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# Pre-study for Mjøsanlegget's introduction of poultry manure in the anaerobic digestion process.

*Forstudie for Mjøsanleggets introduksjon av kyllingmøkk tilført i metaniseringsprosessen.*

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Sammendrag:
**Bakgrunn:** Mjøsanlegget produserer gjødsel til bruk i gårdsdrift og biogass som brukes i lokale søppelbiler og busser i Oslo. Dette gjøres ved gjenvinning av søppel og kumøkk fra partnere i regionen. Mjøsanlegget har som intensjon å introdusere møkk fra fjærkre i biogassprosessen i håp om økt utbytte og kapasitet til å utnytte lokalt produsert møkk.

**Metode:** Studien samler vitenskapelige artikler relatert til metanisering av møkk fra fjærkre, sam-metanisering av møkk fra ku og fjærkre og prosesser for kontroll av ammoniakkproduksjon ved metanisering av møkk fra fjærkre. Dette vil gi Mjøsanlegget kunnskap til å kunne vurdere mulighetene for introduksjon av møkk fra fjærkre og utfordringer som dette kan medbringe. I tillegg er økningen i metanproduksjon fra de vitenskapelige artiklene inkludert som referanse til forskjell i produksjon.

**Resultater:** Sam-metanisering av møkk fra fjærkre med avfall fra agrikultur med høyt karboninnhold har resultert i senket produksjon av ammoniakk, noe som gir en bedre forhold mellom karbon og nitrogen. Dette fører til mindre hemning av metanisering og økt utbytte av metan. I likhet med dette har bruk av kumøkk som inokulasjonsmateriale med mais og møkk fra fjærkre som substrat demonstrert økning i metanproduksjon med en faktor på 1.2.

To-stegs metanisering med bruk av en membran som fjerning av ammoniakk har vist resultater der konsentrasjonen av ammoniakk er redusert helt ned til 2 g/kg i løpet av en periode på 21 timer. Bruk av ammoniakkstripping via gassgjenbruk har demonstrert reduksjoner i ammoniakkonsentrasjoner så høye som 82%.

**Konklusjon:** På grunn av økningen i stabilitet og metanutbytte, både gjennom sam-metanisering mellom møkk fra ku og fjærkre og sam-metanisering av kumøkk og avfall fra agrikultur, anbefaler studien en kombinasjon av de to metodene. Dette er for både å stabilisere og maksimere utbyttet av prosessen. I tillegg vil det medføre at få og små endringer i konfigurasjonen ved dagens anlegg, men fortsatt utføre den ønskede endringen i råstoff. Ammoniakkstripping og to-stegs før-hydrolyse med en membran ekstraktor anbefales videre studert med grunnlag i fordelen de kan ha ved å kunne utføre metanisering uten bruk av kumøkk, senket risiko for hemning av metaniseringen og nødvendige endringer i råtnetankene.

Stikkord:

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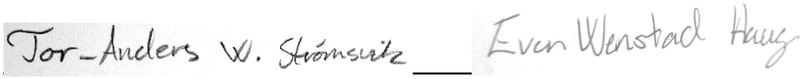
|---|
| Metanisering |
| Biogass |
| Kylling møkk |
| Mjøsanlegget |

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# Abstract

**Background:** Mjøsanlegget produces farm fertilizer for its surrounding regions and biogas for local garbage trucks and Oslo's busses; utilizing municipal solid waste and cattle manure from their partnered regions. Their intent is to introduce poultry manure into their process configuration with the hopes of increasing methane yield and expanding their capability of utilizing different locally produced manures.

**Method:** The study gathers scientific studies related to anaerobic digestion of poultry manure, co-digestion of poultry manure, and ammonia controlling processes used in poultry manure digestion. This enables the study to provide the necessary knowledge for Mjøsanlegget to assess their possibilities for introducing poultry manure, be prepared for the possible challenges of doing so, and knowing means to deal with said challenges. Additionally, the increase in methane yield in the studies are included for a referential difference in production, noting that any small-scale experiment will only serve as a relative suggestion for expected change.

