of herds by 50% through helping the farmers go out of business and lowering speed limit on roads, which have resulted in a public outrage especially by the farmers (Laurence G. Smith, 2018). For this reason, alternative methods need to be developed so that farmers can reduce the nitrogen emissions of their farms instead of shutting them down. Some of the developed methods include covering manure storage, injection of manure into the fields and solid-liquid separation of slurry (Rotz, Oenema, & Keulen, 2006). The focus of this report will be on nitrogen emissions and their reduction from dairy farms through the application of available strategies. To reach this goal, different mitigation methods will be studied and compared to create the best integrated system capable of achieving the lowest nitrogen emissions from dairy farms (R. A. Spears, 2003).

1.1. Gap in Knowledge

Many of previous studies on nitrogen emissions of farming activities, have focused on modelling the sources rather than their mitigation. The studies with a focus on reduction of nitrogen emissions have mainly assessed the strategies that lead to reduction of N_2O as the nitrogen containing GHG; however, ammonia emissions from dairy farms are substantial and hold an even bigger share of the total emissions, 86% compared to 70%. NH_3 can be problematic either through conversion into N_2O or deposition on land or water (Möller, 2015). Furthermore, there have been little focus on the reduction of NH_3 and N_2O on farm level from a systematic approach. Most studies have focused on single issue problems without taking the complete chain into account, this approach can only result in shifting the emissions from one step to another instead of an overall reduction from the farm. However, in order to achieve an actual reduction in nitrogen emissions of a farm, all of the emitting sources should be considered. In this study, all the nitrogen sources in a dairy farm will be considered and the best integrated system of different mitigation strategies will be identified. To the author's knowledge, no literature has discussed the highest reduction in nitrogen emissions that can be achieved through the combination of different mitigation strategies. The selected approach for conducting this research will be explained in detail in the following chapters.

2. RESEARCH AIM AND QUESTIONS

The main goal of this research is to find the most promising strategies capable of efficiently reducing the nitrogen emissions from dairy farms. The final choice will be based on the environmental impacts of the systems and the amount of reduction that they can achieve. The most promising integration of the identified strategies will be finally designed to reach a maximum reduction in nitrogen emissions. This brings us to the research question of this report:

- To what extent can nitrogen emissions (NH_3 and N_2O) be mitigated on dairy farms from a system perspective?

This question will be answered through finding the answer to the following sub-questions:

- What are the sources of nitrogen emissions in a dairy farm?
- What are the strategies that result in reduced nitrogen emissions?
- How much reduction can be achieved through each strategy?
- What is the highest amount of reduction that can be achieved through the combination of the identified strategies from a system perspective?
- What happens to the nitrogen prevented from being emitted to the atmosphere?
- What is the impact of each scenario on the environment?
- What are the main costs associated with the application of the best scenarios?

3. METHOD AND BOUNDARIES

In order to answer the main and sub-questions mentioned on the previous chapter, the flow of nitrogen in a dairy farm should first be studied; then the technologies that can reduce the emissions will be identified and finally the best combination of the most promising technologies will be defined as a scenario. The boundaries of the research and the methods used in this study are described in the following.

3.1. System Boundaries

The main source of nitrogen emissions in a dairy farm is the excretions by cattle. The nitrogen content of cattle feed will partially end up in urine and manure that are initially produced in the barn, excretions will consequently be transferred to the storage facility and finally applied to land as fertiliser; therefore, the boundaries as illustrated on figure 3-1 are considered for this study. The boundary of the system includes the nitrogen entering the body of the cow to the final content lost to the surrounding atmosphere and soil. The direct emissions through the mouth of cows is minimal and hence excluded (Möller, 2015) (A. F. Bouwman, 2002). Even though nitrogen leaching is also included in the boundaries of the study, more general strategies in order to minimise leaching are included and its environmental impact.

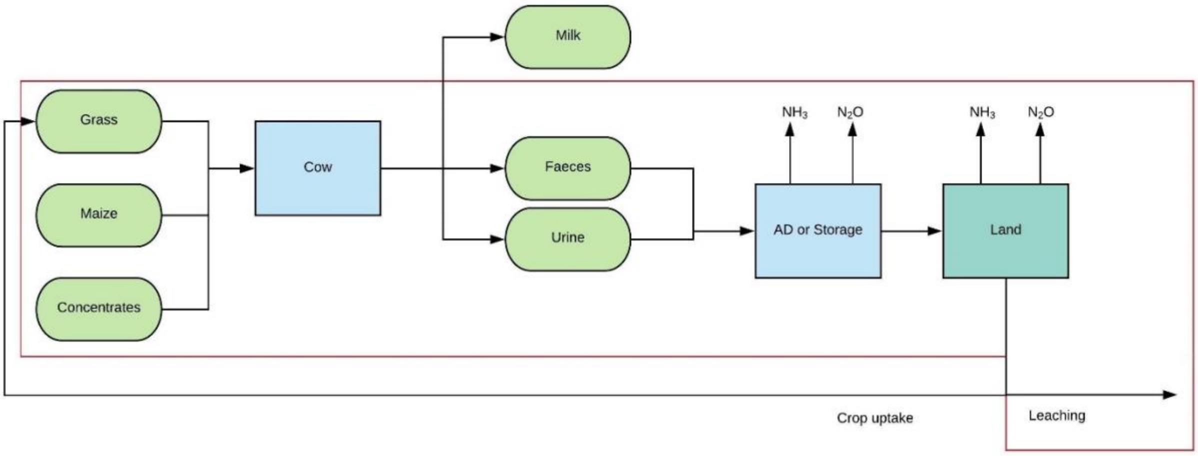


Figure 3-1. System boundaries of this study

3.2. Literature Review

An initial literature review is performed to create an overview of nitrogen flow in a dairy farm and the methods that can be practical in reducing the emissions. Daily emissions of NH_3 and N_2O by an average dairy cow directly and through its excretions are taken from available literature; priority is given to recent studies on similar climate and farming characteristics to the Netherlands (Michael A. Holly R. A., 2017) (Nederlandse Zuivel Organisatie, 2019) (Möller, 2015).

The quantification of emissions in this study is through process-driven emission factors (Möller, 2015). In this method, the amount of emission is calculated with regards to the type of process and by a certain factor; for instance, the emissions from a barn will be based on the type of flooring as a function of intake crude protein.

After identifying the sources, the strategies used in literature to reduce the nitrogen emissions will be investigated. The amount of reduction achieved through application of each strategy individually will be identified. The environmental impact of the emitted and leached nitrogen in each scenario will be considered and compared.

3.3. MEFA Method

To measure the impact of different parameters on emissions and identification of the relations between different sources of the system, material and energy flow analysis (MEFA) will be performed. The following diagram illustrates a general overview of nitrogen flow in a farm, relevant data from literature will be reported in the following chapters. The gathered data on emissions and the flow of nitrogen will be modelled in Microsoft Excel for later investigations on the mitigation. The nitrogen flow and its reduction need to be considered from a system perspective since the emissions from each step will affect the following step.

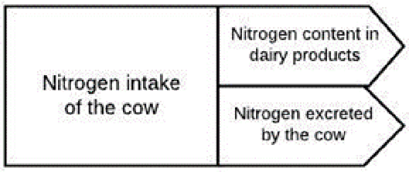


Figure 3-2. Distribution of nitrogen in a ruminant

3.4. SimaPro

The main goal of this research is to find the scenario with least nitrogen emissions to the atmosphere, however since the nitrogen flow is assessed from a system perspective the impact of the nitrogen that is not emitted to the air should also be considered. To compare and quantify the impact of emissions and leaches on the environment, SimaPro 9 is used. The main emitting components to the air, water and soil are created on SimaPro and analysed using ReCiPe 2016 Endpoint and Midpoint. The results from this analysis will be included in the developed model to compare the overall impact of each scenario on the environment.

3.5. Scenarios

To calculate the reduced emitted nitrogen from a dairy farm, two reference scenarios are considered; this is because of the attention drawn to anaerobic digestion due to its environmental benefits such as depletion of fossil fuels and its noticeable impact on emissions. The reference scenarios will include an average Dutch dairy farm with a free stall cowshed and slatted flooring, a crust will be formed on the stored raw manure and in the case of the AD, the digestates will be pumped out every 6 months with no subsequent separation. Finally the stored manure or digestate will be applied to the grassland of the farm through surface spreading. These data are taken from the experts of the field and visit to some farms. The final scenarios will include individual and combination of abating technologies.

3.6. Modelling in Excel

As mentioned on the previous section on MEFA, the gathered data in literature review will be converted into a model on Microsoft Excel. The model will be first designed based on the reference scenarios in the Netherlands; resulting in the nitrogen emissions without any mitigation strategies. Consequently, the mitigation methods (individually and combined) and the amount of reduction that they can achieve will be included to calculate the reduced amount of emissions in different scenarios. The other part of the model is the impact of the emitted nitrogen to the air, soil and water. This data will be gathered from SimaPro 9, more details can be found on section 3.4. SimaPro.

3.7. Expressions and Comparison

After the creation of the model on Microsoft Excel which includes the sources of nitrogen emissions, abating technologies and the impact of each scenario on the environment, different combinations of the technologies will have to be assessed. To accurately compare the results of different scenarios, specific units and expressions will have to be considered. Since both the N_2O and NH_3 emissions are considered in this study, each compound, NH_3 and N_2O, will be compared individually and the sum of the nitrogen element in both. The results will be compared for the daily amount of emissions from each cow to the air; the environmental impact of emissions and leaching to water and soil will be considered too. Finally, in order to better assess the feasibility of the scenarios, some estimations on the will be made.

4. LITERATURE REVIEW

4.1. Sources of Nitrogen in a Dairy Farm

In order to reduce the nitrogen emissions and deposition of dairy farms, it is crucial to first understand the main sources of nitrogen and the parameters that influence the emissions. The focus of this chapter will be on sources of nitrogen emissions in a dairy farm.

Figure 4-1 illustrates the flow of nitrogen, initially taken by the cow and then excreted through the produced milk (20%) or faeces and urine (80%), i.e. urine and faeces. Urine and faeces will be first produced in the housing facility where the cattle are located and will then be transferred to the storage area and finally deposited on the land as fertiliser. The excreted nitrogen will be emitted to the atmosphere mainly as N_2O and NH_3 throughout all these steps (Nederlandse Zuivel Organisatie, 2019). In other words, the possible sources of emission in a dairy farm are the housing facility, storage area and grazing land. The characteristics of the environment and method of management in each step determines the amount of emission from them (Rotz C. A., 2017) (Sudmeyer, 2019).

After a general description on processes leading to nitrogen emissions, each source will be studied in more detail in the following.

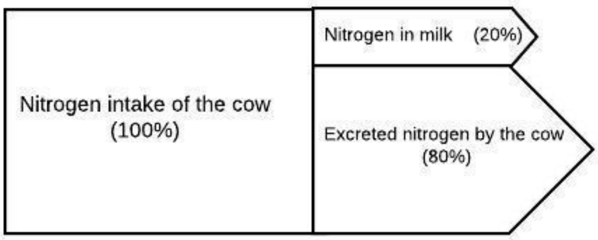


Figure 4-1. Nitrogen mass balance in a lactating dairy cow

4.1.1. Main Processes Leading to Nitrogen Emissions

NH_3 and N_2O are the main forms of nitrogen emissions from dairy farms; the main processes leading to these emissions will be explained in this section.

The total amount of nitrogen in slurry consists of ammoniacal (also known as urinal) and organic nitrogen. The undigested N is excreted in manure as organic compounds and the remainders such as urea, NH_4^+ and other N compounds that can be transformed into NH_4^+ are excreted in the urine (G.L. Velthof, 2011). A big share of the urinal nitrogen is usually converted to ammonia after mixing with faeces; ammonia can then be easily emitted to the air. The conversion of TAN into ammonia (hydrolysis) depends upon urea concentration, temperature and pH. Due to the fact that pH is usually constant within slurry mixture, its affect is ignored; however, temperature and urea concentration depend on method of farming and the excess nitrogen intake of cows. The excess intake of nitrogen by cattle increases the concentration of TAN in the slurry (T. Nyorda, 2012).

The emission and production of N_2O depends upon different parameters than ammonia. Nitrous oxide is produced from combined or individual nitrification and denitrification processes. The ammonium content in manure can be transformed to nitrate in aerobic conditions with N_2O and NO as intermediates (nitrification); nitrate converts to N_2 in anaerobic conditions (denitrification). However, this process can be incomplete with NO and N_2O as final products (Paul Jun, 2000) (Rotz C. A., 2017). Temperature, pH, ammonia concentration and co-existence of aerobic and anaerobic conditions affect the rate of N_2O formation (Paul Jun, 2000).

Other determining characteristics in gaseous emissions include the difficulty of mass transfer within the manure and finally to the air (T. Nyorda, 2012).

4.1.2. Feed

Cows are not efficient in utilising the nitrogen content of their feeds. The excess N composition of the feed is usually excreted in urine and as previously mentioned, the N in urea is more easily lost compared to faecal nitrogen. This is why a reduction in the N content of feed while providing enough protein for milk production minimise N excretion (Jan Dijkstra, 2018). The excreted organic matter, carbon and nitrogen components are all functions of diet composition, but not only the protein content (Jan Dijkstra, 2018). For instance, the N content of milk produced by the same amount of protein intake varies depending on the carbohydrate content, fibre composition and the ratio of other feed components (Jan Dijkstra, 2018). Hence, to minimise N excretion, the ratio of energy and protein supply should be considered as they directly affect the main source of N emissions. About 56% of the available nitrogen of the feed ends up as ammoniacal nitrogen in excretions (G.L. Velthof, 2011).

4.1.3. Ruminants

Enteric fermentation in ruminants are known as a large source of GHG emissions due to high emissions of methane; however, the emitted amount of N_2O directly by this source is relatively small (Rotz C. A., 2017). Enteric N_2O is equal to roughly 0.8 g/(kg of N intake) or 0.4g/(cow.day) (Rotz C. A., 2017). The characteristics of feed together with genetics of the cow can affect enteric emissions; but there is a lot of uncertainty and controversy among the developed models for identification of the relation between these parameters (Rotz C. A., 2017). Hamilton et al. have found little relation between the GHG emissions and different feed scenarios (Scott W. Hamilton, 2010). Due to the low share of nitrogen emission from this source, potential influence on productivity of the ruminants and uncertainty in previous studies, the focus of this research will be on the other sources of nitrogen, i.e. from manure and urine in the housing facility, manure storage and land.

4.1.4. Housing Facilities

The sources of nitrogen in housing facilities of a dairy barn are the animals' entrant emissions, manure and urine. The entrant emissions as previously mentioned are relatively small and hardly modifiable; on the other hand, the emissions by manure and urine are very dependent on the housing conditions and their method of handling (Rotz C. A., 2017).

Temperature, pH, solid or liquid state, slurry thickness and urea concentration are determining in the amount of nitrogen emissions because of their effect on hydrolysis, mass transfer and nitrification-denitrification processes. The influence of each of these parameters will be discussed in the following paragraphs.

The pH range of fresh manure is usually within an optimum range for hydrolysis, but in case of 1 unit change in pH, NH_3 fraction in TAN can increase by an order of magnitude (Ling Ng, Chen, & Edis, 2016). When manure is exposed to air, CO_2 will be more rapidly lost and because of the acidic structure of CO_2, this process leads to a 0.5-1 unit increase in pH (Ling Ng, Chen, & Edis, 2016). Usually the surface pH of manure in the barn is estimated to be 0.7 units above the mixture pH of manure and urine which is 7 and 8 respectively (Coenen, et al., 2018).

Another parameter with influence on NH_3 emissions is temperature, a 10°C in temperature can double the share of NH_3 in TAN (Ling Ng, Chen, & Edis, 2016); however, significant changes are only observed in temperatures above 25°C (Coenen, et al., 2018), which doesn't happen very often in the Netherlands.

Moreover, mixing urine and faeces can result in increased NH_3 emissions, both because of the pH and availability of bacteria that facilitate this conversion. Furthermore, the liquid state of urine decreases the resistance of manure to mass transfer leading to more emissions to the air.

Finally, a longer residence time of manure in the housing facility, even in a very thin layer can contribute to NH_3 emissions (Ling Ng, Chen, & Edis, 2016). Rapid removal of manure doesn't allow the mass transfer of ammonia to the air or nitrification and denitrification processes to happen and is very determining in the amount of nitrogen emissions from barns (Sikkema, 2019).

Because of the mentioned parameters and the influence of housing on determining them, IPCC has reported emissions of N_2O and NH_3 as a factor of excreted N by the cattle based on the type of flooring (Rotz C. A., 2017). Main flooring types are slatted floors, solid floors and bedded floors (Rotz C. A., 2017). Flooring determines the removal rate of manure and consequently its thickness, whether urine and faeces are mixed and their pH, the available surface for volatilisation, aerobic and anaerobic conditions, etc (Ling Ng, Chen, & Edis, 2016).
The type of flooring considered for the reference scenario and quantification of the emissions in this study will be explained in the next chapter. The nitrogen content that is not converted to NH_3 or N_2O in the housing facility will be transferred to the storage facility which will be discussed in the following section.

