Final Abstract

Final Report Approved on November 4, 2025

M.L. 2020 Project Abstract

For the Period Ending June 30, 2025

Project Title: Technology For Energy-Generating Onsite Industrial Wastewater Treatment

Project Manager: Paige Novak

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Funding Source:

Fiscal Year:

Legal Citation: M.L. 2021, First Special Session, Chp. 6, Art. 5, Sec. 2, Subd. 04b and M.L. 2022, Chp. 94, Sec. 2, Subd. 20c and M.L. 2024, Chp. Sec. 2, Subd. 18

Appropriation Amount: $372,000

Amount Spent: $370,855

Amount Remaining: $1,145

Sound bite of Project Outcomes and Results

In this research we advanced a wastewater treatment technology to improve the treatment of high strength industrial wastewater. This technology relies on bacteria that are encapsulated in a plastic-like matrix, allowing us to add the bacteria in large quantities and retain them for more efficient treatment.

Overall Project Outcome and Results

In Minnesota the food- and beverage-processing industry is vibrant and provides economic opportunities for the state. These industries are water intensive, and many do not treat their wastewater onsite. Instead, they discharge their untreated wastewater, typically 20-100 times more concentrated than municipal wastewater, to a centralized municipal treatment plant. As a result:

- The industry is required to pay fees to the municipality to discharge the water to the municipal treatment plant, and
- The municipality has to expend energy to treat the (much stronger, more challenging, and potentially disruptive) industrial wastewater.

Our goal for this project was to advance a wastewater treatment technology to enable widespread onsite industrial wastewater treatment to turn pollutants into methane fuel. This also provides benefits to municipalities in the form of more predictable and easier wastewater treatment and lowered treatment costs. The technology works by using bacteria that are encapsulated, or trapped, in a plastic-like matrix so that they can be added in high concentrations and easily retained in the treatment system.

This work complemented a federally-funded project to better leverage LCCMR dollars.

This project was successful, improving the activity of the encapsulated bacteria, improving mathematical models that describe the treatment technology, and advancing this technology to pilot-scale. Our system was able to treat real brewery wastewater in as little as 3 days, turning about 90% of the influent waste into methane (70%) and carbon dioxide to use as fuel.

Multiple industries and municipalities could benefit from this technology if it could be scaled up. We are currently pursuing efforts to commercialize this technology.

Project Results Use and Dissemination

This research was broadly disseminated and will be further disseminated in the following months. We published one paper, a second is accepted and will be published soon, and a third is in preparation. Talks were given at conferences. The Principal Investigator spoke on MPR's Climate Cast about the project. The research, which was also supported by a complementary federally-funded project to better leverage LCCMR dollars, was accepted by Chevron Studio, a collaboration between Chevron Technology Ventures and the National Renewable Energy Laboratory, to explore the scale-up and commercialization of the technology.

Environment and Natural Resources Trust Fund

M.L. 2020 Approved Final Report

General Information

Date: November 12, 2025

ID Number: 2020-062

Staff Lead: Lisa Bigaouette

Project Title: Technology For Energy-Generating Onsite Industrial Wastewater Treatment

Project Budget: $450,000

Project Manager Information

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Project Reporting

Final Report Approved: November 4, 2025

Reporting Status: Project Completed

Date of Last Action: November 4, 2025

Project Completion: June 30, 2025

Legal Information

Legal Citation: M.L. 2021, First Special Session, Chp. 6, Art. 5, Sec. 2, Subd. 04b and M.L. 2022, Chp. 94, Sec. 2, Subd. 20c and M.L. 2024, Chp. Sec. 2, Subd. 18

Appropriation Language: $450,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to improve water quality and generate cost savings by developing off the shelf technology that treats industrial wastewater on-site and turns pollutants into hydrogen and methane for energy. This appropriation is subject to Minnesota Statutes, section 116P.10.

Subd. 20. Transfers

(c) $78,000 is transferred from the amount appropriated under Laws 2021, First Special Session chapter 6, article 5, section 2, subdivision 4, paragraph (b), to the appropriation in subdivision 11. The commissioner must provide documentation to the Legislative-Citizen Commission on Minnesota Resources on the expenditure of these funds.

(d) The amounts transferred under this subdivision are available until June 30, 2025.

EFFECTIVE DATE. Subdivision 19 is effective the day following final enactment. Subdivision 20 is effective June 29, 2022.and (a) The availability of the appropriations for the following projects is extended to June 30, 2025: (6) Laws 2021, First Special Session chapter 6, article 5, section 2, subdivision 4, paragraph (b), Technology for Energy-Generating On-site Industrial Wastewater Treatment, as amended by Laws 2022, chapter 94, section 2, subdivision 20, paragraph (c);

Appropriation End Date: June 30, 2025

Narrative

Project Summary: We will advance an "off the shelf" technology to treat industrial wastewater onsite, turning pollutants into energy and treated water. This will lead to water quality benefits and cost savings.

Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.

In Minnesota the food- and beverage-processing industry, including dairies, malting plants, potato processing facilities, and breweries, is vibrant and provides economic opportunities in both urban and greater Minnesota communities. These industries are water intensive and many do not treat their wastewater onsite. Instead, they discharge their untreated wastewater, typically 20-100 times "stronger" or more concentrated than municipal wastewater, to a centralized municipal treatment plant. As a result:

- The industry is required to pay fees to the municipality to discharge the water to the municipal treatment plant, and
- The municipality has to expend energy to treat the (much stronger, more challenging, and potentially disruptive) industrial wastewater.

