BC Water & Waste Association

Student Design Competition 2013

Project Statement

Microalgae Cultivation and Harvesting:
Design of Pilot Facilities at the Sustainability Academy - Annacis Wastewater Centre

November 2012

metro vancouver

BCWWA
BC WATER & WASTE ASSOCIATION

BCWWA Student Design Competition 2013

Project Statement

Students interested in entering the 2013 BCWWA Student Design Competition are encouraged to form interdisciplinary teams to:

1) Design a pilot-scale microalgae cultivation and harvesting system for installation at Metro Vancouver's Sustainability Academy – Annacis Wastewater Centre.
2) Develop concepts and budget for the longer term goal of co-locating operational-scale microalgae cultivation processes at Metro Vancouver's Iona Island Wastewater Treatment Plant.

Background

Introduction to Microalgae

The world's algae population is said to produce roughly one-half of the oxygen in the atmosphere, and consumes substantial quantities of carbon dioxide to grow its biomass. Additionally, algae is a source of food for fish, animals and humans, and also provides a means to produce valuable compounds used in the pharmaceutical and food industries. The displacement of petroleum with algal biomass would practically complete algae's full potential, giving it significant commercial and environmental importance.

While initial use of algae involved harvesting naturally occurring blooms, the focus over the last few decades has been deliberate farming or cultivating of microalgae. Early research into the cultivation of microalgae was for its use as a photosynthetic exchanger to produce oxygen from carbon dioxide as part of space exploration initiatives in the 1940s and 1950s. Subsequent cultivation work focused on the value of microalgae as food or a food supplement, and Japan established the first commercially successful culturing facility in the 1960s. While the number of cultivation facilities increased with the demand for microalgae-derived food supplements, it was the energy crisis in the 1970s that initiated extensive research into developing renewable fuels from algae. The U.S. Department of Energy funded several programs to examine effective means of producing biodiesel from high-lipid algae typically grown in open pond systems, using carbon dioxide emissions from combustion facilities and/or nutrients from wastewater treatment plants. Research and development activities on algae biofuels waned and flat-lined in the 1980s as oil prices eventually fell, but were again stimulated as peak oil occurred in the 2000s.

Environmentalists became more globally-aligned on the issues associated with greenhouse gas emissions, and recognized that there is insufficient agricultural land for crops to produce enough biofuels to displace petroleum for current and future oil demands. Microalgae, with its voracious appetite for carbon dioxide, has the ability to double its biomass daily, far exceeding growth rates of any terrestrial plant. This reduces space requirements for cultivating microalgae on a commercial scale, does not compete with traditional crops such as corn or canola for arable land, and avoids the "farming for food vs. farming for fuel" conflict. Furthermore, microalgae can grow in fresh, saline, brackish, and wastewaters, and can serve to recover or remove excess nutrients from the growing media.

Given microalgae's potential to capture carbon dioxide, supply oxygen, and provide a source for food supplements, biofuels, biochemicals, and fertilizers, the pace of investments into further developing microalgae products has accelerated. Over the past few years, there have been substantial gains in the effectiveness of in-vessel algae cultivation systems and supporting technologies that are seemingly near commercialization. These 'next generation' systems will add to the dozens of existing commercial microalgae operations running primarily open pond systems. Current microalgae-based products include: nutraceuticals (e.g. beta-carotenes, astaxanthin, omega-3), food colouring, pigments used in cosmetics, and other dyes.

The future looks bright for increased commercialization of microalgae-based products, as research and development investments continue to support initiatives such as NASA's OMEGA Project, and many other projects in the private sector. The number of scientists, engineers, and entrepreneurs eyeing the vast commercial potential of microalgae has never been higher, all seeking to harness its potential to displace petroleum as the feedstock for the production of plastics, polymers, and chemicals, and for the development of new pharmaceuticals, food supplements, fertilizers, and fiber.

