Environment and Natural Resources Trust Fund
Research Addendum for Peer Review

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Project Title: Demonstrating innovative technologies to fully utilize wastewater resources

Project number:

1. **Abstract** - Summarize the research and its essential qualities including a clear statement on the purpose of the research.

   The purpose of the project is to demonstrate innovative technologies to utilize and treat wastewater streams. Specifically, research will be conducted to optimize processes and develop demo systems for converting oily scum, sludge, and centrate to renewable bio-fuels. The essential qualities of the proposed research lie in the following features: (1) the project, taking an integrated approach, appropriately and timely addresses the needs of wastewater treatment industry to utilize various waste streams for renewable fuels and energy production, to reduce environment impact and treatment cost; (2) the project is largely built on the excellent outcomes from the previous research funded by LCCMR and others; (3) the project involves strong academic and industry partnership; (4) the project is loaded with high impact and achievable objectives; and (5) the project will generate large amounts of data for more realistic evaluation of energy balance and economic performance of the proposed technologies. The success of the project is expected to reduce landfill, improve water quality, reduce GHG emission, produce renewable energy, create revenue for wastewater treatment operators, and lower the overall wastewater treatment costs. The “packaged” solution developed from the project is anticipated to attract broad interests from related industries and investors.

2. **Background** - Provide the basic information and other relevant work that are the context for this research.

   **Significance/impacts of the project**
   Minnesota municipal wastewater treatment plants (MWTP) generate large amounts of oily scum, concentrated liquid (also called “centrate”), and sludge each year. For example, each year, the 7 Metropolitan Council Environment Services (MCES) MWTPs treat more than 100,000 million gallons of wastewater and at the same time generate 1,000 tons of scum, 500 million gallons of centrate, and 85 million kg of dry sludge. These waste streams are either used as landfill (scum) and direct burning (sludge), or subjected to additional treatment (centrate). New technologies, developed by UMN researchers led by Dr. Ruan through several projects funded by federal and state grants, especially two ENRTF grants, can help capture the values from and lower the treatment costs for these waste streams (Figure 1). The goal of the project is to demonstrate the feasibility and effectiveness of implementing innovative technologies in municipal wastewater treatment plants. This project is expected to generate significant impacts including: (1) producing significant amounts of renewable energy for internal use or distributed to the market. About 5 million gallons of biofuels and similar quantity of other biochemicals
could be produced from the waste streams in MCES’ facilities alone; (2) generating considerable revenues. Estimated potential annual revenue of $20 million could be generated from the fuels and other chemicals derived from scum, centrate, and sludge in these facilities; (3) improving wastewater treatment efficiency and cost effectiveness. The waste streams are effectively treated while they are converted to renewable energy; utilization of scum results in hundreds of thousands of dollars savings in landfill cost; algae are more effective than current processes in removing low level phosphorus; and (4) reducing environment pollutants. Landfill and fossil fuel and coal use will be significantly reduced; algae will sequester a large amount of carbons; CO₂ emission from sludge burning will be reduced.

Currently, there are approximately 20,000 municipal wastewater treatment facilities operating in the US serving 226.4 million people (CSS, 2013). Many wastewater facilities are in the midst of a financial struggle, and face lower revenues combined with the potential of increasing costs (Menendez, 2010). This scum-to-biodiesel conversion could not only bring them economic benefit but greatly reduce environmental impact. Take the wastewater treatment plant at St. Paul, MN (Metro Plant) as an example, the plant generates 3.5 wet ton scum per day; if all converted to biodiesel, it could bring $350,000/year revenue and save $100,000 landfill fee/year to the Metro Plant. This is an attractive financially sound and environmentally friendly approach to solving the scum problem.

Figure 1. A comparison of waste stream pathways between the current and proposed new technologies.

Technical background

Scum to biodiesel technology

Scum is the floatable materials skimmed from the surface of primary and secondary settling tanks of the wastewater treatment plant. It contains grease, vegetable and mineral oil, animal fats, waxes, soaps, food wastes, plastic materials and other impurities. High energy content was found in scum that could be recycled and reused. In our lab study, it was found at least 60% of the dry matter of the scum can be converted to high quality biodiesel (Figure 2). The conventional technology to recover energy from scum is to co-process scum with sludge in anaerobic digestion (AD) where the biogas produced is used to generate electricity for plant use (Outwater 1994). However, this technology causes many problems in operation. For example, the scum
floats on the top of the digester and forms a thick layer that impedes digester performance. As a result, many wastewater treatment plants choose to directly dispose scum in landfills. The scum disposal increases the cost of treatment facilities. For instance, the Metropolitan Wastewater Treatment Plant at St. Paul, MN (Metro plant) spends $100,000 a year just for landfilling the scum. Therefore, there is an urgent need to develop other technology to recover energy stored in scum effectively. In addition, the biodiesel produced from scum oil will be more desirable than biogas produced from traditional AD process. It is also expected that the economic benefits for scum-to-biodiesel production will be superior over the traditional AD process. With this in mind, we propose to develop and demonstrate a scum-to-biodiesel technology with following objectives: (1) to develop a cost effective conversion process capable of converting scum oil to biodiesel that meets ASTM standard, and (2) compare the optimized biodiesel production process with traditional anaerobic digestion system for LCA and economic analysis.

![Scum, Biodiesel, Glycerol](image)

Figure 2. In our lab, oil was extracted from scum (left) and converted to biodiesel and glycerol.

