Anaerobic Membrane Bioreactors as a Next-Generation Technology to Address the Food-Energy-Water Nexus

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Abstract: In this talk, we will provide an overview of this EPSCoR/Idea Stimulus Research Program project and summarize the first-year accomplishments. The project promotes the perspective of municipal wastewaters and, in the long-term, food wastes as resource pools that include potable water, embedded energy, and fertilizers, which is consistent with the emerging concept of the *circular economy*. The anaerobic membrane bioreactor (AnMBR) system is the key to this paradigm shift in treatment approach, serving as the *resource factory* that lies at the center of a broader network of food, energy, and water systems.

The objectives of this project are to (i) create innovations in membrane science and AnMBR process configurations to control membrane fouling, increase biogas production, and minimize the energy intensity of wastewater purification; (ii) analyze anaerobic soluble microbial products to assess membrane fouling potential and incorporate these findings into anti-fouling membrane design; and (iii) assess potable water quality and potential for energy and nutrient recovery from waste sludge (i.e., biosolids). *These objectives align very closely with two industry focus areas highlighted in the South Carolina Vision 2025:* (i) energy and (ii) environment and sustainability. Attainment of these objectives will provide a deeper overall understanding of AnMBR technology that is needed to realize its full potential, and will generate key research findings that will strongly support the development of center-type proposal submissions in the arena of the food-energy-water nexus.

In pursuit of these objectives, we have completed the construction of an automated AnMBR test system that is adaptable to a variety of experimental modes. This test unit is being used to discover operating modes and feeds that produce high methane yields with low energy. We have validated operation of this system by initial experiments, demonstrated the production of methane, and initiated water quality testing on AnMBR effluent. Testing was done with three different membrane configurations. We also prepared and characterized the first-generation of micropatterned, fouling-resistant membranes to be tested in the AnMBR test system. Flat-sheet UF membranes were patterned with a herringbone pattern and characterized using microscopy and fluorescence imaging. Scale-up work is being pursued to configure these membranes as plate-and-frame (submerged) modules for data collection in the AnMBR. Computational fluid dynamics models were created to aid in design of new membranes and module configurations.

The project has provided training and mentoring to one postdoctoral scholar, three PhD students, and two undergraduate students. Collaborations have been facilitated by having students from Furman University and Benedict College working Clemson and the University of South Carolina during summer months.

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Anaerobic membrane bioreactor for treatment of domestic wastewater

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Keywords: Anaerobic membrane bioreactors, Fouling, Methane, Biological wastewater treatment, Chemical oxygen demand removal

Abstract: Anaerobic processes for domestic wastewater treatment have several advantages over aerobic treatment processes. The first of which is that anaerobic processes require less energy input than conventional activated sludge systems; they can use the energy embedded in organic matter, and convert it to methane (CH_4)-rich biogas and operate as energy-neutral or even as energy-positive systems. They also produce less biosolids and allow for possible nutrient recovery from the effluent [1]. Efficient operation of anaerobic wastewater treatment requires heating wastewater to mesophilic or thermophilic temperatures. In cold climates conditions, operating anaerobic bioreactors is a challenge because the energy consumed to heat a large volume of wastewater outweighs the potential energy retrieval. To reduce the capital cost of wastewater treatment plants, it is important to treat high volume flow rates of wastewater with short hydraulic retention times. The slow growth of microbes at cold temperature, impacts the efficiency of anaerobic bioreactors; therefore, long solid retention times (SRTs) are needed. Anaerobic membrane bioreactors (AnMBRs) recently gained attention for their ability to (1) treat high rate treatment of wastewater at a high flow rate, (2) eliminate sludge washout, and hence, increase in SRTs, which eventually allows for treatment of wastewater at low temperatures. However, membrane fouling and reliable treatment at low temperatures remain as two primary challenges in AnMBRs. In order to understand these challenges and introduce innovative solutions, we have built an automated, continuously-running bench scale AnMBR system for the treatment of domestic wastewater.

To operate the bench scale AnMBR system, feed solution (primary clarifier effluent from ReWa Mauldin Road Resource Recovery Facility in Greenville, SC) is transported to a 2 L bioreactor which is inoculated with 10% anaerobic digester sludge from ReWa Mauldin Road Resource Recovery Facility in Greenville, SC. The mixture of feed solution and inoculum is recirculating between the bioreactor, hollow fiber membrane unit, and a heater/ chiller unit to maintain a certain temperature inside the AnMBR system. Effluent permeate is taken from the membrane unit and is weighed. The bioreactor is equipped with a 1 L Tedler bag to collect the produced biogas and a pH/ temperature transmitter probe (Sensorex pH/ORP Transmitter TX 300). A pressure transducer (Omega PX309-015CGI, Omega Co.) reads the transmembrane pressure on the permeate line. To maintain the water level constant inside the bioreactor, a

webcam takes a picture of the bioreactor every minute, measures the water level inside the bioreactor and controls the rate of the feed pump accordingly. In order to reduce membrane fouling, the membrane unit is back-washed every hour for 2 minutes.