**Results:** Co-digestion of poultry manure with agricultural wastes high in carbon content has shown to decrease ammonia production to a more beneficial carbon to nitrogen ratio, resulting in less methanogenic inhibition and higher methane yields. Likewise, the usage of cattle manure for inoculum and maize and poultry manure for substrate has demonstrated large increases in methane yield up to 1.2-fold increases.

Two-stage digestion using a membrane contractor with ammonia extraction has shown ammonia levels decreasing to concentrations as low as 2 g/kg over the period of 21 hours, and ammonia stripping via gas recycle has demonstrated reductions of ammonia concentrations as high as 82%.

**Conclusion:** Due to the demonstrated increases in stability and methane yield in both co-digesting cattle and poultry manure, and co-digesting cattle manure with agricultural wastes, the study recommends a combination of the two methods to both stabilize and maximize the yield of the process; presenting a very small change in configuration from the current process, but accomplishing the wanted feedstock change. Ammonia stripping and two-stage pre-hydrolysis with a membrane extractor are recommended further studies due to their

applicability of enabling digestion without cattle manure without risks of ammonia inhibition, but necessity for equipment changes in the digesters.

# Foreword

We would like to take this opportunity to thank GLØR and Mjøsanlegget AS through Tom Werven for meeting with us, supplying plentiful and useful data, and being very helpful in answering our questions.

We would also like to thank our advisor Shiplu Sarker for theoretical support, helping revise our writing and helping make decisions.

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Thank you to our family and friends for continued support and encouragement, especially in the last few months of writing this thesis.

Lastly, we would like to thank Ane Olastuen and David Hurst for assistance in proofreading the final thesis draft.

Tor-Anders W. Strømsvik & Even W. Haug.

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# Abbreviations

**AD** - Anaerobic digestion

| | |
|---|---|
| **AW** | Agricultural wastes |
| **CM** | Cattle manure |
| **C:N** | Carbon to nitrogen ratio |
| **FAO** | Food and Agriculture Organisation (of the UN) |
| **FLW** | Food loss and waste |
| **FW** | Food waste |
| **HRT** | Hydraulic retention time |
| **MSW** | Municipal solid waste |
| **ss-MSW** | Source-separated municipal food waste |
| **PM** | Poultry manure |
| **TAN** | Total ammonia |
| **TCM** | Treated chicken manure |
| **TS** | Total solids |
| **VFA** | Volatile fatty acids |

## Chemical abbreviations

| | |
|---|---|
| **C** | Carbon |
| **$CH_4$** | Methane |
| **$H_2$** | Hydrogen |
| **N** | Nitrogen |
| **$NH_3$** | Ammonia |

# 1 Introduction

The intention of this study is to provide an assessment of the viability for the different configurations with which Mjøsanlegget can introduce *poultry manure* (PM) into their *anaerobic digestion* (AD) process. The assessment is conducted as a pre-study in the form of a meta-study, focusing on gathering the information necessary to enable Mjøsanlegget to enter an experimental production phase with the PM added to the feedstock; possessing the necessary knowledge to circumvent and adapt to the challenges related to fully or partially replacing *cattle manure* (CM) with PM. The study will in this regard produce an assessment for the risk factors for methanogenic inhibition, suggestions for optimal feedstock configurations with a focus on efficiency and stability, and an expected change in methane production based on comparative data from the studies gathered.

As a means to assure the thesis is readable for a broader audience, it includes an introduction to the global waste and waste management situation touching on subjects like source separation and bioenergy. The theory section also includes a brief introduction on the core aspects of AD biogas production, as well as an overview of Mjøsanlegget's plant as to assure the clarity of information regarding how the plant operates at the time of writing, and how the suggested changes will alter this operation.