4.1.5. Manure Storage/AD

The remaining TAN, organic N and urea in the manure and urine will be transferred from the barn to the storage facility or anaerobic digester to generate energy. Storage/AD can be a very big or small source of emissions depending on their management strategy. The emissions will continue until they are injected into soil and taken up by other organisms such as plants (Rotz C. A., 2017).

4.1.5.1. Conventional Storage Facilities

Urea hydrolysis is assumed to be complete before manure placement into storage, therefore the amount of ammonia emission from storage facilities mainly depends on diffusion properties of manure and available surface area per unit of volume (Ling Ng, Chen, & Edis, 2016). The solid, liquid or slurry state of manure storage is determining in mass transfer inside the slurry (Rotz, Montes, Hafner, Heber, & Grant, 2014), (Rotz C. A., 2017). The closer the manure state to solid, the lower the rate of ammonia emission is. Another affecting parameter is the available surface area per unit of volume, which is low at the start of the storage period, but eventually decreases in long-term periods of storage (T. Nyorda, 2012) (Ling Ng, Chen, & Edis, 2016). During long-term storage, the remaining organic nitrogen in slurry can be converted to TAN in suitable conditions for hydrolysis. Since temperature is usually not controlled in these facilities, pH is the determining parameter in hydrolysis and consequent ammonia emissions. Manure pH depends on the solid content of manure. Higher solid content will decompose into CO_2, which will be emitted to the air and result in increased pH. This effect is especially important for fresh manure with unconverted organic N which is usually the case (Sikkema, 2019).

The most determining parameter in N_2O emissions is crust formation (Horacio Andres Aguirre-Villegas, 2014). A crust can provide the required aerobic and anaerobic conditions for N_2O formation (Rotz C. A., 2017). A higher than 7% solid content will lead to crust formation (Horacio Andres Aguirre-Villegas, 2014). However, crust formation will increase the resistance to transferring of ammonia to the atmosphere and the effect on each of these emissions needs to be compared (Horacio Andres Aguirre-Villegas, 2014) (Rotz C. A., 2017). A solid or semi-solid storage leads to reduced methanogenesis and an increase in produced CO_2 which again provides a suitable environment for incomplete nitrification and denitrification and therefore N_2O (Rotz C. A., 2017).

The annual emissions for slurry with or without crust and solid storage are 0.01, 0.13 and 0.1 kg of N_2O/m^3 respectively. Another reported unit by IPCC for nitrogen emissions is based on the excreted nitrogen, which is 0, 0.5, 5 and 100 g N_2O/(kg of excreted N) for liquid, slurry without crust, slurry with crust and solid respectively (Rotz C. A., 2017). The quantification of emissions from the reference cases will be performed on the next chapter.

4.1.5.2. Anaerobic Digestion

Anaerobic digestion includes a series of reactions that convert organic matter into methane and carbon dioxide (Wilkie, 2000). The products of this process can be used as sources of energy and are assumed to make farming practices friendlier to the environment through decreasing the use of fossil fuels and reduction of the odorants from animal farming (Wilkie, 2000). Because of the increased installation of anaerobic digesters in dairy farms; the potential improvements that can be applied to the digestate of a digester will be evaluated.

The remainders of anaerobic digestion are called digestates consisting of water, organic and inorganic compounds, suspended dissolved and decomposed particles (Möller, 2015).

AD involves mineralisation of organic nitrogen that can increase the NH_4^+ and NH_3 concentration in digestates by 22% (Michael A. Holly R. A.-V., 2016). However, the comparison of ammonia emissions from digestates are more complicated than only the TAN concentration. The reduced solid matter in the remainders of AD, will result in faster transfer of TAN to deeper parts of the soil and reduce the emissions during land application. On the other hand, a natural crust will not be formed and the emissions will be higher during storage. An increased NH_3 concentration can increase the pH of the mixture and consequently the ammonia emissions, hence the overall amount of NH_3 emissions is expected to increase (Möller, 2015) (Michael A. Holly R. A.-V., 2016). The increased level of the nitrogen ions that can be taken up by plants means an easier mobility of them through water too (Möller, 2015).

Nitrous oxide emissions from both storage and field application highly depend on the conditions of storage and soil (Möller, 2015). N_2O emissions from digested and raw manure were similar in winter while in higher temperatures N_2O emissions from digested manure was twice of that of the raw manure (Möller, 2015). The reduced solid content of manure through AD results in fewer anoxic microsites creating unfavourable conditions for anaerobic digestion, while the increased ion concentration can increase the amount of emissions. This is why most findings have observed similar N_2O emissions in raw and digested manure (Möller, 2015).

The increase in nitrogen ions concentration in digestates means that even more effective reduction methods should be implemented in dairy farms with an AD system. The average AD system here is not followed by digestate separation, but the digestates can be separated into liquid and solid fractions. But the effect of this process on N emissions will be analysed in the following chapters.

4.1.6. Soil

The next and final source of nitrogen emissions in a dairy farm is manure application to the grassland in the form of N_2O or NH_3. The emissions from field depend on the method of manure application, time of application, soil conditions and remaining nitrogen content (Rotz C. A., 2017) (Rotz, Montes, Hafner, Heber, & Grant, 2014), (A. F. Bouwman, 2002). The emitted nitrogen through the excreted manure and urine of the pasturing cow can be another source of emission on the land (Rotz C. A., 2017), (Rotz, Montes, Hafner, Heber, & Grant, 2014). The NH_3 emissions after field application account for 30 to 50% of agricultural NH_3 emissions in European countries (Häni, Sintermann, Kupper, Jocher, & Neftel, 2015), besides, soil is the biggest producer of N_2O in terrestrial ecosystems (Brouceck, 2017)

The method of application can vary from spray irrigation, surface spreading to direct injection (Ling Ng, Chen, & Edis, 2016). Ammonia losses will occur even during application in methods that involve moving manure in the air, this amount is fixed at 1 to 10% of the applied TAN depending on the method (T. Nyorda, 2012). If manure is applied to the soil surface, the remaining NH_3 will be directly emitted to the air, this source will continue emitting until it is incorporated in the soil (T. Nyorda, 2012). A shallow injection can decrease ammonia emissions up to 76% (Häni, Sintermann, Kupper, Jocher, & Neftel, 2015). On the other hand, manure incorporation into the soil can increase the N_2O emissions by providing the suitable environment for denitrification processes (Brouceck, 2017). These emissions can vary between 0.38 kg N/ha to 0.45 kg N/ha (Brouceck, 2017).

The time of application is another important parameter determining N emissions. Higher N_2O emissions are measured when slurry is applied right after grazing (Brouceck, 2017). Time of application affects the temperature, irrigation and wind speed and hence both NH_3 and N_2O emissions (Brouceck, 2017) (Häni, Sintermann, Kupper, Jocher, & Neftel, 2015) (T. Nyorda, 2012). Temperature affects the equilibria between NH_4^+ and NH_3 in TAN, a higher temperature results in higher losses of NH_3 (Häni, Sintermann, Kupper, Jocher, & Neftel, 2015). Temperature is very determining in N_2O emissions too, an increase from 10 to 20 increased the nitrous oxide emissions by 3 and 10 times in an irrigated and non-irrigated condition respectively, the temperature effect is highest in cold and wet periods (Brouceck, 2017). Water content itself, including both soil moisture and rainfall increases N_2O emissions too (Brouceck, 2017). Furthermore, high wind speed together with a higher solid content in manure can increase ammonia emissions. The high solid content will reduce the movement of manure inside the soil resulting in a higher availability of NH_3 in low depths, wind blow will increase the mass transfer of NH_3 to the air (T. Nyorda, 2012) (Häni, Sintermann, Kupper, Jocher, & Neftel, 2015).

Furthermore, the type of crop on land can affect the amount of emissions too (Rotz, Oenema, & Keulen, 2006); however, since the cropped plant on the land will be fed to the cows and cannot be modified without studying the biological effect, this parameter is excluded from the boundaries of this research.

Around 50% of the applied nitrogen to cropland is emitted to the environment (Laurence G. Smith, 2018). The IPCC reports an emission of 1.6 and 3.1 kg N_2O/kg of applied N to cropland and pasture respectively (Rotz C. A., 2017). The uncertainty in this reported value is very high because of the many different available types of soil. Ammonia loss is estimated to be 5% of the total ammoniacal nitrogen content for deep injection into the land and 8% for shallow injection (Ling Ng, Chen, & Edis, 2016). Because of the large availability of sandy soil in the Netherlands, nitrogen compounds could be stabilised faster by the soil, hence the rate of volatilisation can be assumed as 38% instead of 50% (Rotz, Montes, Hafner, Heber, & Grant, 2014)

The quantification of the emissions from the reference scenarios in this study and creation of a model representing these amounts will be performed in the next chapter.

4.2. Mitigation Strategies

There is a number of different strategies that are capable of reducing NH_3 and N_2O emissions, however, not all these strategies are equally effective. Some strategies include dietary additives, reduction of crude protein in feed, manure acidification, manure injection, solid-liquid separation, manure cooling, genetic modification, natural or artificial covers, aeration, etc. In this chapter, the most effective strategies in nitrogen emissions will be described. These strategies are applied to the main sources, i.e. housing, storage and land application; however, the main source of all these emissions is the nitrogen content of cattle feed. The effect of the installation and combination of these strategies will be introduced in the next chapter.

4.2.1. Feeding Management

According to the FAO a dairy cow needs on average 0.46 kilograms of crude protein per day (Lee S.D, 1998). This number can vary depending upon the weight, age and the physical situation of the cattle. However, by taking this average number and a rough estimation of 16% nitrogen content of proteins (Tontisirin, 2003), a dairy cow requires 73.6 grams of nitrogen every day for its physical maintenance and milk production. This number is assumed to be 134 in The Netherlands due to the advanced dairy industry and enhanced cow genetics. However, cows are not efficient in using the nitrogen intake of their feed, a very wide range of nitrogen efficiency has been reported, and the average of 29% has been considered in this research (Elisabet Nadeau, 2007). By taking the efficiency into account, the feed of a dairy cow should consist of 464 grams of nitrogen. By taking the numbers reported by the Dutch Dairy Organisation and Statistics Netherlands the average nitrogen content of the dairy cow feed is currently 496 grams (Organisatie, 2019) (CBS, 2012). Hence, there is not much room for improvement in this step. The current intake of cows is very close to the amount of nitrogen they need.

In Netherlands, the excretions of cattle are eventually applied to the grassland owned by the farmer so that there is less need for artificial fertilisers, but the total impact of production of ammonia fertilisers are about 10 times less than that of the leaching or emitted nitrogen from the manure according to SimaPro9 by using the ReCiPe 2016 Endpoint method. This is why the required nitrogen for the plants should be precisely calculated and application of any excess nitrogen amount to the land should be prohibited. However, the comparison of fertiliser and manure application involves more aspects than only the total environmental impact. The organic N content of manure is more stable than the available N in fertilisers, hence it will be more resistant to leaching compared to the soluble nitrogen ions in the fertilisers (J.J. Schroder, 2006). The considerations during manure or fertiliser application and the preferred method of application will be discussed later in this chapter.

4.2.2. Coverage

Installing covers on the manure storage facilities can increase the resistance to mass transfer from the slurry surface to the air and reduce ammonia emissions (Michael A. Holly R. A., 2017). Covers can be made out of different materials such as straws, wood, biochar or plastic. The main drawback of coverage using natural materials is their short durability and a potential increase in nitrous oxide emissions because of providing the aerobic and anaerobic conditions in close proximity.

Even though some studies have reported reduction of N_2O emissions by installing natural covers, because of the higher reduction of ammonia emissions through artificial covers and more certainty on its negative impact on nitrous oxide, plastic covers are the preferred type of covering. The achieved amount of reduction through plastic covers can vary but 90% and 92.5% reduction in N_2O and NH_3 emissions respectively are considered in the developed model (Yong Hou, 2015). The reported changes for N_2O vary widely among different research groups and a reduction of 10% to increased emissions by 9 times can be found (Rotz C. A., 2017) (Michael A. Holly R. A., 2017). Covering can prevent the emission of some other harmful gases such as methane too.

4.2.3. Acidification

Another method of nitrogen abatement is the addition of acids to the slurry. This method could be done during the storage period or right before application to land. Lowering the pH of slurry through adding acids to the mixture shifts the equilibrium between NH_3 and NH_4^+ towards more NH_4^+ (Achim Seidela, 2017). Besides, an increase in ammonium concentration provides plants with more nutrients since ammonium is one of the nitrogen components that can be taken up by plants. Since most of the soil in the Netherlands has a lower pH than 6, there would be no consequences for slurry application to the land (Christian Mulder, 2005). pH reduction up to 5.5 have been done and tolerated by the land (I. Kavanagh, 2019).

Although the studied literature has observed a reduction of ammonia emissions by at least 50% to thorough prevention; there are different claims regarding the impact on nitrous oxide emissions. The median of 70% reduction is considered in the developed model (Yong Hou, 2015). That being said, the total amount of GHG emissions have been reduced even with a slight increase in N_2O emissions, making acidification seem like a suitable option for reduction of N emissions.

4.2.4. Solid-Liquid Separation

A third technique that has been studied regarding its impact on reduction manure’s negative impact on the environment is solid-liquid separation. The products of this process are a liquid and a solid fraction with higher nutritious value in the solid part (E. Dinuccio, 2007). There is certainty in different studies on N losses in the liquid fraction. The amount of NH_3 emission in liquid storage is increased compared to slurries due to less resistance to the transfer of ammonia molecules to the air (Michael A. Holly R. A.-V., 2016). Because of the same reason, i.e. less solid content and no crust formation to provide the suitable environment for production of N_2O, a reduction in nitrous oxide emissions is observed (E. Dinuccio, 2007); however, N_2O emissions from the storage especially in lower temperatures such as the Netherlands are in general not a significant amount. The increase in ammonia emissions is assumed to be 20% and N_2O is reduced by 40% as an average in the Excel model (F. Montes, 2013). On the other hand, the reduced solid content of manure in the liquid fraction results in a faster penetration of the soil and therefore less ammonia emissions compared to slurry; but the existence of aerobic and anaerobic locations together with the preserved NH_4^+ concentration are likely to increase the nitrous oxide emissions, but it stays constant which can be due to the increased moisture and less oxygen in deeper layers of soil (F. Montes, 2013).

The other fraction is the separated solid content of the manure. The ammonia emissions from the solid fraction were much lower compared to the liquid or slurry manure; however increased aeration can increase the NH_3 emissions from this source up to 77% than that of the anaerobically stacked solids (Michael A. Holly R. A.-V., 2016). The reduced N_2O emissions from the liquid fraction is usually neglected by the increase in N_2O emissions of the solid part, thus an overall increase in losses through N_2O is observed (Michael A. Holly R. A.-V., 2016). This could be due to the air-filled porosity of the solid samples (E. Dinuccio, 2007). The increase in N_2O emissions can be prevented through aeration by providing the unsuitable environment for denitrification by 75%, however this would increase the NH_3 emissions and the total gaseous N losses (F. Montes, 2013). Emissions from land application of the solid manure increase by up to 3 times due to the increased carbon and therefore better conditions for mineralisation of available N (Broucek, 2017). The increase in NH_4 concentration and less emissions of ammonia could be another reason that leads to higher emissions of N_2O (Michael A. Holly R. A.-V., 2016).

Another advantage of SLS is that the solid content has far less volume than the initial manure hence it is very suitable for transportation to another location if the nitrogen content of the liquid digestate meets the needs of the crops. However, its application to land could be very beneficial especially for semi-arid lands that have low carbon content (European Biogas Association, 2015).

SLS has the same effect on AD digestate too. Most of the organic matter and phosphate content of digestate will end up in the solid fraction and the remaining components that consist of mostly nitrogen end up in the liquid part (Livestock Research Wageningen UR).

It should be noted that the method of separation also plays a role in the quality of the liquid and solid fractions. The dry matter in each part and their composition depends on the method of separation (S. Fournel, 2019). According to Fournel et al. the best method of separation from a financial and functional point of view is screw and lower presses (S. Fournel, 2019).

To sum up, solid-liquid can only have desirable impact on total N losses if the solid fraction is stocked in anaerobic conditions and eventually applied to the land and instantly incorporated since there is not any commercial methods for subsurface application of solid manure yet. Besides, the liquid fraction should be stored with an artificial cover before land application and the application should be through injection and best applied during periods with no rain before spring when plants need the highest amount of nitrogen. More information on the application will be given in the next section.