The AnMBR temperature was first maintained at 35ºC for 80 days. The temperature of the bioreactor was then decreased to 25ºC over the course of a week and maintained at 25ºC for 100 days. Currently, the AnMBR is operating at 15ºC. Samples of the feed and permeate solutions are taken every 2-3 days and analyzed for the following parameters: pH, TSS, VSS, COD, ammonia, sulfate, and total phosphorus. The volume of biogas produced is measured every 2 days and analyzed for percentage of methane and carbon dioxide through gas chromatography. Samples are also taken for intermediate volatile fatty acid analysis using High Performance Liquid Chromatography (HPLC). Samples of the suspended biomass from the bioreactor is taken at each operational temperature and analyzed for TSS, VSS, and microbial community analysis. Membrane performance is assessed through the continual recording of transmembrane pressure (TMP) and flux through the membrane.

The TSS of the feed, bioreactor, and the permeate is averaged around 100 mg/L, 3000 mg/L , and 2 mg/L, respectively. During operation at 35°C and 25°C , the methane production increased gradually, stabilizing around 28 mL CH_4/(L of bioreactor · day). The COD removal was also similar at different operational temperatures, averaging around 83%, with the permeate having an average concentration of 66 mg/L. On average 60 mg/L of sulfate was measured in the feed solution. Since reducing sulfate is more energetically favorable than other carbon sources, it is often one of the first constituents to be reduced[2]. If the microbes spend their energy reducing sulfate rather than carbon sources, the methane production values would be expected to be less. In this research, about 7% of the COD removal was attributed to the sulfate reduction. Due to the anaerobic environment of our system, there was no observed nutrient removal.

Assuming that 50% of the COD is BOD_5, the AnMBR achieved effluent concentrations close to typical discharge permit limits. This along with the low TSS concentration in the permeate shows that AnMBRs have potential to be applied to the treatment of domestic wastewater in warm climate environments while producing energy in the form of methane. With similar performance at 35°C and 25°C, operation at ambient temperatures allows for energy savings. Further analysis of current operation at 15°C will give insight into the feasibility of AnMBRs in cold climate conditions. The high-nutrient content of the AnMBR effluent requires post-treatment for nutrient removal or recovery. During the next year, as part of a project funded through the Stimulus Research Program, we will evaluate the change in microbial community with change in temperature. We will also assess different methods for mitigating membrane fouling, including determining the influence of soluble microbial products (SMPs) in fouling as well as studying effect of different membrane modifications.

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Biosketches:

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Understanding the Role that Patterning Plays on Membrane Fouling Through Experimental and CFD Simulation Studies

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Abstract: The goal of this project is to develop the basic science needed to design new fouling-resistant membranes. We present findings on the relationship between membrane surface patterning and fouling that test two hypotheses: (i) geometric patterns will reduce membrane fouling compared to the control, and (ii) computational models will accelerate the discovery of new membrane surface morphologies and methods to improve membrane fouling resistance. Experimental efforts combined flux decline measurements with light microscopy to study the fouling of as received and patterned membranes during filtration of model foulant. Patterned membranes were prepared by embossing a "tire-tread" micropattern on the membrane surface. For visualization experiments, membranes were labeled with a green fluorophore. A model protein foulant labeled with Alexa Fluor 488 was used to visualize the fouling profiles with confocal laser scanning microscopy, which provided three-dimensional images of membrane surfaces patterns and co-localized protein foulant. In parallel, simulations using computational fluid dynamics (CFD) methods were conducted to study the hydrodynamic influences of surface features on concentration polarization (CP), which is a mass-transfer related phenomenon that often leads to fouling. Elementary patterns including lines and grooves, pyramids, and pillars were designed and simulated. Experimental results shows that a membrane surface with a regularly ordered pattern is an effective strategy for designing membranes with improved resistance to for fouling by different foulant type. However, the simulation results showed that patterns did not reduce CP, and the reduced fouling seen in the experiments might be due to other reasons.

Biosketches:

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Resource Recovery from Waste Streams Using Hydrothermal Carbonization

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Keywords: hydrothermal carbonization; waste; recovery; resources

Abstract: Hydrothermal carbonization (HTC) is a unique process that is gaining significant attention as a beneficial approach for recovering resources from wet waste streams. HTC is a wet, relatively low temperature thermal conversion process that occurs under autogenous pressures. During carbonization, valuable solid, liquid, and gaseous products are generated through a series of simultaneous reactions, including hydrolysis, dehydration, decarboxylation, aromatization, and condensation. These generated products, particularly the solids (referred to as hydrochar), have the potential to be used in a large variety of applications, including as a soil amendment/fertilizer, energy source, environmental sorbent, and/or a material for energy and/or hydrogen storage. The carbonization of wet wastes also provides a unique opportunity to maximize the extraction, recovery, and/or generation of resources from the wet waste streams. Nutrients from wet wastes may be recovered in a form that has the potential to be directly used as a fertilizer, potentially reducing the need for acquisition of virgin nutrients and thus reducing energy demands associated with fertilizer manufacturing. In this presentation, potential strategies, associated implications, and preliminary results associated with work focused on recovering resources from wet wastes using HTC will be discussed.

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Saitu Wilford is a senior environmental engineering major at Benedict College. His senior research project focuses on the use of HTC food waste as a soil amendment for improved water retention and nutrient levels. He completed an EPSCoR-funded summer research internship at University of South Carolina in 2018, developing protocols for HTC of bioreactor waste.