# 2 Theory

## Global waste situation

Despite the lack of a universally accepted definition of ‘food waste’, such a definition should include food in the primary stages of production, as well as products entering the supply chain, and products coming out of the end-stage of food production.

This would among other things include crops that are not harvested and ploughed in, crops harvested and exported for other markets than food consumption, and crops harvested but later disposed of; the primary categories of primary stage food waste. It would likely also encompass all edible and non-edible materials used in the food production process, as well as all food not consumed and disposed of after finished production, such as household food waste, restaurant waste, and grocery store waste.

Quality of available data on food loss and waste (FLW) in the world is rather poor due to lack of input data and clear definitions, but the Food and Agriculture Organisation of the United Nations (FAO) has estimated that ⅓ of food produced for human consumption is lost or wasted; equating to approx. 1.3 billion tons annually.

The proportion of *municipal solid waste* (MSW) varies widely from region to region, but most commonly, the largest proportion is from household consumption. Here *food waste* (FW) can be categorized into three categories: unavoidable, avoidable, and partially unavoidable (Banks et al., 2018).

The first category encompassing unavoidable FW generally consists of residues and by-products from food preparation such as seeds, cores and inedible stems.

The second category concerning avoidable food waste generally consists of unused food, often discarded due to excess purchase, passing of expiration date, or inefficient preparation.

The third category, involving partially avoidable FW, considers food that would be considered unavoidable to some, but not to others, such as edible but often discarded parts of prepared food and dry bread.

### Source separation

Source separation is defined as separating waste into categories based on their material makeup before transport, e.g., plastics, into different processes for handling. This allows for recycling of some materials, while decomposition, incineration, or disposal of others.

Typically, the categories of separation are determined by the available waste management services connected to the municipality, as waste deliveries have to be tailored to the processes used by these companies.

However, due to the ever-present problem of failed separation of municipal waste, waste management stations have to apply means of machine separation to supplied waste when necessary for the efficiency or success of the waste treatment for the category. Among these means are sorting through a filter to remove larger objects, using magnetic systems to remove metals, washing or burning to remove impurities, etc. Some of these measures are generally present in waste management plants to constantly guarantee a certain level of purity; especially concerning plants that recycle, as non-belonging materials to the process can lower the quality of the recycled material or inhibit proper function in the recycling process (Banks et al., 2018).

### Bioenergy and biogas

Before defining biogas, it’s important to know the definition of bioenergy; being all energy derived from usage of biological material as a fuel source.

The advantage of bioenergy over other kinds of renewable energy is its availability, as a result of the diversity of different materials applicable, and the ways to harness their energy; everything from burning wood for heating, to the usage of biogas and other biofuels to fuel transport such as cars or busses. Considering the burning of wood and grasses that humanity has done for thousands of years, bioenergy is the oldest form of human energy production, but it is only during the last few decades that new, varied, and more efficient ways of utilizing bioenergy have been explored and put to use (Hohle, 2005).

Among these methods, one of the more recent is the production of biogas through AD; producing a mixture of gasses from decomposition of organic waste, with the help of methanogens to control this production to be largely methane centric; a process called anaerobic digestion (Hohle, 2005).

### Anaerobic digestion

The first necessary step for anaerobic digestion is the breakdown of carbohydrates and organic polymers into soluble derivatives, accessible for bacteria to further break down. At this point the created derivates will be in the form of simpler sugar compounds, amino acids, and fatty acids.

After the breakdown of these solids, the fermentative (acidogenic) processes inside the digester tank breaks down some of the remaining solids, and creates ammonia ($NH_3$), hydrogen sulfide, and *volatile fatty acids* (VFA). As this goes on, acetogenesis starts, where VFAs are converted into acetic acid, hydrogen and carbon dioxide.

The final stage in the production process is methanogenesis where methanogens break down the produced derivates from the previous processes into methane, carbon dioxide, and water. This step is where the desired production of methane happens, and ammonia production, pH levels, and temperature consistency requires some attention as the methanogens have a certain range of tolerance for the aforementioned conditions. Greater deviations in these conditions will lead to inhibition, causing full stop of the methanogenic process.

