CLEAN RESOURCES FINAL REPORT PACKAGE

Project proponents are required to submit a Final Report Package, consisting of a Final Public Report and a Final Financial Report. These reports are to be provided under separate cover at the conclusion of projects for review and approval by Alberta Innovates (AI) Clean Resources Division. Proponents will use the two templates that follow to report key results and outcomes achieved during the project and financial details. The information requested in the templates should be considered the minimum necessary to meet AI reporting requirements; proponents are highly encouraged to include other information that may provide additional value, including more detailed appendices. Proponents must work with the AI Project Advisor during preparation of the Final Report Package to ensure submissions are of the highest possible quality and thus reduce the time and effort necessary to address issues that may emerge through the review and approval process.

Final Public Report

The Final Public Report shall outline what the project achieved and provide conclusions and recommendations for further research inquiry or technology development, together with an overview of the performance of the project in terms of process, output, outcomes and impact measures. The report must delineate all project knowledge and/or technology developed and must be in sufficient detail to permit readers to use or adapt the results for research and analysis purposes and to understand how conclusions were arrived at. It is incumbent upon the proponent to ensure that the Final Public Report **is free of any confidential information or intellectual property requiring protection**. The Final Public Report will be released by Alberta Innovates after the confidentiality period has expired as described in the Investment Agreement.

Final Financial Report

The Final Financial Report shall provide complete and accurate accounting of all project expenditures and contributions over the life of the project pertaining to Alberta Innovates, the proponent, and any project partners. The Final Financial Report will not be publicly released.

PROCESS DEVELOPMENT FOR THE CANNABIS WASTE MANAGEMENT: ON THE WAY TO SUSTAINABLE WASTE DISPOSAL AND BIOENERGY PRODUCTION

G2018000617

Public Final Report
Submitted on: March 31, 2021

Prepared for
Alberta Innovates, Susan Carlisle

Prepared by
University of Alberta
Yang Liu, Professor, PhD, PEng
Tel: 780-492-5115; Email: yang.liu@ualberta.ca

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PROJECT PARTNERS

Please provide an acknowledgement statement for project partners, if appropriate.

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We would like to convey our acknowledgement to our project partners, Alberta Innovates and Atlas Growers for their tremendous support to us throughout this project. Without their support, we could not have completed this project successfully. Atlas Growers Ltd., established in 2015, is an industry leading producer of cannabis products for medical use. Their pharmaceutically viable cannabis flower and cannabis products are cultivated in a state-of-the-art, 38,000 square foot controlled-environment agricultural facility outside of Edmonton, Alberta. Their team of professionals is dedicated to creating high-quality, safe and consistent cannabis products. Throughout the project duration, Staff members from Atlas Growers committed their time by participating in project meetings and discussions, and donated pre-sorted sample cannabis waste materials to our research team. Special thanks to Mr. Jim Hole, who contributed his time and efforts to assist our research.

During the project, Alberta Innovates kindly provided the cash contributions needed to cover the cost for the hiring of highly skilled personnel and for conducting all experimental work. Staff members from Alberta Innovates were always responsive and supportive to our needs, especially when our progress was challenged and experiencing unexpected delays due to licensing issues and the COVID-19 lockdown.

A. EXECUTIVE SUMMARY

Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.

RESPOND BELOW

The legalization of cannabis cultivation in Canada in the summer of 2018 was anticipated to foster a boom in the cannabis industry and significantly increase the burden of cannabis waste disposal on municipalities. It was estimated that the Canadian cannabis industry would generate up to 6,000 tonnes of cannabis waste in 2020 [1, 2]. A huge market need for cannabis waste disposal exists, but few efforts have been made for efficient cannabis waste disposal. Several conventional waste management methods, such as composting, landfilling, and incineration, are being used, although they are facing various challenges. Composting facilities and landfills are often unwanted due to land use considerations, and incineration is energy intensive. The greenhouse gasses (GHG) generated from these processes are rarely collected and are therefore released into the atmosphere. Further, as a regulated substance, transportation of cannabis waste to the disposal facilities must be in accordance with Alberta provincial regulations and municipal by-laws, which specify that the waste leaving the cultivation facilities and entering disposal facilities must

be tracked down to the gram. The cost of cannabis waste disposal incurred by cannabis producers significantly decreases revenues. In particular, following the Alberta Government's guidance for cannabis waste disposal, cannabis waste disposal involves mixing cannabis waste with cat litter to generate a mixed waste with at least 50% non-cannabis waste [3, 4], hence the cost of cat litter required ($582/ton), and doubled transportation and management cost for cannabis waste and cat litter mixture (e.g., landfill or compositing) can be substantial [5]. As such, there is an urgent business need to develop innovative and cost-effective on-site treatment technology solutions for the disposal of cannabis waste.

As very limited information is available on this topic, this project was primarily a feasibility study focusing on the development and optimization of cannabis waste pretreatment options and the evaluation of anaerobic treatment conditions for effective cannabis waste treatment and energy recovery. Cannabis waste is rich in lignocellulosic biomass which, when subjected to anaerobic digestion (AD), can generate methane. Compared to aerobic waste treatment processes, AD has a lower operational cost and generates methane, which, with appropriately designed gas collection systems, can be recycled and used for energy, significantly decreasing GHG emissions [2]. In this project, several pretreatment methods, aimed at improving the biomass treatability, were tested. Efficiency of the pretreatment methods was evaluated by determining the biomass solubilization and the methane production potential. We further operated continuous laboratory reactors and demonstrated stable operation for treating cannabis waste via anaerobic digestion. The microbial community structure of the digestor sludge were evaluated and the linkage between the microbial community structure and AD reactors were revealed. These aims were achieved after a full characterization of the cannabis waste upon receipt, the information of which was generally lacking. The project is intended to help lead to development of Alberta-made cannabis waste treatment processes that are fit for different scales of operation.

B. INTRODUCTION

Please provide a narrative introducing the project using the following sub-headings.