Microalgae Cultivation in Wastewater Effluent

Through its National Biofuels Program (2010 – 2012) and Algal Carbon Conversion Program (2012 -), the National Research Council (NRC) has built Canadian knowledge and capacity to cultivate microalgae to be used as a feedstock to produce bioproducts. One of the many findings of the NRC Algal Program is that municipal wastewater effluent, rich in nitrogen and phosphorus, can be well-suited for the intensive large-scale cultivation of microalgae. A side benefit is the recovery of these nutrients from the effluent stream to further improve its characteristics before final discharge.

Microalgae can be considered single-celled plant-like photosynthetic systems. Energy from the sun is captured by microalgae, which photochemically reduces inorganic compounds like CO_2 and ammonia (or nitrates) and phosphate to their respective organic forms. These compounds are, in turn, used to synthesize proteins, carbohydrates, lipids, and nucleic acids which promote cell growth and division and the subsequent proliferation of biomass. Further, dissolved metals in wastewater such as iron, zinc, copper, and manganese are essential enzymes and co-factors for algal metabolism and are taken up by microalgae to support its growth. Replication of an ideal algal growing medium in the absence of municipal wastewater would require careful mixing of carbonaceous materials, nitrogen, phosphorous, and essential trace metals, which would be expensive and impractical for large-scale algal cultivation.

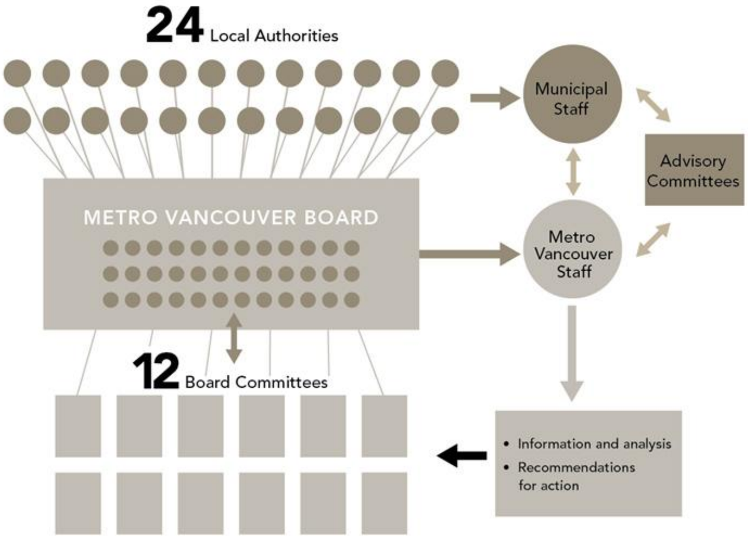
While the potential for microalgae to be a replacement for petroleum is evident, the practicality of cultivation at a wastewater facility remains a key question. More development is required to find the most efficient and effective ways to achieve this for each step of the process, involving: i) cultivation, ii) harvesting, iii) processing and extraction, and iv) manufacturing of bioproducts.

This project targets the design of the above first two steps of the process (i. and ii.), and also includes a high-level evaluation of co-locating a microalgae cultivation facility with a wastewater treatment plant.

The formation of interdisciplinary teams involving students from mechanical, biological, chemical and civil engineering and sciences is encouraged.

About Metro Vancouver

Metro Vancouver is a political body and corporate entity operating under provincial legislation as a regional district that delivers regional services, policy, and political leadership on behalf of its 22 municipalities, one electoral area, and one treaty First Nation. Metro Vancouver's main areas of planning and regulatory responsibility are: utilities, air quality, regional growth, and regional parks. Metro Vancouver's core services, provided principally to municipalities, are: drinking water, sewerage and drainage, and solid waste management. In terms of sewerage and drainage, Metro Vancouver manages sewage conveyance and treatment infrastructure, including 3,200 km of pipe, 25 sewage pumping stations, and five major wastewater treatment plants (WWTPs) treating 1,200 MLD.