### Inoculum & manure type

The term inoculum refers to the living bacterial portion of the input feedstock, responsible for the digestion processes in the digester. Among these bacteria are the methanogens; the archaea responsible for producing methane in the last stage of the process. The use of manure to develop desired bacterial communities is common as it tends to produce a large amount of methane producing bacteria (methanogens). Reuse of digestate from biofertiliser and feedstock is also suitable for the same purpose, as the reused digestate already contains parts of the bacterial community present in their previous batch.

As the digestion of pure manure isn’t feasible for methane production in a commercial scale relative to its alternatives, it is a common practice to co-digest manure with farm waste or food waste. This does not only create a more complex mixture of nutrition for the digestion process, but also leads the plant to some degree of control of the carbon: nitrogen ratio, and the amount of “accessible” solids for the bacteria as municipal food waste tends to contain higher levels of digestible solids than manures.

There are certain attributes for different kinds of manures to consider before choosing which ones to use in the co-digestions process. CM is good for stable methane production, but low in nitrogen which diminishes maximum methane capacity. PM can produce higher amounts of methane per volume but is high in nitrogen which runs the risk of over-producing free ammonia in the digesters, inhibiting or ending the methane production if not addressed properly. Pig manure tends to show the same instability as PM but has a lower potential for methane production in similar processes and is for that reason less commonly used.

Finally, it’s worth mentioning that even though methanogens can acclimate to high levels of ammonia concentrations, this takes a substantial amount of time which results in decreased methane production efficiency and considerable delays in the next batch of production and consequently unutilized production potential after acclimatization.

### Mjøsanlegget

Mjøsanlegget is a facility located in Lillehammer, more specifically Roverudmyra environmental park, south of the city. At Mjøsanlegget MSW is converted into wet-fertilizer, compost, and biogas.

*Figure 1: Mjøsanlegget’s main operative building and buffer tank.*

(Om oss, 2019) Mjøsanlegget receives MSW from the inhabitants of the 18 co-owning municipalities, in addition to their stores, hotels, and restaurants. Due to an increased interest in more environmentally conscious handling of waste, the department of environmental protection decided to fund a pilot project of handling waste in larger coherent areas, such as Hedmark and Oppland; resulting in the establishment of source separations of municipal waste in these areas. This opened up the opportunity for a collaborative effort to recycle the municipal waste in the areas around Mjøsa. HLAS, GLØR, and GLT then decided to work together, creating

Mjøsanlegget. With the plant becoming operational in the year 2000, it has been continuously upgraded and expanded upon. On the time of writing, Mjøsanlegget has the capacity to process 30 000 tons of FW, over doubling their capacity of 14 000 tons before recent expansions.

### Mjøsanlegget's process

(Om oss, 2019) When the solid waste first arrives at the plant, it is mechanically sorted and grinded. Metals are removed with the usage of magnets, and a rotating separator sorts out plastics and other foreign materials from the FW. The separated glass and metal are then washed to remove any last bits of FW. Once the FW has been separated from other materials, it is transported into a stirring buffer tank with a throughput time of 7 days, allowing for a more mixed content substrate; improving predictability of the process further on. Here the fermentation process starts, producing bacteria and microbes that start breaking down the FW.

*Figure 2: Mjøsanlegget's old and new digester (front and back respectively) and gas washers to the right.*

From the buffer tank, the FW is sent through a pressure heater system keeping 138℃ for at least 20 minutes, before being sent through a flash tank quickly releasing pressure and helping to mix the microbes and bacteria with the food waste. The pressure heater system helps removing harmful bacteria and makes it easier for the remaining bacteria and microbes to decompose the FW. Once the FW has passed through the pressure heater system, it is delivered to the digester tank where it is mixed with the inoculum to start methanogenesis, producing heat and biogases, as well as breaking down the remaining materials into biofertilizer and sludge. The gasses produced are collected, utilizing a small fraction for the heating process, and sending the rest through a cleaning process where $CO_2$ and water vapor is removed, leaving a concentration of 97 to 99% methane gas; ready to be used as fuel.