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

RESPOND BELOW

Section Introduction

<u>What is cannabis waste?</u> *Cannabis sativa L.* and *Cannabis indica* are the most widely cultivated species. *C. sativa* and *C. indica* cultivated for medical and recreational use are generally referred to as cannabis [6]. Cannabis contains genetically different biotypes of non-intoxicant industrial hemp and marijuana, which are usually classified based on the concentrations of the medical active ingredient - Δ9-tetrahydrocannabinol (THC) [7]. Under Canada's Industrial Hemp Regulations, varieties of *C. sativa L.*, with a THC level of 0.3% w/w or less in the flowering heads and leaves are cultivated for food and industrial purposes and are commonly referred hemp [8, 9]. For the clarification, the word "cannabis" will be used in this report to describe marijuana. In general, cannabis waste refers to the solid and liquid wastes generated during the production and processing of cannabis products [3]. Since most THC is located in the resin heads of capitate-stalked glandular trichomes [10], cannabis waste usually includes 1) the cannabis plant waste, such as roots, stalks, leaves, and stems that have not been processed with solvents; 2) solid cannabis sample plant waste in the possession of a cannabis testing facility; and 3) other waste as deemed appropriate [11].

Market needs for cost-effective cannabis waste management solutions. In April 2017, the federal government introduced legislation to legalize cannabis by the summer of 2018, after which, the Government of Alberta developed the Alberta Cannabis Framework and legislation to set the stage for the legal and responsible use of cannabis by Albertans. Applications for private cannabis retail licenses in Alberta were opened on March 6, 2018, resulting in an immediate spike in the cannabis facility development in Alberta. Since legalization, Health Canada has issued 287 cannabis licenses as of January 22, 2021 [12]. Currently, there are 681 license holders as of June 10, 2021, and 75 of them are in Alberta [13]. With increased production and consumption, more cannabis waste would be generated. Municipalities will thereafter experience higher than usual pressure in the proper disposing and management of cannabis waste, which however, hasn't been fully explored.

Although the federal *Cannabis Act* has regulated the production and consumption of cannabis [14], no direct guidance or prescribed methods were provided for the disposal of cannabis waste [5]. The disposal of cannabis wastes is largely guided by provincial and/or local municipalities. The rule of thumb disposal requirement is that cannabis waste must be rendered unusable and unrecognizable. This requirement is usually achieved by mixing the waste with at least an equal amount of 1) other compostable waste, such as food waste and yard waste, prior to delivery to a licensed compositing or organic waste treatment facility, or 2) non-compostable materials such as paper and cardboard prior to delivery to a licensed landfill or a solid waste incinerator [11, 15, 16]. In Alberta, liquid cannabis waste is recommended to be disposed of by deep well injection, at a wastewater treatment facility (WWTF), or at a hazardous WWTF if the liquid is hazardous. Solid cannabis waste can be disposed of at a compost facility, an anaerobic digestion facility or at a landfill, depending on the materials used to render the solid cannabis waste unusable and unrecognizable [3]. However, these options often require a substantial amount of space, time, and/or energy input, thus could potentially increase carbon footprint. Further, the transportation of cannabis waste to disposing facilities is another contributing source to increased carbon footprint. Further, conventional landfilling often fails to collect the landfill gas, especially methane, which eventually leads to methane migrating into the atmosphere and contributing to local smog and global climate change. Composting can also increase greenhouse gas emission (GHG) as CO_2 generated during composting easily escapes into the atmosphere.

Very limited commercial technologies for the on-site rapid treatment of cannabis waste are available. For instance, Eco-Growth, a Canadian company in Calgary, provides solution for cannabis wastes by converting the wastes to a solid, combustible biofuel. An American company utilizes anaerobic fermentation process to convert cannabis waste to fertilizer (Bokashicycle LLC, Cheyenne, WY, US). As such, there is an increasing market need for environmental-sound, cost-effective treatment solutions for cannabis waste.

Knowledge or Technology Gaps

To the best of our knowledge, direct research using cannabis waste as an energy source is not available. However, industrial hemp has been reported to be used as a high-yielding energy crop for the production of bioenergy. To provide a sense of scale, a study in Sweden demonstrated that AD of industrial hemp generated an average gross methane energy yield of 136 ± 24 GJ per hectare of hemp harvested, which equals to 16 tonnes of dry matter [7]. The transformation from crop to bioenergy can be achieved via a series of pathways, such as AD (methane and hydrogen), hydrolysis/fermentation (bioethanol), combustion (methanol), and hemp oil (biodiesel) [7-11]. The high energy yield of industrial hemp is mainly due to its rich lignocellulosic biomass content. For example, fresh green hemp fiber is composed of 55% cellulose, 16% hemicellulose, 18% pectic substances, and 4% lignin. The stem, being one of the main components of the cannabis waste, contains 35% bast fiber (contains 57-77% cellulose and 5-9% lignin) and 65% woody core (40-48% cellulose and 21-24% lignin). AD of lignocellulosic biomass is a promising option to produce renewable energy, recover nutrients, and mitigate GHG release. However, a key challenge is the slow rate of microbial biodegradation of lignocellulosic biomass, which significantly limits biomass hydrolysis, the first step of AD [12]. Studies have demonstrated that methane production from lignocellulosic biomass can be improved through various pretreatment methods, such as chemical methods using acids, alkalis or oxidants, mechanical methods, thermal methods within a common range of 150-200 °C, ultrasonication, and biological methods [12-14]. In Dr. Liu's Industrial Research Chair in Sustainable Urban Water Development (IRC) program, several pretreatment strategies were applied to test the digestibility improvement of food waste and blackwater [17]. Blackwater consists mainly of feces, urine and water. The bacterial biomass accounts for 25–54% of the dry solids in feces, and the rest is undigested carbohydrates, fibres, proteins and fats [18-23]. Laboratory-scale and pilot-scale anaerobic digestion reactors have also been developed. However, the feasibility to recovery energy from cannabis waste via anaerobic digestion has never been evaluated.

C. PROJECT DESCRIPTION

Please provide a narrative describing the project using the following sub-headings.

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

RESPOND BELOW

Knowledge or Technology Description

The ***main objective*** of this project was to develop environmentally-sound, energy-efficient strategies for on-site treatment of cannabis waste that can reduce transportation and landfill needs and enhance biogas/energy production. The principle is that cannabis waste is rich in lignocellulosic biomass (carbon content) which, when appropriately pretreated, has been proven to improve the efficiency of energy production in the form of methane [24]. Specifically, Dr. Liu and her research group explored several pretreatment strategies to improve the digestibility of food waste and blackwater in her IRC program. It was hypothesized that pretreating the cannabis waste could increase the methane production from the AD process, which would lead to a multitude of sustainable bioenergy production and waste disposal benefits. Further, the treatment strategies could also be applied to other agricultural/organic wastes rich in lignocellulosic biomass.