4.2.5. Manure Application

The last stage of farming that includes nitrogen losses is the manure application to land. During this step a loop could be closed through nutrient take up by plants or the saved nitrogen in the previous stages could be leaked or emitted in this stage. As a result, it is very important that nitrogen is either immobilised in the soil or taken up by the plants. The main methods of application include injection, surface application, surface application followed by incorporation. The temperature and moisture of the soil has proved to be determining factors on the amount of emissions but the reported numbers and the numbers included in the model will be taken from the experiments conducted in similar conditions to the average farm in the Netherlands. There is controversy among different studies upon dependency of N_2O emissions on temperature but most studies agree upon the effect of soil moisture on N_2O emissions.

Ammonia emissions like every other step depend on the parameters affecting mass transfer from manure to the air such as temperature, wind velocity and dry matter content; therefore, a deeper placement of manure would result in lower emissions of ammonia. On the other hand, there is controversy on the change in N_2O emissions. Deeper placement can increase N_2O emissions due to the existence of mini anaerobic and aerobic spots and increased N content in the soil due to the prevention of ammonia emissions. However, the longer distance of the Nitrate pool to the surface provides the molecules to take part in denitrification processes. In this step N_2O is converted to nitrogen in anoxic conditions if the right population of microbes are available (Dominika Lewicka-Szczebak, 2017).

Shallow injection of slurry manure can increase the N_2O emissions up to 20 times compared to surface application; the median that is used in the model is 2 (Rotz C. A., 2017) (R E Thorman, 2008). The production of N_2O could be reduced through the addition of nitrification inhibitors (NI); but the effectiveness of nitrification inhibitors is affected by low soil pH, which is the case in the Netherlands, and may not give us expected results (Ruijiao Xi, 2017) (Xiuzhen Shi, 2016).

The timing of manure application should be in spring because application in late autumn or winter can increase N_2O emissions up to 3 times (R E Thorman, 2008). This is due to the increased temperature and uptake by the crops (R E Thorman, 2008). In case of solid manure application N_2O emissions can reduce up to 4 times by ploughing and due to the high emissions of NH_3 with surface application this method of application should be strictly avoided.

The numbers associated with the application of each method can be found in table 4.1.

Table 4.1. Changes in nitrogen emissions through different methods (conventional reference case is considered as 100% and the final emissions after method implication are relatively reported)

Changes in NH_3 emissions by technologies implied during storage	• Artificial cover: best (5%), worst (10%), median (7.5%) • Straw cover: best (10%), worst (50%), median (25%) • Solid fraction of SLS: best (10%), worst (220%), median (10%) • Liquid fraction of SLS: best (70%), worst (220%), median (220%) • Acidification: best (10%), worst (45%), median (20%)
Changes in N_2O emissions by technologies implied during storage	• Artificial cover: best (10%), worst (14%), median (10%) • Straw cover: best (300%), worst (1100%), median (1000%) • Solid fraction of SLS (raw): best (1100%)worst (1870%), median (1100%) • Solid fraction of SLS (AD): best (25%), worst (44%), median (25%) • Liquid fraction of SLS: 60% • Acidification: 30%

Changes in NH_3 emissions by technologies implied during land application	• Injection: best (15%), worst (25%), median (20%) • Instant incorporation: best (20%), worst (50%), median (25%)
Changes in N_2O emissions by technologies implied during land application	• Injection: best (240%), worst (300%) median (300%) • Instant incorporation: best (240%), worst (400%) median (300%)

5. MODEL AND SCENARIOS

The sources of nitrogen in a dairy farm and the parameters that affect the relevant emissions were discussed in the previous chapter. In this chapter, emissions from each source will be quantified, followed by creation of their model on Excel. This quantification will be done for two scenarios, an average dairy Dutch farm and a farm with an installed anaerobic digester. The results of this chapter will be used to assess the capability of mitigating technologies in the following chapter.

5.1. Model

The model was created on Microsoft Excel using the average Dutch feed to dairy cattle and different scenarios were created using the available data found on literature including the error bars that were studied on some of the methods.

The cowshed options are free stall with slatted flooring, free stall with solid flooring, free stall with packed flooring and open lot. The second stage could be either anaerobic digestion or conventional storage. The storage options include storage with acidification, storage with artificial or straw cover or creation of crust. Anaerobic digestion could be followed by either of the mentioned methods too. The last step which is the land application include injection, surface application or instant incorporation.

Based on the amount of emissions and the effect on the environment, different scenarios were made; because of the high number of scenarios, two scenarios, one with and one without an anaerobic digester are explained here with their impact on the environment according to the data gathered from SimaPro 9.

A summary of the main inputs of the model are included in Table 5.1.

Table 5.1. Summary of the main inputs of the Excel model

Input	Specifications
Feed	• Total weight: 60 kg/day.cow • Composition: 68,75% grass, 22.92% corn, 8.33% concentrate • Dry matter: 37%
Nitrogen Distribution	• Milk production: 3% protein, 28 kg/day.cow • Manure: 50% of the remainders of milk • Urine: Remainders of the manure and milk • Manure excretion: 83 kg/day.cow • Manure composition: 52% TAN, 48% organic N • Urine composition: 70% TAN, 30% organic

5.2. Reference Scenarios

Two reference scenarios are described in this section so that the effect of the application of mitigation strategies can be compared. The reason that farm with an AD is considered as an individual reference scenario is that some methods, such as solid-liquid separation can have different effects on raw or digested manure. Besides, because of the increased use of AD system and its negative impact on nitrogen emissions, special attention should be given to this type of farms.

5.2.1. Average Farm Scenario

The first reference scenario is an average dairy farm in The Netherlands without any sustainability improvements. A farm consisting of 100 cows with a free stall cowshed and slatted flooring is the reference case. Stored manure will be pumped out every 6 months and subsequently applied to the grassland of the farm. Each cow produces 27 kilograms of milk per day while consuming 60 kilograms of feed (Nederlandse Zuivel Organisatie, 2019). These data are taken from the experts of the field and through visiting some dairy farms. The average feed of a Dutch dairy cow consists of 69% grass, 23% corn and 8% concentrates, excluding the 100 grams of vitamins and minerals daily intake (Organisatie, 2019). The excreted amount of nitrogen by dairy cattle in Western Europe is estimated to be 0.5 kg N/(1000 kg animal mass.day) according to the latest report by IPCC (Olga Gavrilova (Estonia), 2019), which is similar to the N content in manure reported by Wageningen University and Research that is 4 kg N/1000 kg manure (Wageningen, 2017). The latter will be used in this study due to fewer required estimations on cattle weight and manure production. The ratio of mineral to organic nitrogen in diluted manure is 1.9 to 2.1 (Wageningen, 2017)

5.2.1.1. Emissions from the Barn

Since the conventional type of flooring in the Netherlands is slatted, the emissions from the barn and storage are combined. The cumulative emissions of these sources are included in the following section.

5.2.1.2. Emissions from Storage

Manure storage with slatted floors are in the form of slurry, just as they are excreted with formation of crust. The emitted N_2O from the described storage is 0.005 kg N_2O/kg excreted N (Olga Gavrilova (Estonia), 2019). The other type of nitrogen emission from storage is ammonia. Nitrogen loss through ammonia emissions is reported as a fraction of TAN, 0.32, and is used in the model (Rotz C. A., 2017) (G.L. Velthof, 2011).

5.2.1.3. Emissions from Land

Denitrification ranges from 11 to 37% from the applied N to the land (Brouceck, 2017). The emitted nitrogen in the form of ammonia and nitrous oxide is on average 44% and 1% of the remaining TAN when applied to the land through surface spreading respectively (Michael A. Holly R. A.-V., 2016) (Olga Gavrilova (Estonia), 2019). The sum of these emissions can represent an estimation of emissions from the manure after it is applied to the land.

5.2.2. Average Farm with AD Scenario

The other reference scenario is identical to the previously mentioned average Dutch farm, with an anaerobic digester as the storage method instead. Since anaerobic digestion results in different solid-liquid ratio during storage and consequently the later application to land, it is included separately in this section. Digester does not perform solid-liquid separation, the digestates will be applied to land through surface spreading.

5.2.2.1. Emissions from the Barn

Manure is collected from the barns hence minimal emissions will be produced inside the barn, the emissions from the stored manure after digestion will be studied in the next section.

5.2.2.2. Emissions from Storage

Due to the transformation of organic nitrogen to ammonia and ammonium during digestion, AD is assumed to increase ammonia emissions by 80% during storage and minimal change in N_2O emissions on the model. (Michael A. Holly R. A.-V., 2016). Higher emissions are due to the increased pH of slurry, reduced solid content and therefore an easier mass transfer of ammonia to the surface and air (T. Nyord, 2010).

Even though the formation of crust is minimised which can decrease nitrous oxide emissions, the anaerobic conditions and higher concentration of ammonium will have a positive impact on the production of N_2O, and the overall amount of N_2O emissions from storage will stay constant (Michael A. Holly R. A.-V., 2016) (Möller, 2015).

5.2.2.3. Emissions from Land

The reduced solid content of the digestates results in a faster and deeper transmission of ammonia to deeper layers of soil, making mass transfer to the atmosphere harder (Michael A. Holly R. A.-V., 2016). On the other hand, the increased availability of ammonia in slurry reduces the impact of this effect and 44% of the remaining TAN will be emitted to the air as NH_3, similar to the conventional scenario.

Nitrous oxide emissions reduce by 31% after field application even though we expect an increase due to lower emissions of ammonia resulting in higher availability of ammonium and ammonia compounds for nitrification-denitrification processes. This could be associated with the increased moisture of the soil in the experiment, resulting in less oxygen availability and reduced pH of the slurry (Michael A. Holly R. A.-V., 2016).

5.3. Improved Symbiotic Scenarios

In this section, the least nitrogen emitting scenarios, one with AD and one without will be explained. Even though the main source of nitrogen is the protein content of cattle feed, due to many controversies on feeding strategies (because of the potential impact on cattle efficiency and milk production), it will not be considered as a mitigation strategy. Furthermore, the current amount and content of the average feed in the Netherlands is very close to the calculated amount in theory and minimal enhancements are expected. Mitigation strategies with focus on crop uptake is another part that is excluded from the scope of this study, this is due to the fact that this part is concerning the ions and leachates and therefore a different topic than emissions.

5.3.1. Enhanced Raw Scenario

Based on the given explanations, the scenario with lowest emissions of nitrogen compared to the reference conventional farm includes the use of an artificial cover during storage followed by land application through injection. As mentioned in section 4.2.5 (manure application), manure should be

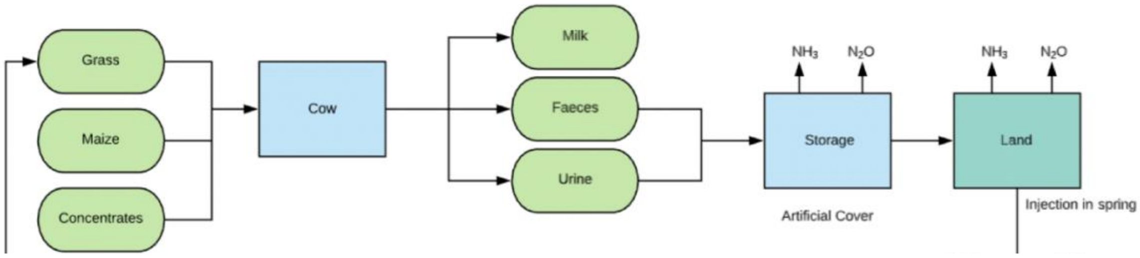


Figure 5.1. Flow of nitrogen and the mitigation strategy used in each stage of enhanced raw scenario

applied as deep as possible, in spring where crops take up the most nitrogen, and avoiding precipitation periods as much as possible so that the nitrogen ions which are mainly transferred through water stay still. Figure 5.1 illustrates the flow of nitrogen.

5.3.2. Enhanced AD Scenario

As previously mentioned, adding an anaerobic digester to a dairy farm will result in an increase of N emissions at farm level. However, due to the benefits that adding an anaerobic digester could bring to a farm, such as prevention of fossil fuel depletion, another scenario that minimises the adverse effects of this method on N emissions will be considered and explained.

This scenario includes the installation of a solid-liquid separator that separates the digestates of the digester. The liquid fraction has to be covered with an artificial cover and the solid fraction is stored in anaerobic conditions. The liquid part will be consequently injected to the land and the solid fraction will be incorporated instantly and deeply into the soil.

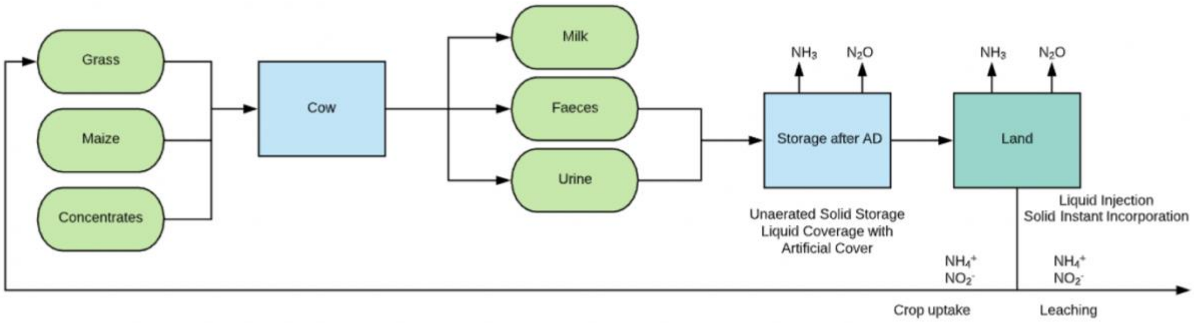


Figure 5.2. Flow of nitrogen and the mitigation strategy used in each stage of enhanced AD scenario

The impact of the application of the mentioned strategies on dairy farms and their quantification, and some financial aspects of the scenarios is included in the next chapter.

6. RESULTS

The different combinations of the mentioned methods were assessed in the developed excel model and the results with least nitrogen emissions are described here.

6.1. Enhanced Raw Scenario

This scenario can result in 79% reduction of N-emissions, i.e. ammonia emissions reduce by 82% and nitrous oxide increases by 32%. According to IPCC, a maximum of 5% of ammonia is converted into nitrous oxide, therefore a total increase of 28% is considered for N_2O in this scenario. There is 20% uncertainty in the results of this method; however, in both the worst- and best-case scenarios the emissions of ammonia and total N decrease and nitrous oxide increase. The main parameter contributing to the uncertainty is the environmental factors such as soil moisture and precipitation that affect the emissions of N_2O.

Figure 6-1 illustrates the share of each outflow of nitrogen compared to the intake. The share of milk in this scenario stays constant due to the constant physical characteristics of the cattle and minimal change in their feed, the main observed change is the share of leachate and emissions. This is due to the fact that the excreted nitrogen stays constant in all scenarios, by preventing N emissions, more nitrogen will be available for leaching. Fewer prevention methods are available for leaching, but since the nitrogen ions available in leachates are only mobile through water, by applying the manure in spring when plants need the ions the most, and periods with minimal precipitation unwanted leaching can be minimised.

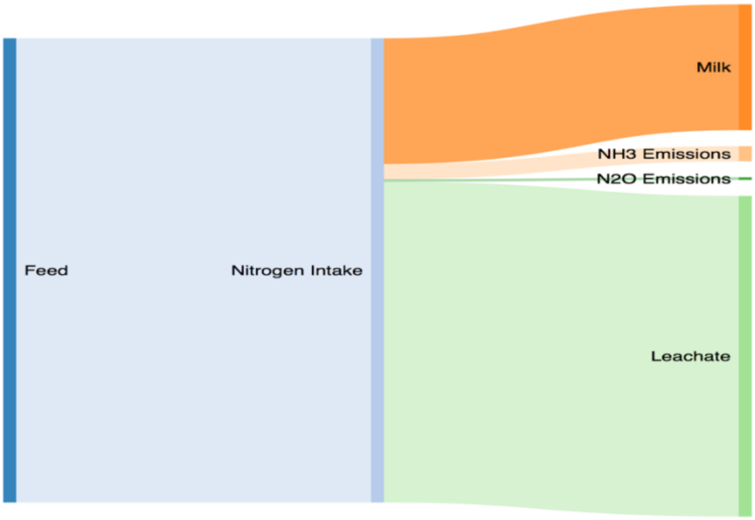


Figure 6-1. Nitrogen flow in Sankey diagram in the enhanced raw scenario

Figures 6-2 and 6-3 compare the amount of NH_3 and N_2O emissions in enhanced and reference scenarios. Mass transfer of ammonia molecules to the air can be easily reduced easily through the application of a physical barrier, i.e. the artificial cover and injection in soil during storage and application respectively. On the other hand, such method has led to an increase in N_2O emissions. The increased amount of remaining nitrogen in the manure, and existence of anaerobic conditions (caused by the cover) and anaerobic conditions (caused by the not 100% prevention of air through coverage) results in increased N_2O emissions.

