A Preliminary Life Cycle Assessment of the Pilot-Scale Staged Anaerobic Fluidized Bed-Membrane Bioreactor (SAF-MBR) System

Edward Apraku[1,3], Andrew H. Kim[2,3], and Craig Criddle[2,3]
[1]Arizona State University, School of Sustainable Engineering and the Built Environment
[2]Stanford University, Department of Civil and Environmental Engineering
[3]Re-inventing the Nation's Urban Water Infrastructure (ReNUWIt) Engineering Research Center

Introduction

As fossil fuels continue to exacerbate the climate crisis facing the planet, there has been increased motivation in implementing energy-efficient practices in wastewater treatment. Currently, drinking water and wastewater treatment systems account for approximately 3-4% of the nation's energy usage and result in more than 45 million tons of greenhouse gas emissions annually (U.S. EPA, 2015). Both the aeration in aerobic secondary treatment as well as the treatment and disposal of biosolids are major contributors to this energy-intensive process. Recently, researchers have begun exploring anaerobic treatment as an innovative replacement for conventional aerobic treatment. Anaerobic treatment produces a lower amount of biosolids and converts organic material into methane gas, which can then be used as a renewable energy source. It was previously thought that anaerobic treatment would require long solids retention time due to the slow growing anaerobic organisms and could not treat wastewater to effluent requirements. However, the Staged Anaerobic Fluidized Bed-Membrane Bioreactor (SAF-MBR) was shown to successfully alleviate these issues during several South Korean pilot-scale studies (Shin et al., 2014), (Yoo et al., 2012).

The SAF-MBR process includes two reactors in series, the first being an anaerobic fluidized bed reactor (AnFBR) and the second being an anaerobic fluidized membrane bioreactor (AnFMBR). Granular activated carbon (GAC) is fluidized in the AnFBR, and anaerobic archaea attach themselves onto the GAC surface. The wastewater is then circulated to the AnFMBR where ultrafine hollow fiber membranes filter the remaining solids to produce high-quality effluent. The SAF-MBR system was replicated at the Codiga Resource Recovery Center (CR2C) at Stanford University and treats wastewater taken from campus housing. Figure 1 above shows a graphic representation of the system.

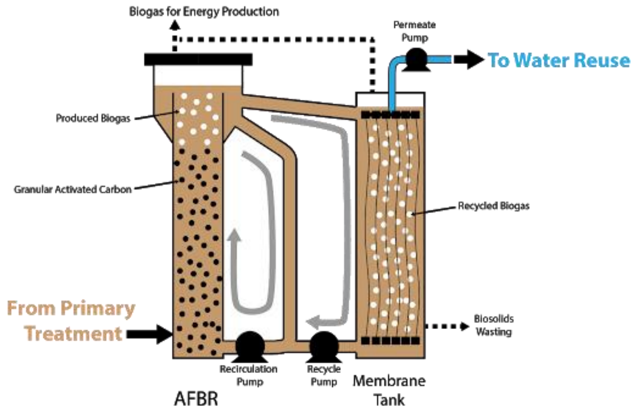

Figure 1. Diagram of pilot-scale SAF-MBR system

The SAF-MBR at Codiga has produced high quality secondary effluent comparable to activated sludge systems standards and has been operational for a year. However, CR2C is not a licensed wastewater treatment plant and does not fully treat common constituents such as primary and secondary solids disposal. Several factors such as greenhouse gas emissions and total energy usage have not been adequately studied for this system, and there lacks a comprehensive assessment of the environmental impact associated with the SAF-MBR. Thus, a preliminary life cycle assessment (LCA) was conducted for SAF-MBR to better understand what the overall environmental impacts would be throughout its construction and use phase as well as the landfilling for dry solids.

Methods

LCA Definition

The LCA framework was developed by the International Standards Organization (ISO) and the four phases are defined as: goal and scope, inventory analysis, impact assessment, and interpretation (ISO 14044, 2016).

Functional Unit

The functional unit is a crucial element for the LCA and allows for the inputs to be standardized and comparison to be made. A functional unit of 1 m^3 of treated wastewater was chosen for this study.

System Boundary

The system boundary defines all of the inputs, outputs, and processes to be evaluated in the LCA. The inputs include the materials needed for SAF-MBR construction, bleach and citric acid for membrane cleaning, and energy usage. The experimental outputs include hydrogen sulfide (H_2S), ammonium (NH_4), and dissolved methane (CH_4) emissions, as well as the produced biogas which can then be utilized for energy production. Sludge handling processes were included as a theoretical output to simulate a full-scale anaerobic wastewater treatment system. Primary solids from the initial microscreen and secondary solids from the SAF-MBR were diverted into a sludge thickening process and later to an anaerobic digester (AD). The biosolids from the AD were then completely dewatered and sent to a landfill. Several cogeneration systems were included to convert collected biogas into electricity and heat. The electricity was then rerouted back into the AnFBR and AnFMBR systems while heat was rerouted into the anaerobic digester and sludge dewatering process.

LCA Software and Database

Inventory data from construction, anaerobic secondary treatment, and sludge handling were quantified and entered into the LCA software SimaPro8. A combination of the European-based Ecoinvent v3, U.S. EPA's TRACI 2.1, and the U.S. DOE's LCI databases were all available in SimaPro and used for analysis.

Scenarios

Three life cycle scenarios were investigated: 1-year operational period, 40-year operational period, and 40-year period with a methane air stripper to decrease the dissolved methane emissions.

Results and Discussion

Data from the operational period showed that the average electrical energy usage for the SAF-MBR was 0.371 kWh/m^3. Methane production from the SAF-MBR produced 0.456 kWh/m^3 of electrical energy; this indicates a net-positive energy balance. Figure 2 shows the emissions associated with energy usage and the emissions recovery associated with energy generation.

