Effect of temperature optimization on the efficiency of Membrane Distillation for removing ammonia in wastewater

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Abstract

The most common nitrogenous water pollutant is ammonia. Excess ammonia levels in water can be problematic for aquatic organisms and human health. Because of this, industries are required to treat water for its removal. Recently membrane distillation has gained attention as a new method of ammonia removal. Membrane distillation is often considered as an alternative to conventional measures because it can be more productive while being operated at lower temperatures. Ammonia removal through membrane distillation at various temperatures was compared through an extensive review of available literature and data. It was found that higher temperatures allow for more efficient removal of ammonia. From this, future work on the optimization of membrane distillation should be focused on temperature conservation within the system to produce greatest efficiency at the lowest cost.

Introduction

Wastewater is composed of 99.9% water and 0.1% of organic matter, microorganisms, and inorganic compounds (Environmental Protection Agency). Organic matter can consist of nitrogen, sulfur, and phosphorus, as well as other compounds that, once broken down by microorganisms, are converted into inorganic compounds. Current wastewater treatment plants in California are only required to test and treat nitrogen pollutants. Ammonia (NH3) is the most common nitrogen pollutant found in wastewater as a result of agricultural, industrial, and domestic discharges and is known as a nitrate (Hasanoglu et al., 2010). Ammonia has a trigonal pyramidal shape as a result of the placement of its lone pair of electrons and is a polar molecule. The polarity of ammonia allows it to interact with the hydrogen bonds in water and makes it readily soluble in water. This trait plays a vital role in the effects ammonia can have on water treatment and how it interacts with the environment, which will be discussed throughout the paper.

Nitrates and other excess nutrients in water can dramatically increase water treatment costs amounting to billions of dollars each year according to the EPA. Wastewater from industrial and agricultural sources can contain ammonia in concentrations ranging from 5-1000 ppm (Rezakazemi et al., 2011). Agricultural wastewater comes from runoff from fields as a result of excess water from watering crops. Industrial sources include manufacturing and refining plants that use water in their production and must eventually discharge it as waste. Discharge from any industrial source must meet specific standards set by the EPA as to what the wastewater is allowed to contain. However, most nitrogen waste can be sourced from municipal wastewater, or water that has been used by humans and belongs to a city, town, or governing body (Miladinovic and Weatherley, 2007). Municipal wastewater sources from communities or households and can also be known as sewage. This kind of wastewater is the type that is treated at a wastewater treatment plant; however, treatment plants can also receive water generated by industrial and commercial sources.

Regardless of the source, removal of ammonia and nitrogen pollutants is desirable due to its effect on the environment, economy, and human health. Ammonia leads to eutrophication, or the excessiveness of nutrients, and can be directly toxic to species of fish (Fig. 1). Moreover, these environmental effects often lead to economic problems for aquaculture industries, industries based on the cultivation of aquatic animals or organisms, and other related businesses (Rezakazemi et al., 2011)

Fig. 1: Excess nutrients leading to eutrophication in an urban river. Human health, environmental health, as well as economic success can all be affected by eutrophication (EPA, 2017)

Environmental Detriments

To elaborate, eutrophication, which can be caused by excess ammonia, leads to many environmental detriments. The process of eutrophication occurs due to various factors (Fig. 2).

The higher presence of nutrients, such as nitrogen, act as fertilizers leading to increased algal growth. Algae blooms, in turn, can cause blockage of sunlight to organisms beneath the surface causing the submerged aquatic vegetation (SAV) to die, resulting in a loss of habitat, source of food for many aquatic organisms and a decrease in the amount of oxygen present in the water. This is because oxygen is unable to be produced by vegetation through photosynthesis and the concentration of dissolved oxygen (DO) is further depleted as the algae die off (Miladinovic and Weatherley, 2007). As aerobic bacteria and fungi break down the dead algae, they consume large amounts of DO in order to maintain homeostasis through cellular respiration.