Currently Mjøsanlegget supplies biogas as fuel for the garbage trucks collecting waste delivered to Mjøsanlegget, as well as the buses in Oslo.

In addition to the biogas production, the decomposed solids and remaining liquids produced during AD are sold as compost and fertilizer; the liquid content after the AD batch is cooled and sold to regional farmers for use as fertilizer in food production, and the digested solids are sold to a company called Mjøsvekst AS. Here the solids are mixed with yard waste and sand to create soil for gardening use.

# 3 Method

## 3.1 Research

### 3.1.1 Target studies

The study is conducted primarily in the form of a meta study, aiming to gather applicable information surrounding the usage of poultry manure; focused on minimizing risk of methanogenic inhibition, and maximizing production output. The target studies for the meta study is primarily small-scale comparisons to evaluate the difference between CM and PM based configurations, and experimental studies of altered/supplemented substrates to increase productivity and minimize the risk of methanogenic inhibition.

Studies that are not of the small-scale comparison type are filtered based on how well they compare to Mjøsanleggets AD facility to avoid unnecessary variables and differences in production. This will contribute to lowering the likelihood of not producing similar results.

Additionally, the processes present at Mjøsanlegget will be compared to the optimal processes found in PM studies, making a basis for suggested changes that will benefit Mjøsanleggets ability to improve their utilization of poultry manure.

### 3.1.2 Information usage

Information is for the necessity gathered into two main groups; one consisting of knowledge around the functioning of PM in an AD process relative to CM. This accumulation of knowledge around the characteristics of poultry manure digestion is used as a basis for analyzing the feasibility of adapting PM usage to the plant in question, identifying probable challenges, and accessing expected beneficial outcomes of successfully implementing the PM.

The second group acompasses studied means for controlling the challenges identified in the process of PM digestion. This category of information is used to provide a 'toolset' for successfully implementing PM digestion, and controlling the process.

Such a list of ‘tools’ will be directly related to the characteristic challenges surrounding PM identified in the formerly mentioned group of information; tying together the link between potential problems and solutions.

## 3.2 Presentation of findings and results

As the primary goal of presenting the findings is making awareness around the changes in predisposition for the AD process chain utilizing PM instead of CM, it is necessary to compare the function and challenges of each manure configuration and compare the relative differences between the two. In the process of doing so, there is also focus on identifying the critical variables to each inoculum type; leaving the non-common critical variables of the PM as the primary challenges in switching from CM to PM. This comparison will serve as to identify the points of focus for the research and development of the necessary ‘toolset’ and knowledge for changes in the plant.

As the aforementioned ‘toolset’ is developed, the major focus is on the in-practice applicability of the individual ‘tools’, determining whether or not they are efficient, unlikely to produce other challenges when applied, and consistent.

To accomplish a good assessment for each individual ‘tool’, they’re assessed towards their targeted areas, with the focus on how well they combat the problem/challenge at hand, which other areas they affect, and how they compare to alternative measures that target the same area or challenge/problem. Depending on risk of new complications versus the benefit of the ‘tool’, they study either filters based on a risk versus reward principle or lists both with preference towards each, depending on the severity of the problem/challenge, and urgency to solve it.

Finally, the study presents the suggested alterations to the biogas production plant, with respect to changes that either mitigate risks of inefficiency and process complications, and/or improves on the plants’ ability to increase efficiency and stability, considering PM. Suggested changes are listed with their potential benefits, referring to results from gathered studies. The suggested changes are however not subject to construction viability analysis or economic analysis and are therefore in principle only alterations that the study suggests Mjøsanlegget looks further into based on their agreement with their apparent usefulness and viability.