Our goal is to expand previous LCCMR-funded research to enable widespread onsite industrial wastewater treatment that turns pollutants into hydrogen and methane fuels and provides benefits to municipalities in the form of more predictable and easier wastewater treatment and lowered treatment costs. This work complements current federally-funded research to better leverage LCCMR dollars.

What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.

A previous successful LCCMR project formed the basis for this research, resulting in the development of first-generation technology that we have since improved upon. This new technology

- Is designed to be installed onsite at food- and beverage-processing facilities,
- Consists of two reactors, one to turn pollutants into hydrogen and a second to clean the water further and turn remaining pollutants into methane,
- Treats the wastewater using bacteria that are encased (or encapsulated) in non-toxic gel-like beads,
- Easily retains the beads within the reactor and protects the bacteria within the beads,
- Turns pollutants in the wastewater into hydrogen and methane by allowing the encapsulated bacteria to "eat" the pollutants in the wastewater much as we eat food, "exhaling" hydrogen and methane. The hydrogen and methane are used directly onsite as fuels for energy generation.

In addition, this new technology improves upon other treatment options by being very compact, creating energy from pollutants in the waste, and requiring much less energy to operate when compared to competing technologies.

After onsite treatment of this concentrated industrial wastewater, the treated wastewater is discharged to the municipal wastewater treatment plant. Because the industrial waste is pre-treated, it should be easier and cheaper to manage.

What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?

Although we have demonstrated successful laboratory-scale operation of the technology with real wastewater, in its current form it is not easily scaled up and each new application requires customization and time-consuming testing. This limits its use. The proposed research would advance this technology by developing and verifying a predictive model that enables accurate a priori scale-up of the system by identifying the ideal bacteria concentration in the beads, bead size, retention time, and other operational parameters. This model will be verified experimentally. This model will be used to complement federally-funded concurrent research on additional experimental aspects of the technology.

Project Location

What is the best scale for describing where your work will take place?

Statewide

What is the best scale to describe the area impacted by your work?

Statewide

When will the work impact occur?

During the Project and In the Future

Activities and Milestones

Activity 1: Develop a mathematical model that describes the performance of the 2-reactor system incorporating encapsulated bacteria to be used for prediction

Activity Budget: $158,740

Activity Description:
A mathematical model will be developed that can accurately describe bacterial metabolism (i.e., biodegradation of industrial wastewater constituents), growth, escape, and product inhibition. This primarily mechanistic model will be based on a classic diffusion-reaction model; this is in contrast to our existing model which relies heavily on empirical parameters. The model will be built in Matlab or Python and will be verified experimentally (below, Activity 2). Sensitivity analyses will be performed.

Activity Milestones:

Description	Approximate Completion Date
Develop the mathematical framework of the model.	February 28, 2023
Verify the model using experimental data.	May 31, 2024
Translate model findings to ideal scenarios for treatment of a variety of wastewaters	June 30, 2024

Activity 2: Pre-pilot scale testing and model verification of the wastewater treatment system

Activity Budget: $213,260

Activity Description:
Perform pre-pilot laboratory experiments with several real wastewaters (brewery, candy, potato chip) to determine parameters for the model and verify the model predictions with additional experiments. For this activity, 100-mL to 1-L and larger flow-through reactors will be established with encapsulated biomass. The biomass leakage will be determined by monitoring the protein that leaves the reactor over time in reactors supplied with no food source. The biomass growth rate will be determined by harvesting encapsulated biomass and measuring the increase in bacteria with time. The inhibition will be determined by performing experiments with known quantities of inhibitory products present and observing the impact on biomass activity. These values will be incorporated into the model.

Model accuracy will be determined through experiments supplied with a variety of wastewaters and run under a variety of conditions (reactor volume, residence time, wastewater strength, bead size, initial biomass density, gas extraction rate).

Activity Milestones:

Description	Approximate Completion Date
Experimental determination of parameters for incorporation into model	April 30, 2023
Test model accuracy via additional experiments with multiple wastewater types	May 31, 2024

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
William Arnold	University of Minnesota College of Science and Engineering	Dr. Arnold is a co-investigator on the project. He is an expert in chemical fate, transport, and water treatment. For the past 10 years he has been a pioneer in the development and modeling of polymer films for chemical containment. We have worked together on similar projects.	Yes
Natasha Wright	University of Minnesota College of Science and Engineering	Dr. Wright is a co-investigator on the project. She focuses on the design, modeling, and system optimization of decentralized water treatment systems, with a specialty in membrane-based separation processes. Over the last 6 years, she has piloted combined energy generation / water treatment systems in the United States, India, and Gaza.	Yes

Dissemination

Describe your plans for dissemination, presentation, documentation, or sharing of data, results, samples, physical collections, and other products and how they will follow ENRTF Acknowledgement Requirements and Guidelines.
The target audience for results from this research will be environmental engineers and scientists in academia, professionals in the area of wastewater treatment, city managers and other local government officials, industry and trade organization personnel (for example, the Minnesota Craft Brewers Guild), the Minnesota Pollution Control Agency, Minnesota Department of Employment and Economic Development (DEED) and Metropolitan Council Environmental Services (MCES). Results will be disseminated through scholarly publications in peer-reviewed journals such as Environmental Science and Technology and Environmental Science: Water Research and Technology. Results from the research project will also be presented at regional conferences such as the Conference on the Environment and seminars and roundtables hosted by project partners (DEED and MCES).