The main steps in conventional process to convert scum to biodiesel include separation of oil from water, solid and other impurities, esterification/transesterification of scum oil to crude biodiesel, and refining/upgrading biodiesel. Solvents and catalysts can be recovered and recycled during the process. Since oil from scum contains high free fatty acids and soap, a two-step conversion process, involving a first acid-catalyzed esterification reaction followed by a second alkaline-catalyzed transesterification reaction, is used. Currently a process has been developed in our lab to convert the scum oil to biodiesel. The basic process is described as: (1) filtration to remove large particles, (2) acidification and graviton settling to separate water and fine particles; soap will be converted to free fatty acid at the same time, (3) acid-catalyzed esterification reaction to convert free fatty acid to FAME and reduce acid value, (4) alkaline-catalyzed transesterification reaction to convert the rest of triglyceride to FAME, (5) FAME and glycerol separation, (6) methanol recycle by flash evaporator, (7) fractional distillation to upgrade crude FAME to ASTM standard biodiesel. Advantage of the developed process is moderate conversion condition, low requirement for the equipment and easy to operate. However, recovery and recycling of methanol, poor contacts between methanol and oil, and reversible reaction caused by presence of water remain major challenges (Meher et al. 2006). Due to the complexity of scum oil, recovery of glycerol was proven difficult after step (4) till a glycerol wash was applied. The process also found to be more complicated than traditional biodiesel conversion process due to the various unknown components in the scum. These are the key technical barriers our initial R&D activities are intended to overcome as outline below.
Due to the high free fatty acids, soap and moisture content in the scum, many pretreatment steps to purify the scum oil are usually needed for the alkaline-catalyzed transesterification reaction. An alternative process, which has the potential to simplify the process, is the supercritical methanol conversion process because it is not sensitive to moisture and free fatty acid content and has fast conversion rate (<1 min) at high temperature (>275°C) and pressure (>8.5 MPa). This will greatly reduce the complexity of conversion process described above. Different catalysts, temperature and pressure will be investigated for the optimize conversion condition.

Since there has no commercially available process developed for the scum-to-biodiesel conversion on the market, and the conventional biodiesel conversion process cannot convert scum without significant modification, the proposed process in this project will provide an innovative alternative to scum oil conversion which has the potential to improve the economic performance for municipal wastewater treatment plants.

There are many economic model developed for the biodiesel production. If virgin vegetable oil is used as feedstock, the feedstock will account for 80% of total cost (APEC, 2010). Since scum is essentially free feedstock, the capital cost and operation cost was estimated to be lower compared with the vegetable oil-based process. In the preliminary estimation, the payback of biodiesel system was about 2 year. The system is estimated to be net energy producer. From the data obtained via personal communication with an industry contact, the input energy accounts for about 20% of the output energy. The system to be developed in the project will provide much more data for more accurate energy balance and economic analysis. The biodiesel produced will meet the ATSM standard. The scum to biodiesel was estimated about 60% as indicated in the proposal. A 300 ton/year conversion facility will be able to handle all the scum produced by a large wastewater treatment plant. Table 1 shows the preliminary economic analysis of operating a scum-based biodiesel production facility using the scum from the Metro wastewater treatment plant at St. Paul, MN.

Table 1. Preliminary economic analysis of operating a scum-based biodiesel production facility using the scum from the Metro wastewater treatment plant at St. Paul, MN.

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scum availability</td>
<td>3.5 Wet ton/day</td>
<td></td>
</tr>
<tr>
<td>Total solid</td>
<td>55 %</td>
<td></td>
</tr>
<tr>
<td>Biodiesel conversion rate</td>
<td>60 %</td>
<td>Assume 60% of TS</td>
</tr>
<tr>
<td>Biodiesel production</td>
<td>1.155 Ton/day</td>
<td></td>
</tr>
<tr>
<td>Biodiesel production</td>
<td>347 Gallon/day</td>
<td></td>
</tr>
<tr>
<td>Biodiesel production</td>
<td>126,567 Gallon/year</td>
<td>365 d/year</td>
</tr>
<tr>
<td>Glycerol production</td>
<td>57.75 Kg/day</td>
<td>5% of biodiesel</td>
</tr>
<tr>
<td>Glycerol production</td>
<td>20.90 Ton/year</td>
<td></td>
</tr>
<tr>
<td>Biodiesel selling price</td>
<td>3.5 $/gallon</td>
<td></td>
</tr>
<tr>
<td>Revenue from biodiesel</td>
<td>442,985 $/year</td>
<td></td>
</tr>
<tr>
<td>Landfill saving</td>
<td>100,000 $/year</td>
<td></td>
</tr>
<tr>
<td>Capital cost</td>
<td>442,985 $</td>
<td>Equal to one year revenue</td>
</tr>
<tr>
<td>Material cost</td>
<td>46,070 $/year</td>
<td></td>
</tr>
<tr>
<td>Operation cost</td>
<td>88,597 $/year</td>
<td>20% revenue</td>
</tr>
</tbody>
</table>
Microalgae technology

The second wastewater stream of interest to this project is “centrate”, which is generated from centrifuging of activated sludge. Centrate contains highest amount of ammonia nitrogen and active phosphorus among several wastewaters at different stages in a municipal wastewater treatment plant, which could be a suitable growth medium for microalgae for the dual purposes of removing nutrients and obtaining a feedstock for biofuel production.

In projects funded by ENRTF and MCES, we found that centrate is highly adequate for algae growth with very high removal rates for chemical oxygen demand (COD), nitrogen (N), and phosphorus (P) (Min et al., 2011). One issue with centrate for algae growth is that there is insufficient carbon source to support complete utilization and removal of N and P. In this project, before we develop a demo system, we will investigate the addition of crude glycerol from biodiesel process to centrate to provide additional carbon source for further removal of N and P. Crude glycerol was found to be a better additive than pure glycerol because crude glycerol is not only a carbon source but also contains other nutrients suitable for algal growth. Figure 3 shows that 0.1 g/L addition of crude glycerol to the culture media almost doubled the growth in a mixotrophic growth mode.