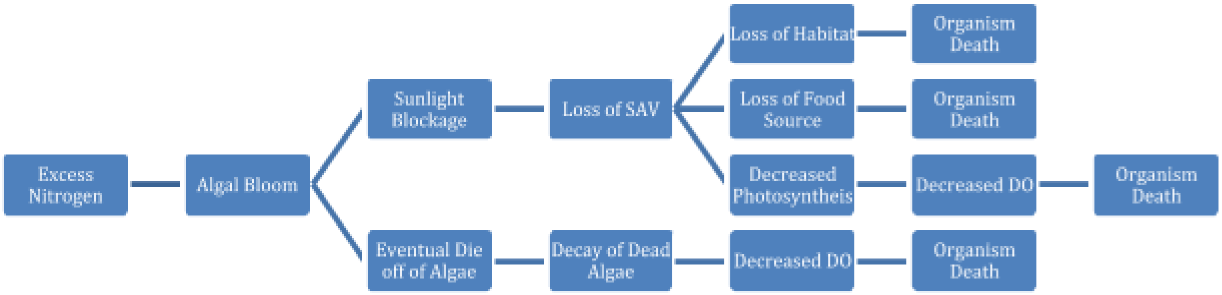

Fig. 2: The effects of excess nitrogen on a typical aquatic ecosystem. Diagram illustrates how eutrophication can lead to organism death (Howorth, 2008).

From the depletion of DO, which can be caused by sun blockage and other factors, such as water temperature and turnover, or the cycling of water from the top to bottom of water supply, fish and other aquatic organisms can be negatively affected. In DO concentrations from 2-4 ppm, organisms can become distressed and more susceptible to disease, while at concentrations below 2 ppm, mortality begins to occur as a result of suffocation, affecting larger organisms first (Francis-Floyd, 2011). Overall, the process of eutrophication harms food sources, habitat, water quality, and decreases oxygen levels in the water. In turn, these issues lead to fish death and sickness.

In addition to eutrophication leading to the suffocation and death of aquatic organisms, ammonia can be directly toxic to these organisms in concentrations as little as .2-.5 ppm (Miladinovic and Weatherley, 2007). As ammonia toxins build up in the bodies of aquatic life, cells and tissues are harmed, eventually leading to death. Natural populations of fish, as well as commercial aquaculture, can be adversely affected by this as a resulting in decreased productivity.

Detrimental Economic Effects

Not only is the death of marine life detrimental to the survival of ecosystems, but it can lead to economic harm to the fishing and aquaculture industries. The EPA estimates that annual losses to industries dependent on the success of aquatic life as a result of nutrient pollution are in the tens of millions of dollars. Fish death as a direct result of ammonia toxicity and indirectly through eutrophication both contribute to the losses that aquatic based industries feel. Moreover, even industries not dependent on aquatic organisms have a relationship with nutrient pollution. Waste discharged from a multitude of industries requires treatment before being discharged. This treatment detracts billions of dollars each year for water treatment costs but is set by the EPA in order to promote the health and safety of humans as well as the environment (Hasanoglu et al., 2010).

Health Detriments

Additionally, ammonia is harmful to human health because it is often bio-oxidized by microorganisms to form nitrates which are possibly carcinogenic and may present additional health risks, according to the International Agency for Research on Cancer (Marjani and Shirazian, 2011). Nitrates' carcinogenic qualities derive from its interactions with amino compounds which leads to the formation of N-nitrosation compounds. From here these compounds allow for uncontrolled growth of cancer cells and the development of masses which, if malignant, can lead to death (Eichholzer and Gutzwiller, 2009). Moreover, ammonia can also lead to non-chronic, immediate illnesses. Some strains of cyanobacteria produced excessively as a result of nutrient pollution can produce toxins including neurotoxins, hepatotoxins, and toxic alkaloids (World Health Organization, 1999). Direct contact with water containing toxin-producing cyanobacteria can result in skin irritation, vomiting, and allergic reactions. It can be seen that ammonia pollution is a highly relevant issue, not only for the preservation of the environment and economic prosperity but also to insure health standards for humans.

Current Regulations

Due to the many environmental, health, and economic impacts excess nutrients have, the government has imposed environmental regulations in regards to the amount of nutrient discharge allowed from wastewater treatment plants. According to section 303 of the Clean Water Act (1977), publicly owned treatment works, such as municipal wastewater treatment plants, require the application of the best practicable control technology currently available for the treatment of wastewater before the discharge of wastewater effluent. Treatment plants must use technology that removes the maximum amount of harmful pollutants and must optimize current technologies. In addition, permits to discharge pollutants are required. Applications for the permits must assess the effect of disposing pollutants on human health and welfare, and marine life, among other things (section 403(a-f) Clean Water Act, 1977). Moreover, according to the EPA, public water treatment plants should sample for several pollutants of concern, including ammonia.