The Liquid Waste Function

Metro Vancouver provides sewage collection and treatment at one of five wastewater treatment plants in the region. In addition to continuous operation and ongoing maintenance of the system, long-range and capital plans are established and updated to ensure the liquid waste function is well managed to achieve alignment with regulatory, environmental, municipal, and regional goals. Over the past several years, Metro Vancouver and its local authorities developed an Integrated Liquid Waste and Resource Management Plan (ILWRMP) that sets out the long-term vision, strategy, goals, and actions for the regional and municipal sewerage collection and treatment system. Being a regulatory instrument, the ILWRMP was submitted to the Provincial Government for consideration and received approval in 2011. In the Plan are a number of commitments, including the examination of integrated resource recovery opportunities. As part of this, Metro Vancouver wishes to:

- In the long-term, determine the viability of co-locating microalgae cultivation processes at the future Iona Island Wastewater Treatment Plant.
- In the shorter term, assess emerging microalgae cultivation technologies, identify the most promising value proposition, conduct a future scenario business case, and establish a design for a pilot-scale microalgae cultivation system to be installed at the Sustainability Academy – Annacis Wastewater Centre.

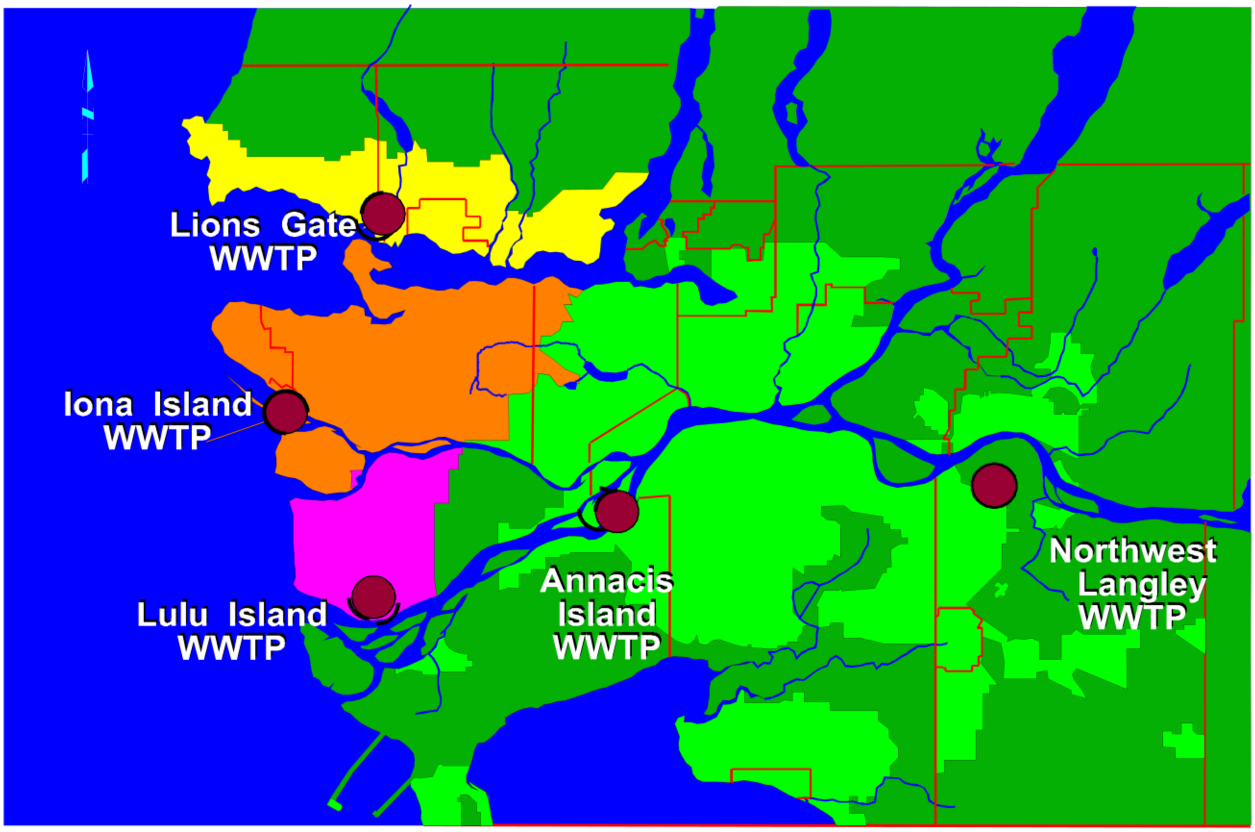


Figure 1: Map of Metro Vancouver's five wastewater treatment plants.