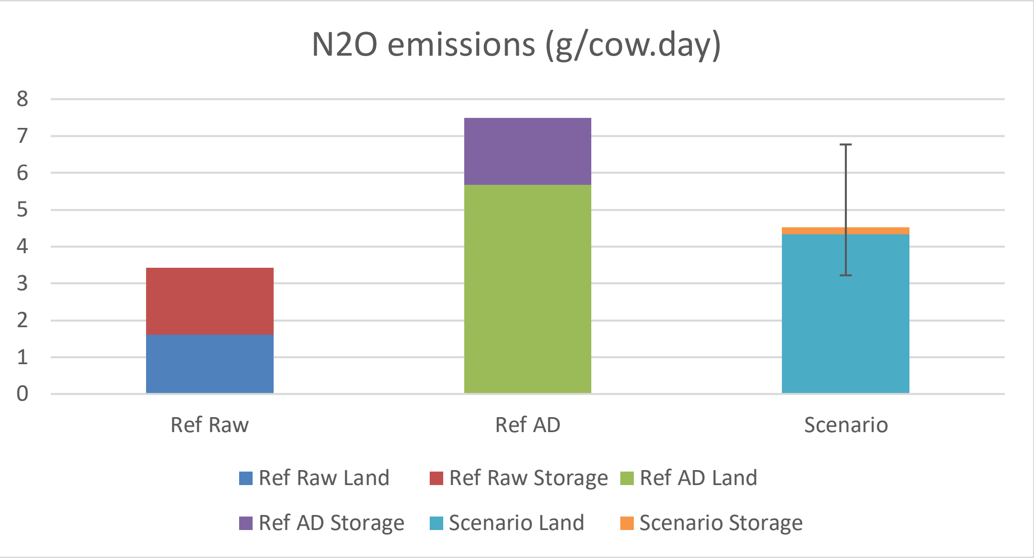


Figure 6-2. Nitrous oxide emissions comparison between reference and enhanced raw scenarios

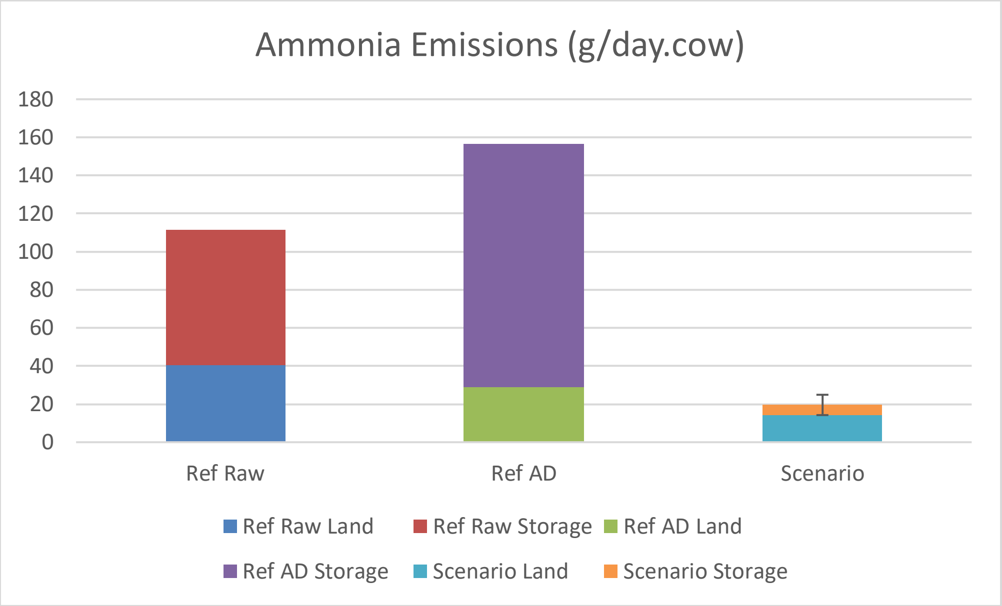


Figure 6-3. Ammonia emissions comparison between reference and enhanced raw scenarios

Finally, figure 6-4 shows the impact of each scenario in total environmental impacts to be more easily comparable. The included mid-points (ReCiPe 2016 H) in SimaPro can be found in appendix 1 for more information. The high reduction in emissions have contributed highly to the reduction of the impact, however, the same reason has led to an increase in the leachate and consequently the environmental impact of it mainly to aquatic environments, but it can be reduced through the right application of manure. The higher environmental impact of the enhanced scenario compared to the AD scenario is due to the higher leachates.

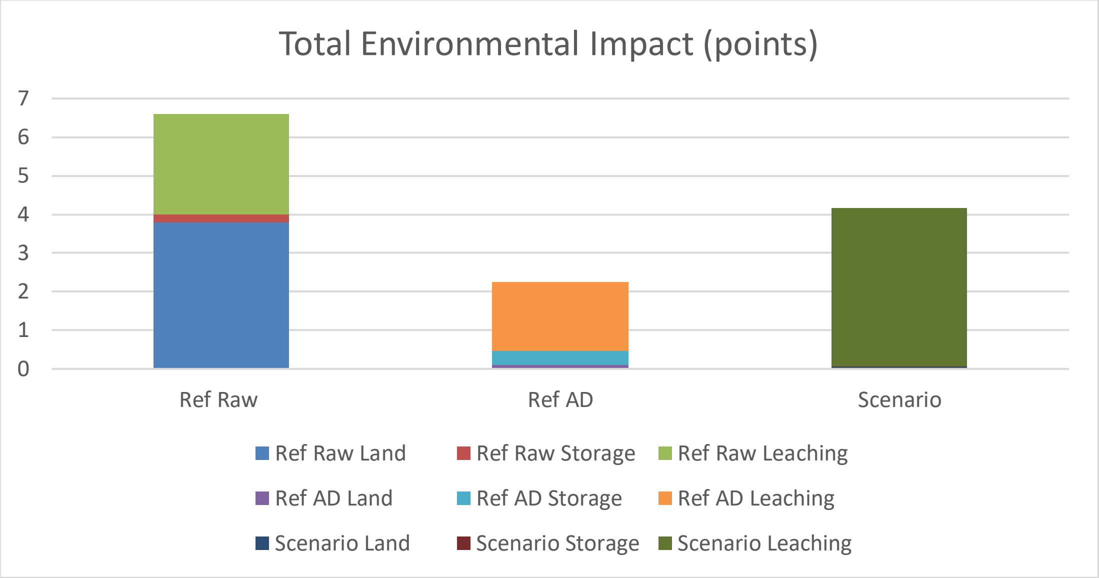


Figure 6-4. Total environmental impact of each cow per day in reference and enhanced raw scenarios according to SimaPro 9

Regarding the financial aspects of this method; the main investment is associated with purchasing the injector machine. The costs vary widely but a minimum of 56,000 and maximum of 200,000 euros can be expected with a lifetime of at least 10 years depending on the number of applications of manure which is equivalent to 5600 to 20,000 euros per year.

6.2. Enhanced AD Scenario

The emissions in this scenario, individually and cumulatively are lower than the previous conventional scenario. The main drawback of this method is the costs associated with the application of the utilised

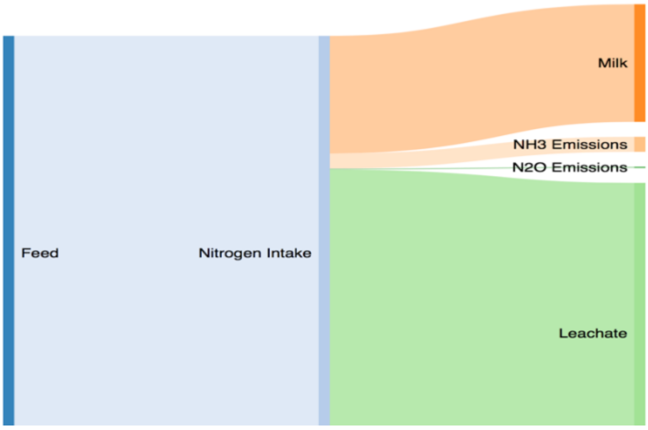


Figure 6-5- Nitrogen flow in Sankey diagram in the enhanced AD scenario technologies in this system. Figure 6-5 shows the share of each outflow of nitrogen in the total nitrogen intake. The share of milk in this scenario is same as the other scenarios due to the previously mentioned reason. The remaining nitrogen is divided between the leachates, NH_3, N_2O and leachates. The higher NH_3 share compared to the previous enhanced scenario is the increased NH_3 emissions, this is because of the increased amount of mineral nitrogen after the digestion process. The results are very similar to the previous scenario as shown in figures 6-6 and 6-7 too. Lower leachates has led to a slightly lower environmental impact in this scenario. This reduction is due to the changed structure of the nitrogen composition, and a better control over emissions since the solid and liquid fractions are separated.

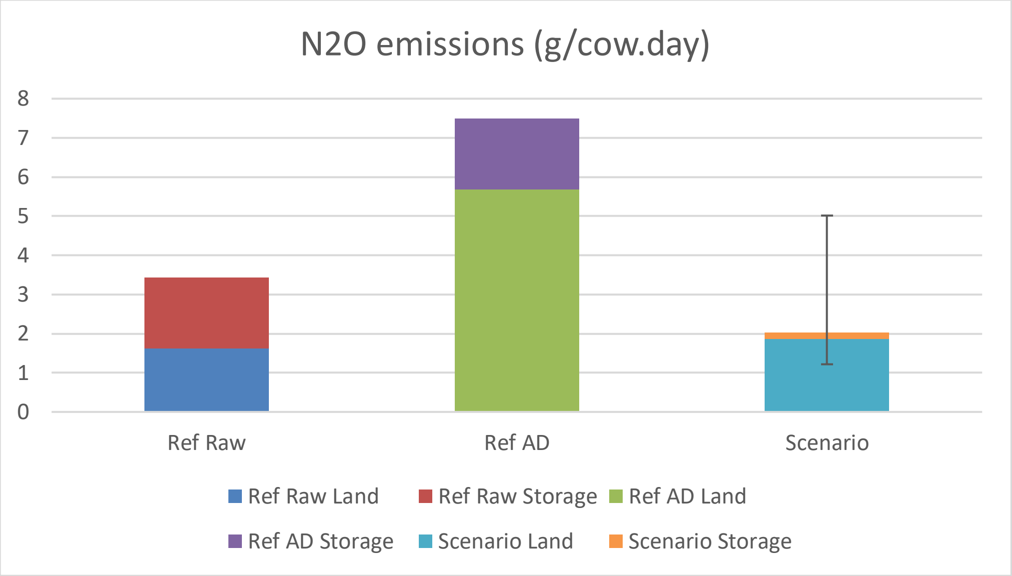


Figure 6-6. Nitrous oxide emissions comparison between reference and enhanced AD scenarios

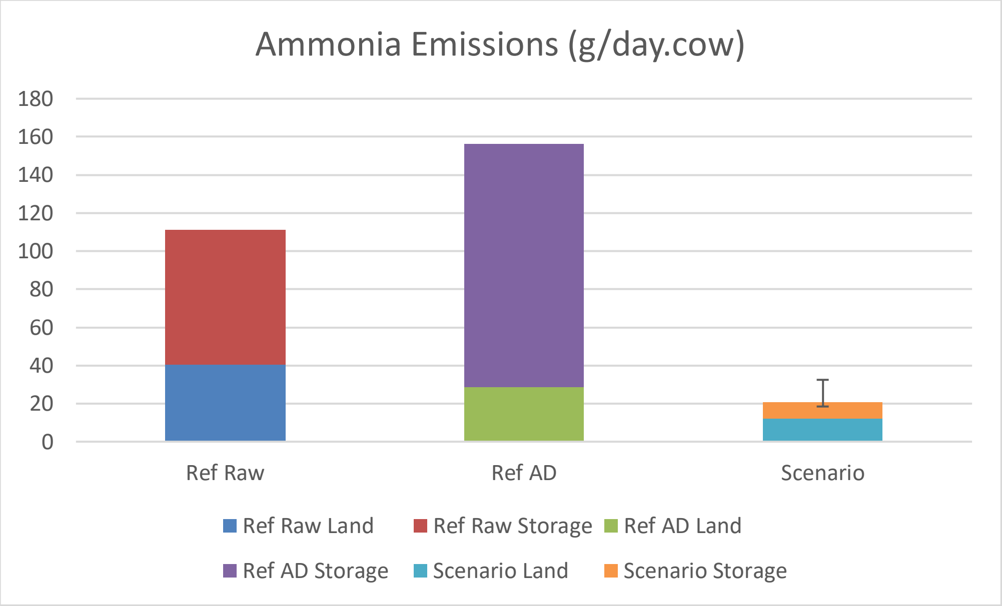


Figure 6-7. Ammonia emissions comparison between reference and enhanced AD scenarios

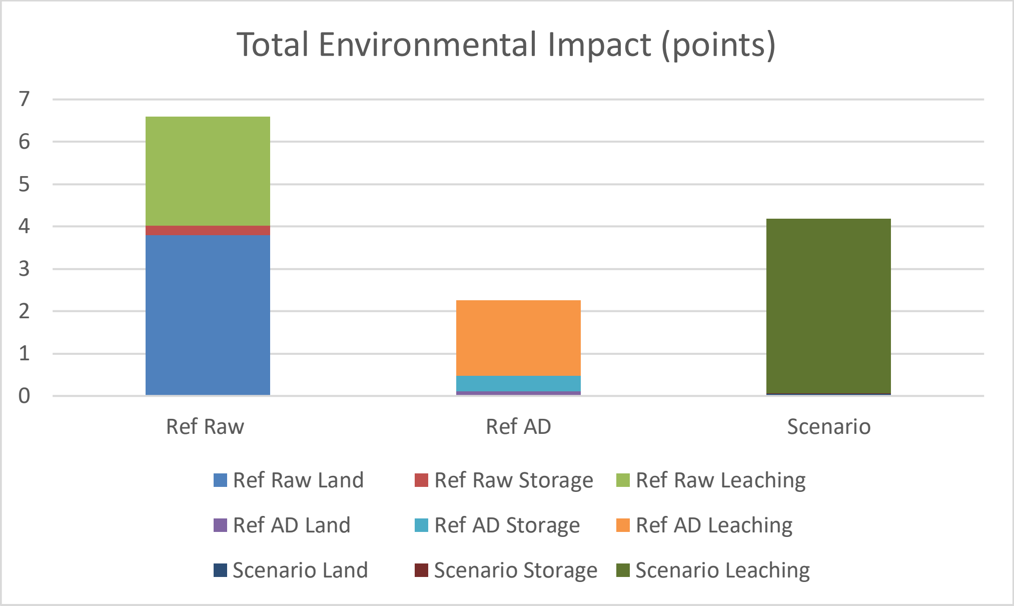


Figure 6-8. Total environmental impact of each cow per day in reference and enhanced AD scenarios according to SimaPro 9

The price of the separator can vary from 10 to 50,000 euros with a standard separator costing 23,500 euros and a pump costing around 4500 euros resulting in 28,000 euros with 12 years of lifetime excluding the same injector machine costing 56,000 euros (Kässi Pellervo, 2013). The sum of the investments is equal to 7933 euros annually for 10 years. The price of an anaerobic digester which can be up to a million euros is excluded in this section, this is due to the fact that the costs of an AD system can be made up for though using a circular symbiotic system by the costs saved in the use of energy and artificial fertilisers (Frank Pierie, 2017).

6.3. All Reference Case and Scenarios

In order to better compare and analyse the developed scenarios, the best performing scenarios, enhanced raw and AD, and reference scenarios are all included in this part.

As shown in figure 6-9, very high reductions of NH_3 can be achieved through prevention of transfer of ammonia molecules to the air, such as covering. However, nitrous oxide emissions are harder to reduce because of the more complicated processes that lead to the production of N_2O. It should also be noted that many methods that can reduce the emission of NH_3 will increase the emissions of nitrous oxide, since the coverage of the manure can increase the co-existence of aerobic and anaerobic conditions and therefore the production of N_2O.