The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENRTF Acknowledgement Guidelines.

Long-Term Implementation and Funding

Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If additional work is needed, how will this work be funded?
We have recently been awarded federal funding that complements the proposed research and can therefore be leveraged for greater benefit. The project was tested at a small pilot-scale at the Fulton Brewery and the research and development needs are clearly identified. Our federal grant will facilitate complementary scale-up and experimental efforts, providing additional improvements that can be captured by the predictive mathematical models created in this research. MCES and state-wide trade organizations will be used to disseminate the work and ready the technology for wide deployment.

Other ENRTF Appropriations Awarded in the Last Six Years

Name	Appropriation	Amount Awarded
Methods to Protect Beneficial Bacteria from Contaminants to Preserve Water Quality	M.L. 2014, Chp. 226, Sec. 2, Subd. 03b	$279,000

Evaluation of Wastewater Nitrogen and Estrogen Treatment Options	M.L. 2014, Chp. 226, Sec. 2, Subd. 03d	$500,000
Wastewater Nitrogen Removal Technology to Protect Water Quality	M.L. 2017, Chp. 96, Sec. 2, Subd. 04b	$450,000
Improving Nitrogen Removal in Greater Minnesota Wastewater Treatment Ponds	M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 04e	$325,000
Degrading Chlorinated Industrial Contaminants with Bacteria	M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 04s	$150,000

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	$ Amount	$ Amount Spent	$ Amount Remaining
Personnel										
Novak, PI		Overall project supervision, experimental set up and operation, data interpretation.			27%	0.12		$43,951	-	-
Arnold, Co-PI		Provide guidance on the model construction and the experimental validation of the model.			27%	0.12		$40,211	-	-
Wright, Co-PI		Provide guidance on the model construction, verification, and sensitivity analysis.			27%	0.12		$27,159	-	-
Postdoctoral Researcher		Will focus on the experiments for model parameterization and verification.			20%	1.62		$91,455	-	-
Graduate Research Assistant		Will focus on the development of the model and its verification. Will perform sensitivity analysis.			43%	1.11		$116,074	-	-
Undergraduate Research Assistant		Will help with development of model and it's verification. Will perform sensitivity analysis			0%	0.1		$5,000	-	-
							Sub Total	**$323,850**	**$323,370**	**$480**
Contracts and Services										
							Sub Total	**-**	**-**	**-**
Equipment, Tools, and Supplies										
	Tools and Supplies	Laboratory supplies, services, and analytical costs (includes, but is not limited to, chemicals for all analyses, supplies to maintain analytical equipment, supplies for reactor construction, pumps for lab-scale systems). A computer will be needed for the model development and testing. This computer will only be	Supplies, pumps, are needed to construct and operate reactors in the lab. A computer is needed to develop and run the model. Additional supplies and chemicals are required to perform the experiments described, including analyses					$31,878	$31,762	$116

		used for this project. These are all required and standard costs.	to determine treatment efficacy, analysis of the gases produced (quantity and chemical make-up) to determine how efficient the system is. A small amount of funds are included for maintenance of laboratory equipment.							
	Equipment	gas chromatography system	Justification - The GC is needed for hydrogen and methane measurements which are needed to evaluate reactor performance. The current instrument is no longer supported by the manufacturer and failing. Portion of purchase based on estimated usage. ENTRF is funding 34% of cost. Other funding is $28,500 from federal and UMN sources.	X				$15,000	$15,000	-
							Sub Total	**$46,878**	**$46,762**	**$116**
Capital Expenditures										
							Sub Total	**-**	**-**	**-**
Acquisitions and Stewardship										
							Sub Total	**-**	**-**	**-**
Travel In Minnesota										
	Miles/ Meals/ Lodging	Mileage costs to go pick up wastewater from industries for use in experiments.	Travel to industrial sites is needed for wastewater collection.					$1,272	$723	$549
							Sub Total	**$1,272**	**$723**	**$549**

Travel Outside Minnesota										
							Sub Total	**-**	**-**	**-**
Printing and Publication										
							Sub Total	**-**	**-**	**-**
Other Expenses										
							Sub Total	**-**	**-**	**-**
							Grand Total	**$372,000**	**$370,855**	**$1,145**

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request
Equipment, Tools, and Supplies		gas chromatography system	Justification - The GC is needed for hydrogen and methane measurements which are needed to evaluate reactor performance. The current instrument is no longer supported by the manufacturer and failing. Portion of purchase based on estimated usage. ENTRF is funding 34% of cost. Other funding is $28,500 from federal and UMN sources.

Non ENRTF Funds

Category	Specific Source	Use	Status	$ Amount	$ Amount Spent	$ Amount Remaining
State						
			State Sub Total	**-**	**-**	**-**
Non-State						
In-Kind	Because the project is overhead-free, overhead costs are provided in kind. The University of Minnesota overhead rate is 55% (equivalent to $186,530).	Laboratory space, electricity, and other overhead costs are provided in kind.	Pending	$186,530	$175,888	$10,642
			Non State Sub Total	**$186,530**	**$175,888**	**$10,642**
			Funds Total	**$186,530**	**$175,888**	**$10,642**

Attachments

Required Attachments

Visual Component

File: 00e0ad92-dd6.pdf

Alternate Text for Visual Component

The visual shows a picture of our current small pilot system set up at the Fulton Brewery and shows how the system can provide electricity for use at the industry site and discharges wastewater that has been pre-treated to a municipal wastewater treatment plant. The following benefits are shown: 1) Decreased costs for the municipality and industry, 2) Decreased energy use for the municipality for treatment, and 3) Resource Recovery. The following project outcomes are shown: Verified mathemati...