The ***scope*** of project was focused on exploring the pretreatment strategies of cannabis waste for improved digestibility and optimizing methane production from the AD process. Key to the success of this project was to increase the hydrolysis rate of biomass, which is the rate limiting step of AD. As such, this proposal was divided into three tasks: cannabis material characterization, evaluation of pretreatment methods, and evaluation of AD performance (see details under Section D, Methodology). Specifically, different pretreatment methods were tested, and their efficiencies were evaluated in a solid-state AD reactor. The chemical oxygen demand (COD) removal efficiency and energy generation in the form of methane production from the pretreated cannabis waste were determined. Further, the carbon/nitrogen (C/N) ratio of the feedstock is critical to facilitate the conversion of lignocellulosic biomass to methane [24]. Given that the cannabis waste is rich in carbon but low in nitrogen, co-digestion of the pretreated cannabis waste with nitrogen rich wastes, such as blackwater (toilet wastewater) was also tested. This would help to maintain an optimal C/N ratio (20-30 %) that is favorable for methane production [24].

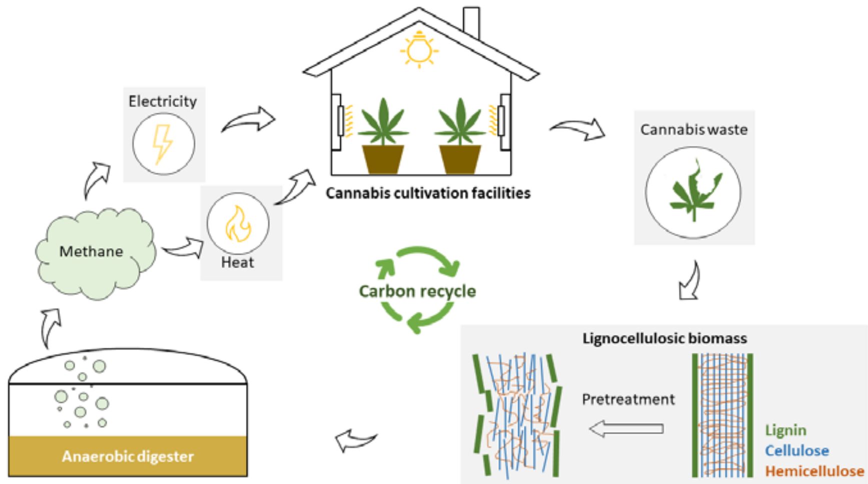


Figure 1. Project overview on cannabis waste treatment. The treatment strategies developed can also be applied to other agricultural/organic wastes, rich in lignocellulosic biomass.

Updates to Project Objectives

There were no changes compared to the original objectives of the project.

Project Specific Metrics

The project success will be measured based on the following project success metrics/milestones:

1) ***Characterization of cannabis waste.*** We aimed to characterize the moisture content, pH, total nitrogen, total phosphorous, total solids, and volatile solids of cannabis waste.

2) ***Evaluation of pretreatment methods.*** We aimed to select pretreatment methods and conditions for cannabis waste treatment. The effects of pretreatment would be evaluated by examining the solubilization and biodigestibility of the pretreated cannabis waste. The solubilization and biodigestibility of cannabis waste without pretreatment would also be investigated as a comparison.

3) ***Performance evaluation for anaerobic digestion of cannabis waste.*** We aimed to demonstrate process stability for cannabis waste treatment and reveal the functional microbial communities in the process.

D. METHODOLOGY

Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.

RESPOND BELOW

This project was completed in three tasks.

Task 1 - Cannabis waste collection and characterization

Methodology. The cannabis waste was provided by Atlas Growers as two types (plant parts): branches and leaves. Upon receiving, the plants (leaves and branches) were firstly processed by drying at 60 ^{o}C for 24 h. The dried cannabis waste was then cut into small pieces, milled and stored at room temperature (20 ^{o}C), following procedures described previously [12]. The processed cannabis waste (branches and leaves) were then characterized separately for their moisture content, pH, total nitrogen (TN), total phosphorous (TP), total solids (TS) and volatile solids (VS) in Dr. Liu's laboratories using methods previously developed [13, 14], and used in subsequent experiments.

Table 1. Summary of pretreatment options examined

Pretreatment Method	Pretreatment Conditions	Energy input for each condition (KJ/kg)
Control with no pretreatment	-	-
Ultrasound	100 W – 20 mins	60,000
	100 W – 30 mins	90,000
	100 W – 40 mins	120,000
	200 W – 20 mins	120,000
	200 W – 30 mins	180,000
	200 W – 40 mins	240,000
Hydrothermal	120 ^{o}C – 30 mins	4,220
	140 ^{o}C – 30 mins	5,050
	160 ^{o}C – 30 mins	5,880
Microwave	360 W – 10 mins	108,000
	480 W – 10 mins	144,000
	720 W – 10 mins	216,000
Microwave-advanced oxidation	360 W – 10 mins + 3 % H_2O_2	108,000
	480 W – 10 mins + 3 % H_2O_2	144,000

Facilities. This part of work was completed in Dr. Liu's laboratories at the University of Alberta. The cannabis waste was kindly pre-sorted and provided by Atlas Growers.

Task 2 - Evaluation of Pretreatment Efficiency

Methodology. Four pretreatment methods, including ultrasound, hydrothermal, microwave, and microwave-advanced oxidation were selected to pretreat the processed cannabis waste. These methods were chosen as they have been reported to promote the hydrolysis of lignocellulosic biomass in plants [25, 26]. Table 1 shows the conditions that we have tested for each selected pretreatment methods. We evaluated the effects of selected pretreatment methods and their representative conditions on promoting cannabis waste biomass disintegration and solubilization (as represented by soluble COD [sCOD]), as well as their effects on enhancing cannabis waste biodigestibility through evaluating the methane production via anaerobic mono-digestion or co-digestion with source-diverted municipal wastewater. Finally, we performed an analysis on the net energy production to identify conditions under which the highest energy efficiency can be achieved.

Facilities. This part of work was completed in Dr. Liu's laboratories at the University of Alberta.