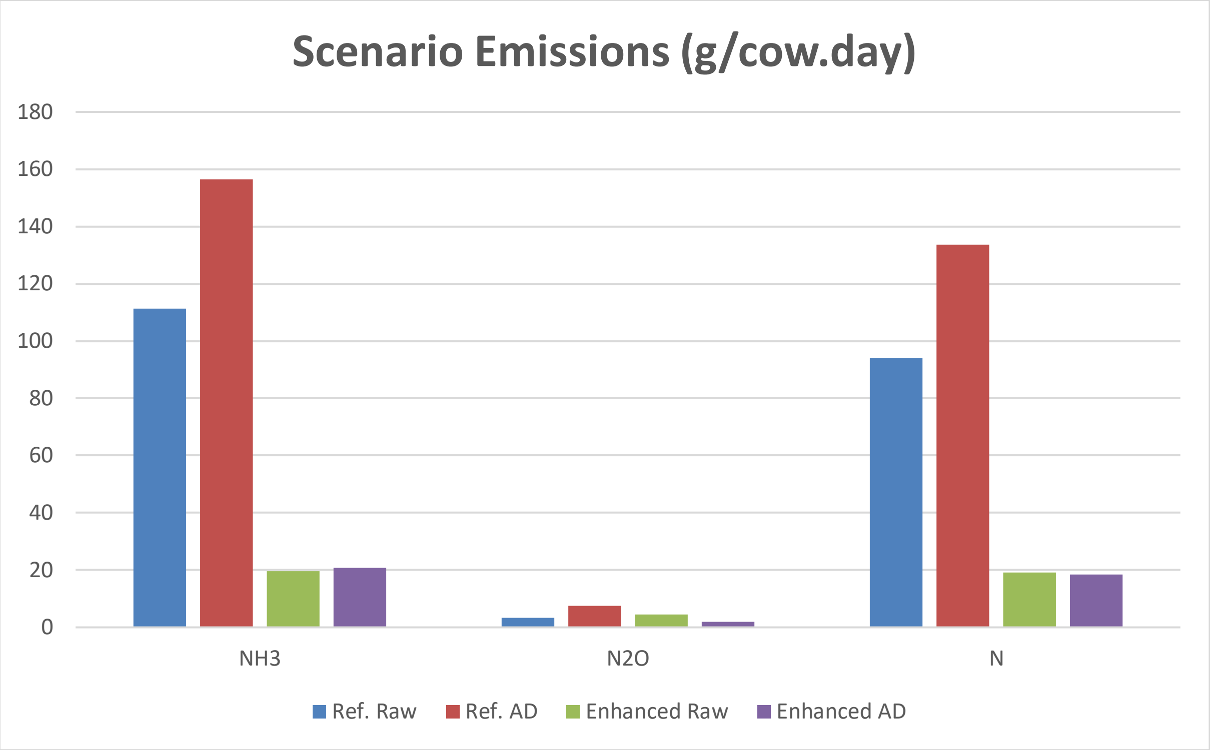
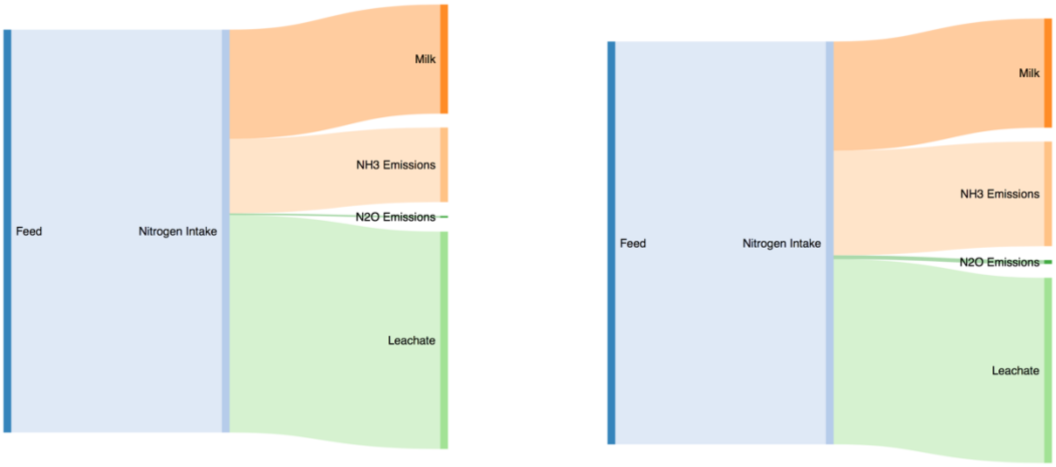


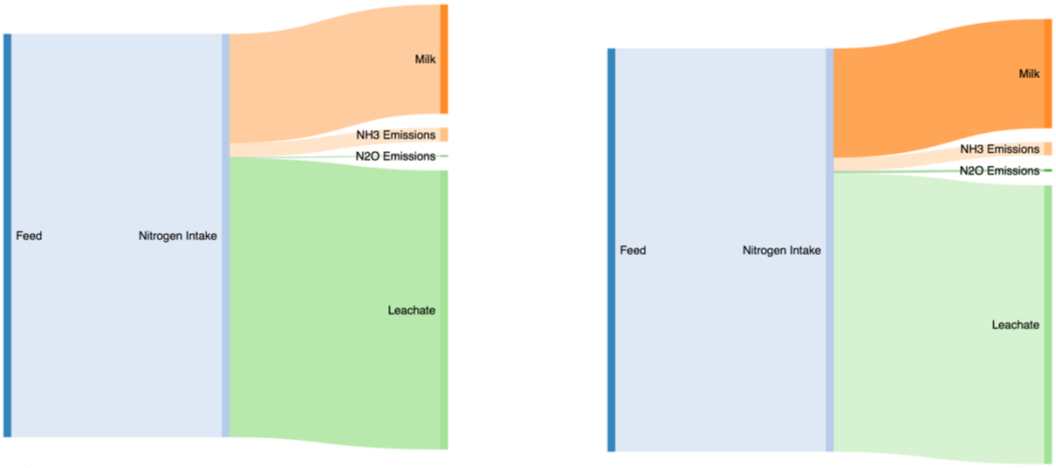
Figure 6-9. The amount of ammonia, nitrous oxide and total N emissions in the best performing and reference scenarios

Figure 6-10 illustrates the ratio of the emissions and leachates of each scenario as Sankey diagrams. The reduction of emissions results in a higher concentration of nitrogen that remains in the manure. The remaining nitrogen content can either be taken up by plants or transferred to aqueous environments through underground water flows. The high reduction in emissions greatly increases the leachates resulting in a high environmental impact compared to an AD reference scenario with high emissions and low leachates. Leachates are harder to control, therefore, in case of reduction of the emissions, more focus should be on the methods that can prevent the amount of leaching.



Reference Conventional Scenario

Reference AD Scenario



Enhanced AD Scenario

Enhanced raw Scenario

Figure 6-10. Comparison of the Sankey diagrams of each reference and enhanced scenario

Figure 6-11 includes the environmental impact of each scenario. As mentioned in the previous section, the lowest environmental impact is made through the enhanced AD scenario because of the better control over the emissions through the separation of solid and liquid.

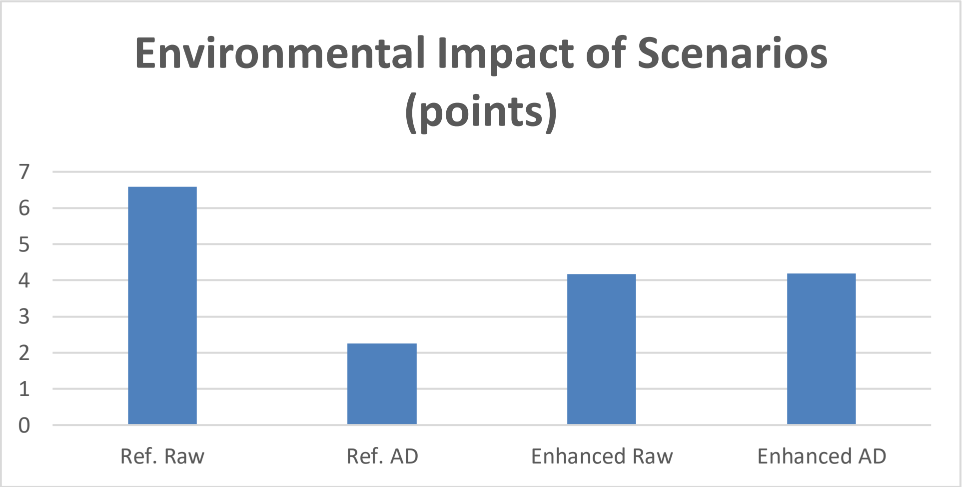


Figure 6-11. Environmental impact of the reference and enhanced scenarios in total end points

The amount of emissions and achieved reduction in each scenario are included in table 6.1.

Table 6.1. Summary of the main characteristics of the reference and enhanced scenarios

Scenario	Main Characteristics	Emissions (gram/cow.day)
Conventional Reference	• Housing with slatted flooring • Slurry storage with formation of crust • Application to land through surface spreading	• NH_3 : 111.4 (100%) • N_2O : 3.42 • (100%) • N : 93.9 (100%)
Minimum N-Emissions without Anaerobic Digester	• Housing with slatted flooring • Slurry storage with artificial cover • Application to land through deep injection	• NH_3: 19.57 (18%) • N_2O: 4.52 (132%) • N: 19.13 (21%)
Reference Scenario with Anaerobic Digestion	• Housing with slatted flooring • Anaerobic digestion followed by digestate storage may be without crust formation • Application to land through surface application of the digestates	• NH_3: 156.42 (140%) • N_2O: 7.48 (218%) • N: 133.64 (142%)
Minimum N-Emissions with Anaerobic Digester	• Housing with slatted flooring • Anaerobic digestion followed by solid-liquid separation with a screw press separator • Storage of liquid fraction with an artificial cover and the solid fraction with no aeration • Application to land of the liquid part through injection and the solids through deep and instant incorporation	• NH_3: 20.82 (14%) • N_2O: 2.02 (27%) • N: 18.49 (14%)

6.4. Model Validation

Since a number of different sources were studied for the development of the model, in order to ascertain the validity of the developed model; the achieved results were compared with research studies that have investigated the overall nitrogen emissions of dairy farms (Mark Powell, 2014) (Dieu Linh Hoang, 2019) (Michael A. Holly R. A.-V., 2016). The amount of emissions from the reference scenarios matched very closely with the reported numbers by the Powell et al. and Hoang et al. The difference of 10-30% where detected and they are assumed to be acceptable since the difference in numbers reported by some sources on this topic have differed by up to 100%. The results of different scenarios are taken from review papers that have assessed a range of different sources in order to increase the accuracy of the model with regards to the time restriction (Yong Hou, 2015) (Horacio A.

Aguirre-Villegas, 2017) (Michael A. Holly R. A.-V., 2016). This is due to the different experimental conditions of the research and the sensitivity of the results to such environmental conditions. A sensitivity analysis is performed in the next section.

The initial data for achieving these results, i.e. the components of cattle feed and the ratio of organic and inorganic nitrogen are compared with sources too, and match very closely (K.F. Reed, 2015) (Wageningen, 2017). Therefore, the model is valid in each sub-model that represent the steps of farming and includes data that match real experiments. More details of the model can be found in appendix 2.

6.5. Sensitivity Analysis

The model consists of three main sections including feed, ruminant, manure storage and land application. The feed section is the main input to the model, therefore any changes made to the elements of this section would directly affect the results. A 10% decrease to the dry matter ratio of the feed would change the emissions by 7%. The dry matter content, available protein in the feed and feed composition (maize, grass and concentrates) are the main elements in this section. The second section is the ruminant, which determines the division of the input nitrogen into the main outputs including milk, manure and urine. The nitrogen content of urea determines the amount of a big share of emissions, a 10% decrease of the mentioned parameter changes the emissions by 8%. The ratio of the organic and non-organic nitrogen also affects the results but this ratio is taken from KWIN 2017-2018 and there is very little uncertainty in it (Wageningen, 2017). The mentioned parameters are the main inputs of the model that can be adjusted and the results will change accordingly.

The two other main parts of the model include the storage and application of manure to land. The amount of reduction, or in some cases increase in the emissions are taken from review papers that have studied a wide range of research studies, or when available from similar conditions as the Netherlands. The uncertainty in the use of some technologies are very high and some lower and more reliable. For instance, the uncertainty in using a straw cover during storage can be up to 8 times in N_2O emissions while there is very little variability in the reported results on the use of artificial covers.

7. CONCLUSION AND DISCUSSION

The main goal of this research was to find methods that can be effective in reducing the nitrogen emissions from dairy farms; for this purpose, a number of scenarios have been developed that emit less reactive nitrogen compounds. Two scenarios with lowest amount of emissions have been introduced in the report. However, the amount of reduction achieved by some of these methods vary very greatly, some have even resulted in an increase of emissions. The characteristics of soil, i.e. pH and moisture and the surrounding environment conditions such as wind speed, temperature, precipitation and humidity are some of the parameters that affect the amount of emissions and the effectiveness of mitigating strategies. By considering the mentioned parameters, less variability can be seen upon the application of the strategies. In this study, even though the mentioned parameters are not included directly, the impact of the mitigation strategies are taken from sources focusing on either similar condition to the Netherlands or from reviewed papers that have included a high number of research studies in their results. That being said, conducting experiments in each individual region of the Netherlands before applying the technologies, could provide us with more promising strategies. The method that can reduce the emissions of NH_3 and N_2O with minimal controversy among different sources is artificial covering of the manure storage which should be applied in all storage facilities of dairy farms, including the farms with an anaerobic digester installed. It should also be noted that anaerobic digestion will increase the emissions of both compounds and should not be used individually without a subsequent mitigating strategy.

In case of application of the mentioned mitigation strategies, about 1.8 times of the required nitrogen intake of the plants can be provided by manure (134 kg vs 76), making farmers self-sufficient in nitrogen fertilisers, resulting in roughly 22 euros of savings per hectare per year which can partly make up for the investment costs of the scenarios (Schnitkey, 2020). However, the investments should not be a problem since It has been reported by different sources that the Dutch government is willing to spend millions of euro on this matter and farms can be provided through subsidies and other types of funding. Organic fertiliser has other benefits than financial too, in such humid conditions like the Netherlands, the organic content in manure is more stable and resistant to leaching compared to industrial fertilisers (Rotz, Oenema, & Keulen, 2006).

It is important to include a mitigation strategy on each stage of manure management, i.e. housing facility, storage and land application. In case the focus is on only one stage of management, the prevented nitrogen from transfer to the air will be emitted or leached in the next stage. This is the main reason that a systematic approach was taken in this study. It should be noted that applying the chosen scenarios can only be effective if all the specified measures are considered. For instance, in case of slurry application in winter rather than spring, emissions could increase to levels higher than the reference cases since more nitrogen is remained in the manure. This is extremely important since the impact of leaching ions on the environment are higher than NH_3 and N_2O emissions.

The major costs associated with the application of the mentioned strategies are included for the best performing scenarios. Even though relatively high initial investments are required for both scenarios; excluding them could eventually lead to lands that are not arable anymore. The consequences for farmers would be buying all the cattle feed resulting in high expenses, for ecosystems the omission of less-resistant species and on the country level the extremely high amounts of emissions since the nitrogen content of the manure will not be taken up by the plants anymore resulting in fewer job opportunities. According to the EIB, the increase in nitrogen emissions can put 40,000 jobs at risk by 2021 because only in the construction sector (Meijer, 2020). The increase in the nitrogen concentration of the soil and air would greatly harm the eco-system of the area by decreasing the biodiversity, such harms will be extremely hard or impossible to compensate for.

Last but not least, in order to reduce the nitrogen emissions, improved policies and regulations should be implemented. Policies should be applied to smaller regions, i.e. provinces rather than the whole country to be more precise since the varying soil conditions and moisture of different areas can play an important role in determining the specific methods that should be carried out. The main reason that previous regulations have proven to be ineffective can be associated with the mentioned aspects, i.e. not considering the varying characteristics of different regions, focus on only one of the stages rather than a systematic approach and specifically for PAS compensations rather than preventions. The remaining nitrogen content in manure, after the mitigation technologies aiming at emissions, there is uncertainty on the leakages to water and land, therefore reducing the number of the farms or cows is another method that could be considered. The mentioned method is not included in the boundaries of this study; however, it can lead to major improvements in the sector since the damage made to the environment is considerably lower than the economic value of dairy industry in the Netherlands (1.2%) (Zuivel NL, 2016).

7.1. Recommendations for further research

Because of the uncertainties and only basic assumptions on the leaching of the remained nitrogen of manure, it is important that more studies analyse the amount of nitrogen leaking after application and the methods through which leaches could be prevented. Another focus of study could be on the amount of manure that the Netherlands as a whole country can still bear in its soil with minimal adverse effects. This number could be very important to decide between making investments on the mitigation technologies or helping some farmers go out of business. Finally, experiments should be performed in different regions of the country, based on the soil characteristics to calculate the exact amounts of emission, the potential of the mitigation technology and the methods that can process the remainders of nitrogen in the land.

BIBLIOGRAPHY

A. F. Bouwman, L. J. (2002). Emissions of N2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*.

Achim Seidela, A. P. (2017). Effects of acidification and injection of pasture applied cattle slurry on ammonia losses, N2O emissions and crop N uptake. *Agriculture, Ecosystems and Environment*, 23-32.

Brouceck, J. (2017). NITROUS OXIDE PRODUCTION FROM SOIL AND MANURE. *NPPC – Research Institute for Animal Production Nitra*, 21-32.