Supplemental Attachments

Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other

Title	File
Background check form	fdb4635e-6f8.pdf
Manuscript published from this research	73d72da2-7f3.pdf

Difference between Proposal and Work Plan

Describe changes from Proposal to Work Plan Stage

Because the project was in limbo for about 2 years we submitted a proposal on similar work to that initially proposed to the LCCMR to the US Department of Energy. We have recently been awarded that grant. This means that the federal funding can be leveraged for greater overall benefit and that the LCCMR project scope needed to change slightly to be complementary rather than overlapping. This decreased the LCCMR requested budget by $78,000 and narrowed the scope. This is reflected in the category of "other" under the budget page and in Activity 3. This "other" amount is the amount that should be removed from the $450,000 allocated to the project (the project only requires $372,000 now).

Additional Acknowledgements and Conditions:

The following are acknowledgements and conditions beyond those already included in the above workplan:

Do you understand and acknowledge the ENRTF repayment requirements if the use of capital equipment changes?

N/A

Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?

Yes, I understand the UMN Policy on travel applies.

Does your project have potential for royalties, copyrights, patents, sale of products and assets, or revenue generation?

No

Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?

N/A

Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?

N/A

Does your project include original, hypothesis-driven research?

Yes

Does the organization have a fiscal agent for this project?

Yes, Sponsored Projects Administration

Work Plan Amendments

Amendment ID	Request Type	Changes made on the following pages	Explanation & justification for Amendment Request (word limit 75)	Date Submitted	Approved	Date of LCCMR Action
1	Amendment Request	• General Information • Activities and Milestones • Budget - Other • Budget - Personnel • Budget - Capital, Equipment, Tools, and Supplies	Eliminate Activity 3 due to awarding of federal funds for this portion of the project. Rebudgeting requests: 1)Move $5000 from Postdoctoral salary + fringe to an undergraduate to assist with project work. 2)Rebudget total of $15000 ($10,000 from postdoc salary + fringe; $5000 from laboratory supplies) to support the purchase of a new gas chromatography (GC) system.	July 13, 2023	Yes	July 27, 2023
2	Completion Date	Previous Completion Date: 06/30/2024 New Completion Date: 06/30/2025; Governor Approved on 04/15/2024	It was initially unclear whether the project would be awarded; therefore, we were unable to hire a researchers until May/September, 2022. One researcher unexpectedly received a faculty position offer last summer and left the project after only one year. We have not yet filled this position, putting us behind schedule. If an extension is granted, we will be able to fill the position and complete the work, providing LCCMR with a more complete product.	November 21, 2023	Yes	August 23, 2024
3	Amendment Request	• Other • Budget - Personnel • Budget - Capital, Equipment, Tools, and Supplies	We would like to request rebudgeting the project as follows: 1) Move $11,606 from postdoctoral salary + fringe to graduate student salary + fringe + tuition, and 2) move $1000 from repairs and $9,311 from postdoctoral salary + fringe to lab supplies. The reason for this is that we have not hired a postdoc but instead have had a grad student working on the project. This rebudgeting will support that change. Also we are overspent on supplies.	November 19, 2024	Yes	November 26, 2024

4	Amendment Request		We would like to request rebudgeting the project as follows: Move $1,218.73 from "Personnel" to "Capital, Equipment, Tools, and Supplies". The reason for this is that we went over budget on needed supplies to complete our pilot study. The pilot study was very involved and it was not always easy to anticipate the exact costs that would be needed for laboratory supplies.	June 12, 2025	Yes	June 30, 2025
5	Amendment Request	• Budget • Budget - Personnel • Budget - Capital, Equipment, Tools, and Supplies	When I do the math, taking the original budget and incorporating the approved amendments below, the numbers do not add up; personnel should be $323,850 and tools and supplies should be $31,878. I request that the numbers be fixed so that they reflect the original budget with the amendments incorporated (i.e., this is not really a change request, just a correction request since the online system is incorrect). Thank you!	July 30, 2025	Yes	August 5, 2025

Status Update Reporting

Final Status Update August 14, 2025

Date Submitted: November 4, 2025

Date Approved: November 4, 2025

Overall Update
Amendment request 6/12/25.

Overall improvements to the activity of the encapsulated community were observed when methanogenic biofilms grown on biochar were encapsulated. This was attributed to a higher relative abundance of methanogens in the encapsulated biochar-supported biofilms and the fact that biochar protected the biofilm from the harsh chemicals used in encapsulation, but not to the extent that it interfered with the encapsulant polymerization chemistry. This work was published and is uploaded as an attachment.

A commonly used model was modified and tested on laboratory data in collaboration with a sister project to better describe hydrogen production during fermentation. The new model performed better. This work has been accepted for publication and will be uploaded to the LCCMR system.

Finally, a pilot study was performed at a local brewery, again, in collaboration with a sister project. This work showed that encapsulated bacteria enabled successful high rate anaerobic treatment of high strength brewery wastewater with a rapid start-up. The system successfully treated around 90% of the organic material in the wastewater influent, generating a gas stream of approximately 70-80% methane (balance assumed to be CO_2). The system worked well at hydraulic residence times of 13, 7, and 3 days.