![Mixotrophic Growth](image)

**Figure 3.** Algae growth on culture media supplemented with pure and crude glycerol.

In addition to glycerol from biodiesel process, byproducts from other conversion processes can also provide additional carbon source. For example, the aqueous phase of algae hydrothermal dewatering pretreatment, which contains a lot of dissolved organic carbon, and the CO₂ obtained from fMAG and fMAP to enrich our mixotrophic algae cultivation for improved centrate wastewater stream treatment and utilization. Figure 4 shows the growth curves of *C. vulgaris* cultivated in an artificial medium BG11 and three algae hydrothermal liquefaction (HTL) water based media. The biomass productivities were 0.013, 0.160, 0.092 and 0.054 g L⁻¹ d⁻¹ for BG-11, 50×, 100× and 200× diluted process water, respectively. Algae had significant higher productivities and biomass...
concentrations on the three dilutions of process water than BG-11 medium. Different from HTL carried out at high temperatures with many growth inhibitors produced, polysaccharides and proteins were mainly hydrolyzed to mono-sugars and amino acids in HTC. These mono-sugars and amino acids provided adequate carbon and nitrogen nutrients which can be readily used by algae. However, algae need to sequester CO$_2$ as the sole carbon source when grown on inorganic BG-11 medium photoautotrophically. Many reports showed that mixotrophic growth can result in higher biomass production than phototrophic growth. Among the three dilutions of the process water, both biomass productivity and final biomass concentration were in the following order: $50\times > 100\times > 200\times$. This indicates that algae can endure the higher concentration of potential growth inhibitors in the more concentrated process water. It is noticed that algae grew rapidly in the first 4 days and then decreased significantly on the fifth day on the $50 \times$ process water. However, algae grew at a lower rate on the $100\times$ and $200 \times$ process water and then leveled off after the third day. The stationary phase occurred so early mainly due to the limitation of phosphorus.

![Growth curves for algae grown on the four different media (Du et al. 2012).](image)

The proposed demo system will be based on the multi-layer hybrid photobioreactors technology developed through previous ENRTF funded project. This multi-layered structure (Figure 5) renders the system a very small footprint, and is therefore feasible to co-locate with wastewater treatment plants where land/space is limited. The open shallow trays significantly reduce the impact of wall fouling on light transmission, minimizing maintenance (cleaning) need.
Fast microwave assisted pyrolysis (fMAP) and fast microwave assisted gasification (fMAG) technology

The third waste stream of interest to the project is sludge, a solid biomass from primary and secondary settling processes. The sludge typically contains around 70% organic matter. Landfilling, land application and incineration are the common disposal processes for sludge. It is possible and beneficial to capture the energy contained in sludge biomass through thermochemical conversion because we not only capture the economic value, but also minimize pollutants associated with sludge. Thermochemical conversion (e.g., pyrolysis and gasification) of sludge to produce bio-oil, syngas and other products is an attractive solution to the sludge problems. However, the acceptance of this idea has been limited due to the low economic value of the products and the relative complexity of the processing equipment. Traditional gasification operated at temperature around 1,000°C may not be able to destroy pollutants and toxic compounds such as dioxin. Therefore, we must improve the technology to enhance overall economic viability and environmental friendliness of the technology.

In our previous projects funded by ENRTF, IREE, and federal agencies, we developed the microwave assisted pyrolysis (MAP) process for converting solid biomass to bio-oil, syngas, and biochar and successfully demonstrated a mobile MAP system (Figure 6). The disinfected biochar is a great soil amendment agent which not only provides mineral nutrients but also improves soil physical and biological properties. Compared with conventional heating processes where heat is transferred from the surface to the core of the material through conduction driven by temperature gradients, microwaves induce heat at the molecular level by direct conversion of the electromagnetic energy into heat (Sobhy and Chaouki, 2010), and therefore, they can provide uniform internal heating for material particles. In addition, the instantaneous response of microwave makes it easier for a rapid start-up and shut-down. Furthermore, the process
operation involves a simple set-up and can be easily adapted to currently available large-scale industrial technologies. Microwave heating is a mature technology and development of microwave heating system is of low cost.

A lab scale microwave assisted biomass conversion system has been developed and tested in our lab (Du et al., 2011; Wang et al., 2012). Du et al. (2011) investigated microwave assisted pyrolysis of Chlorella sp. with char as microwave reception enhancer and obtained the maximum bio-oil yield of 28.6% under the microwave power of 750 W. The algal bio-oil had a density of 0.98 kg/L, a viscosity of 61.2 cSt, and a higher heating value (HHV) of 30.7 MJ/kg. The results of preliminary experiments on microwave assisted sludge pyrolysis showed that about 17.6% of bio-oil could be obtained without catalyst and the yield could be improved to 29.8% with HZSM-5 as the pyrolysis catalyst.

One of the major breakthroughs achieved in the endeavor to improve the microwave assisted pyrolysis process is the result of using properly designed microwave absorbents. Our research found that some microwave absorbents such as silicon carbide (SiC) are excellent in enabling rapid temperature rise, making fast pyrolysis and gasification feasible and efficient, and can achieve very efficient high temperature gasification, such as above 1,200°C to avoid hazardous gas emission, therefore eliminating the need of expensive downstream gas treatment.

![Image](image.png)

Figure 6. Pilot scale mobile MAP system developed through previous LCCMR and other projects; with incorporation of microwave absorbents, it becomes fMAP, a superior fast thermochemical conversion process.

3. **Hypothesis** - State the premise or propositions set forth to explain and achieve the described outcome of the research.

There are substantial uncaptured values in several waste streams such as scum, centrate, and sludge generated in municipal wastewater treatment operations. Converting these waste streams to liquid fuels, syngas, biochar, and heat is expected to improve the economic outlook of municipal wastewater treatment operations and at the same time reduce environment pollution. These are the propositions on which we set our project goal, that is, we will develop and demonstrate technologies enabling the complete utilization and treatment of these waste streams and generating extra revenue for wastewater treatment operators.
4. **Methodology** - Describe the methodology to be employed to carry out the proposed research. Including descriptions of the sample design(s), if applicable.