Broucek, J. (2017). NITROUS OXIDE PRODUCTION FROM SOIL AND MANURE APPLICATION: A REVIEW. *Slovak Journal Animal Science*, 21-32.

CBS. (2012). *Standardised calculation methods for animal manure and nutrients.* The hague/Heerlen: CBS.

Christian Mulder, H. v. (2005). Numerical abundance and biodiversity of belowground taxocenes along a pH gradient across the Netherlands. *Journal of Biogeography*.

Coenen, P., Zanten, M., Zijlema, P., Arets, E., Baas, K., van den Berghe, A., . . . Koch, W. (2018). *Greenhouse gas emissions in the Netherlands 1990–2016 National Inventory Report 2018.* Bilthoven, Netherlands: National Institute for Public Health and the Environment (RIVM).

Dieu Linh Hoang, C. D. (2019). Impacts of biogas production on nitrogen flows on Dutch dairy system. *Journal of Industrial Ecology*, 1-16.

Dominika Lewicka-Szczebak, J. A. (2017). Quantifying N2O reduction to N2 based on N2O isotopocules - validation with independent methods (helium incubation and 15N gas flux method). *Biogeosciences*, 711-732.

Dutch News. (2019, 09 12). *Nitrogen emission failing may hit 18,000 building projects*. Retrieved from www.dutchnews.nl/news/2019/09/nitrogen-emission-failings-may-hit-18000-building-projects-nrc/

E. Dinuccio, W. B. (2007). Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation. *Atmospheric Environment*, 2448-2459.

Elisabet Nadeau, J.-E. E. (2007). Nitrogen efficiency of dairy cows as affected by diet and milk yield. *Livestock Science*, 45-56.

En Ling Ng, D. C. (2019, 09 12). *Nitrogen pollution: the forgotten element of climate change*. Retrieved from The Conversation: theconversation.com/nitrogen-pollution-the-forgotten-element-of-climate-change-69348

European Biogas Association. (2015). *the value of organic fertilisers for Europe's economy, society and environment.* European Biogas Association.

F. Montes, R. M. (2013). Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *Journal of Animal Science*.

Frank Pierie, A. D. (2017). *Improving the Sustainability of Farming Practices through the Use of a Symbiotic Approach for Anaerobic Digestion and Digestate Processing.*

G.L. Velthof, C. v. (2011). A model for inventory of ammonia emissions from agriculture in the Netherlands. *Atmospheric Environment*, 248-255.

H. chaoiui, F. M. (2009). Volatile Ammonia Fraction and Flux from Thin Layers of Buffered Ammonium Solution and Dairy Cattle Manure. *American society of agricultural and biological engineers*.

Häni, C., Sintermann, J., Kupper, T., Jocher, M., & Neftel, A. (2015). AmmoniaemissionafterslurryapplicationtograsslandinSwitzerland. *AtmosphericEnvironment*, 92-100.

Horacio A. Aguirre-Villegas, R. A. (2017). Evaluating greenhouse gas emissions from dairy manure management practices using survey data and lifecycle tools. *Journal of Cleaner Production*, 169-179.

Horacio Andres Aguirre-Villegas, R. L. (2014). From waste-to-worth: energy, emissions, and nutrient implications of manure processing pathways. *Biofuels, Bioproducts & Biorefining*, 770-793.

I. Kavanagh, W. B. (2019). Mitigation of ammonia and greenhouse gas emissions from stored cattle slurry using acidifiers and chemical amendments. *Journal of Cleaner Production*.

Ishler, V. A. (2016). Nitrogen Ammonia Emissions and the Dairy cow . *Pennstate Extension*.

J.J. Schroder, H. A. (2006). Permissible manure and fertilizer use in dairy farming systems on sandy soils in The Netherlands to comply with the Nitrates Directive target. *European Journal of Agronomy*, 102-114.

Jan Dijkstra, A. B. (2018). Modeling the Effect of Nutritional Strategies for Dairy Cows on the Composition of Excreta Nitrogen. *Frontiers in Sustainable Food Systems 2:63*.

K.F. Reed, L. M. (2015). Predicting nitrogen excretion from cattle. *Journal of Dairy Science*, 3025-3035.

Kässi Pellervo, L. H. (2013). *Economics of manure logistics, separation and land application.* JTI-Swedish Institute of Agricultural and Environmental Engineering.

Laurence G. Smith, N. H. (2018). Greener farming: managing carbon and nitrogen cycles to reduce greenhouse gas emissions from agriculure. *Academic Press, Managing Global Warming*.

Lee S.D, K. R. (1998). *FEED REQUIREMENTS FOR DAIRY COWS.* Western Samoa: FAO.

Ling Ng, E., Chen, D., & Edis, R. (2016, 12 5). *Nitrogen pollution: the forgotten element of climate change*. Retrieved from The Conversation: https://theconversation.com/nitrogen-pollution-the-forgotten-element-of-climate-change-69348

Livestock Research Wageningen UR. (n.d.). *Manure, A Valuable Resource.* Wageningen: Dutch Minstries of Economic Affairs and Infrastructure and the Environment.

Mark Powell, M. W. (2014). Estimating ammonia and nitrous oxide emissions from dairy farms using milk urea nitrogen. *Journal of Environmental Quality*.

Meijer, B. (2020, 02 18). *Dutch construction boom set to end as EU nitrogen rules bite*. Retrieved from Reuters: https://www.reuters.com/article/us-netherlands-construction/dutch-construction-boom-set-to-end-as-eu-nitrogen-rules-bite-idUSKBN1XA1GI?smbl=esg

Michael A. Holly, R. A. (2017). Thermochemical Conversion of Biomass Storage Covers to Reduce Ammonia Emissions from Dairy Manure. *Water Air Soil Pollution*.

Michael A. Holly, R. A.-V. (2016). Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land application. *Agriculture, Ecosystems and Environment*, 410-419.

Möller, K. (2015). Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and. *Agronomy for Sustainable Development, Springer*, 1021-1041.

Nederlandse Zuivel Organisatie. (2019, 10 16). *Cattle Feed*. Retrieved from NZO: www.nzl.nl/quality/cattle-feed/

Olga Gavrilova (Estonia), A. L. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories- Chapter 10.* IPCC.

Organisatie, N. Z. (2019, 10 16). *Cattle Feed*. Retrieved from NZO: https://www.nzo.nl/en/quality/cattle-feed/

Paul Jun, M. G. (2000). CH4 and N2O emissions from livestock manure. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* , 321-338.

R E Thorman, S. Y. (2008). NITROUS OXIDE EMISSIONS FOLLOWING LIVESTOCK MANURE APPLICATION TO LAND. In *Agriculture and the Environment VII: Land Management in a Changing Environment* (pp. 175-182). Edinburgh.

R. A. Spears, R. A. (2003). Whole-farm Nitrogen balance on western dairy farms. *Journal of dairy science*.

Rijksoverheid. (2019, 09 12). *Infographic: Stikstofdepositie per bron*. Retrieved from Rijksoverheid: www.rijksoverheid.nl/onderwerpen/aanpak-stikstof/documenten/oublication/2019/10/04/infographic-stikstofdeposite-per-bron

Rotz, C. A. (2017). Symposium review: Modeling greenhouse gas emissions from dairy farms. *Journal of Dairy Science* (pp. 6675-6689). Pittsburgh, Pennsylvania: FASS Inc. and Elsevier Inc. on behalf of the American Dairy Science Association.

Rotz, C., Montes, F., Hafner, S., Heber, A., & Grant, R. (2014). Ammonia emission model for whole farm evaluation of dairy production systems. *Journal of Environmental Quality, 43*(4), 1143-58.

Rotz, C., Oenema, J., & Keulen, H. (2006). Whole Farm Management to Reduce Nutrient Losses From Dairy Farms: A Simulation Study. *Applied Engineering in Agriculture, 22*(5), 773-784.

Ruijiao Xi, X.-E. L. (2017). pH rather than nitrification and urease inhibitors determines community of ammonia oxidizers in a vegetable soil.

S. Fournel, S. G. (2019). Production of recycled manure solids for bedding in Canadian dairy farms: I. Solid–liquid separation. *Journal Dairy Science*, 1832-1846.

Schnitkey, G. (2020, 02 18). *Nitrogen Fertilizer Prices and Costs Lower for 2018*. Retrieved from FarmDocDaily: https://farmdocdaily.illinois.edu/2017/11/nitrogen-fertilizer-prices-and-costs-lower-for-2018.html

Scott W. Hamilton, E. J. (2010). Greenhouse Gas, animal performance, and bacterial population structure responses to dietary Monensin fed to dairy cows. *Journal of Enivornmental Quality*.

Sikkema, A. (2019, 10 16). *Wagenignen UR*. Retrieved from How can we halve nitrogen emissions in the livestock sector? - 'Concentrate on the cowsheds': https://resource.wur.nl/en/show/How-can-we-halve-nitrogen-emissions-in-the-livestock-sector-Concentrate-on-the-cowsheds.htm

Sudmeyer, R. (2019, 10 16). *Managing manure to reduce greenhouse gas emissions*. Retrieved from Australian Agriculture: www.agric.wa.gov.au/climate-change/managing-manure-reduce-greenhouse-gas-emissions

T. Nyord, M. H. (2010). Ammonia volatilisation and crop yield following land application of solid–liquid separated, anaerobically digested, and soil injected animal slurry to winter wheat. *Agriculture, Ecosystems and Environment*, 75-81.

T. Nyorda, M. H. (2012). Ammonia volatilisation and crop yield following land application of solid–liquid separated, anaerobically digested, and soil injected animal slurry to winter wheat. *{Agriculture, Ecosystems and Environment*.

Tontisirin, K. (2003). *Food energy - methods of analysis and conversion factors.* Rome: FAO.

Wageningen, U. (2017). *KWIN 2017-2018 - Kwantitatieve Informatie Veehouderij.* Wageningen: Wageningen Livestock Research.

Wever, D., Coenen, P., Dröge, R., Geilenkirchen, G., 't Hoen, M., Jimmink, B., . . . Vonk, J. (2018). *Informative Inventory Report 2018 : Emissions of transboundary air pollutants in the Netherlands 1990-2016.* Bilthoven - the Netherlands: Rijksinstituut voor Volksgezondheid en Milieu RIVM.

Wilkie, A. C. (2000). Anaerobic digestion: Holistic bioprocessing of animal manures. *Animal Residuals Management Conference* (pp. 1-12). Alexandria, Virginia: Water Environment Federation.

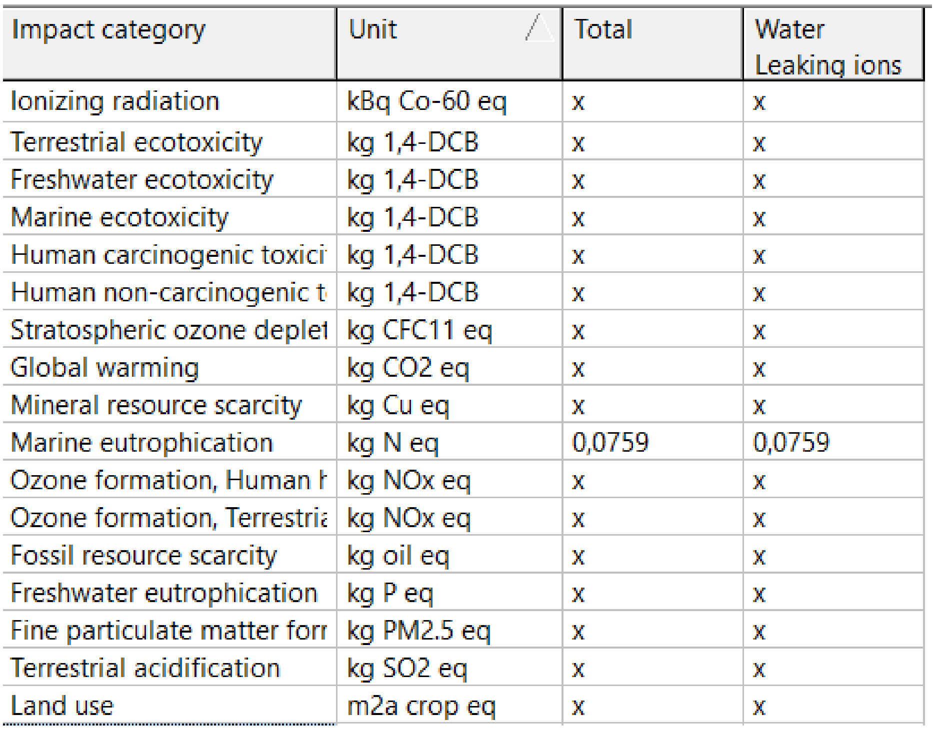
Xiuzhen Shi, H.-W. H.-Z. (2016). Effects of the nitrification inhibitor 3,4-Dimethylpyrazole phosphate on nitrification and nitrifiers in two contrasting agricultural soils. *Applied and Environmental Microbiology*.

Yong Hou, G. L. (2015). Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Global Change Biology*, 1293-1312.

Zuivel NL. (2016). *Dutch dairy in figures.* Zuivel NL.

APPENDICES

Appendix 1 – Midpoints in SimaPro

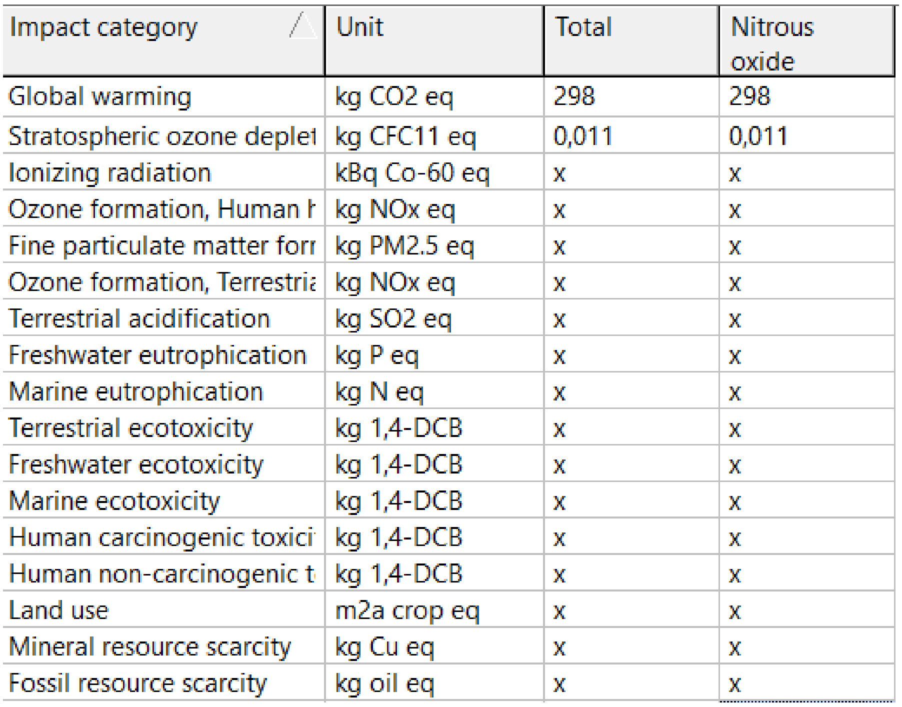


Impact category	Unit	Total	Water Leaking ions
Ionizing radiation	kBq Co-60 eq	x	x
Terrestrial ecotoxicity	kg 1,4-DCB	x	x
Freshwater ecotoxicity	kg 1,4-DCB	x	x
Marine ecotoxicity	kg 1,4-DCB	x	x
Human carcinogenic toxici	kg 1,4-DCB	x	x
Human non-carcinogenic t	kg 1,4-DCB	x	x
Stratospheric ozone deplet	kg CFC11 eq	x	x
Global warming	kg CO2 eq	x	x
Mineral resource scarcity	kg Cu eq	x	x
Marine eutrophication	kg N eq	0,0759	0,0759
Ozone formation, Human h	kg NOx eq	x	x
Ozone formation, Terrestria	kg NOx eq	x	x
Fossil resource scarcity	kg oil eq	x	x
Freshwater eutrophication	kg P eq	x	x
Fine particulate matter forr	kg PM2.5 eq	x	x
Terrestrial acidification	kg SO2 eq	x	x
Land use	m2a crop eq	x	x

Figure A1-1. Midpoints of water leaching ions analysed through SimaPro 9, Midpoint ReCiPe Method H

