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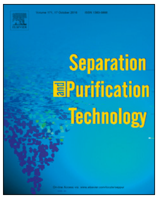

Membrane distillation process for concentration of nutrients and water recovery from digestate reject water

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ABSTRACT

During low-solids anaerobic digestion (AD) of substrates with a high solids content, substrate dilution can be obtained by recycling the liquid phase (reject water) of dewatered digestate. However, this can lead to accumulation of compounds, which inhibits the AD process. This laboratory-scale study assessed the potential of thermally driven air gap membrane distillation (AGMD) for concentrating nutrients in the reject water and recovering process water suitable for use in AD. The results showed that the removal rate of COD, P, S, and K was > 98% and the removal rate of total ammonia nitrogen (TAN) reached nearly 100%. The corresponding yield of recovered permeate water was > 56%. The concentration of TAN and PO_4-P in the recovered permeate was < 0.05 mg/L, while the COD concentration was 400–500 mg/L. The flux was 3.3 L/(m^2 h) at 60 °C inlet temperature and showed a 28% decline by the end of the experiment. There was no leaking, wetting, or fouling of the membrane over the entire three consecutive day's test duration. Specific heat demand for AGMD ranged from 900 to 1300 kWh/m^3 without heat recovery and was as low as 66–170 kWh/m^3 with heat recovery. The performance results reported here highlight the potential and robustness of the AGMD process.

1. Introduction

Recovery and reuse of resources from waste and wastewater streams has been identified as key to achieving the main objectives and essential preconditions for sustainable development, since it helps to reduce the negative effects on the environment and increases the efficiency of resource use [1]. Anaerobic digestion (AD) of organic waste and biological sludge is a technology for producing biogas as a renewable energy source and a nutrient-rich digestate, which can be used in agriculture as an organic fertilizer. At AD plants treating solid organic wastes (e.g., the organic fraction of source-separated municipal solid waste), the substrate must be diluted before digestion in conventional completely stirred digesters. Therefore, the digestate is phase-separated (dewatered) with screw presses or decanter centrifuges into a solid and a liquid phase (reject water), with part of the liquid phase used as process water for substrate dilution. The solid phase and the remaining liquid phase are transported to farmers for use as organic fertilizers.

The quality and features of the input feedstock material to the digester, the digestion and digestate treatment technology have a significant influence on the final composition and quality of reject water. The reject water from an anaerobic co-digestion process typically contains high concentrations of dissolved ammonium nitrogen (NH_4-N), phosphorus (PO_4-P), and suspended and colloidal solids [2,3]. In general, the concentrations of total solids (TS), chemical oxygen demand (COD), total nitrogen (N), total ammonium nitrogen (TAN), total phosphorus (P), total potassium (K), and total sulfur (S) etc. in AD reject water are higher than those in effluent water at conventional municipal wastewater treatment plants. The total N load, which includes organic-N and TAN, is 40- to 200-fold higher than that in conventional wastewater [4,5]. Moreover, the total P and COD concentrations can be 10- to 100-fold and 40- to 250-fold higher, respectively, than in conventional municipal wastewater [4,5]. In addition, co-digestion with agricultural waste and household waste is reported to increase the P content in reject water [3]. Furthermore, a high solids concentration in the reject water is correlated to high COD [4]. The separated reject water has a relatively high pH, typically within the range 8.1–8.8 [2], and, if dewatering of the digestate is improved by addition of lime, the pH can be even higher [6]. Extremely high alkalinity and buffering capacity are typical characteristics of AD reject water that can cause difficulties in terms of its purification [7]. The approach of recycling reject water back into the main flow line of the AD plant leads to gradual build-up of nutrients in the digester, which may cause process instability and inhibition of the AD process [8]. In addition, the build-up of nutrients can result in gradual struvite precipitation, causing blockages and equipment scaling.

Many arable farmers agree that synergistic effects arise from

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applying digestate as an organic fertilizer compared with conventional fertilizer. However, the digestate reject water is rather dilute with respect to nutrients and use as an organic fertilizer, which makes the costs of transportation relatively high compared with conventional fertilizers. Long-range transport of digestate with approximately 95% water is very expensive, particularly with increasing global diesel prices [9]. Other significant costs relate to investments in storage capacity, as required by environmental regulations in many countries (e.g., Denmark, Germany, Sweden, and France), whereby nutrient input per hectare is restricted and the period of application is limited to the growing season [10]. In addition, because of high water content, application of whole digestate reject water could lead to waterlogging of soil in very rainy, humid climates or in water-sensitive areas. Thus processing digestate reject water to increase the nutrient concentration, lower transportation costs and facilitate final spreading on arable land is an attractive option [11]. However, there are various challenges and difficulties in developing processing techniques that are techno-economically viable, due to the complex nature of digestate reject water.

Advanced membrane technologies such as nanofiltration (NF), reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD) show great potential for sustainable wastewater treatment and reuse. A number of recent studies have investigated the feasibility of these membrane processes for dewatering and nutrient removal from sidestreams [12,13]. High-rejection membrane processes, such as NF and RO, have demonstrated huge potential in wastewater nutrient recovery. However, drawbacks such as formation of a polarization film, fouling, wetting, and high electricity demand are limiting factors [14]. Furthermore, NF and RO processes are prone to membrane fouling in wastewater nutrient recovery where the feed streams are challenging (high TS content). The tradeoff between water permeability and solute selectivity limits accomplishment of high water permeability for FO membrane materials without decreasing solute selectivity [15], which restricts the achievement of high nutrient concentration levels. Moreover, conventional membrane technologies are usually energy-intensive and conventional energy sources either cause environmental pollution or are finite.