Three activities, each with focus on one waste stream, are planned for the project. While the preparatory R&D and system development activities will be conducted at UMN, MCES Metro Plant in St. Paul, and FreightMaster/Minnesga Inc in Eagan, the final demonstration will be conducted in MCES Metro Plant and FreightMaster/Minnesga site. In the second half of the third year of the project, at least five demonstrations will be made to stakeholders including state agencies, private investors, academic researchers, and the public. Any intellectual properties and related revenues as a result of the program will be shared between UMN and LCCMR. The technologies, if demonstrated successfully, may be implemented to many MWTPs in the State of Minnesota and beyond.

4.1. Develop and demonstrate scum to biodiesel process and system

Since the trans/esterification process has been developed in our lab, we will focus on the supercritical methanol method and compare these two processes with AD process in terms of technical, economic, and environment performance. The specific objectives of the scum to biodiesel component are (1) to optimize trans/esterification process, (2) to develop and optimize supercritical methanol method, (3) to compare these two processes with the conventional AD process, and (4) develop a scum to biodiesel demonstration system based on the optimum process. The process flow chart is illustrated in Figure 7.

Specific task will be:

1. Optimize trans/esterification process. This task is intended to optimize the processes in conversion pathways and determine conversion efficiency, chemical use, and operation parameters.
   a. Minimize acid usage during the acidification process; investigate the possibility of using recycled acid from acid-esterification process to reduce the material cost.
   b. Investigate effect of catalyst and methanol to oil ratio for oil conversion efficiency
   c. determine optimized parameter incorporated with task 3. Design parameters of unit processes will be determined for process design and modeling. The quality of final products and byproducts will be also examined.
2. Develop and optimize supercritical methanol method
   a. Lab scale system development
   b. Investigate catalysts, temperature and pressure effects on oil conversion efficiency
   c. determine optimized the process incorporated with task 3.
3. Compare these two processes with the conventional AD process
   a. Process modeling for three different pathway indicated in Figure 3 for material balance and energy balance using ASPEN Plus, discuss the relationship and trade-offs among the energy yields and energy/material inputs
   b. optimize the process with the goal of maximum oil conversion rate and minimum energy consumption.
c. Economic analysis. Based on the model established, an economic analysis will be conducted to show the initial investment and estimated operational costs, and to prove the economic validity of scum-to-biodiesel technology. ASPEN Plus has a function for economic analysis, which will be used as a tool in our analysis. Costs of equipment and chemicals will be based on literature review and supplier’s information.

4. Development of scum to biodiesel demonstration system. Based on the information provide in task 3, a scum to biodiesel demonstration system will be developed according to the optimized parameters. An estimated capacity of 300 ton biodiesel/year facility or smaller system will be developed depends on the budget. A complete scum to biodiesel production system will be designed and then bided for contract-fabrication. More accurate data will be obtained through the demonstration system that can be used for further comparison.

5. Environmental impacts analysis (Optional). Our analysis will follow the LCA standards created by International Organization for Standardization (ISO): ISO 14040 and ISO 14044. The LCA analysis will include all direct impacts and upstream impacts of chemicals and energy inputs. The process simulation models combined with existing modeling software will be applied in developing life cycle inventory. Software for modeling efforts, including Excel, GREET, GaBi, and Ecoinvent database, are currently owned by the research group. The LCA will include of environmental impact of fossil fuel use (MJ) and GHG emissions (kg CO₂ eq.) and final results of scum-to-biodiesel technology are supposed to compare with conventional biodiesel production.
4.2. Develop and demonstrate centrate to algae system

As described previously, algae consume organic carbon source in the centrate quickly while relatively large amount of N and P remain in the culture broth. In order to completely utilize and remove N and P from the wastewater to meet discharge standards, carbon source may be replenished through addition of glycerol from the scum to biodiesel conversion process, process water from hydrothermal treatment of algae, and CO₂ from fMAP and fMAG processes. The goal of this section is to use byproducts derived from scum to biodiesel process and waste gas from sludge to bio-fuels process to improve nutrients removal efficiency and obtain maximal algal biomass feedstock for biofuels application, and demonstrate a pilot-scale centerate to algae fuel system.

The specific objectives of centrate are (1) to evaluate and optimize the concentration of crude glycerol as sole carbon source for fast growth; (2) to develop and optimize best cultivation growth conditions for fast mixotrophic growth; (3) to develop a mixotro-autotrophic two-stage cultivation strategy for improved nutrient removal and enhanced lipid production; (4) to develop a pilot-scale centrate to bio-fuels demonstration system based on the optimized process.

Specific tasks will be:
1. Evaluate and optimize the concentration of crude glycerol for maximal algal biomass production. Different facultative heterotrophic microalgae strains will be evaluated...
and different concentration of crude glycerol will be added to meet the requirements of enhanced algal biomass accumulation and improved nutrient removal efficiency.

a. Evaluate and compare the capability of different facultative heterotrophic strains to utilize the purify and crude glycerol derived from scum-biodiesel process directly for fast growth;

b. Optimize the concentration of crude glycerol in batch-scale experiment.

2. Optimize CO₂ concentration for fast mixotrophic growth. This task is intended to select appropriate CO₂ concentration to obtain high cell density and fast nutrient removal efficiency.

a. CO₂ concentration levels of 1%, 2%, 5%, 10%, 15% (v/v) will be tested and optimized in batch-scale experiment.

b. CO₂ rich-waste gases collected from fMAP and fMAG processes will also be analyzed and evaluated for the feasibility of replacing above CO₂ to stimulate algae growth;

c. Effect of temperature, light intensity, glycerol and CO₂ concentration on algae growth and nutrient removal under mixotrophic cultivation mode will be evaluated and optimized through Box-Wilson Central Composite design (CCD).