Sustainability Academy – Annacis Wastewater Centre

The Annacis Wastewater Centre (AWC) blends research, education, and training opportunities in a unique facility that is located on the northwest corner of the Annacis Island Wastewater Treatment Plant site. The vision for the AWC is centered on a place of excellence in wastewater research and development, training, and education – a place that challenges us to think about new ways of managing and treating wastewater, promoting energy reduction, and mitigating environmental impacts.

Figure 2: Sustainability Academy - Annacis Wastewater Centre

The AWC provides facilities for research, teaching space, and access to various in-plant wastewater streams for researchers to develop new processes, and for manufacturers and vendors to demonstrate innovative processes. In addition, the AWC contains multi-purpose meeting rooms and a classroom space for public discourse, education, training, and other professional services.

The pilot-scale microalgae cultivation system will be located at the AWC with available source streams from the Annacis Island Wastewater Treatment Plant.

Annacis Island Wastewater Treatment Plant

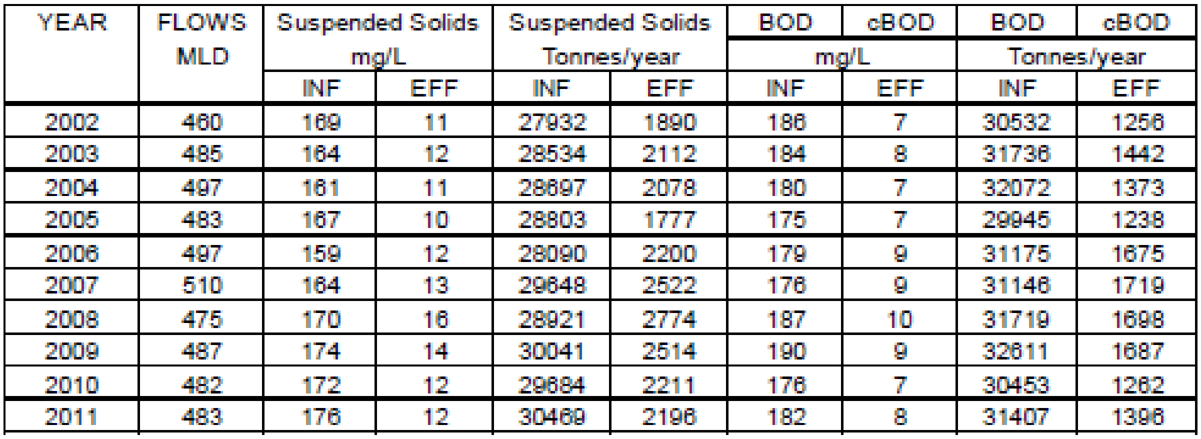
The Annacis Island Wastewater Treatment Plant is the largest regional plant in BC and provides secondary treatment to wastewater from approximately 1,000,000 people in parts of Burnaby, New Westminster, Port Moody, Port Coquitlam, Coquitlam, Pitt Meadows, Maple Ridge, Surrey, Delta, White Rock, City of Langley, and Township of Langley.

Figure 3: Aerial photo of Annacis Island Wastewater Treatment Plant.

Operational Certificate

The operation of the Annacis Island WWTP is largely regulated by an operational certificate issued by the Province of BC. The operational certificate restricts the volume and nature of the effluent released to the environment, with the key parameters being: biological oxygen demand (BOD), total suspended solids (TSS), and maximum daily discharge. Limits and performance of the past several years are provided in the following tables.