Current Methods of Treatment

Treatment of wastewater varies with the treatment plant. However, the most common method employed for nutrient removal is activated sludge (Henze et al., 2008). This process involves the use of microorganisms to break down dissolved pollutants such as ammonia into nitrates. During this phase of the process, the effluent (contaminated solution) is aerated with oxygen gas as aerobic (oxygen requiring) bacteria are used. The converted nitrates are then broken down by different anaerobic (require no oxygen) bacteria and given off as nitrogen gas (Henze et al., 2008). This entire process transitions any remaining dissolved pollutants into suspended solids that are then able to be separated through settling. However, conventional biological treatment processes do not remove nutrients such as phosphorus and nitrogen to any substantial extent, so additional treatment processes are required. Current methods of treatment such as biological adsorption and activated carbon adsorption can be costly or leave a large process footprint (Duong et al., 2012).

Moreover, these methods are not efficient in ammonia removal and allow for the persistence of ammonia pollution in wastewater discharge (Henze et al., 2008). Ammonia removal by membrane distillation (MD) has recently gained attention because of the low energy it requires, low cost, and overall minimal footprint (Xie et al., 2009). Several methods of MD exist, including direct contact, air gap, sweep gas, and vacuum membrane distillation, all of which remain relatively the same at their base. MD involves two different aqueous solutions at different temperatures (Fig. 3). The contaminated, or feed solution, is hot while the receiving solution is cold. A membrane acts as a barrier between the two solutions, and as the feed solution vaporizes, specific vapor molecules can move through the membrane. However, due to the membrane’s hydrophobic nature, water is prevented from moving through the membrane thus allowing for the removal of pollutants such as ammonia. The different techniques vary only in the way that the vaporized particles are condensed and received by the receiving solution.

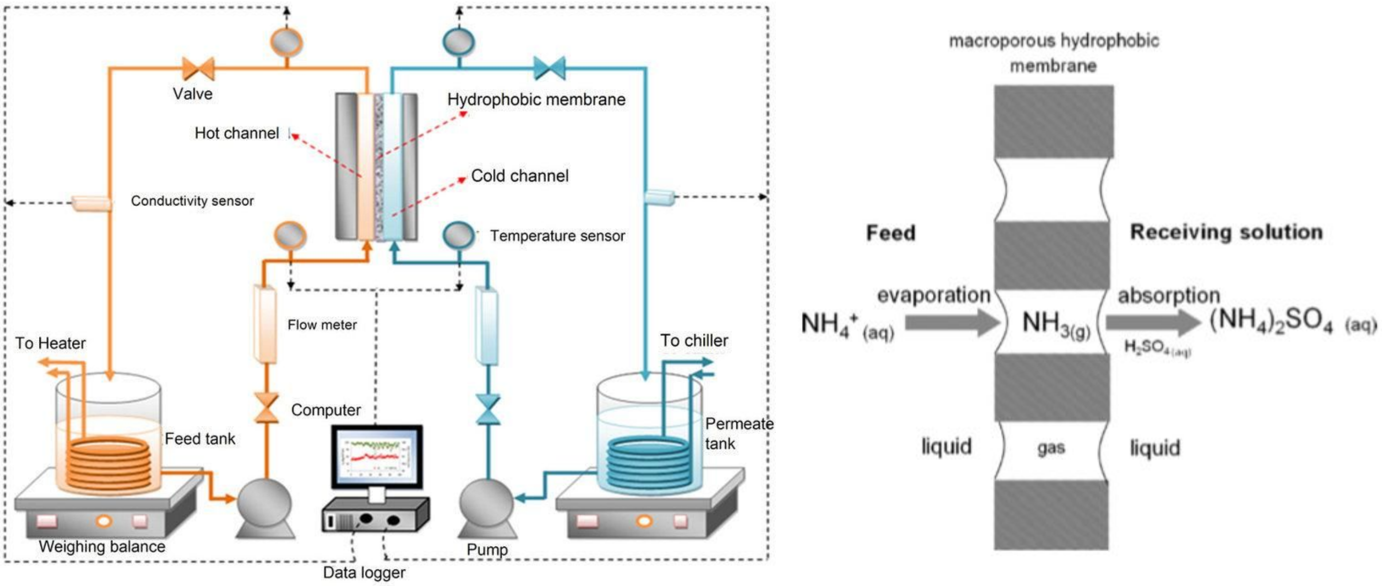

Fig. 3: The MD process (left) showing the feed solution in orange and the receiving solution in blue (Prince et al, 2014). The filtration occurring at the membrane (right) displays a nitrogen pollutant being evaporated, moved through the membrane, and being absorbed by the receiving solution.