Task 3 - Operation and process evaluation of methane production from anaerobic digestion bioreactors treating cannabis waste

Methodology. Two reactors (one mono-digestion and one co-digestion) were operated to demonstrate the feasibility of implementing continuously operated anaerobic digestion bioreactors for energy recovery from cannabis waste. Reactor performance was evaluated by examining the methane production, COD removal, effluent volatile fatty acids (VFAs), as well as specific methanogenic activities. Compositions of the sludge microbial community were also evaluated to reveal their linkage with reactor performance.

Facilities. Sequencing for microbial communities was performed at Centre d'expertise et de services Génome Québec. Evaluation on reactor performance and analysis on sequencing data was completed in Dr. Liu's laboratories at the University of Alberta.

E. PROJECT RESULTS

Please provide a narrative describing the key results using the project's milestones as sub-headings.

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

RESPOND BELOW

Importance of the Key Results

Table 2. Characterization of cannabis waste from different parts of the plant and comparation to other cannabis materials

Substrate	Moisture Content (%)	pH	TN (mg/g)	TP (mg/g)	TS (%)	VS (%)	References
Cannabis branches	70.05	6.36	23.1 ± 0.7	4.3 ± 0.1	81.4 ± 0.3	72.4 ± 0.3	This study
Cannabis leaves	78.08	7.56	25.2 ± 0.6	3.9 ± 0.1	92.6 ± 0.5	76.4 ± 0.5	This study

Cannabis sativa	-	-	26.7	-	92	90.5	[27]
Hemp	64.6 - 84.6	-	-	-	-	88.7 - 94.4	[28]
Hemp	-	-	-	-	31.3	28.8	[29]

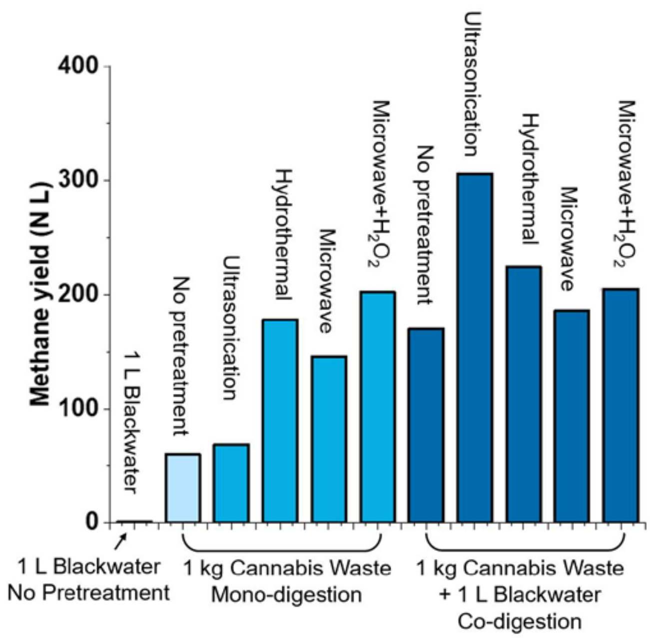
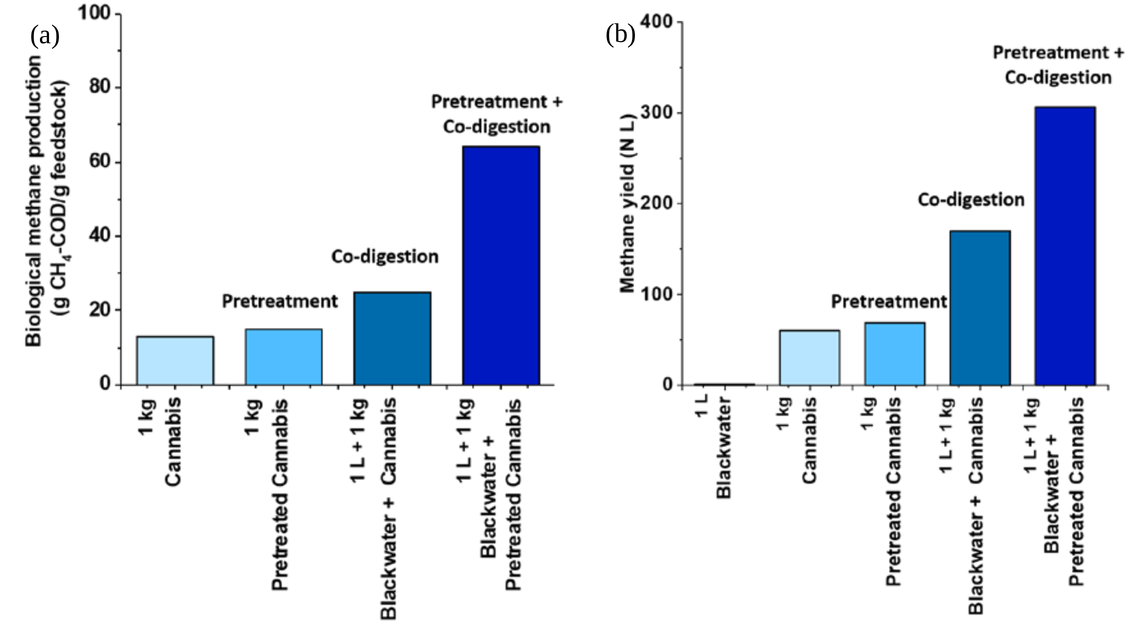


Figure 2. Summary of the highest methane yield from cannabis waste

Key results. In this project, we firstly characterized the properties of cannabis waste (branches and leaves) (results are shown in Table 2). Next, we evaluated the technical feasibility of pretreatment methods on enhancing cannabis waste biomass solubilization and biodigestibility. Overall, the selected pretreatment methods and conditions demonstrated their technical feasibility. All pretreatment methods enhanced cannabis waste biomass solubilization. The microwave and advanced oxidation (H_2O_2) pretreatment produced the highest sCOD, indicating that this pretreatment method was the most effective in enhancing biomass disintegration and solubilization. However, this pretreatment did not yield the higher cumulative methane production, possible due to the toxic effects of residual H_2O_2 on anaerobic sludge. To evaluate the digestibility of pretreatment cannabis waste, we evaluated their biological methane production (BMP) and cumulative methane production under anaerobic digestion conditions. The highest cumulative methane yield from cannabis waste pretreated by different pretreatment methods after mono-digestion and co-digestion is summarized in Figure 2. Our results showed that pretreatment increased the biomethane yield of cannabis waste under all conditions tested, and the co-digestion of pretreated cannabis waste with blackwater could further increase the methane yield. The highest accumulative methane yield was observed when ultrasound pretreated cannabis waste was co-digested with blackwater (399 ± 10.03 mL methane/g-VS of cannabis waste, which was 77% higher than cannabis waste with no pretreatment, as illustrated in Figure 2) , although the sCOD of ultrasound pretreated cannabis waste was slightly greater (~10%) [30].