Activity 1
This activity was previously marked complete.
(This activity marked as complete as of this status update)

Activity 2
Amendment request 6/12/25.

The pilot study, supported by this grant as well as a sister grant from the Department of Energy, showed that the system is capable of robust organic removal with concomitant methane production. The encapsulant beads show no visible signs of deterioration after deployment for approximately 300 days. No clear advantages were seen with the 2-stage system or with active gas extraction from the first phase of treatment. When the temperature dropped to about 25C from around 30C, the fermentation in the first phase reactor did decline. The single-stage reactor was less sensitive to the decline in temperature compared to the two-stage reactor. An additional paper will be submitted on this work (anticipated in fall, 2025).
(This activity marked as complete as of this status update)

Dissemination
One manuscript has been published and is attached. A second has been accepted and will be uploaded in the next month. A third will be submitted some time this fall and will be uploaded when accepted. The work was presented at the Association of Environmental Engineering and Science Professors in May, 2025. The work was presented to a group of entrepreneurs in April and initial discussions around commercialization and scale-up are taking place.

Status Update Reporting

Status Update April 1, 2025

Date Submitted: March 20, 2025

Date Approved: April 3, 2025

Overall Update
Work on this project in conjunction with a sister project funded by the Department of Energy is nearly complete. A model has been developed and verified that accounts for fermentation and extraction of hydrogen from an initial fermentation reactor. Hydrogen extraction, however, does not improve downstream processes and is not likely to be worth implementing.

A pilot system was operated at a local brewery for almost 300 days. Encapsulated biomass was robust and able to achieve high levels of pollutant (organic compound) removal and gas (methane) production at hydraulic residence times as low as 3 days. During winter the temperature dropped in the brewery and performance declined in the two-stage system to about 70% organic removal (as opposed to >90% at higher temperatures), but not in the single-stage system. The pilot system has been taken down and data analysis is taking place.

Activity 1
A gas extraction model in conjunction with a biological process model (ADM1) that takes into account fermentation has been built and verified at the laboratory scale. Specifically, a modified ADM1 model (mADM1) was developed that accounts for the presence of lactate and ethanol in the reactors. Both ADM1 and mADM1 were calibrated against a bench-scale fermenting reactor fed brewery wastewater, and then validated by comparing against a similar reactor with hydrogen extraction. It was shown that the mADM1 model was able to better predict the effects of hydrogen extraction and changing feed concentrations compared to ADM1. The work has been submitted for publication.

Experimental studies conducted with first-stage (fermentative) reactors using brewery and synthetic wastewaters showed increased hydrogen production when the hydrogen was actively removed/extracted. Improvements in fermentation or downstream (second- or methanogenic-stage) COD removal were not observed, however. Membrane-based active gas extraction was able to remove approximately 95% of the hydrogen produced, making it an effective way to collect the gas as it is produced. An analysis showed that the cost of gas extraction was not likely to be worth the improvement in gas collection, however.
(This activity marked as complete as of this status update)

Activity 2
The pilot system, including reactors, beads containing encapsulated biomass, and a control system, was assembled and deployed at a local brewery for almost 300 days. During this time we compared a two-stage (fermentative followed by methanogenic reactors) and one-stage system. Both systems were able to degrade >90% of the wastewater organics fed to the system, generating a gas stream containing 80% methane. This was achieved at a hydraulic residence time (HRT) of 13, 7, and 3 days. Gas extraction in the fermentation reactor did collect more gas, but did not improve organic removal or methane production. Changing the system from an HRT of 3 days to 13 and then back to 3 days did not negatively impact bead/encapsulant integrity. When the temperature of the system decreased at an HRT of 3 days, the two-stage system performance declined to around 70% organic removal. The pilot system has been taken down and data analysis is being performed.

Dissemination
We have submitted a paper on Activity 1. We are planning to have another paper submitted on Activity 1. A paper on Activity two is in progress. We have presented these results at several universities and will present them this summer at

the Association of Environmental Engineering and Science Professors conference. Novak will present these results to a group of entrepreneurs to determine potential interest in advancing the technology to a start-up.

Status Update Reporting

Status Update October 1, 2024

Date Submitted: September 25, 2024

Date Approved: November 26, 2024

Overall Update
The ADM1 process model has been successfully modified to more accurately model the first stage of anaerobic treatment, fermentation. As mentioned previously, these changes are important for ensuring that we are accurately modeling the effect of gas extraction on performance. The model results were compared to published data and to the data collected from Activity 2, where parallel reactor systems were operated with and without gas extraction. A manuscript describing this model has been prepared for publication. Experiments with parallel reactors undergoing gas extraction and no gas extraction are complete. Gas extraction successfully captured all of the gas produced during fermentation but did not improve or change the fermentation process. Operation of the two-stage anaerobic reactor system containing encapsulated bacteria at a pilot scale at Fulton brewery, in collaboration with a sister project funded by the Department of Energy, is on-going. Thus far operation has been successful, with >90% carbon removal, excellent gas production, and stable operation observed at a hydraulic residence time (HRT) of 7 days in both the two-stage system and a one-stage control system. The HRT has been dropped to 3 days to challenge the system further. Gas extraction from the first reactor stage has also started.