By optimizing methods of membrane distillation (MD), a cost-effective alternative to current methods can be established leading to the widespread use of ammonia removal from wastewater and decreased nitrogen pollution. More specifically, one advantage MD can claim over conventional methods is that it can be operated at lower temperatures. This is important because increasing heat requires more energy input and higher cost for the process to occur. Because of this, the optimal temperature for MD was investigated in order to fully understand any advantage MD may have over other methods and see if it can still be as effective at lower temperatures. In addition, the research will help to set standards for what temperatures makes the best use of the MD process; that way costs can be used most effectively to treat ammonia contaminated water.

Research Question

Can temperature influence the efficiency of MD for ammonia removal?

Hypothesis

Alternative:

Temperature optimization will increase the efficiency of MD for removing ammonia in wastewater.

Null Hypothesis:

Temperature optimization will not affect the efficiency of MD for removing ammonia in wastewater.

Methods

Data Sources

ResearchGate, ScienceDirect, Google Scholar, Elsevier, etc. were searched to obtain a review of the current literature. Scientific papers were then used to build a basis of understanding of the topic as well as provide data to support either the null or alternative hypothesis. Literature assesses the amount of ammonia removed from the starting solution after being run through MD, data were taken at different temperatures and over time. Keywords such as “ammonia removal,” “wastewater treatment for nitrogen,” “membrane distillation,” etc. were used to gather relevant articles. From these articles, additional material was gathered by looking through the reference sections of useful papers.

Inclusion and Exclusion Criteria

Papers used in this research were all within the last twenty years. However, articles over ten years old were only used for reference, or to establish background knowledge for the purpose of this research. Older papers only appear in the introduction. Any other papers discussing ammonia removal through any method of MD were examined for data. All methods of MD are used in this case because the main factor that changing the temperature influences is, how well the contaminated solution changes into a gaseous state. Regardless of whether direct contact, sweep gas, etc. are used for data, the trend shown with each data set should be based on the same influencing factor, temperature. Additionally, only papers that specifically tested MD with ammonia were used. MD was not evaluated with additional solutions as the different chemical makeup of molecules other than ammonia could lead to varying data that is not consistent with the research question.

Data Processing

Data were gathered about the membrane distillation process. This includes comparing different methods of MD such as Vacuum MD (VMD), Sweep Gas MD (SGMD), and Direct

Contact MD (DCMD). Within each process, the overall effectiveness of the system at removing ammonia was determined at different temperatures (Table 1). The effectiveness of the system was measured by using various units for each data source collected. However, the units were converted to percent of ammonia remaining from the original when compared in the data analysis. Feed temperature was measured in degrees Celsius within a range of 30 degrees from 50 to 80 degrees Celsius.

In order to compare to current methods, data was then taken from wastewater treatment plants to determine the effectiveness of the current systems by recording the nitrogen discharge. This data was taken from an EPA case study comparing several treatment plants nationwide as well as averages provided by the EPA (Table 4). Nitrogen is measured in parts per million after activated sludge treatments.Data was then interpreted to determine the most optimized configuration for the MD process resulting in the most efficient removal of ammonia, compared to conventional methods of treatment. The differences between the methods were then evaluated to determine if membrane distillation can become a more competitive option for ammonia removal.

Statistical Analysis

Because each study was conducted under different conditions and measured in ways not compatible with each other, statistical analysis was completed on each study separately. In addition, the correlation value was calculated to determine the relationship between the data points recorded by each study. By calculating the correlation value, the credibility of each study is brought to light. Based on the correlation value, it can be decided as to whether the study should be included in the final findings or not. The correlation must first be shown to support the accepted hypothesis that MD removes ammonia. If it is revealed that the data points do not support this accepted hypothesis, then this data set will not be included in the final conclusion as it is not an accurate measurement of whether the alternative hypothesis is correct or not.