# 4 Results

## 4.1 Current state

### 4.1.1 Substrate

The plant primarily runs of the delivered *source-separated municipal food waste* (ss-MFW) delivered from the surrounding region, combined with organic waste from several industries in the vicinity, all of which falls under category 2 & 3 food waste. This results in a steady stream of fairly consistent food waste from households, coupled with periodic shipments of organic waste with significantly variable characteristics such as calorific value, solid content, and volatility.

Considering the plant's lack of ability to regulate the content of these shipments on necessity, its buffer tank is a valuable step into mitigating large fluctuations of substrate characteristics, making sure that the periodic shipments are mixed with the regular shipments of ss-MFW, creating a much more consistent nature to the substrate. This, however, results in an inability to add to or subtract from the amount of materials rich in specific compounds that can regulate the digestion process; a challenge with the more volatile nature of PM in AD processes relative to CM.

### 4.1.2 Inoculum

The plants current process revolves around using purely CM for inoculum in the AD process; on average reusing 18% of the produced bio-fertilizer in new AD batches.

The manure used is supplied from regional farms with a blend of manure from dairy cattle and non-dairy cattle, resulting in a lower *total solids* (TS) value than pure CM, which requires less dilution than pure CM. Additionally, the nutrition values in dairy manure can be influenced by the cattle's diet, and in cases provide a higher potential methane yield.

### 4.1.3 Methane production

Currently, the plant produces biogas with a methane percentage ranging between 63 to 65% from the two digesters at 2200 and 3000 $m^3$ capacity. The produced methane is stored in a balloon storage with 99% methane purity, as well as in a secondary balloon storage, also containing the remaining biogas.

## 4.2 Storage

### 4.2.1 Storage capacity

The current pre-production storage solutions for the plant involves a 600 $m^3$ tank serving as a buffer tank for the substrate with a throughput time of a week, a large-scale lagoon for supplied manure, and two storage tanks for supplied liquid and solid ss-MFW.

### 4.2.2 Considered changes

Mjøsanlegget is considering a possible expansion of the buffer tank and food waste storages, allowing for a larger production capacity, as well as the ability to store larger amounts of substrate during holiday periods where supply for municipal food waste temporarily stops, allowing for continued production through the holiday seasons.

Mjøsanlegget is also planning the installation of a water purification system that will allow cleaning the AD processes liquid portion after a finished batch; producing nearly pure water with capacity for water deodorization.

## 4.3 Poultry manure characteristics

### 4.3.1 Solid contents

(Bujoczek et al., 2000; Nasir et al., 2012) has suggested that the optimal range for TS percentage when anaerobically digesting PM lies between 5-10%, more so leaning towards the lower end of the range when comparing $CH_4$ output. A TS level exceeding 10% is therefore not recommended due to the increased level of ammonia and free ammonia production, risking inhibitory concentrations for the methane production. Tests with high TS digestion (~10%) show that high TS digestion is not beneficial to $CH_4$ production and due to inhibitions related to nitrogen conversion to ammonia, only produces around two thirds of the $CH_4$ as in the low TS comparisons (Bujoczek et al., 2000).

### 4.3.2 Ammonia production

The conversion of nitrogen and $H_2$ to ammonia present after the start of acidogenic activity has the potential to inhibit the methanogenic processes due to its toxicity to methanogens. PM containing relatively high amounts of nitrogen therefore presents the risk of increased ammonia production relative to CM. Levels above 250 mg/L of $NH_3$ creates substantial inhibition of the methanogenic process and is therefore a strong threshold for $CH_4$ viability, as demonstrated by (Bujoczek et al., 2000).

One of the controllable factors with relation to ammonia production is the *carbon to nitrogen* (C:N) ratio, which ideally lies between 13–28:1 (Nasir et al., 2012). With nitrogen levels exceeding this ratio, the risk of ammonia inhibition rises substantially; requiring the addition of high carbon content organic material into the feedstock to restore the preferable C:N ratio.