	Biological Oxygen Demand (BOD)	**Total suspended solids (TSS)**	**Maximum daily discharge**
Limits	45 mg/L	45 mg/L	1,050 MLD (max.)



YEAR	FLOWS MLD	Suspended Solids mg/L		Suspended Solids Tonnes/year		BOD mg/L	cBOD mg/L	BOD Tonnes/year	cBOD Tonnes/year
		INF	EFF	INF	EFF	INF	EFF	INF	EFF
2002	460	169	11	27932	1890	186	7	30532	1256
2003	485	164	12	28534	2112	184	8	31736	1442
2004	497	161	11	28697	2078	180	7	32072	1373
2005	483	167	10	28803	1777	175	7	29945	1238
2006	497	159	12	28090	2200	179	9	31175	1675
2007	510	164	13	29648	2522	176	9	31146	1719
2008	475	170	16	28921	2774	187	10	31719	1698
2009	487	174	14	30041	2514	190	9	32611	1687
2010	482	172	12	29684	2211	176	7	30453	1262
2011	483	176	12	30469	2196	182	8	31407	1396

Annacis Island WWTP 2002-2011 Annual Average Data for Flow, Suspended Solids and BOD (see: http://www.metrovancouver.org/about/publications/Publications/GVSDD_Quality_Control_Annual_Report_2011.pdf)

Iona Island Wastewater Treatment Plant

Should the pilot-scale microalgae cultivation system be successful, an operational-scale microalgae cultivation process could be considered and specified in the design of a new Iona Island Wastewater Treatment Plant.

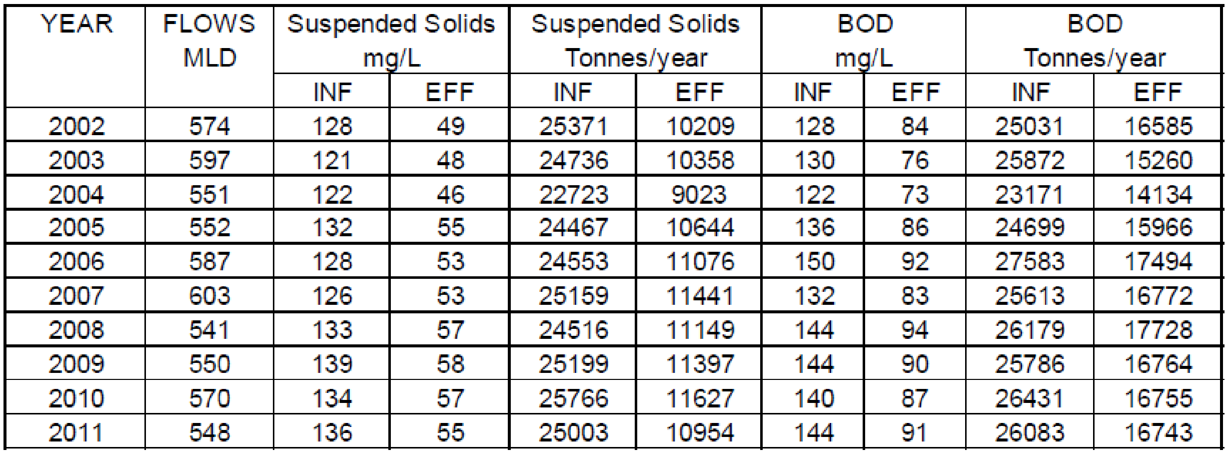
The Iona Island WWTP currently provides primary treatment to wastewater from approximately 600,000 people (in Vancouver, the University Endowment Lands, and parts of Burnaby and Richmond) before discharging it through a 7.5 km, deep-sea outfall into the Strait of Georgia.

The plant opened in 1963, and over the years has been expanded several times for growth and treatment upgrades.

Figure 4: Aerial photo of Iona Island Wastewater Treatment Plant.