Activity 1
Modification of the ADM1 process model so that it can accurately model the first stage of anaerobic treatment, fermentation, is complete. The model was modified to include lactate and ethanol as intermediates, which allowed it to better predict hydrogen production and the effects of dissolved hydrogen on fermentation kinetics. In addition, sensitivity analysis suggested that accurately identifying the influent chemistry to the reactor improved prediction as well. This latter point will enable better prediction when the influent chemistry is known. The improved model showed a good fit with experimental data and also was able to better predict the increase in hydrogen production that was observed when gas was actively recovered. This model will be used to determine how HRT and pH will alter the performance of the system, which can then be used to change the operational parameters of the currently-deployed pilot system. After these model runs have been completed (in the next month) this Activity should be complete. The manuscript describing this ADM1 process model modification and its verification is being finalized and will be submitted for publication in the next month.

Activity 2
The single-stage fermentative reactor experiments are now complete, with the data used to verify the model described in Activity 1. Active gas extraction improved gas production and was able to enable 100% gas collection; nevertheless, it did not improve fermentation or carbon removal. Depending on the objectives of the system (gas collection for use, mitigation of greenhouse gas release, or carbon removal), active gas extraction can be deployed for improved outcomes.

An undergraduate researcher is currently verifying performance in with biochar-supported, PAC-supported, or planktonic encapsulated bacteria to enable better performance of the system.

We have continued to operate a two-stage anaerobic reactor system containing encapsulated bacteria at a pilot scale at Fulton brewery, in collaboration with a sister project. Thus far operation has been successful, with >90% carbon removal, excellent gas production, and stable operation observed at a hydraulic residence time (HRT) of 7 days in both the two-stage system and a one-stage control system. The HRT has been dropped to 3 days to challenge the system further, resulting in less carbon removal (around 75%) but high levels of methane production. Gas extraction from the first reactor stage has recently started, which has improved hydrogen production in the first stage.

Dissemination

The former PD researcher on the project has drafted a manuscript on his research; it has not yet been submitted. A manuscript describing the modified ADM1 model is complete and is currently being finalized for submission. It should be submitted within a month. We also anticipate a paper on the fermentation reactors with and without gas extraction and the pilot system to be submitted within the next 6 months. We expect that a significant amount of dissemination will occur over the next year. We have been presenting on the results and have received interest from several breweries in the treatment system.

Additional Status Update Reporting

Additional Status Update August 14, 2024

Date Submitted: September 25, 2024

Date Approved: November 26, 2024

Overall Update
Please see below for update (April 1 due date). I apologize for forgetting the update. The project has been extended until June 30, 2025 so the status update reporting will need to be extended.

Activity 1
Please see below for update (April 1 due date). I apologize for forgetting the update. The project has been extended until June 30, 2025 so the status update reporting will need to be extended.

Activity 2
Please see below for update (April 1 due date). I apologize for forgetting the update. The project has been extended until June 30, 2025 so the status update reporting will need to be extended.

Dissemination
Please see below for update (April 1 due date). I apologize for forgetting the update. The project has been extended until June 30, 2025 so the status update reporting will need to be extended.

Status Update Reporting

Status Update April 1, 2024

Date Submitted: September 25, 2024

Date Approved: November 26, 2024

Overall Update
Work is continuing on modifying the ADM1 process model so that it can accurately model the first stage of anaerobic treatment, fermentation. These changes are important for ensuring that we are accurately modeling the effect of hydrogen extraction on hydrogen, methane, and fatty acid production, which has important implications for reactor size (and therefore cost) and operation. The model results are being compared to published data and to the data collected from Activity 2, where parallel reactor systems are operated with and without gas extraction. Our recent data showed that the reactor with gas extraction was capable of capturing all of the gas produced during fermentation. We have also deployed a two-stage anaerobic reactor system containing encapsulated bacteria at a pilot scale at Fulton brewery, in collaboration with a sister project funded by the Department of Energy. System operation is just beginning, but has gone smooty, with control systems and data collection proceeding well. Gas production in the first stage is occurring. Full deployment of the biomass is expected in the next two weeks.

Activity 1
Work is continuing on modifying the ADM1 process model so that it can accurately model the first stage of anaerobic treatment, fermentation. Changing Initial conditions and parameters in the ADM1 process model did not improve the model fit. Current efforts are focused on changing the rate coefficients for sugar and hydrogen uptake, as well as pH inhibition limits for the organisms that utilize acid and hydrogen. Work is also focused on modifying ADM1 for variable stoichimetry. These changes are important for ensuring that we are accurately modeling the effect of hydrogen extraction on hydrogen, methane, and fatty acid production, which has important implications for reactor size (and therefore cost) and operation.

Activity 2
The single-stage fermentative reactor experiments have been repeated with synthetic wastewater. Our results suggested that more cumulative hydrogen was collected with gas extraction even though the total hydrogen produced was the same for both reactors. Next steps include a subsequent experiment to optimize flow rates and vacuum pressures to minimize the power consumption associated with gas extraction while maintaining total dissolved hydrogen (and by extension, methane) removal. Additionally, a study will be performed with varying reactor pH, as hydrogen inhibition is expected to depend on pH.

We have also deployed a two-stage anaerobic reactor system containing encapsulated bacteria at a pilot scale at Fulton brewery, in collaboration with a sister project. The pilot system, including reactors, bead volume and biomass quantity and type, and the control scheme, has been assembled. The pilot system was operated for 20 days with no biomass to ensure smooth operation and good pH and level control in the reactors. No COD removal or gas production was observed without biomass present, as expected. The encapsulated biomass has been added to the first-stage reactor and some biomass has been added to the methanogenic bioreactors. Gas production in the first stage is occurring.