Results

Table 1: Overall mass transfer coefficients of ammonia as a function of temperature using two different methods of membrane distillation. As feed temperature increases the overall mass transfer of ammonia increases in both SGMD and VMD (Duong et al., 2015).

Feed Temperature (°C)	Mass Transfer with Sweep Gas MD (10^-5 m/s)	Mass Transfer with Vacuum MD (10^-5 m/s)
50	1.51	1.90
65	2.58	5.58
75	2.82	8.68
80	5.63	12.06

Table 2: The concentration of ammonia in parts per million over time is demonstrated at three different temperatures in Celsius (35, 40, 50) when passed through a flat sheet membrane modules. Data points estimated from Hasanoğlu et al., 2010.

Temperature (°C)	Time (min)	Concentration of Ammonia (ppm)
35	0	440
35	30	300
35	60	200
35	90	128
35	120	100
35	150	85
40	0	415
40	30	305
40	60	195
40	90	130
40	120	95
40	150	75

50	0	420
50	30	265
50	60	140
50	90	85
50	120	25
50	150	15

Table 3: Ammonia removed from an initial starting concentration of 100 ppm over time at different temperatures (50, 65, 75) estimated from Xie et al., 2009.

Temperature (°C)	Time (min)	Ammonia Removal (%)
50	35	27
50	65	42
50	90	56
50	120	65
50	155	70
65	35	39
65	65	58

65	90	68
65	120	79
65	155	84
75	35	45
75	65	77
75	90	89
75	120	95
75	155	NA

Table 4: Total nitrogen concentrations based using activated sludge measured in ppm. Averages established by the EPA after each treatment are shown as well as actual data from wastewater treatment plants (EPA, 2015).

Treatment Type	Total Nitrogen (ppm)	Location
None	40	EPA Average
Primary Treatment	37	EPA Average
Activated Sludge	25	EPA Average
Activated Sludge	6.33	Bay Point, FL

Activated Sludge	17.8	Bozeman, MT
Activated Sludge	7.85	Crewe, VA
Activated Sludge	18.62	Tampa, FL
Activated Sludge	5.67	Titusville, FL
Activated Sludge	8.93	Victor Valley, CA
Activated Sludge	6.32	Wolfeboro, NH

Table 5: The correlation value between time and ammonia remaining from the original solution calculated at 30, 45, 50, 65, and 75 °. Correlation value was calculated using data points estimated from Xie et al., 2009 and Hasanoğlu et al., 2010.

Temperature (°C)	Correlation Value
30	-.95
45	-.96
50	-.96
65	-.97
75	-.91

Summary of Results

Table 1: The results show that with Sweep Gas MD, the mass transfer of ammonia increases by a factor of approximately four as the temperature increases from 50 to 80°. With each increase in temperature, the mass transfer increases; however the most dramatic change is from 75 to 80°. The mass transfer goes from 2.82 to 5.63, almost doubling over a temperature change of 5°. To compare at 50 to 75 °, the mass transfer slightly less than doubles. The results of the Vacuum MD show an increase by a factor of approximately six as the temperature increases from 50 to 80°. The mass transfer consistently increases with temperature; however, the most dramatic change is from 75 to 80 º. With a difference of 5°, the mass transfer increases by 3.38 x 10^-5 m/s. Overall, the results of this table show a general increase of mass transfer with increased temperature and Vacuum MD shows an overall higher mass transfer than Sweep Gas.

Table 2: At each temperature (35°, 40°, 50°) the concentration of ammonia decreases over the time interval of 0 to 150 minutes. At 35°, the ammonia concentration in the feed solution decreases by 355 pp or a factor of approximately five. Within the first 30 minutes, the most dramatic decrease occurs at 140 ppm. At 40°, the ammonia concentration decreases by 340 ppm or a factor of about five and a half. The most considerable decrease is 110 pmm which occurs within the first 30 minutes and also in the 30 minutes (adding up to 60 minutes total) following. At 50°, the concentration decreases by 405 ppm, a factor of 28. Although the change in ppm does not increase corollary to the temperature, as the temperature increases, the factor by which ammonia is removed increases.