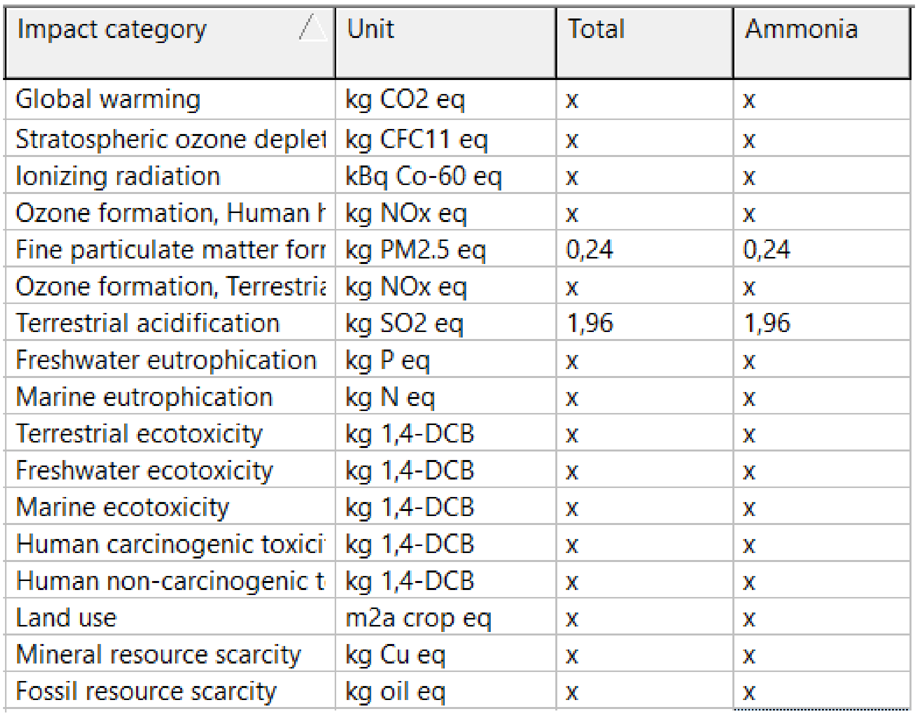
Table A1-1. Components of the water leaching ions

Component	Amount
Nitrite Compounds	33%
Nitrite	33%
Ammonium, ion	33%



Impact category	Unit	Total	Nitrous oxide
Global warming	kg CO2 eq	298	298
Stratospheric ozone deplet	kg CFC11 eq	0,011	0,011
Ionizing radiation	kBq Co-60 eq	x	x
Ozone formation, Human h	kg NOx eq	x	x
Fine particulate matter forr	kg PM2.5 eq	x	x
Ozone formation, Terrestria	kg NOx eq	x	x
Terrestrial acidification	kg SO2 eq	x	x
Freshwater eutrophication	kg P eq	x	x
Marine eutrophication	kg N eq	x	x
Terrestrial ecotoxicity	kg 1,4-DCB	x	x
Freshwater ecotoxicity	kg 1,4-DCB	x	x
Marine ecotoxicity	kg 1,4-DCB	x	x
Human carcinogenic toxici	kg 1,4-DCB	x	x
Human non-carcinogenic t	kg 1,4-DCB	x	x
Land use	m2a crop eq	x	x
Mineral resource scarcity	kg Cu eq	x	x
Fossil resource scarcity	kg oil eq	x	x

Figure A1-2. Midpoints of Nitrous Oxide emissions analysed through SimaPro 9, Midpoint ReCiPe Method H



Impact category	Unit	Total	Ammonia
Global warming	kg CO2 eq	x	x
Stratospheric ozone deplet	kg CFC11 eq	x	x
Ionizing radiation	kBq Co-60 eq	x	x
Ozone formation, Human h	kg NOx eq	x	x
Fine particulate matter forr	kg PM2.5 eq	0,24	0,24
Ozone formation, Terrestria	kg NOx eq	x	x
Terrestrial acidification	kg SO2 eq	1,96	1,96
Freshwater eutrophication	kg P eq	x	x
Marine eutrophication	kg N eq	x	x
Terrestrial ecotoxicity	kg 1,4-DCB	x	x
Freshwater ecotoxicity	kg 1,4-DCB	x	x
Marine ecotoxicity	kg 1,4-DCB	x	x
Human carcinogenic toxici	kg 1,4-DCB	x	x
Human non-carcinogenic t	kg 1,4-DCB	x	x
Land use	m2a crop eq	x	x
Mineral resource scarcity	kg Cu eq	x	x
Fossil resource scarcity	kg oil eq	x	x

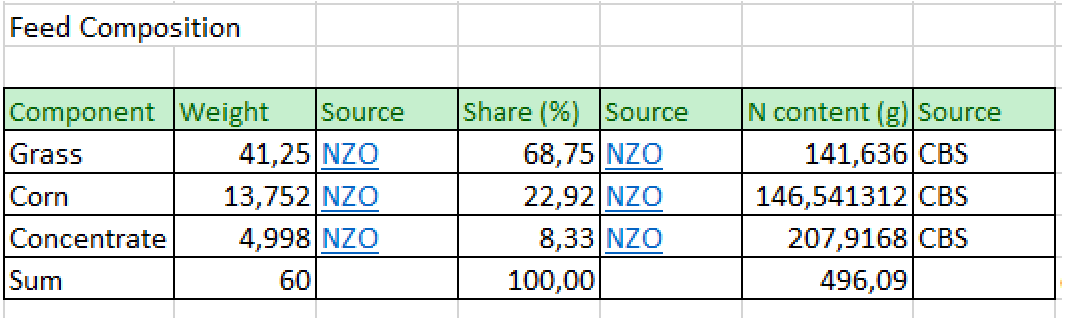
Figure A3-1. Midpoints of Ammonia emissions analysed through SimaPro 9, Midpoint ReCiPe Method H

Appendix 2 – Excel Model Sheets

The model consists of 6 sheets.

The first sheet includes the results and it is where the method of management in each step can be chosen.

The second sheet includes the information on cattle feed.

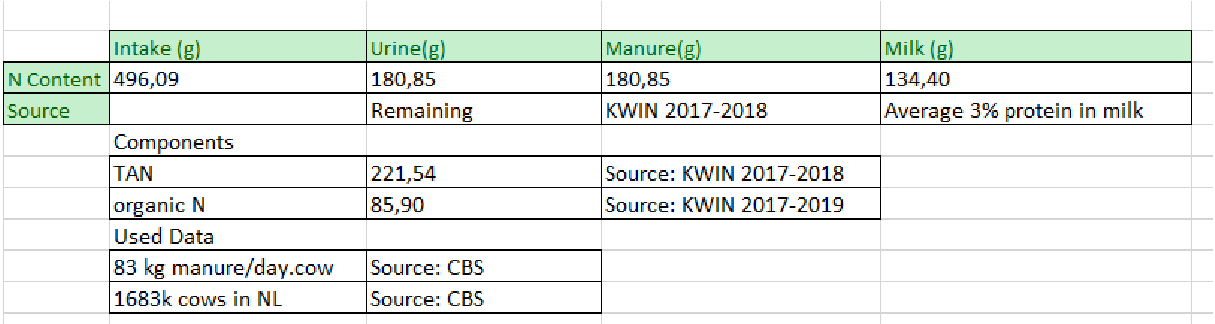


Feed Composition

Component	Weight	Source	Share (%)	Source	N content (g)	Source
Grass	41,25	NZO	68,75	NZO	141,636	CBS
Corn	13,752	NZO	22,92	NZO	146,541312	CBS
Concentrate	4,998	NZO	8,33	NZO	207,9168	CBS
Sum	60		100,00		496,09	

Figure A2-1. Feed composition sheet on Excel model

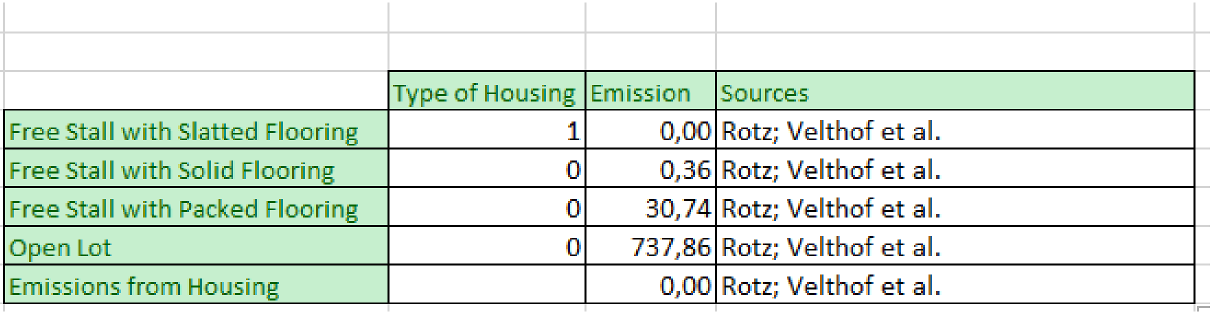
The third sheet includes information on cattle and how the intake nitrogen is divided between the excretions.



	Intake (g)	Urine(g)	Manure(g)	Milk (g)
N Content	496,09	180,85	180,85	134,40
Source		Remaining	KWIN 2017-2018	Average 3% protein in milk
	Components			
	TAN	221,54	Source: KWIN 2017-2018	
	organic N	85,90	Source: KWIN 2017-2019	
	Used Data			
	83 kg manure/day.cow	Source: CBS		
	1683k cows in NL	Source: CBS		

Figure A2-2. Ruminant information on Excel model

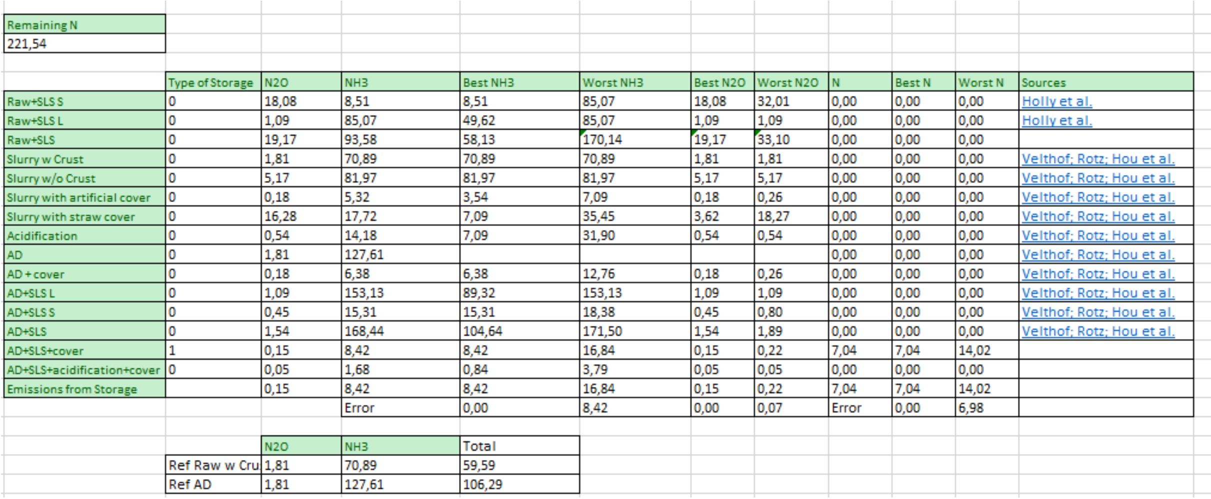
The fourth sheet is where the amount of emission in the cowshed is calculated based on its type. However in this study only slatted flooring is investigated since it is the most common case in the Netherlands and is considered as the reference scenario here.



	Type of Housing	Emission	Sources
Free Stall with Slatted Flooring	1	0,00	Rotz; Velthof et al.
Free Stall with Solid Flooring	0	0,36	Rotz; Velthof et al.
Free Stall with Packed Flooring	0	30,74	Rotz; Velthof et al.
Open Lot	0	737,86	Rotz; Velthof et al.
Emissions from Housing		0,00	Rotz; Velthof et al.

Figure A2-3. Emissions from housing facility on Excel model

The fifth sheet is the storage facility that includes the different strategies that could be applied to a storage.



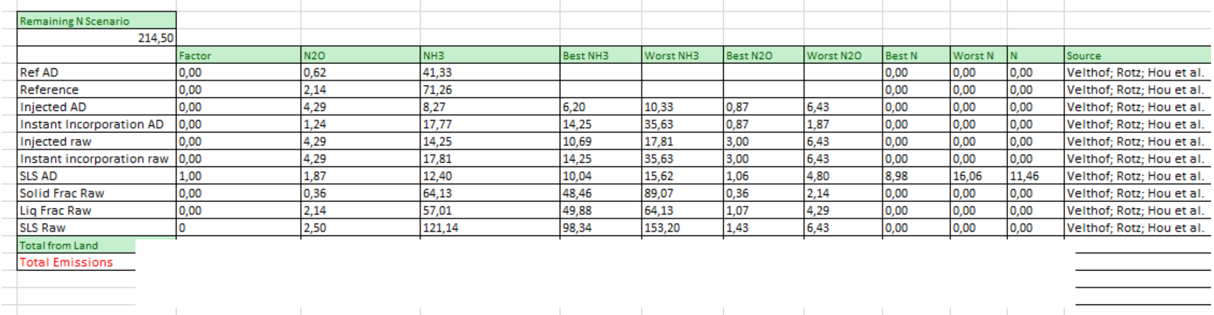
Remaining N
221,54

	Type of Storage	N2O	NH3	Best NH3	Worst NH3	Best N2O	Worst N2O	N	Best N	Worst N	Sources
Raw+SLS S	0	18,08	8,51	8,51	85,07	18,08	32,01	0,00	0,00	0,00	Holly et al.
Raw+SLS L	0	1,09	85,07	49,62	85,07	1,09	1,09	0,00	0,00	0,00	Holly et al.
Raw+SLS	0	19,17	93,58	58,13	170,14	19,17	33,10	0,00	0,00	0,00	
Slurry w Crust	0	1,81	70,89	70,89	70,89	1,81	1,81	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Slurry w/o Crust	0	5,17	81,97	81,97	81,97	5,17	5,17	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Slurry with artificial cover	0	0,18	5,32	3,54	7,09	0,18	0,26	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Slurry with straw cover	0	16,28	17,72	7,09	35,45	3,62	18,27	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Acidification	0	0,54	14,18	7,09	31,90	0,54	0,54	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
AD	0	1,81	127,61					0,00	0,00	0,00	Velthof; Rotz; Hou et al.
AD + cover	0	0,18	6,38	6,38	12,76	0,18	0,26	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
AD+SLS L	0	1,09	153,13	89,32	153,13	1,09	1,09	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
AD+SLS S	0	0,45	15,31	15,31	18,38	0,45	0,80	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
AD+SLS	0	1,54	168,44	104,64	171,50	1,54	1,89	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
AD+SLS+cover	1	0,15	8,42	8,42	16,84	0,15	0,22	7,04	7,04	14,02	
AD+SLS+acidification+cover	0	0,05	1,68	0,84	3,79	0,05	0,05	0,00	0,00	0,00	
Emissions from Storage		0,15	8,42	8,42	16,84	0,15	0,22	7,04	7,04	14,02	
			Error	0,00	8,42	0,00	0,07	Error	0,00	6,98	

	N2O	NH3	Total
Ref Raw w Cru	1,81	70,89	59,59
Ref AD	1,81	127,61	106,29

Figure A2-4. Emissions from storage facility on Excel model

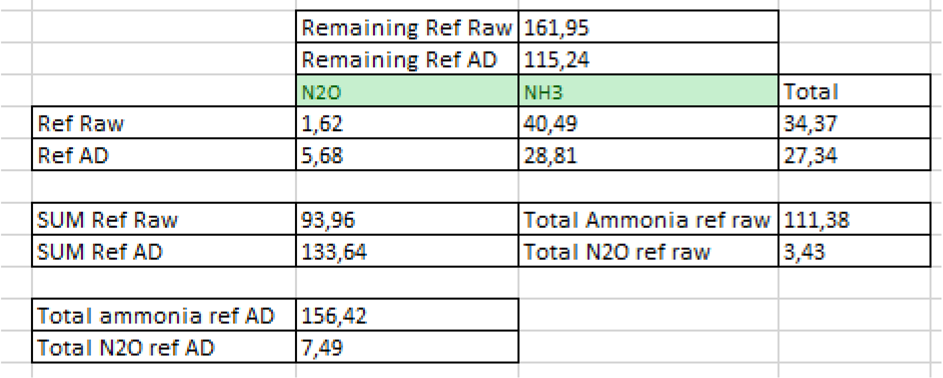
The last sheet includes the emissions that happen through land application, the remainders of nitrogen in manure and the amount that will be leached.