Iona Island WWTP’s Operational Certificate limits and performance of the past several years are provided in the following tables:

	Biological Oxygen Demand (BOD)	**Total suspended solids (TSS)**	**Maximum daily discharge**
OC limits	130 mg/L	100 mg/L	1,530 MLD (max.)



YEAR	FLOWS MLD	Suspended Solids mg/L		Suspended Solids Tonnes/year		BOD mg/L		BOD Tonnes/year	
		INF	EFF	INF	EFF	INF	EFF	INF	EFF
2002	574	128	49	25371	10209	128	84	25031	16585
2003	597	121	48	24736	10358	130	76	25872	15260
2004	551	122	46	22723	9023	122	73	23171	14134
2005	552	132	55	24467	10644	136	86	24699	15966
2006	587	128	53	24553	11076	150	92	27583	17494
2007	603	126	53	25159	11441	132	83	25613	16772
2008	541	133	57	24516	11149	144	94	26179	17728
2009	550	139	58	25199	11397	144	90	25786	16764
2010	570	134	57	25766	11627	140	87	26431	16755
2011	548	136	55	25003	10954	144	91	26083	16743

Iona Island WWT 2002-2011 Annual Average Data for Flow, Suspended Solids and BOD (see: http://www.metrovancouver.org/about/publications/Publications/GVSDD_Quality_Control_Annual_Report_2011.pdf)

Objectives

1. **Pilot-Scale Design**. Research and design a pilot-scale microalgae cultivation system for installation at Metro Vancouver's Sustainability Academy – Annacis Wastewater Centre. The design is to include processes for: cultivation, harvesting, and dewatering. The pilot unit must be designed to fit within the AWC Research Hall and/or outside on the AWC land. The main source streams available for the pilot at the AWC are: secondary effluent (pre-disinfection) and centrate. Assume CO_2 will be available from pressurized cylinders.
2. **Operational-Scale Concepts**. Develop conceptual plans and a budget for the longer term goal of co-locating operational-scale microalgae cultivation processes at Metro Vancouver's Iona Island Wastewater Treatment Plant. The microalgae plan should include the following processes: cultivation, harvesting, dewatering, and biomass handling/short-term storage. Exclude subsequent biomass processing such as lipid extraction, fiber processing, and final product manufacturing.

Design Considerations

The scope of the project involves the cultivation and harvesting (including dewatering) of photosynthetic monoculture microalgae strains (e.g. Scenedesmus sp. AMDD and Chlorella sorokiniana) in secondary effluent. While the decision on microalgae strain for cultivation is dependent on the desired final product, a robust system will be able to grow a number of different green algae. The cultivation should target maximizing biomass per unit of input (e.g. energy, capital, materials) and the harvesting mechanism should assume that the target of algal biomass dewatering is 15% solids, with a minimum of 10% solids. Efficiency in design must be a consideration for each element of the design.

Cultivation

While there are a few different mechanisms for cultivating microalgae, only the photoautotrophic technique should be considered for this project. The photoautotrophic technique relies on microalgae's photosynthetic mechanism with the key inputs being: light, CO_2, and nutrient-rich liquid growing media. Given the Vancouver climate, the design should assume photobioreactors (PBR) rather than open raceways, and the growing media will be secondary effluent with the inevitable use of artificial light sources. Hybrid PBR/open raceway designs can be considered, as well as the integrated use of natural light to enhance algal growth. For the pilot-scale design, assume CO_2 will be supplied via commercially available CO_2 cylinders. The operational-scale design should consider possible capture of CO_2 from onsite sources for cultivation purposes. Onsite CO_2 could be made available as a fraction of biogas produced in anaerobic digesters, combustion in boilers, or combined heat and power (CHP) units. Conceptually, each PBR unit can operate as a batch reactor rather than a continuous flow-through system. For the operational-scale system, a 'piece-wise' batch process involving multiple PBR units with algal growth at various stages could enable continual biomass dewatering and harvesting at regular intervals.