Dissemination
The former PD researcher on the project has drafted a manuscript on his research. We expect that a significant amount of dissemination will occur over the next year.

Status Update Reporting

Status Update October 1, 2023

Date Submitted: October 6, 2023

Date Approved: January 19, 2024

Overall Update
The PD researcher working on the project has taken a faculty position.

A model describing the system was derived and implemented within an open-source simulation framework, QSDSan. Additional modeling work is focused on better resolving the first-stage activity (hydrogen production and fermentation), which is not well-resolved in current models. The model will be compared to the data collected from Activity 2, where parallel reactor systems with and without gas extraction will be used to verify the model as well as identify the benefits of gas extraction on the system. Our recent data showed that the reactor with gas extraction produced much more hydrogen gas than the parallel reactor without gas extraction. This should result in more energy production as well as efficient gas collection during wastewater treatment. Experiments have also been performed to clarify why biofilms grown on biochar produce more methane gas in the second-stage reactor after encapsulation than either encapsulated suspended microorganisms or encapsulated biofilms grown on activated carbon. It appears that the biochar protects the microorganisms during the harsh encapsulation process and also facilitates thicker biofilm growth on the biochar, increasing the concentration of microorganisms that can be encapsulated.

We would like to discuss a no-cost extension.

Activity 1
A solution-diffusion model for the encapsulation beads was derived and implemented in Python, within a simulation framework, QSDSan, which is open-source. The model can be compared to the data collected from Activity 2. Literature review shows that a commonly used process model that describes anaerobic biological systems like ours, the ADM1 process model, has not yet been validated for hydrogen production and dissolved hydrogen concentration. The ADM1 process model will be compared with data from Activity 2, specifically the synthetic brewery wastewater data, to calibrate the model for dissolved hydrogen concentrations, which is expected to allow for better prediction of hydrogen production increase in the case of side-stream gas recovery. This will make the predictions of our two-stage system much more robust and be useful to other researchers that are looking at separate fermentation reactors, like our first-stage reactor.

Activity 2
A single-stage parallel reactor system was built to assess the impact of gas extraction on the microbial community, ultimately leading to improved VFA and hydrogen gas production. As anticipated, the reactor equipped with a side stream gas extraction system generated more hydrogen than a simple flow-through reactor. However, we are still uncertain about the effect of gas extraction on VFA production due to the significant fermentation occurring in the influent wastewater from the brewery. To address this issue, the same experiment will be performed under identical operating conditions but with lab-made synthetic wastewater.

The PD researcher working on the project has taken a faculty position. Before leaving he completed experiments to understand how biochar protects microorganisms grown on it from toxicity during encapsulation. When grown on biochar and then encapsulated, second-stage biomass produces much more methane than encapsulated suspended microorganisms. This may be because the biochar allows a thicker biofilm of microorganisms to grow. This hypothesis will be tested. This discovery will be used as the basis for a part of a provisional patent application on the system. This discovery should make the second stage of our system more efficient.

Dissemination

The PD researcher presented his work at a conference organized by the Association of Environmental Engineering Science Professors that was held in Boston on June 19, 2023. Work is beginning on drafting a manuscript for publication.

Additional Status Update Reporting

Additional Status Update July 11, 2023

Date Submitted: July 12, 2023

Date Approved: July 27, 2023

Overall Update
We are requesting an amendment for help in purchasing needed equipment.

Activity 1
Amendment request.

Activity 2
Amendment request.

Activity 3
We have adjusted the budget. It should be $0, but we cannot have a $0 activity so this is now $1.

Dissemination
We will update the dissemination with the next report.

Status Update Reporting

Status Update April 1, 2023

Date Submitted: April 4, 2023

Date Approved: April 6, 2023

Overall Update
Since our last update, the master's (MS) student has begun work on the project. The MS student is collaborating closely with a PhD student on a sister-project (funded through U.S. DOE and discussed in the Project Activity 3), who has developed a mathematical model for side-stream (i.e., external to the reactor) gas extraction. The model developed for that project will be compared to experimental data collected by the MS student and expanded by the student as needed. The objective for this set of experiments is to validate (i) the rate of gas extraction under varying membrane operating parameters, and (ii) biomass inhibition by the hydrogen that is produced, with and without active gas extraction.

Through batch tests, the postdoctoral (PD) researcher has observed that adding biochar- or activated carbon (AC)-supported biofilms as additives to the PEG encapsulant (referred to as "biochar-PEG" and "AC-PEG," respectively) significantly increases biological methane production. He is now performing flow-through experiments with parallel second-stage reactors to monitor performance differences between biochar-PEG and AC-PEG encapsulants, determine how these additives benefit performance, and verify and parameterize the models that we are constructing on our sister-project. These experiments are in progress.

Activity 1
Since he started, the MS student has been trained regarding the required experimental analyses and procedures to use for the project including training in data acquisition in the LabView software program, sample collection, and gas composition analysis using gas chromatography. He has set up two 1-L reactors that will be run in parallel to compare overall gas production and COD removal with and without active gas extraction. The experimental setup includes automatic collection of the extracted gas volume and active control of the vacuum pump to control for the expected change in gas production with time; we expect the setup to provide finer resolution gas production data than previous experiments, which will enable us to verify, and if needed, expand our current predictive mathematical models. Wastewater will be collected from our partner brewery and serve as the influent for both reactors. In one reactor, we will vary the recirculation flow rate and vacuum pressure in order to vary the rate of gas extraction by PDMS hollow fiber membranes. Seeding of the reactors with encapsulated bacteria is expected in the next 1-2 weeks and experiments will start shortly thereafter.