Rather than adjusting the feedstock to compensate for high levels of nitrogen or excessive ammonia production, measures of ammonia stripping are also existent.

### 4.3.3 Methane yield

As shown in the results of the ref. (Nasir et al., 2012) PM demonstrates the largest potential $CH_4$ yield compared to the other manures; exceeding the potentials demonstrated for swine manure and cattle manure by 13.6% and 35% respectively (referenced from conclusions iv, v and vi). Poultry manure in the aforementioned study shows its highest potential efficiency through a batch process operating at 35 degrees celsius, co-digesting PM with PM + digested sludge.

Additionally, the ref. (Abouelenien et al., 2014) demonstrates that the usage of *treated chicken manure* (TCM) improved the $CH_4$ output by 42% relative to the best comparison with fresh PM. The study however notes that the cost of TCM doesn't necessarily compete with fresh PM usage economically, depending on the viability of utilizing fresh PM with the food waste supplied to the plant.

## 4.4 Process alteration

### 4.4.1 Two-stage digestion and membrane contractor

As demonstrated by the ref. (Wang et al., 2018) the usage of a two-stage digestion process with pre-hydrolysis and a membrane contractor with an ammonia extraction setup, *total ammonia* (TAN) levels could be brought down to 2 g/kg in 21 hours under ideal membrane and manure conditions; noting that a larger membrane surface area would further speed up the ammonia extraction. This was done by subjecting PM to pre-hydrolysis, followed by the membrane contractor and ammonia extraction. Following this, the PM was introduced to a secondary tank with inoculum for digestion.

In the first stage of the process a residence time of 3-5 days was deemed sufficient, and acidogens showed little inhibition from rising TAN concentrations; leading to conclude that the concentrated PM was usable as long as it's pumpable. Their suggested conditions for optimal performance of the ammonia removal process are a dilution of PM of 1:2 with a pH of 9, and a threshold for changing the extraction solution between a pH of 6-7 (3-4 g/L TAN).

Along with the reduction of TAN levels, removing the issue of methanogenic inhibition, they also demonstrated a substantially shortened lag phase in digestion with TAN = 2 g/kg.

### 4.4.2 Ammonia stripping

As discussed in the ref. (Nasir et al., 2012) ammonia stripping is a valuable asset to a single-stage or batch digester. Their referenced study by (Abouelenien, et al., 2010) shows the promise of using thermophilic conditions over a 10 days *hydraulic retention time* (HRT) coupled with ammonia stripping via biogas recycle. This recycling of biogas was then coupled with a washing with an ammonia absorber; bringing the degree of ammonia removal to a peak of 82%.

This process, however, demonstrated a substantial oxidation of acetate, necessitating measures to reduce oxygen contamination; which in this study, a container of ferrite powder placed in the exterior end of the ammonia absorber was able to solve.

## 4.5 Feedstock alterations

### 4.5.1 Co-digestion with agricultural waste

Co-digestion of PM with carbon rich organic waste can contribute to balance the C:N to a more preferable ratio, leading to increased methane production, and lowered production of ammonia; resulting in lower risk of methanogenic inhibition.

As seen in the ref. (Abouelenien et al., 2014), the co-digestion of *agricultural wastes* (AW) and PM produced a 50% increase in $CH_4$ production compared to the control of only PM (both in mesophilic conditions), while simultaneously resulting in a 15% decrease of ammonia accumulation.

In the aforementioned study, a combination of coffee grounds, cassava-, and coconut waste was utilized, which is less likely to be sufficiently obtainable for Mjøsanlegget. Therefore, it is suggested to assess the possibilities of obtaining other commonly used agricultural wastes such as wheat straws, potato tuber, and potentially coffee grounds from regional businesses with high coffee bean throughput.