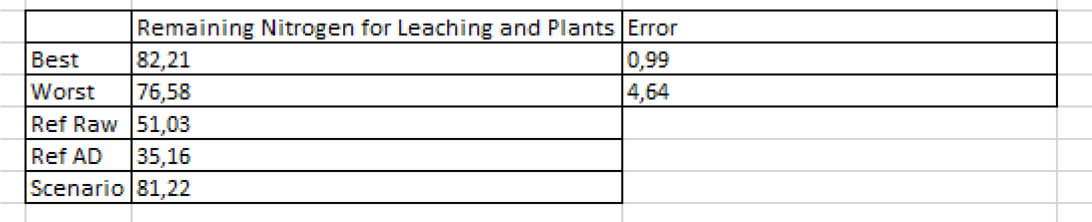
Remaining N Scenario
214,50

	Factor	N2O	NH3	Best NH3	Worst NH3	Best N2O	Worst N2O	Best N	Worst N	N	Source
Ref AD	0,00	0,62	41,33					0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Reference	0,00	2,14	71,26					0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Injected AD	0,00	4,29	8,27	6,20	10,33	0,87	6,43	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Instant Incorporation AD	0,00	1,24	17,77	14,25	35,63	0,87	1,87	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Injected raw	0,00	4,29	14,25	10,69	17,81	3,00	6,43	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Instant incorporation raw	0,00	4,29	17,81	14,25	35,63	3,00	6,43	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
SLS AD	1,00	1,87	12,40	10,04	15,62	1,06	4,80	8,98	16,06	11,46	Velthof; Rotz; Hou et al.
Solid Frac Raw	0,00	0,36	64,13	48,46	89,07	0,36	2,14	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Liq Frac Raw	0,00	2,14	57,01	49,88	64,13	1,07	4,29	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
SLS Raw	0	2,50	121,14	98,34	153,20	1,43	6,43	0,00	0,00	0,00	Velthof; Rotz; Hou et al.
Total from Land											
Total Emissions											

Figure A2-5. Emissions from land application on Excel model



	Remaining Ref Raw	161,95	
	Remaining Ref AD	115,24	
	N2O	NH3	Total
Ref Raw	1,62	40,49	34,37
Ref AD	5,68	28,81	27,34
SUM Ref Raw	93,96	Total Ammonia ref raw	111,38
SUM Ref AD	133,64	Total N2O ref raw	3,43
Total ammonia ref AD	156,42		
Total N2O ref AD	7,49		



	Remaining Nitrogen for Leaching and Plants	Error
Best	82,21	0,99
Worst	76,58	4,64
Ref Raw	51,03	
Ref AD	35,16	
Scenario	81,22	

Figure A2-6. Remainders of Nitrogen to apply to land

Appendix 3 – Other (Enhanced) Scenarios

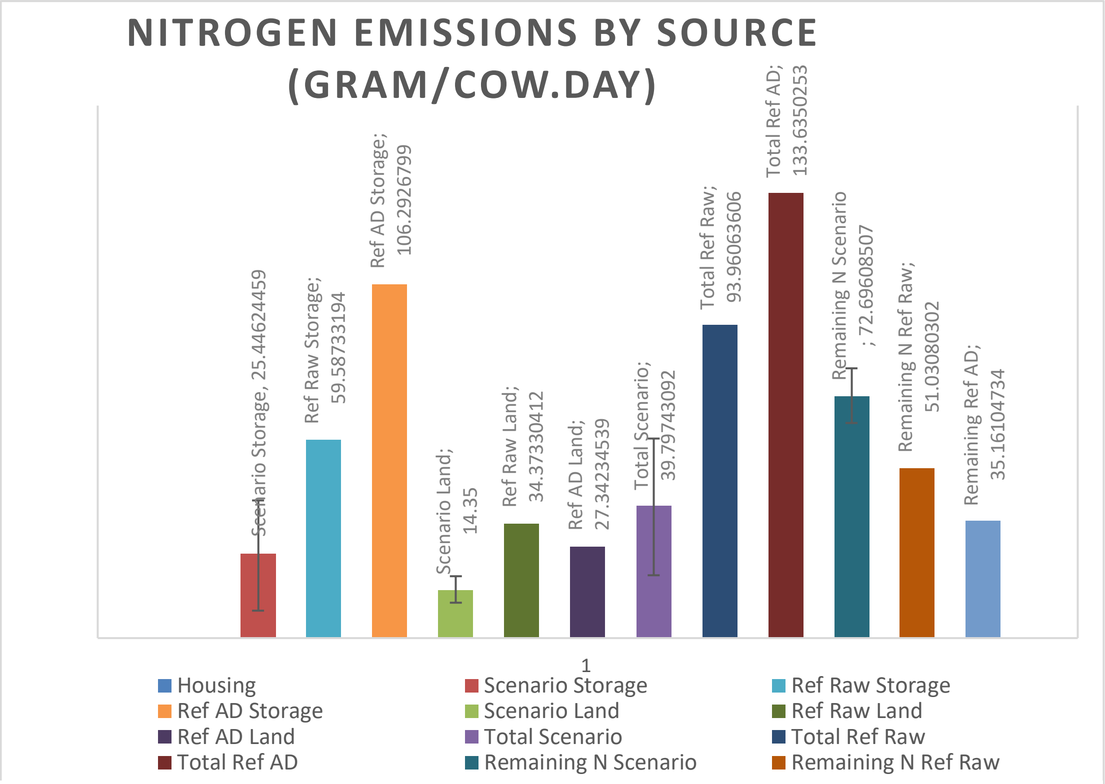


Figure A3-1. Scenario with straw cover and injected manure in land application

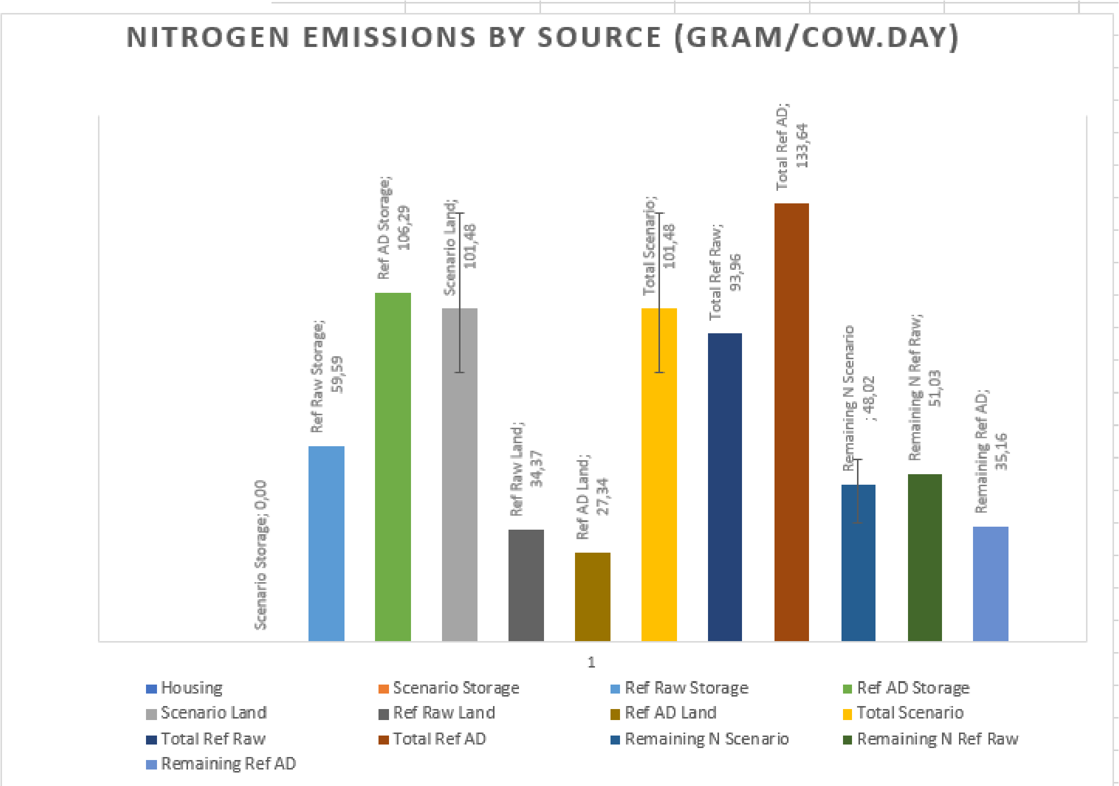


Figure A3-2. Scenario with acidification and solid-liquid separation in land application

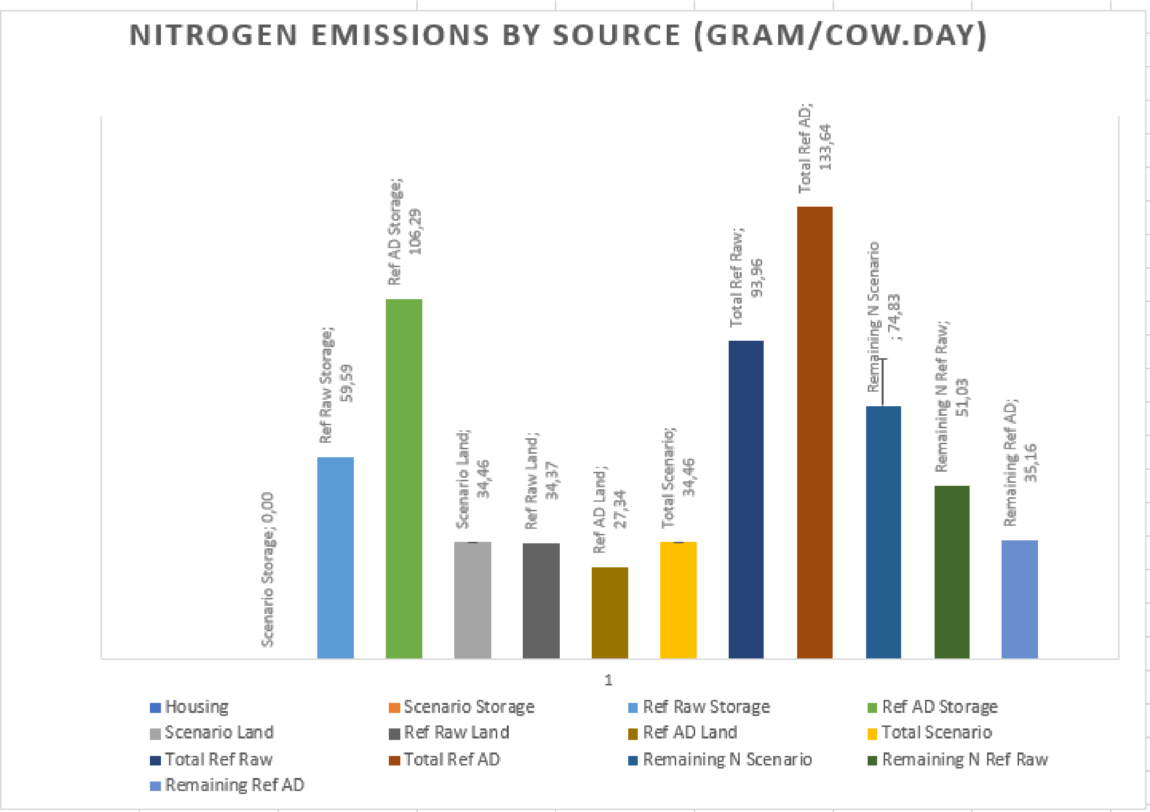


Figure A3-3. Scenario with anaerobic digestion followed by coverage for digestates and surface applied to land

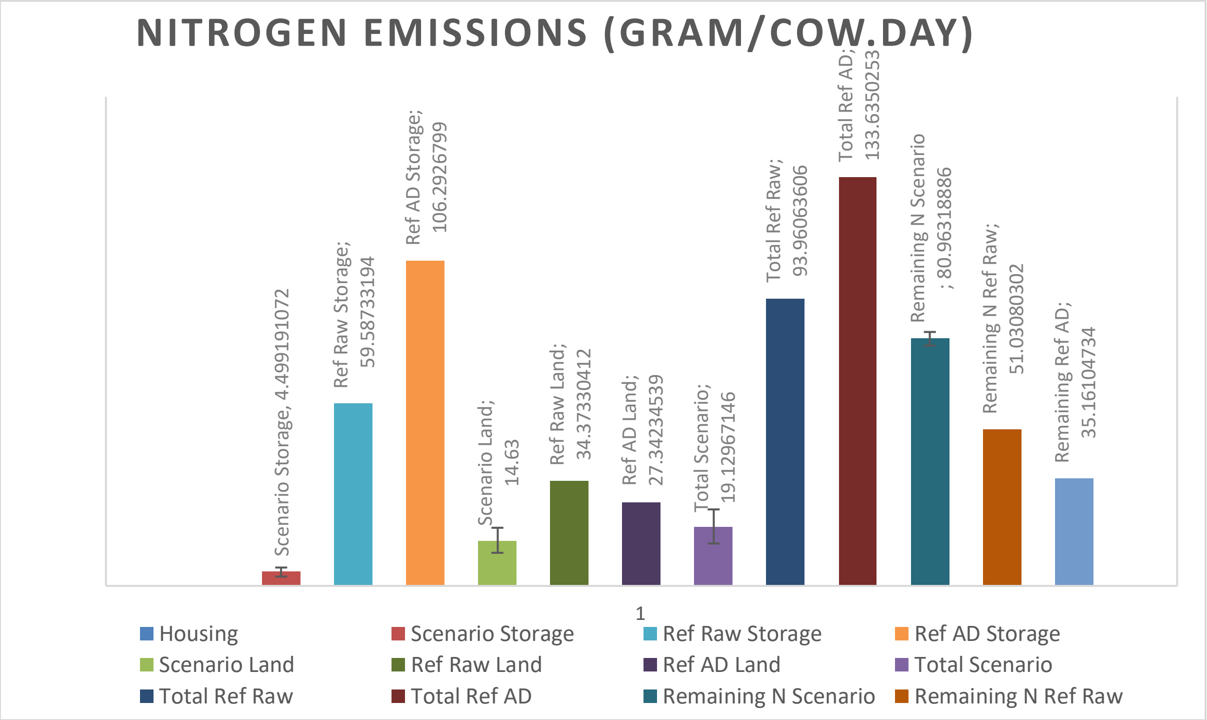


Figure A3-4. Emissions from each source in enhanced raw scenario as included in main text

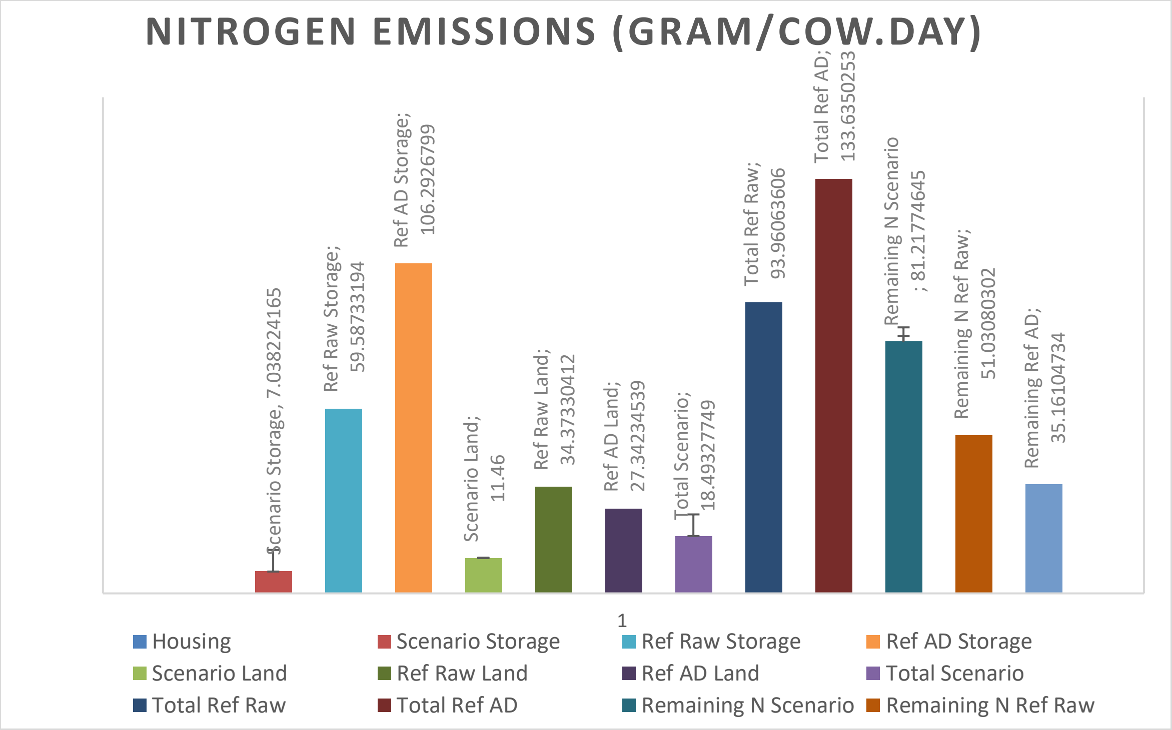


Figure A3-5. Emissions from each source in enhanced AD scenario as included in main text