Activity 2
The PD reseracher is currently investigating the mechanism behind why PEG-encapsulated biochar- and AC-supported biofilms improve methane production. He has started batch experiments to extend his previous investigations regarding how exposure to ammonium persulfate (APS) affects the microorganisms, by determining how biochar and activated carbon may protect the microorganisms from APS toxicity. AC can react with APS, which may reduce microorganisms' exposure to (toxic) APS. Nevertheless, as AC reacts with APS, APS becomes unavailable for polymerizing the encapsulant, leading to less stable encapsulants. This in turn limits the amount of AC (and therefore AC-supported biofilm) that can be added to the encapsulant to 5% by weight. Biochar behaved differently, seemingly protecting the biomass, but not in such a way as to negatively impact PEG polymerization. This allowed more biochar-supported biofilm (7.5% by weight) to be added to encapsulants, and as a result, more methane production per encapsulant bead. Experiments are underway to further clarify why this occurs and how biochar benefits the encapsulated microorganisms. At the same time, flow-through experiments to further verify the predictive model are also in progress.

Activity 3
Activity 3 constitutes funds that we believe will not be needed to meet the new proposed scope.

Dissemination
The PD researcher will be presenting his work at a conference organized by the Association of Environmental Engineering Science Professors to be held at Boston on June 19, 2023. Work is beginning on drafting a manuscript for publication.

Status Update Reporting

Status Update October 1, 2022

Date Submitted: September 20, 2022

Date Approved: September 27, 2022

Overall Update
As planned, we hired a postdoctoral (PD) researcher who started this past summer and have identified a master's student who will begin work on the project soon. Since he started, the PD researcher has been trained regarding the required analyses and procedures to use for the project. He has set up a two-stage flow-through reactor that can be used to monitor both gas production as well as overall carbon removal. The system has been seeded with encapsulated bacteria and testing is underway. Plans are in place to perform experiments with different encapsulated communities and different wastewater feed streams to monitor performance.

In experiments performed for a different project, it was observed that encapsulant chemistries that are harsher and more inhibitory/toxic to bacteria tend to produce more durable beads. This bead/encapsulant durability is desired for wastewater treatment. To better understand how to modulate this toxicity/inhibition, experiments were performed to understand how different components in the encapsulant impact microbial survival and activity. This should enable the chemistries to be modified to preserve microbial activity. Finally, experiments with biochar as an encapsulant additive are underway to determine whether this additive can enhance microbial activity and aid in survival during encapsulation.

Activity 1
We have hired a master's student to perform the work described for Activity 1 and plan to have him start on this work soon. Reactor set-up and wastewater tests are expected over the next 1-2 months. The student has begun a literature review of alternate membrane architectures to better remove gas as it is produced from the bacteria in the system.

Activity 2
See above. We have hired a PD researcher and he has started experiments to monitor activity of encapsulated bacteria using different additives to the encapsulant (e.g., biochar), and different encapsulant chemistries. Specifically, we have selected polyethylene glycol (PEG) as our encapsulant chemistry for its durability and ability to retain bacteria without leaking for at least 30 days. To polymerize PEG we must utilize ammonium persulfate (APS), a strong oxidant. This can result in microbial death. To understand how to modify the PEG encapsulant chemistry and select the appropriate amount of APS, experiments were performed with different quantities of APS to identify when the mixture became toxic to the bacteria. We also hypothesize that certain additives, particularly those that bacteria can grow on in thicker layers and that might have electron transfer capability, such as biochar, might better protect bacteria during encapsulation and enhance microbial activity during normal operation. Experiments to test this hypothesis are also underway.

The experiments will also be performed with different wastewater feedstocks so that models describing this work can be appropriately parameterized and modified. To do this a flow-through reactor has been constructed.

Activity 3
Activity 3 constitutes funds that we believe will not be needed to meet the new proposed scope.

Dissemination
No work has begun on dissemination.

Status Update Reporting

Status Update April 1, 2022

Date Submitted: March 30, 2022

Date Approved: March 31, 2022

Overall Update
Because it was unclear whether this project would be awarded until very late, we were unable to hire a graduate student to perform the work. We are currently searching for a postdoctoral researcher and hope to hire someone by the end of April, 2022 who can begin work this summer. We also plan to hire a master's student to begin work this coming summer or, more likely fall, to perform the modeling work. The work should be able to be completed in two years, so we do not believe that this will negatively impact the project.

Activity 1
We plan to hire a master's student to perform the work described for Activity 1, beginning this summer or fall (2022). This should not negatively impact our ability to meet our project goals.

Activity 2
We are currently searching for a postdoctoral researcher and hope to hire them by the end of April, 2022 so that they can begin work on Activity 2 this summer. Although this work is designed to verify the model (Activity 1), the experimental set-up will take some time, making it more efficient to begin Activity 2 work as soon as possible. This should not negatively impact our ability to meet our project goals.

Activity 3
Activity 3 constitutes funds that we believe will not be needed to meet the new proposed scope.

Dissemination
No work has begun on dissemination.