3. Develop a mixotro-autotrophic two-stage cultivation strategy for improved nutrient removal and enhanced lipid production. At the first mixotrophic dominated stage, both glycerol and CO₂ will be used to support the mixotrophic growth, the supernatant will be reused as culture media in the second autotrophic dominated stage and CO₂ will be injected to provide inorganic carbon source.

a. A lab-scale two-stage cultivation system using 1-L PYREX Roux culture bottle as bioreactor will be used for process development and optimization;

b. Investigate the effects of temperature, light intensity, glycerol and CO₂ concentration on biomass accumulation and nutrient removal in the two-stage cultivation system.

c. The two-stage system will be further scaled up and the process will be optimized.

4. Develop a pilot-scale centrate to bio-fuels demonstration system based on the optimized process.

a. A pilot-scale two-stage system based on multi-layer bioreactors will be developed and constructed.

b. Light intensity, Temperature, pH, and glycerol and CO₂ concentration were further optimized in large-scale cultivation system.
c. The 3M Building Illumination & Photo Voltiac (BIPV) power modules provided through a grant from the 3M Foundation will be incorporated into the system to provide power for pumping and mixing.

d. Demonstrate the pilot-scale centrate to bio-fuels demonstration system.

5. Environmental impacts analysis (Optional). Our analysis will follow the LCA standards created by International Organization for Standardization (ISO): ISO 14040 and ISO 14044. The LCA analysis will include all direct impacts and upstream impacts of chemicals and energy inputs. The process simulation models combined with existing modeling software will be applied in developing life cycle inventory. Software for modeling efforts, including Excel, GREET, GaBi, and Ecoinvent database, are currently owned by the research group. The LCA will include of environmental impact of fossil fuel use (MJ) and GHG emissions (kg CO2 eq.) and final results of centrate to algae technology will be compared with previous cultivation models.

4.3. Develop and demonstrate sludge to bio-fuels system

The goal is to use and compare fast microwave assisted pyrolysis and gasification processes for sludge conversion, and demonstrate a fast microwave assisted conversion system capable of providing processing conditions to meet fast pyrolysis and high temperature gasification requirements. While sludge will be the main feedstock, algal biomass harvested from Activity 4.2 can also be processed using this system.

The specific objectives of sludge to bio-fuels component are (1) to develop a cost effective sludge dewatering system, (2) to develop and optimize fast microwave assisted pyrolysis process, (3) to develop and optimize fast microwave gasification process, (4) to develop and optimize bio-fuel upgrading processes, and (5) develop a sludge to bio-fuels demonstration system based on the optimized process.

Specific tasks will be:
1. Develop a cost effective sludge dewatering system. As the sludge from primary and secondary settling processes still contains much water, this task is to develop a dewatering system to dry the sludge and meet the requirements of following processes.
   a. Compare different dewatering processes based on dewatering efficiency and the cost;
   b. Lab scale dewatering system development;
   c. Investigate the effect of feed rate on sludge dewatering efficiency.

2. Develop and optimize fast microwave assisted pyrolysis process. This task is intended to select appropriate microwave absorbents and develop a fast
microwave assisted pyrolysis system to covert sludge or algal biomass to bio-oil, syngas, and bio-char.

a. Develop a lab scale microwave assisted pyrolysis system and analyze the components of bio-oil, syngas, and bio-char;

b. Investigate the effect of different microwave absorbents on heating rate and product distribution;

c. Examine the effects of temperature, catalyst and catalyst to feed ratio on the yield of bio-fuels.

3. Develop and optimize fast microwave assisted gasification process. This task is to produce syngas from sludge or algal materials using a fast gasification system.

a. Lab scale system development;

b. Investigate the effects of temperature, catalyst, catalyst to feed ratio and steam addition on syngas yield and quality;

c. Study the stability of catalyst during gasification process using X-ray Diffraction (XRD) technique.

4. Develop and optimize bio-fuel upgrading processes. This task is to upgrade the products of bio-oil, syngas, and bio-char for direct application.

a. Develop a catalytic upgrading process to treat the bio-oil and make it mixable with gasoline for fuel;

b. Introduce syngas into centrate system mentioned in 4.2 and CO₂ will be utilized and consumed by algae. Compare this novel system with traditional syngas conditioning processes based on CO₂ removal efficiency. Remove hydrocarbons from raw syngas by steam conditioning;

c. Develop processes to separate bio-char from catalyst and further improve the quality of the bio-char to meet the requirements of soil amendment agent or activated carbon.

5. Development of a continuous sludge to bio-fuels demonstration system. Based on the data obtained from the above tasks, a pilot scale continuous fast microwave assisted conversion system with capacity estimated at 50 kg/h will be designed and fabricated. The key features of the system is expected to include fast heating, high temperature, mechanisms for easy feeding of feedstock and discharge of solid residues, a motor-driven mixer/conveyer, air cooled condensers, integrated gas turbine power generator, multiple-point temperature detection, and automatic and accurate temperature control. The Pilot testing and demonstration facilities will be carried out in MCES St. Paul Wastewater Treatment Plant (Figure 7) and/or FreightMasters/Minnesga Inc. Warehouse in Eagan (Figure 8). The space in FreightMasters/Minnesga Inc. warehouse is also appropriate for future potential commercial operations.

6. Environmental impacts analysis (Optional). Our analysis will follow the LCA standards created by International Organization for Standardization (ISO): ISO 14040
and ISO 14044. The LCA analysis will include all direct impacts and upstream impacts of chemicals and energy inputs. The process simulation models combined with existing modeling software will be applied in developing life cycle inventory. Software for modeling efforts, including Excel, GREET, GaBi, and Ecoinvent database, are currently owned by the research group. The LCA will include environmental impact of fossil fuel use (MJ) and GHG emissions (kg CO₂ eq.) and final results of fast microwave assisted sludge to bio-fuels technology are supposed to compare with conventional pyrolysis and gasification processes.