Hence, there is a strong need to develop less energy-intensive technology for robust water purification or separation with high separation efficiency [14,7]. Among the different wastewater handling methods available, MD-based water recovery unit operations are recommended due to advantages such as high stability, low energy consumption, robustness, and easy operation [14,7].

Air-gap membrane distillation (AGMD) is a thermally driven separation/purification process where water vapor is transported through a hydrophobic microporous membrane by temperature gradient-induced vapor pressure (see Fig. 1). Because water is transported through the membrane only in a vapor phase, AGMD can achieve complete rejection of all non-volatile constituents in the feed solution. More importantly, AGMD can achieve high water recovery, because water vapor transport through the microporous membrane is not significantly influenced by the feed osmotic pressure. Due to this unique transport mechanism, MD processes have been explored for recovery of valuable components and process water. Energy demand in AGMD systems consists of thermal energy required to heat the feed and to cool the permeate and electrical energy required to drive the circulation pumps. A number of studies have examined the cost of MD compared with conventional technologies, including other thermal processes [14,16]. These show that MD becomes favorable when it can harness a waste heat source and thermal efficiency is less of a concern [7,14]. AGMD can operate at lower temperatures than other thermal techniques and temperature levels on the hot side (up to 90 °C) are amenable to thermal integration with a variety of heat sources [14]. The integration of AGMD with industrial or power plant waste heat or with solar thermal systems offers several advantages including lower thermal energy consumption, reduction of overall energy consumption, reduction of greenhouse gas emissions, reduced pure water production costs due to waste heat recovery, and effective process integration for multiple products [7,14,16].

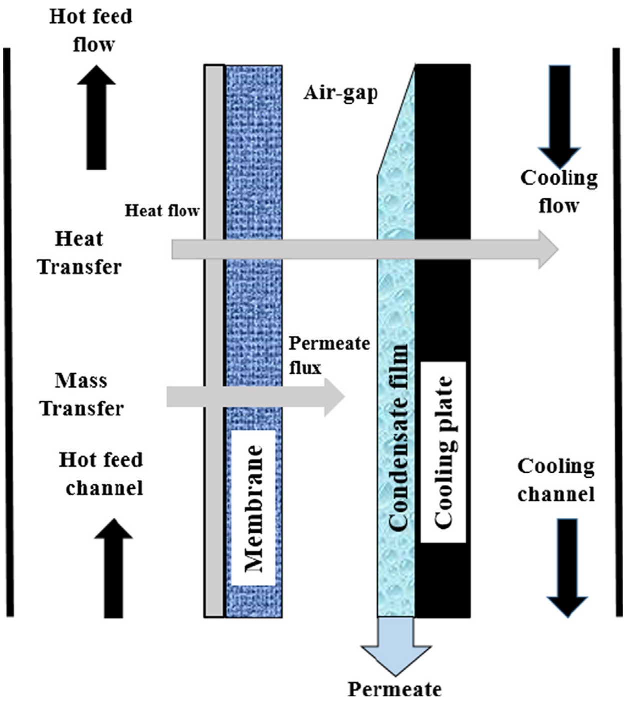

Fig. 1. Transport Mechanism (heat and mass transfer) of air-gap membrane distillation (AGMD) process [16].

To date, no comprehensive study has examined the feasibility of digestate sludge reject water (challenging and complex feed solution) separation with AGMD. Research to date indicates that AGMD could be a promising technological option for handling digestate sludge reject water (e.g., [14]) but further research is required to firmly quantify actual performance in terms of separation efficiency and thermal energy consumption for near-commercial modules. The aim of the present study was thus to investigate the potential of an integrated AGMD system for treating reject water from dewatered digestate, in order to concentrate nutrients and recover process water suitable for use in the AD process. Laboratory-scale studies were conducted to evaluate the performance of AGMD in terms of flux performance, permeate quality, separation efficiency, and thermal energy demand in order to provide results for assessing long term performance in industrial scale applications.

2. Materials and methods

2.1. Source of digestate sludge reject water (process water)

The reject water used in the MD experiment originated from dewatered digestate produced at the co-digestion plant of Vafab Miljö AB, Västerås, Sweden. This biogas plant treats mainly the organic fraction of source-separated municipal solid waste, food waste from restaurants, grease trap sludge, and ley crops (see Fig. 2). The digestion process is semi-continuously operated under mesophilic conditions. The biogas produced is upgraded to vehicle fuel standard. Some of the digestate is supplied to farmers as a biofertilizer and the remainder is dewatered by a decanter centrifuge, which generates a solid phase and a liquid effluent, i.e., reject water/process water. The reject water is recycled back into the main flow line of the digester plant for incoming substrate dilution (see Fig. 2). No polymer or ferric sulfate is added during the decanter centrifuge process.

For the purposes of the present study, fresh reject water sample was collected and left for one week of sedimentation in the plastic cane. The