Table 3: At each temperature (50, 65, 75) the ammonia removed decreases over the recorded time of 35 to 155 minutes. At 50° the maximum ammonia removed is 70% of the original concentration meaning that 30% of the ammonia remains. At 65° the maximum ammonia removed is 84% leaving 16% of the original ammonia remaining. At 75 ° the maximum ammonia removed is 95% leaving 5% of the ammonia that was in the original solution.

Table 4: The EPA established values show that without any treatment, 40 ppm of ammonia. At the secondary treatment (activated sludge), the ammonia present is 25 ppm. The lowest amount of ammonia recorded from this case study is 5.67 ppm after activated sludge treatment while the highest is 18.62 ppm.

Table 5: The average correlation values calculated for each temperature are all negative and close to -1, at no more than -0.9. At each temperature, the correlation value varies but with a range no higher than .06.

Overall Results: The results of each data table show a trend of ammonia concentration in the feed solution as decreasing over time. In each data set, the ammonia decreases by a significant amount. In addition, the higher the temperature, the lower the ending concentration of ammonia there is, showing a trend that at higher temperatures, more ammonia is removed (Fig. 4). The results of this study refute the proposed null hypothesis that temperature has no effect on the efficiency of MD, so the alternative hypothesis was accepted.

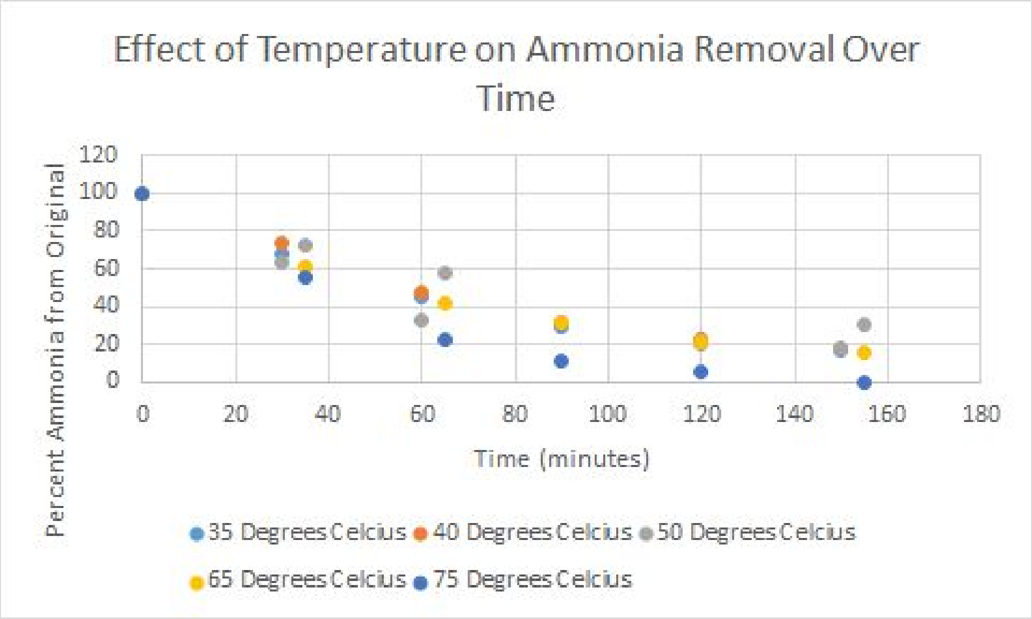

Fig. 4: The overall trends taken from gathered data showing the dependence of ammonia percentage on temperature (ranging from 35-75 °) over time.

Discussion

The results of the first three tables show that as temperature increases, more ammonia is removed thus making the membrane distillation process more efficient. Some variance in this general trend can be seen at 35° in Table 2. When comparing the data from Table 2 and Table 3 in Fig. 4, it can be seen that although 35° was the coldest temperature measured, it is not the one with the highest percentage of ammonia remaining. This indicates variation from the alternative hypothesis; however, this can be attributed to the different sources that data was taken from. As two different studies were compared in this figure, the conditions within each study were as similar as possible however not identical. This difference could have led to a discrepancy in the data's trends. Despite this, the overall trend observed supports the alternative hypothesis, which is likely due to the nature of the MD process. MD is dependent on the phase change of the contaminated solution into a gaseous state. With higher temperatures, the kinetic energy of the liquid solution increases eventually allowing for a phase change to gas. Once in the gas phase, the receiving solution can pass through the “filter” separating contaminants from water. Because of the role evaporation plays in the success of MD, it is reasonable to think that conditions that promote faster evaporation rates will allow for greater success in ammonia removal.