Figure 7. Metropolitan St. Paul Wastewater Treatment Plant.

Figure 8. FreightMaster Warehouses.

a. Test the facility and collect data; conduct TEA and LCA

By the end of 2016 (2.5 years into the project), all demonstration systems would have been operational. We will begin to test these systems and collect data on product yields and properties, mass and energy balance, water usage and emission, costs, labors, etc. These data will be used for preliminary technoeconomic analysis (TEA) and life cycle assessment (LCA). These preliminary TEA and LCA results may be used to adjust the operational parameters for optimal financial and environment performance.

b. Demonstrate the systems to stakeholders

Once the systems are optimized and operation is smooth, we will organize demonstration activities. At least five demonstrations will be made to stakeholders including state agencies, private investors, academic researchers, and the public. Demonstration events will be broadly
publicized through various channels and media. The demonstration events will be one of our major findings dissemination efforts.

7. **Results and Deliverables** - Describe in detail the expected outcomes of each of the results and deliverables.

   a. **Scum to biodiesel**

   An innovative scum to biodiesel technology will be developed and demonstrated, which is expected to:
   
   1. utilize waste scum stream to biodiesel and generate $350,000 from MCES’ facilities alone
   2. improve wastewater treatment efficiency and cost effectiveness
   3. reduce landfill and fossil fuel and coal usage

   b. **Centrate and glycerol for algae cultivation**

   An innovative model for cultivation of algae on centrate and glycerol will be developed and demonstrated, which is expected to:
   
   1. Utilize/remove extra N and P from centrate (total P removal reaches 90%)
   2. Provide a solution to low quality glycerol, a byproduct of biodiesel production
   3. Produce biofuels from algal biomass and generate additional revenue of $450,000/year.

   c. **Sludge to biofuels**

   A fast microwave assisted conversion system will be developed and demonstrated, which is expected to:
   
   1. Convert sludge to bio-oil, syngas, and biochar
   2. Reduce landfill and pollution
   3. Bring savings and generate revenue in the amount of $19 million

8. **Timetable** - Layout the proposed times for completing the proposed research including proposed dates for individual results and deliverables.

<table>
<thead>
<tr>
<th>Results and deliverables</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Develop and demonstrate scum to biodiesel process and system</td>
<td></td>
</tr>
<tr>
<td>1.1. Develop and optimize oil recovery, conversion, and upgrading processes; Streamline processes and design the complete system</td>
<td>6/30/2015</td>
</tr>
<tr>
<td>1.2. Fabricate and install the system at demonstration site</td>
<td>12/31/2016</td>
</tr>
<tr>
<td>1.3. Test the system and collect mass and energy balance data; conduct TEA and LCA</td>
<td>03/31/2017</td>
</tr>
<tr>
<td>1.4. Demonstrate the systems to stakeholders</td>
<td>06/30/2017</td>
</tr>
</tbody>
</table>
2. **Develop and demonstrate centrate to algae fuel system**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Develop and optimize algae growth and nutrient removal involving crude glycerol; design the complete processes.</td>
<td>6/30/2015</td>
</tr>
<tr>
<td>2.2</td>
<td>Design and construct a greenhouse based algae based wastewater treatment facility</td>
<td>12/31/2016</td>
</tr>
<tr>
<td>2.3</td>
<td>Test the facility and collect mass and energy balance data; conduct TEA and LCA</td>
<td>03/31/2017</td>
</tr>
<tr>
<td>2.4</td>
<td>Demonstrate the systems to stakeholders</td>
<td>06/30/2017</td>
</tr>
</tbody>
</table>

3. **Develop and demonstrate sludge to bio-fuels system**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Develop cost effective dewatering process; design microwave absorbent device; optimize catalytic bio-oil upgrading process</td>
<td>6/30/2015</td>
</tr>
<tr>
<td>3.2</td>
<td>Design and construct a complete facility for dewatering and conversion of sludge to bio-oil and syngas; the facility is expected to be fully or partially self-powered.</td>
<td>12/31/2016</td>
</tr>
<tr>
<td>3.3</td>
<td>Test the facility and collect mass and energy balance data; conduct TEA and LCA</td>
<td>03/31/2017</td>
</tr>
<tr>
<td>3.4</td>
<td>Demonstrate the systems to stakeholders</td>
<td>06/30/2017</td>
</tr>
</tbody>
</table>

9. **Budget** – See attached budget file

10. **Credentials -**

   a. **Background of Personnel (see Appendixes for PIs’ biosketches)**
   b. **Roles and responsibilities**

**UMN:** Dr. Roger Ruan - PI & project director, will be responsible for overall project planning and budget control, development, design and evaluation of the demonstration facilities; Dr. Paul Chen - co-PI, will be responsible for experiment design and coordination, monitoring and documentation of project progress and results, and publicizing the project; Dr. Min Min will assist Drs. Ruan and Chen with process development and facility design and construction, and conducting the economic and environmental life-cycle analysis.

**MCES Metro Plant:** Mr. Larry Rogacki, Director of Plant Services, will provide necessary support to the project and is committed to meeting with the project team, developing a work plan and system details, and providing raw material samples, space at the plant for conducting studies, and technical feedback. A support letter from Metro Plant is enclosed. They will not receive fund from LCCMR.
**FreightMasters/Minnesga Inc:** Mr. John Snyder and Mr. Ron Have will provide space necessary for equipment development, help with equipment and fuel testing as described in their support letter. They will not receive fund from LCCMR.

11. **Dissemination and Use** – Describe how the findings of the research will be disseminated and describe the expected audience and potential use.