The digestibility of cannabis waste (untreated and ultrasound pretreated brunches) under anaerobic mono-digestion and co-digestion conditions was further compared. Figure 3 shows the highest BMP and cumulative methane production achieved among key conditions tested, i.e. when cannabis branches were pretreated using ultrasound at 100 W for 30 mins and co-digested with vacuum toilet collected blackwater. Our results showed that co-digestion of cannabis waste with blackwater almost doubled BMP of cannabis waste to 25 g CH_4-COD/g feedstock, while the highest BMP was achieved when pretreated cannabis waste was co-digested with blackwater (64 g CH_4-COD/g feedstock). Anaerobic co-digestion provides the benefit of balancing nutrient (C:N) ratio for enhanced biomethane production.



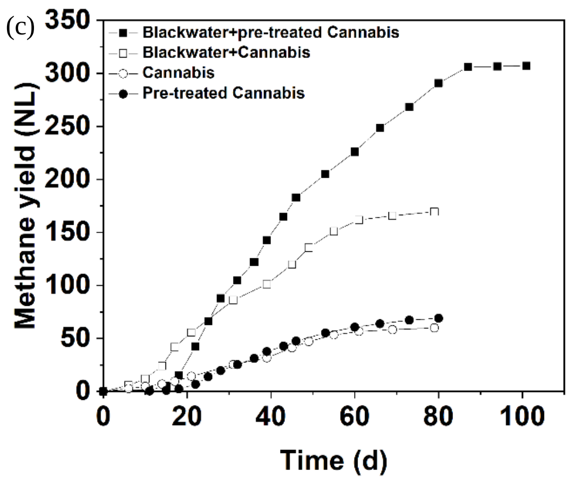


Figure 3. Comparison of (a) BMP; (b) cumulative methane production; and (c) daily methane yield of cannabis waste branches under different anaerobic digestion conditions. Pretreatment condition: ultrasound at 100 W for 30 mins. (NL refers to normal liter, representing the volume occupied by a gas returned to normal temperature and pressure conditions under T = 298 K and p = 101325 Pa).

A net energy production analysis revealed that under all conditions tested, co-digestion of blackwater and cannabis waste without pretreatment was the most energy effective (Figure 4). As shown in Figure 4, out of all conditions, positive net energy production was achieved for the mono-digestion of blackwater (40 KJ/L blackwater), cannabis waste without pretreatment (2,400 KJ/kg cannabis waste) and hydrothermal pretreated cannabis waste (160 ^oC for 30 mins, 2,105 KJ/kg cannabis waste), and for the co-digestion of blackwater with cannabis waste without pretreatment (6,800 KJ/L blackwater · kg cannabis waste, the **highest** positive net energy production), and blackwater with hydrothermal pretreated cannabis waste (5,848 KJ/L blackwater · kg cannabis waste).

Although the highest methane yield was achieved when ultrasound pretreated (100 W for 30 mins) cannabis waste was co-digested with blackwater (Figure 2), the net energy production under such condition was -48,000 KJ/(L blackwater · kg cannabis waste). Under this condition, the energy input for ultrasound at 100 W for 30 mins was significantly higher than the energy generated from the produced biomethane, resulting in a negative net energy production, indicating that ultrasound pretreatment is unfavorable for energy-saving in the current experimental setup. Similar conclusion was reported previously [31].

Lastly, we demonstrated the stable operation of a cannabis waste treatment system utilizing the co-digestion process evaluated in this project.