## 4.6 Co-digestion of cattle and poultry manure

(Yangin-Gomec and Ozturk, 2013) referenced by (Abouelenien et al., 2014) utilized co-digestion of cattle manure and PM with maize silage and demonstrated the impressive methane yield of 693 mL/g VS added; matching the highest yield produced in the study (Abouelenien et al., 2014) under thermophilic conditions, and surpassing their highest yields under mesophilic conditions by 37%.

(Yangin-Gomec and Ozturk, 2013) produced these results using the cattle manure as inoculum for the methanogenic cultures while utilizing the PM as extra substrate; citing the synergetic combination of the food wastes with the manures leading to a 1.2-fold increase in methane yield compared to their controls.

# 5 Discussion

The current state at Mjøsanlegget is highly optimized for the process that is conducted today; using the buffer tank to regulate the substrate composition to be more consistent, the process is less plagued with having large fluctuations in the FW composition because of the variable waste collected. Although Norwegian household FW remains fairly consistent, anomalies do occur, especially around holiday seasons. CM in this regard is good for a more irregular substrate composition due to its inherently stable nature in AD; also providing the possibility for the co-digestion of more CM and less FW to conserve the FW storage until the next shipment.

The addition of PM does not require construction at the facility as no new technology is needed and can increase methane production as long as it is configured and dealt with correctly. Using PM, in combination with the existing CM and FW has also shown to result in better methane production due to the PMs function as rich substrate. Additionally, combining PM as substrate with the increased CM digestion for conservation of FW can help increase the methane yield to mitigate losses in production.

On the topic of ammonia stripping via gas recycle, the viability of the processes discussed show great promise for providing more stable digestion with the TCM. It does, however, present the problem of not being doable without the alteration of a digester to provide the necessary equipment and piping to both direct the produced gasses to the washers and filtration units, construction of the washers and filtration units themselves, and a gas bubbling pump, as represented in Fig.1 in ref. (Abouelenien, et al., 2010).

Likewise, the potential use of the older digester for pre-hydrolysis of PM and ammonia filtering with a membrane contractor in a two-stage digestion process would require a reconfiguration of the connections between the tanks. The study group was informed in their meeting with Mjøsanleggets CEO Tom Werven that the tanks were already capable of series-utilization; making a two-stage configuration possible; but the addition of the membrane contractor unit would still necessitate alterations on the old digester, were this configuration to take place.

Alterations such as the two aforementioned, would require Mjøsanlegget to conduct their own further assessments of viability; both economically and with regards to prospective improvements to production.

Considering the results of co-digestion of PM with AW showing great promise for improving the C:N ratio of the feedstock, improving efficiency and mitigating risks of inhibition, a separate storage of AW supplied from regional farms could be a valuable asset to Mjøsanlegget, but depending on the storage space available, and the projected storage necessities for this measure; the construction of a separate storage unit might be necessary.

Worth commenting is also the numbers in results from all studies by the ref. (Yangin-Gomec and Ozturk, 2013), but as they're done in small scale, replicating the actual improvement of methane yield is unlikely. The results from these studies however serves as a general pointer to the expected change of methane yield as a suggestive, comparative value differing between the studies' experiments and controls.

# 6 Conclusions

The studies have demonstrated a larger methane yield potential utilizing PM than with CM in mesophilic conditions, which is an existing practice at Mjøsanlegget at present. The usage of AW proved beneficial to skewing the C:N ratio towards the optimal range; providing a useful option for Mjøsanlegget if the nitrogen content proves a challenge to keep within the bounds of the optimal C:N ratio (13–28:1).

Co-digestion of PM as additional substrate with CM as inoculum introduction, together with AW (at Mjøsanlegget, FW) was demonstrated to provide both stability and high methane yields, requiring the least change in AD configuration to achieve with Mjøsanleggets current process.

The options for (pre-) treatment of PM are viable to stabilize the process of PM co-digestion with FW, which is promising for the utilization of PM without CM but require either physical changes to the connection between the old and new digesters, or a completely new module for pre-treatment at the plant. Such changes would however require further research on the viability of construction and *use.*

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