However, there are still several limitations to the research conducted. The most apparent limit is the lack of available literature required in order for a full analysis to be conducted. Due to each study being operated at various conditions, in this case, the best approach was individual statistical analysis as to the correlation between each individual data sets. To compare between each data set, non-statistical comparison through graphs determined the relationships between the trends shown in the data sets. While this was the method used in this review, a more comprehensive approach that involves determining if the average values of each temperature group were statistically significant would be a highly beneficial next step. This process would further explain any variance seen in the research and analysis and overall deliver a greater understanding of the temperature optimization process. Ultimately, given the opportunity, temperature variations of MD should be further tested at standardized controls and conditions in order to thoroughly verify the alternative hypothesis.

In comparison to conventional methods of water treatment, table 4 shows that even after conventional treatment methods, amounts of ammonia remain in the now deemed clean wastewater. Although activated sludge does remove much of the ammonia that is found in the original contaminated solution, the averages determined by the EPA as well as the examples from the case study show that there is still substantial amounts of ammonia present in water after it has completed treatment. However, this is still the case for MD. In no cases did any MD treatment result in 100% removal of ammonia. Even so, the value of this review has shown that temperature can be used as an effective optimization technique in MD for ammonia removal, meaning that as MD continues to be developed, the importance of temperature must be impressed upon those that seek to make the process a competitive method for ammonia removal.

The research has shown that optimization of MD can occur as a result of higher temperature. However, it minimally addressed the comparison to current methods. The purpose of the research was to determine if the temperature could make MD more efficient which was largely addressed in the study. However, the comparison to activated sludge was included, not to answer the research question, but to add validity and reason behind why the research question needed to be asked. The contrast between MD and commonly used nitrogen removing treatment (activated sludge) was evident in the research as a control or baseline as to the importance of developing MD.

Moreover, this adds value to the scientific community at the moment because much attention has been focused on using MD for water treatment; however, it has several limitations. This research compiles individual studies to make a general consensus about the optimal temperatures for MD. This in itself is a useful gap to fill in the scientific community. Moreover, the paper also illustrates that although MD is often praised on its ability to be successful at low temperatures, it is more valid at higher ones.

Conclusion

As a result of my analysis, I accept the alternative hypothesis and reject the null. By determining that ammonia removal through MD becomes increasingly more efficient as temperature increases, the research is able to provide a basis for optimization. This optimization is essential to improving ammonia removal of municipal wastewater at treatment plants. Previous research suggests that one of the main benefits of MD is that it can be operated at lower temperatures than conventional methods. However, these results suggest that in order to make MD most effective, higher temperatures should be used. while this may optimize the process, it is still not enough to make MD competitive with conventional methods and overall decrease ammonia discharge from wastewater treatment plants. In order for the process to be further optimized, the conservation of heat in a system could be further investigated in order to make the process low cost. As the research has indicated that high temperatures are essential to the success of MD, conservation of heat in a system is a viable option to improve the efficiency of MD. By determining techniques as to which heat can be conserved in a system, MD will be able to be run at higher temperatures, allowing it to become more effective while at the same time not increasing treatment costs. It is essential that the process is optimized in order to provide a method of ammonia removal that minimizes nutrient discharge. To thus avoid nutrient pollution which can lead to eutrophication. Overall, with the development of MD the adverse effects on the environment, economy, and human health can be reduced.

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research as membrane distillation is a complicated process that I have not received any formal teaching on. Dr. Malhotra and Nikki Razal were essential for me to understand how to conduct my research process and effectively communicate my results in the paper.