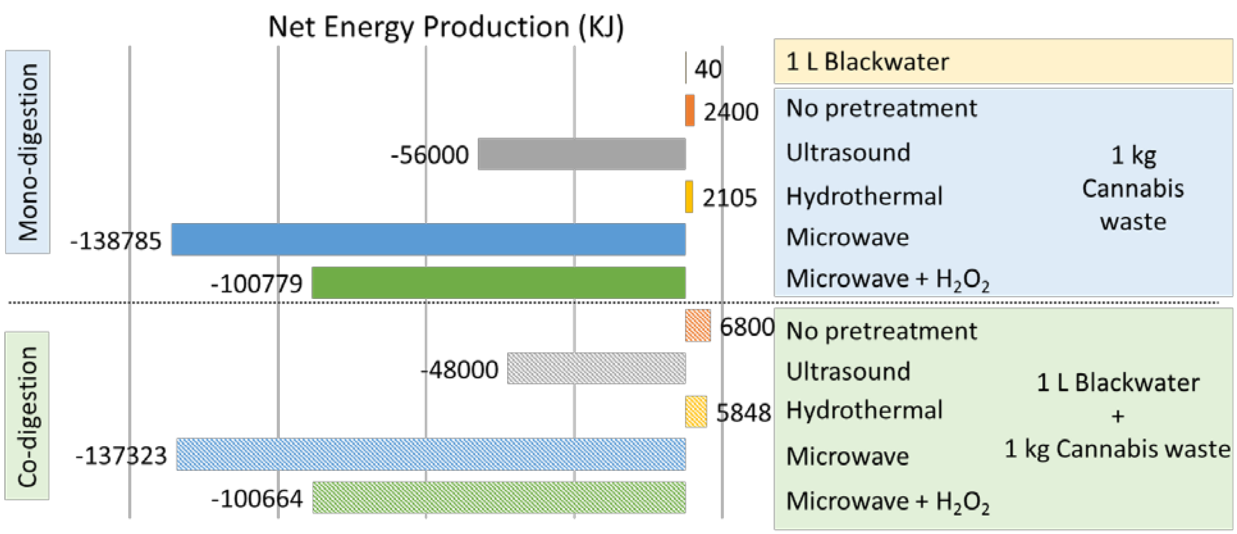


Figure 4. Evaluation of net energy production

Importance. Overall, our results demonstrated a clear technical feasibility of applying pretreatment to improve the biodigestibility of cannabis wastes, yet to achieve economic feasibility, a well-balanced management between the energy input and energy production is needed, as evidenced by the analysis of net energy production. Future studies should focus on the evaluation of feasibility and energy efficiency at large scale application and the life-cycle environmental impacts and cost analysis before such processes are implemented (initial CRS drying, grinding/milling and ultrasonic pretreatment). At current stage, not enough data are available online during the different processing stages to model a life cycle analysis (LCA) for cannabis waste treatment via anaerobic digestion; however, we expect that more work related to cannabis waste management and analyses on its energy consumption, GHG reduction and life cycle cost will be published (from the PI's group and other research groups nationally and internationally), and that these work will help with better determination of energy-efficient sustainable cannabis waste management. As a matter of fact, based on a literature search on Scopus, a total of 22 papers were found from 1994 to 2021 using key words "anaerobic digestion of industrial hemp/cannabis", and 9 of them were published after 2018. On the other hand, strategies developed in this project can be applied to the future processing of cannabis waste to convert waste to value-added products. Specifically, co-digestion of cannabis onsite can be an interesting option for energy recovery from the waste. The methane generated from the anaerobic digester could be collected and re-used to generate heat and electricity that are essential for cannabis growth. The digestate can be re-applied as liquid fertilizer as the blackwater is rich in nutrient (phosphorus and nitrogen) with low heavy metal contents, or further treated for disposal.

Project Specific Metrics

We successfully met the project specific metrics set for this project (as mentioned in Section C). no variance occurred. Specifically,

1) ***Characterization of cannabis waste:*** We have determined the moisture content, pH, total nitrogen, total phosphorous, total solids, volatile solids of cannabis waste as planned.
2) ***Evaluation of pretreatment methods:*** We selected 4 pretreatment methods (ultrasound, hydrothermal, microwave and microwave+H_2O_2) and for each pretreatment, we picked different pretreatment conditions (as detailed in Table 1), and evaluated their effects on enhancing cannabis waste solubilization and biodigestibility by evaluating the soluble COD (sCOD) and methane yield (under anaerobic mono-digestion and co-digestion) of pretreated cannabis waste for all methods and conditions selected. We also evaluated the solubilization and biodigestibility of cannabis waste without pretreatment as a comparison. We then conducted an analysis on net energy production for the tested pretreatment methods and conditions to estimate their energy efficiencies.
3) ***Performance evaluation for anaerobic digestion of cannabis waste:*** We demonstrated the process stability for cannabis waste anaerobic digestion (COD removal and methane production). Analysis of bacterial and archaeal communities during anaerobic digestion of cannabis waste was completed. Enrichment of different bacterial and archaeal communities in the continuously operated bioreactors indicated differentiated community shifts towards different engineering operation conditions. Publication for work described in this task is pending.

F. KEY LEARNINGS

Please provide a narrative that discusses the key learnings from the project.

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes

RESPOND BELOW

Key Learnings for Each Task and Their Importance

Milestone 1*: *Characterization of cannabis waste

Cannabis leaves had 10.3% less moisture content, 8.3% less total nitrogen, 12.1% less total solids, and 5.2% less volatile solids but 10.3% higher total phosphorous than cannabis branches. Further, cannabis leaves were more acidic (pH = 6.36) than branches (pH = 7.56).

Milestone 2*: *Evaluation of pretreatment methods

The selected pretreatment methods and conditions could enhance cannabis waste biomass hydrolysis and increase methane production from cannabis waste. Co-digestion of cannabis waste with blackwater significantly enhanced methane production from cannabis waste by providing a balance C/N ratio that is favorable for anaerobic digestion, presenting a feasible energy positive treatment option, which can be easily implemented with no additional infrastructure or chemical inputs. Lastly, although co-digestion of ultrasound pretreated cannabis waste with blackwater yielded the highest methane production (64 g CH_4-COD/g feedstock, Figure 3a), the net energy production was still negative (-48,000 KJ/(kg ultrasound pretreated cannabis waste · 1 L non-pretreated blackwater), Figure 4). On the other hand, hydrothermal pretreatment represents an energy positive pre-treatment option for cannabis waste management. However, the economic feasibility of hydrothermal pretreatment is dependent on the working scale and equipment efficiency, and should be explored in future studies.

Milestone 3: Performance evaluation for anaerobic digestion of cannabis waste

Stable energy recovery from cannabis waste was achieved with laboratory continuous operating anaerobic digesters. Different reactor operation conditions selectively enriched different bacterial and archaeal communities that are more effective for cannabis waste methane production.

Broader Impacts

Overall, our study assessed strategies for energy-efficient cannabis waste treatment. Our evaluation on different pretreatment options provided solutions for enhancing cannabis waste hydrolysis, which usually is the rate-limiting step during the anaerobic digestion process. Our stable reactor operation demonstrated that continuous anaerobic digestion is technically feasible for treating cannabis waste and source-diverted municipal wastewater on site, which also generated added benefits as this process eliminates the need to transport municipal wastewater generated on site to centralized waste and wastewater treatment facilities or landfill sites. As this process advances to larger pilot scale, more data would be generated to support regulation or policy development for cannabis waste management.

G. OUTCOMES AND IMPACTS

Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

RESPOND BELOW

Project Outcomes and Impacts

Overall, this project demonstrated the technical feasibility to treat cannabis waste via anaerobic digestion process. Specifically, we showed that for all pretreatment methods and conditions tested, pretreatment is an effective way to enhance lignocellulosic biomass solubilization, the later often limits the hydrolysis rate of lignocellulosic biomass during anaerobic digestion thus leading to ineffective treatment for lignocellulosic biomass-rich wastes, such as the cannabis waste studied in this project. We also showed that comparing to cannabis waste with no pretreatment, pretreatment also significantly increased biomethane production from cannabis waste during anaerobic mono-digestion, for all pretreatment methods and conditions tested in this project. Further, by conducting an analysis on net energy production, we demonstrated that comparing to pretreating cannabis waste, co-digesting cannabis waste (without pretreatment) with source-diverted municipal wastewater is more energy-effective to simultaneously treat cannabis waste and recovery energy. Yet, the economic feasibility of the tested processes require further exploration at larger scales, as previous studies have demonstrated that lab-scale devices wasted more energy than a full-scale devices [32] and that this project was mainly conducted at lab-scale. It was highly possible that more energy could have been wasted during pretreatment, leading to largely ineffective utilization of the input energy. Lastly, we demonstrated that stable anaerobic digestion process could be maintained using continuous operating cannabis waste treatment bioreactors. To our best knowledge, this study was the first to demonstrate the technical feasibility to treat cannabis waste for energy recovery.