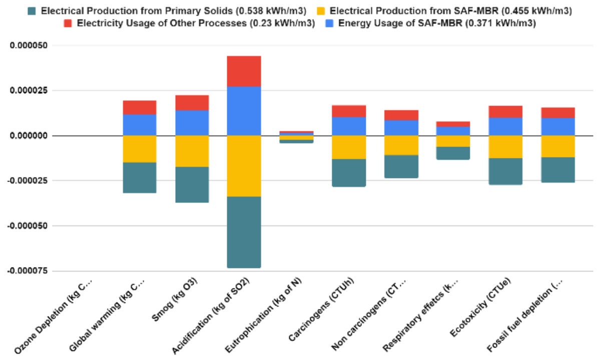

Figure 2. Environmental impacts for energy

Emissions to the environment were recorded to be 0.023 kg/m^3 of dissolved CH_4, 0.082 kg/m^3 of NH_4, and 0.186 kg/m^3 of H_2S. For the scenario with an air stripper it was assumed that the methane recovery was 99% and the dissolved methane emissions became 0.00023 kg/m^3.

The one-year scenario showed that steel was a major emitter, but this was alleviated in the forty-year case once construction emission $\cong$ 0 since materials would only be emitted once during initial construction. This is shown in Figure A1 and A2.

The inclusion of the methane air stripper decreased greenhouse gas emissions by 55%. The decrease in methane is shown in the global warming category of Figure A4 and A5.

Previous literature cited dissolved methane emissions as a drawback to full-scale anaerobic treatment, however our results indicate that ammonium had a larger detrimental environmental impact through eutrophication. The results showed that citric acid was a major contributor and dominated many of the impact categories aside from eutrophication.

Future Work

Future work involves comparing the data to aerobic treatment, adding a denitrification step in downstream treatment to remove ammonium, and looking into more sustainable ways to clean the membrane fibers to mitigate citric acid emissions.

References

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Appendix

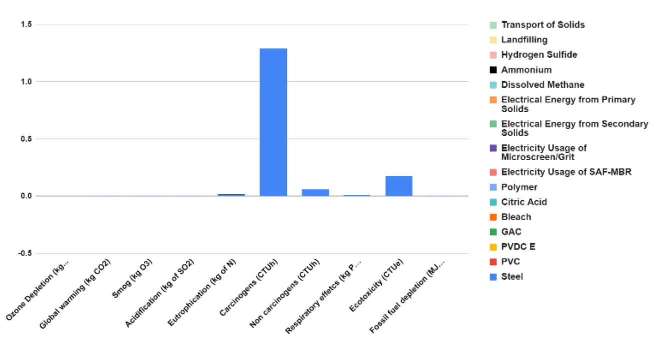

Figure A1: Emissions for the one-year scenario

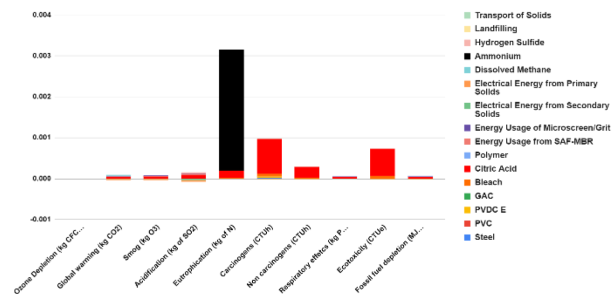

Figure A2: Emissions for the forty-year scenario

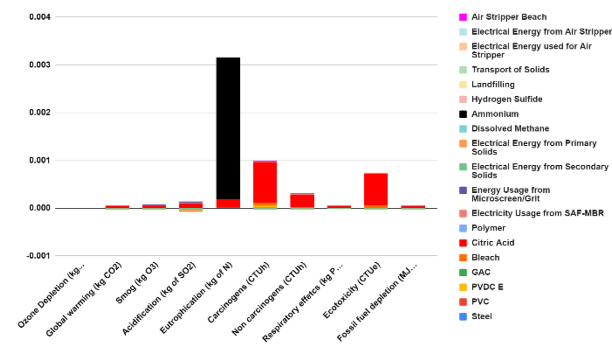

Figure A3: Emissions for the air stripper scenario

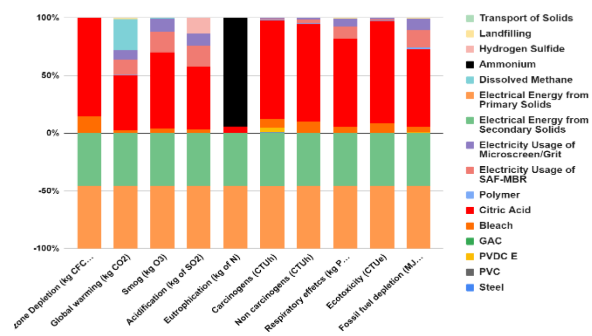

Figure A4: Stacked emissions for the forty-year scenario by relative input percentage

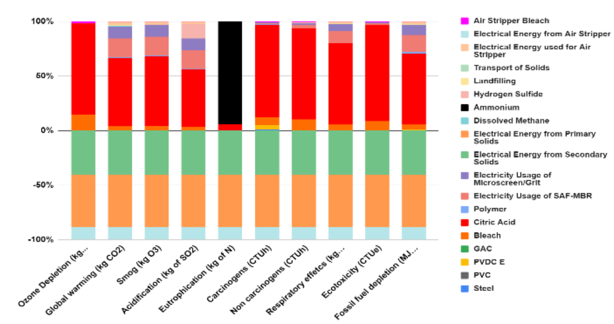

Figure A5: Stacked Emissions for the air stripper scenario by relative input percentage