The findings will be disseminated through:
(1) On site demonstration as described in Activity 4.5  
(2) Public seminars  
(3) Progress update on www.biorefining.cfans.umn  
(4) Presentations at national and international technical conferences  
(5) Communications with interested entrepreneurs  
(6) Peer reviewed papers  
(7) Collaboration with UMN extension  

The technologies, if demonstrated successfully, may be implemented to many MWTPs in the State of Minnesota and beyond. Any intellectual properties and related revenues as a result of the program will be shared between UMN and LCCMR.

**References**
- Du, Zhenyi, Bing Hu, Aimin Shi, Xiaochen Ma, Yanling Cheng, Paul Chen, Yuhuan Liu, Xiangyang Lin, Roger Ruan, Cultivation of a microalg Chlorella vulgaris using recycled aqueous phase nutrients from hydrothermal carbonization process, Bioresource Technology, Volume 126, December 2012, Pages 354-357  
- Marco R. Menendez, How we use energy at wastewater plants…and how we can use less. www.ncsafeewater.org/...Wastewater/WW_T.AM_10.30_Menendez.pdf  


APPENDIXES: BIOSKETCHES OF PRINCIPAL INVESTIGATORS

R. ROGER RUAN

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University of Minnesota
206 BAE Building, 1390 Eckles Avenue, St. Paul, MN 55108, USA

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Phone: (612) 625-1710  Fax: (612) 624-3005

E-mail: ruanx001@umn.edu  http://biorefining.cfans.umn.edu/
www.bbe.umn.edu/staff/ruan.html

(a) Professional Preparation
China Agricultural University  Mechanical Engineering  B.S., July, 1983
Oklahoma State University  Biosystems and Agricultural Engineering  M.S., May, 1988
University of Illinois at Urbana-Champaign  Agricultural and Biological Engineering  Ph.D., August, 1991

(b) Appointments
6/2001 – Present: Professor, Department of Bioproducts and Biosystems Engineering, and Department of Food Science and Nutrition, University of Minnesota. Director, Center for Biorefining (since 2002).
6/1998 – 6/2001: Associate Professor and Director of Undergraduate Studies, Department of Biosystems and Agricultural Engineering, and Department of Food Science and Nutrition, University of Minnesota.
1/1994 – 6/1998: Assistant Professor, Department of Biosystems and Agricultural Engineering, and Department of Food Science and Nutrition, University of Minnesota.

(c) Selected Recent Peer-reviewed Journal Publications, Books, and Patents (over 300):
1. Zhenyi Du, Xiaochen Ma, Yun Li, Paul Chen, Yuhuan Liu, Xiangyang Lin, Hanwu Lei, Roger Ruan. 2013. Production of aromatic hydrocarbons by catalytic pyrolysis of microalgae with zeolites: Catalyst screening in a pyroprobe. *Bioresource Technology* In press.
5. Ren, Shoujie; Lei, Hanwu; Wang, Lu; Bu, Quan; Wei, Yi; Liang, Jing; Liu, Yupeng; Julson, James; Chen, Shulin; Wu, Joan; Ruan, Roger. 2012. Microwave torrefaction of Douglas fir sawdust pellet. *Energy & Fuels* 26(9):5926-5943.

(d) Selected Recent Funded Projects
1. MAES. Conversion of turnkey wastes to energy via fast pyrolysis and gasification. 7/1/13 – 6/30/15. $184,366.
2. DOT/Sun Grant. Distributed production of DME based fuels using microwave technology and direct catalytic synthesis. 4/20/12-4/19/15. $473,546.
4. University of Minnesota IREE. Wind to Ammonia with absorbents. 11/1/11-10/31/14. With Alon McCormic (lead), Mike Reese, Paul Chen, and Doug Tiffany. $400,000.
6. Minnesota Corn Growers Association. Adding value to ethanol production byproducts (dried distillers grain) through production of biochar and bio-oil. With Kurt Spokas of USDA lead. 9/1/10 – 8/31/12. $60,000.
7. LCCMR. Wastewater algae pilot project. 7/1/10 – 6/30/14. $900,000.
8. Minnesota Corn Research and Promotion Council. Transforming corn from a commodity crop to a higher-energy, multipurpose biofuel crop. With R. Bernardo lead. 7/1/10 – 7/30/12. $455,513
10. MCES. Mass culture of algae on wastewater as an energy crop for biofuel production. 11/1/09 – 6/30/10. $50,000.
13. University of Minnesota IREE. Catalytic reforming of liquids and gases from thermochemical and biological conversion of biomass. 7/1/09 – 6/30/11. $250,000.
15. USDA NRI. Whole Grain Ingredients: Health Benefits of Bioactive Phytonutrients and Dietary Fibers from Cereal Grains. 12/1/08 – 11/30/12. $750,000.
16. USDA/DOE. Development of Scalable Biorefining Processes for Distributed Biomass Conversion. 01/01/2007 - 06/30/2012. $1,224,055.
19. Minnesota Legislature, MCES, and IREE. Mass culture of algae on wastewater as an energy crop for biofuel production. 7/1/08 – 12/31/09. $1,000,000.
23. LCCMR. Mobil biomass pyrolysis system development and demonstration. 7/1/07 – 6/30/11. $500,000.

(e) Synergistic Activities
1. Started up the Fiberstar Company from our patented HRC technology, the company is doing well with annual sales in tens of millions.
2. Transferred the patented non-thermal plasma technology to SCP Control Company, the company is also doing very well.
3. Established and lead the University of Minnesota Center for Biorefining with a number of innovative bioconversion pilot technologies and facilities.
4. Established and lead the St. Paul Campus Magnetic Resonance Research Laboratory with two permanent magnet MR imaging systems and one low field NMR relaxometry system.
5. Established the Electric Power Research Institute (EPRI) and Northern States Power (NSP) Food Technology Center - Research and Development, which operated for three and a half years.
6. Served on AAAS, NSF, DOE, USDA and many other major proposal review panels. Also served as Chief Editor and Associate Editors in many professional journals as well as serving in many other capacities in various professional organizations.