Clean Energy Metrics

The project outcomes impact the Clean Energy Metrics from the following five aspects, as described in the *Work Plan, Budget and Metrics* workbook and included here.

Clean Resources Metrics (Select the appropriate metrics from the drop down list)

Metric	Project Target	Commercialization / Mobilization Target	Project Actuals	Commercialization / Implementation Target Update	Comments (as needed)
TRL advancement	TRL 1-3 from start to TRL 4-6 at the end		TRL 5		TRL 5 at the end
Publications	4		4		1.Qi, N., Zhao, X., Zhang, L., Gao, M., Yu, N., Liu, Y. Performance assessment on anaerobic co-digestion of Cannabis ruderalis and blackwater: Ultrasonic pretreatment and kinetic analysis. Resources, Conservation and Recycling, 2021. 169: p. 105506. 2.Qi, N., Zhang, L., Hu, X., Zhang, H., Sun, H., Liu, Y. Anaerobic co-digestion of Cannabis ruderalis straw and blackwater: Hydrothermal pretreatment assessment and mono/co-digestion analysis. Renewable energy, 2021. 170: p. 1107-1113. 3.Qi, N., Zhang, L., Liu, Y. Operation performance and insight of microbial dynamics of anaerobic Cannabis waste treatment for biomethane recovery. In preparation. 4.Qi, N., Zhang, L., Liu, Y. Pretreatment of Cannabis waste using microwave. In preparation.
Knowledge Mobilization	6		3		6 knowledge mobilization activities included 4 project meetings and 3 announcements. The latter are counted for this metric and listed below: Announcement for the project 1.Michael Brown, January 22, 2019, 14 U of A clean energy projects receive funding boost. https://www.ualberta.ca/folio/2019/01/16-u-of-a-clean-energy-projects-receive-funding-boost.html 2.PEG, Spring 2019, Cleaning up on Clean-Tech Cash: Alberta Researchers Score Big Bucks, page 46-47, Volume 3, Number 1. https://online.flippingbook.com/view/330834/48/ 3. Alberta Innovates published two page Summary May 2020 Opportunities to share project results at professional/technical eventd Knowledge mobilization was less than anticipated from March 2020 to end of project due to COVID-related reduced engagement and seminar opportunities.
Students Trained (M.Sc., Ph.D., Postdoc)	3		3		A total of 3 HQPs trained in this project (1 PhD and 2 postdoc)
New products/services created	1		1		1 process for cannabis waste treatment was demonstrated with stable performance

For Publications: a total of four papers generated (two published, and two in preparation), as listed below.

i. Qi, N., Zhao, X., Zhang, L., Gao, M., Yu, N., Liu, Y. *Performance assessment on anaerobic co-digestion of Cannabis ruderalis and blackwater: Ultrasonic pretreatment and kinetic analysis.* Resources, Conservation and Recycling, 2021. **169**: p. 105506.

ii. Qi, N., Zhang, L., Hu, X., Zhang, H., Sun, H., Liu, Y. *Anaerobic co-digestion of Cannabis ruderalis straw and blackwater: Hydrothermal pretreatment assessment and mono/co-digestion analysis.* Renewable energy, 2021. **170**: p. 1107-1113.

iii. Qi, N., Zhang, L., Liu, Y. *Operation performance and insight of microbial dynamics of anaerobic Cannabis waste treatment for biomethane recovery*. In preparation.

iv. Qi, N., Zhang, L., Liu, Y. *Pretreatment of Cannabis waste using microwave*. In preparation.

Program Specific Metrics

The project outcomes mainly impact the follow one Program Specific Metrics, as described in the *Work Plan, Budget and Metrics* workbook and included here.

Program Specific Metrics (Select the appropriate program metrics from the drop down list)

Metric	Project Target	Commercialization / Mobilization Target	Project Actuals	Commercialization / Implementation Target Update	Comments (as needed)
Biogas: # GJ renewable fuels produced or enabled	Enabling	6,800 KJ/kg dry cannabis waste	Achieved		In the current controlled laboratory environment, the lowest energy production was obatined when microwave-pretreated cannabis waste was mono-digested while the highest energy production was achieved when non-pretreated cannabis was co-digested with blackwater. Next step would be focused on further improving the process efficiency and methane yield from co-digestion of non-pretreated cannabis waste and other types of wastewater of similar high ammonia and low organics properties.

Project Outputs

Publication list:

i. Qi, N., Zhao, X., Zhang, L., Gao, M., Yu, N., Liu, Y. *Performance assessment on anaerobic co-digestion of Cannabis ruderalis and blackwater: Ultrasonic pretreatment and kinetic analysis.* Resources, Conservation and Recycling, 2021. **169**: p. 105506.

ii. Qi, N., Zhang, L., Hu, X., Zhang, H., Sun, H., Liu, Y. *Anaerobic co-digestion of Cannabis ruderalis straw and blackwater: Hydrothermal pretreatment assessment and mono/co-digestion analysis.* Renewable energy, 2021. **170**: p. 1107-1113.

iii. Qi, N., Zhang, L., Liu, Y. *Operation performance and insight of microbial dynamics of anaerobic Cannabis waste treatment for biomethane recovery*. In preparation.

iv. Qi, N., Zhang, L., Liu, Y. *Pretreatment of Cannabis waste using microwave*. In preparation.

H. BENEFITS

Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

RESPOND BELOW

Economic Benefits. Success of this project is expected to provide technical guidance on an energy-efficient, cost-effective treatment strategy for the cannabis waste. In specific, the project targets on the development of on-site AD of the cannabis waste, which could reduce the need of land as compared to conventional composting and landfilling. Further, opportunities exist to collect and utilize methane generated from the AD process to provide heat and light that are essential for cannabis cultivation, as such to reduce the carbon and investment input for having to provide the growth condition and mitigate GHG emissions. Further, digestion of cannabis waste on-site is more cost-effective than transporting them to centralized facilities for disposal [33], reduces carbon footprint, and also simplifies the bureaucracy associated with cannabis waste disposal. Further, as Canada's population increases, the demand for sustainable organic waste and municipal wastewater management practices will continue to grow and our current conventional landfilling and wastewater management systems may not be the most practical or economical practices for the future. The knowledge gained from this project will provide an insight into the technical feasibility and guide solutions that can gradually replace current practices and serve new promising markets (such as decentralized systems and on-site organic waste disposal), particularly where organic waste management is underdeveloped.