References

Ali, N., Mohammad, A., & Ahmad, A. (2005). Use of nanofiltration predictive model for membrane selection and system cost assessment. *Separation and Purification Technology,41*(1), 29-37. doi:10.1016/j.seppur.2004.04.006

Ding, Z., Liu, L., Li, Z., Ma, R., & Yang, Z. (2006). Experimental study of ammonia removal from water by membrane distillation (MD): The comparison of three configurations, *Journal of Membrane Science, 286(1-2), 93–103.*doi:10.1016/j.memsci.2006.09.015

Duong, T., Xie, Z., Ng, D., & Hoang, M. (2012). Ammonia removal from aqueous solution by membrane distillation. *Water and Environment Journal*. doi:10.1111/j.1747-6593.2012.00364.x

Eichholzer, M., & Gutzwiller, F. (2009). Dietary Nitrates, Nitrites, and N-Nitroso Compounds and Cancer Risk: A Review of the Epidemiologic Evidence. *Nutrition Reviews,56*(4), 95-105. doi:10.1111/j.1753-4887.1998.tb01721.x

Hasanoğlu, A., Romero, J., Pérez, B., & Plaza, A. (2010). Ammonia removal from wastewater streams through membrane contactors: Experimental and theoretical analysis of operation parameters and configuration. *Chemical Engineering Journal,160*(2), 530-537. doi:10.1016/j.cej.2010.03.064

Henze, M., Van Loosdrecht, M., Ekama, G., & Brdjanovic, D. (Eds.). (2008). *Biological Wastewater Treatment: Principals, Modelling, and Design*. London, UK: International Water Association.

Howarth, R. W. (2008). Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae,8*(1), 14-20. doi:10.1016/j.hal.2008.08.015

Khoukhi, B., Tadjine, M., & Boucherit, M. S. (2015). Nonlinear observer to estimate polarization phenomenon in membrane distillation. *International Journal for Simulation and Multidisciplinary Design Optimization,6*. doi:10.1051/smdo/2015004

Marjani, A., & Shirazian, S. (2011). Computational fluid dynamics simulation of ammonia removal from wastewaters by membrane. *Asian Journal of Chemistry,23*(7), 3299-3300.

Miladinovic, N., & Weatherley, L. (2008). Intensification of ammonia removal in a combined ion-exchange and nitrification column. *Chemical Engineering Journal,135*(1-2), 15-24. doi:10.1016/j.cej.2007.02.030

Norddahl, B., Horn, V., Larsson, M., Preez, J. D., & Christensen, K. (2006). A membrane contactor for ammonia stripping, pilot scale experience and modeling. *Desalination,199*(1-3), 172-174. doi:10.1016/j.desal.2006.03.037

Prince, J. A., Rana, D., Matsuura, T., Ayyanar, N., Shanmugasundaram, T. S., & Singh, G. (2014). Nanofiber based triple layer hydro-philic/-phobic membrane - a solution for pore wetting in membrane distillation. *Scientific Reports,4*(1). doi:10.1038/srep06949

Rezakazemi, M., Shirazian, S., & Ashrafizadeh, S. N. (2012). Simulation of ammonia removal from industrial wastewater streams by means of a hollow-fiber membrane contactor. *Desalination,285*, 383-392. doi:10.1016/j.desal.2011.10.030

Semmens, M. J., Foster, D., & Cussler, E. (1990). Ammonia removal from water using microporous hollow fibers. *Journal of Membrane Science,51*(1-2), 127-140. doi:10.1016/s0376-7388(00)80897-2

Shirazian, S., Moghadassi, A., & Moradi, S. (2009). Numerical simulation of mass transfer in gas–liquid hollow fiber membrane contactors for laminar flow conditions. *Simulation Modelling Practice and Theory,17*(4), 708-718. doi:10.1016/j.simpat.2008.12.002

Simulation of the operational conditions of the full-scale municipal wastewater treatment plant to improve the performance of nutrient removal. (1997). *Water Science and Technology,36*(12). doi:10.1016/s0273-1223(97)00712-9

The Effects: Economy. (2019, February 04). Retrieved from https://www.epa.gov/nutrientpollution/effects-economy

United States, Environmental Protection Agency, Office of Wetlands Oceans and Watersheds, Office of Science and Technology, and Office of Wastewater Management. (2015). *Case Studies on Implementing Low-Cost Modifications to Improve Nutrient Reduction at Wastewater Treatment Plants*.

Xie, Z., Duong, T., Hoang, M., Nguyen, C., & Bolto, B. (2009). Ammonia removal by sweep gas membrane distillation. *Water Research,43*(6), 1693-1699. doi:10.1016/j.watres.2008.12.052