   Professor Ruan’s research focuses on various aspects of value-added processing, renewable energy and environment, and food engineering. His current interests are in conversion of renewable biomass into energy fuel, chemical, and material, food quality enhancement, and safety and security assurance, algae production and wastewater treatment, and nonthermal plasma development and application in flue gas and hazardous emission control and disinfection.

   Professor Ruan has published over 300 papers in refereed journals, book, and book chapters, and over 300 meeting papers and other reports, and holds 14 US patents. He has supervised over 50 graduate students, 80 post-doctors, research fellows, and other engineers and scientists, and 9 of his students hold university faculty positions. He has received over 140 projects totaling over $20 million in various funding for research, including major funding from USDA, DOE, DOT, and DOD, and industries, etc. He is an editor-in-chief of International Journal of Agricultural and Biological Engineering, editorial board member of Journal of Food Process Engineering, and Associate Editor of Transactions of ASABE, Engineering Applications in Agriculture, and Transactions of CSAE.

   Professor Ruan has also given over 200 invited symposium presentations, company seminars, and short courses, and has been a consultant for government agencies, and many local, national, and international companies and agencies in bioprocess engineering, food engineering, and renewable energy areas. He has taught many undergraduate and graduate courses, including Renewable energy technologies, Biological processing engineering, Managing water in food and biological systems, Instrumentation and control for biological systems, and Engineering principles and applications, etc.
Paul L. Chen  
Ph.D., Program Director, Associate Research Professor

Center for Biorefining, Department of Bioproducts & Biosystems Engineering  
University of Minnesota  
1390 Eckles Ave., St. Paul, Minnesota 55108  
Phone: (612) 625-7721, Cell: (651) 983-8674, Fax: (612) 624-3005  
Email: chenx088@umn.edu, URL: http://umn.edu/~chenx088

PROFESSIONAL EMPLOYMENT  
06/11 – present  ASSOCIATE RESEARCH PROFESSOR, Dept. Bioproducts & Biosystems Eng., Univ. Minn.

07/01-05/11  SENIOR RESEARCH ASSOCIATE, Dept. Biosystems & Agric. Eng., Univ. Minn.


07/88 – 10/90  ASSISTANT PROFESSOR, DIRECTOR, Division of Agric. Product Storage & Processing, South China Agric. Univ.

08/86 – 6/88  ASSISTANT LECTURER, Division of Agric. Product Storage & Processing, South China Agric. Univ.

EDUCATION/TRAINING  
Ph.D.  FOOD SCIENCE, The Queen's University of Belfast, United Kingdom, 1994  
Adv. Dip.  FOOD ENGINEERING & TECHNOLOGY, South China Institute of Technology, 1988  
M.Sc.  AGRIC-PRODUCT PROCESSING TECHNOLOGY, South China Agric. Univ., 1986  
B.Sc.  POMOLOGY, South China Agric. Univ., 1983

OTHER RESPONSIBILITIES  
05/03 – present  Program Director, Center for Biorefining, Univ. of Minn.

08/03 – present  Secretary, Bioenergy & Bioproducts Cluster, IREE, Univ. of Minn.

07/07 – present  Managing editor of International Journal of Agricultural and Biological Engineering  
10/11 – present  Editor of Energy (guest edit special issue on “Algae Fuels”)

RECENT PROJECTS  
- **MAES.** Conversion of turnkey wastes to energy via fast pyrolysis and gasification. 7/1/13 – 6/30/15.  
  $184,366.

- **DOT/Sun Grant.** Distributed production of DME based fuels using microwave technology and direct catalytic synthesis. 4/20/12-4/19/15. $473,546.

- **University of Minnesota IREE.** Wind to Ammonia with absorbents. 11/1/11-10/31/14. With Alon Mccormic (lead), Mike Reese, Paul Chen, and Doug Tiffany. $400,000.


- **LCCMR.** Wastewater algae pilot project. 7/1/10 – 6/30/14. $900,000.

- **University of Minnesota IREE.** Algae Production System Using Centrate Wastewater from Met Council Treatment Plant. 4/1/10 – 6/30/13. $156,840.

- **MCES.** Mass culture of algae on wastewater as an energy crop for biofuel production. 11/1/09 – 6/30/10. $50,000.

- **Office of Naval Research (ONR) & Luna Innovations.** Biofuels production from nonedible biooils. Phase I. 8/1/09 – 7/31/10. $37,000.

- **University of Minnesota IREE.** Catalytic reforming of liquids and gases from thermochemical and biological conversion of biomass. 7/1/09 – 6/30/11. $250,000.

- **Minnesota Corn Research and Promotion Council.** High oil corn as a higher value commodity. 7/1/09 – 6/30/10. Ron Phillips lead. $80,545.
• USDA/DOE. Development of Scalable Biorefining Processes for Distributed Biomass Conversion. 01/01/2007 - 06/30/2012. $1,224,055.
• Minnesota Legislature, MCES, and IREE. Mass culture of algae on wastewater as an energy crop for biofuel production. 7/1/08 – 12/31/09. $1,000,000.
• Xcel Energy. Mass production of algae as energy crop. 1/11/08 – open. $150,000.
• US DOT and Sun Grant Initiative. Develop sustainable renewable energy systems for practical utilization of bulky biomass. 9/1/07 – 8/31/12.  $1,186,084.
• LCCMR. Mobil biomass pyrolysis system development and demonstration. 7/1/07 – 6/30/11. $500,000.

SELECTED PUBLICATIONS (from over 110)