Environmental benefits. As this project was largely focused on the development of existing technology in novel ways, where quantitative environmental performance including GHG reduction is difficult to quantify, and generally absent. The GHG emissions reductions impact was largely qualitative in nature.

With our best knowledge, we have estimated potential annual GHG emission reductions (for 6,000 tonnes cannabis waste/year) as follows:

- 60 tonnes of CO_2 equivalent emissions by eliminating transportation of cannabis waste to landfills
- 363,000 cubic meters of biogas (contains methane) emissions by capturing for electricity generation
- 595 tonnes of CO_2 equivalent emissions by using biogas generated electricity for operation

Comparing to landfill (assuming the transport distance is 45 km from cannabis cultivation facility to landfill site and no landfill gas recovery), the treatment of every 1 tonne of cannabis waste via in situ anaerobic digestion (0.494 tonne CO_2 equivalent, assuming on site treatment and biogas is flared) would reduce GHG emission by 43%, as based on an estimation using the "Greenhouse gas calculator for waste management" (https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/municipal-solid/greenhouse-gases/calculator.html).

In addition, with increased adoption of energy recovery based waste and wastewater technologies, several environmental benefits can be generated besides reduced GHG emission; including reduced land occupation (replacing landfill by smaller sized anaerobic digesters), reduced air and odor contamination (onsite treatment and through collection and purification of biogas produced during AD of cannabis waste and source-diverted municipal wastewater), reduced energy consumption and sludge production (through anaerobic treatment processes), reduced groundwater (elimination of leaching from conventional landfill) and surface water (elimination of municipal sewage and cannabis waste transportation) contamination.

Social Benefits. This research promotes education, research and exchange of knowledge between the industry partners in our future development. This project addresses technical research issues of strategic importance to Canada; trains well-educated HQP to meet the growing needs of industry; and promotes cooperation and knowledge exchange within the waste disposal industry.

Building Innovation Capacity. This project trained 2 postdoctoral research fellows (PDFs) and attracted one visiting PhD student from abroad (funded by the China Scholarship Council Scholarship). The majority of this budget was invested in training HQSP as we consider it important to have leadership in place to move the proposed project forward beyond the scope of this project. The PDFs led the effort to evaluate the pretreatment options and to optimize the anaerobic digester efficiency as well as the co-digestion options. Further, the PDFs supervised the PhD student, this gave the PDF excellent opportunities developing leadership skills essential for continuing their career. Hands-on training of PhD student occurred in the emerging area of cannabis waste treatment, AD, anaerobic wastewater treatment, biogas production optimization, and energy production. The PhD student was also involved in the fundamental studies on cannabis waste characterization.

I. RECOMMENDATIONS AND NEXT STEPS

Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

RESPOND BELOW

As this project was primarily a feasibility study focusing on the development and optimization of cannabis waste pretreatment options and anaerobic treatment conditions for effective cannabis waste treatment and energy recovery, the next stage would be to evaluate the processes at large-scale and possibly evaluate the co-digestibility of other types of high-strength wastewater, such as ammonia-rich sludge liquor or manure waste, rather than commercialization. In the next two years, studies should focus on the evaluation of feasibility and energy efficiency at large scale application and the life-cycle environmental impacts and cost analysis before such processes are implemented (initial CRS drying, grinding/milling and ultrasonic pretreatment), on the exploration of other possible utilization of cannabis waste, such as biofuel or the reuse of wasted cannabis processing water. At current stage, not enough data are available during the different processing stages to model an life cycle analysis (LCA) for cannabis waste treatment via anaerobic digestion; however, we expect that more work related to cannabis waste management and analyses on its energy consumption, GHG reduction and life cycle cost will be published (from the PI's group and other research groups nationally and internationally), and that this work will help with better determination of energy-efficient sustainable cannabis waste management.

During this project, we develop good collaborating relationship with Atlas Growers. Staff members from Atlas Growers actively participated in the project and kindly supported our work by providing cannabis waste to us.

J. KNOWLEDGE DISSEMINATION

Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.

RESPOND BELOW

Knowledge obtained from this project was shared with the general scientific community via peer-reviewed journal publications (see Section G). We have published two scientific articles at high impact journals and are currently preparing the other two. The manuscripts were also shared with our industrial partner. Further, in addition to this Final Public Report summarizing our key findings, we have also prepared two interim reports and one final milestone report with details on the work that we have conducted, and a comprehensive analysis of the results that we have obtained throughout this project. We will present our results in national and international conferences. We were not able to do that in the past year due to COVID and conference cancellations. An executive summary of this project will be posted on Dr. Yang Liu's research group website. Further, we will seek additional funding continue the research with funding agents and develop additional collaborations with cannabis growers.

K. CONCLUSIONS

Please provide a narrative outlining the project conclusions.

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

RESPOND BELOW

The main objective of this project is to develop environmentally-sound, energy-efficient strategies for on-site treatment of cannabis waste that can reduce transportation and landfill needs and enhance biogas/energy production. In this project, we firstly characterized the properties of cannabis waste (branches and leaves). Evaluation of pretreatment methods on enhancing cannabis waste biomass solubilization and biodigestibility demonstrated the technical feasibility of the selected pretreatment methods and conditions. All pretreatment methods and conditions enhanced the biomass solubilization of cannabis waste. Pretreatment also increased the biomethane yield of cannabis waste under all conditions tested, and the co-digestion of pretreated cannabis waste with blackwater could further increase the methane yield. The highest accumulative methane yield was observed when ultrasound pretreated cannabis waste was co-digested with blackwater. Co-digestion of blackwater and cannabis waste provided optimal C:N ratio for anaerobic digestion. A net energy production analysis revealed that under all conditions tested, co-digestion of blackwater and cannabis waste without pretreatment was the most energy effective. Lastly, we demonstrated a stable operation of a cannabis waste treatment system utilizing the co-digestion process evaluated in this project. Future studies should focus on evaluating the process feasibility and energy efficiency at larger scales.

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