The main design considerations for a PBR include: lighting, mixing, growing medium, nutrient supply, CO_2, pH, and O_2 removal, and temperature regulation (Kunjapur & Eldridge, 2010).

- Light intensity, wavelength, exposure frequency, and penetration into the liquid growing medium are important factors for algal growth. This involves examining: PBR geometry, position of lights, density and shading effects of cultures, light spectrum for species growth, frequency and durations of dark and light cycles, and bulb efficiency.

- Good reactor mixing ensures uniform exposure to light radiation and nutrients in the PBR. The type of agitation, and use of aerators, will need to be specified in the design.

- The growing medium under consideration is secondary effluent. Given the desire for a monoculture, the secondary effluent will first need to be sterilized to rid it of unwanted organisms. Traditional approaches such as chlorination/dechlorination or UV disinfection should be examined. Once the growing medium is disinfected, it can be placed into the PBR and seeded with the selected microalgae strain to establish the desired monoculture.

- Closely related to the growing medium is the availability of centrate (liquids derived from the mechanical dewatering of WWTP biosolids) as the source of additional nutrients. High in nitrogen and phosphorus, a mechanism of metering centrate into the PBR based on culture requirements will need to be designed. Close attention should be paid to managing nitrogen and phosphorus ratios between approximately 30:1 and 5:1. For the purposes of this project, focus on macro nutrient parameters and ignore any potential micronutrients deficiencies.

- CO_2 will likely be the limiting PBR input for algal growth. Bubbling air enhanced with CO_2 concentrations of up to 5% by volume can be considered. For the pilot-scale design, assume CO_2 will be available from commercially purchased cylinders and that there will be no real constraint on the amount of CO_2 enhancement. The most likely constraint will be the available space in the AWC's Research Hall or outside area. On the other hand, for the operational-scale concept design, the maximum available onsite CO_2 may constrain the maximum PBR capacity. The other constraint at the operational-scale will be the amount of available land onsite.

- A means of dealing with the drop in pH due to increased dissolved CO_2 in the growing media may be required. Determine optimal pH range for the identified algal species, and then select commercially available pH controllers to suit.

- Fundamental to the photosynthetic process is the generation of O_2, which needs to be removed from within the PBR. A mechanism for O_2 bubble exhaust or capture could be integral to the PBR design.

- Temperature regulation, including the possible need for cooling, should suit the species being cultivated and the surroundings of the PBR unit.

Harvesting and Dewatering

Harvesting and dewatering to separate the algal biomass from the growing medium can represent a substantial aspect of the microalgae production process. Consider processes such as sedimentation, floatation, filtration, mechanical dewatering (e.g. centrifuges, belt filter presses), the use of flocculants, polymers, and even off-the-shelf pulpers made for the fruit juice industry. Other concepts involve moving contactors on which microalgae grow and can be mechanically scrapped for harvest. While less important for the pilot-scale design, the quality of the final effluent should match its proposed use and should be factored into the selection of the proposed harvesting and dewatering process.

Design Targets

- Algal biomass productivity: 0.4 kg/m^3/d (dry weight, per growing medium volume, per day). Assume 30% lipid content in algal biomass and 90% extraction effectiveness.
- Harvesting effectiveness: 90% (percent biomass capture from growing medium).
- Dewatered biomass: 15% solids (dry weight basis).
- Minimize energy input per unit biomass produced.

Design Assumptions

Required Amount per Unit Algal Biomass Growth

- CO_2: 1.8 kg per kg of biomass cultivated.
- Secondary Effluent: 0.36 L per kg of biomass cultivated.
- Nutrients: assume macro and micro nutrients are sufficiently provided by secondary effluent and centrate.

Footprint

- Operational-Scale: assume size of PBR and harvesting equipment will be constrained by onsite CO_2 available and/or maximum area of 50 m x 50 m.
- Pilot-Scale: PBR and harvesting equipment to be housed within the AWC's Research Hall and/or the exterior area east of Research Hall doors.

Relevant Budgetary Information

The approximate budget for the detailed design, manufacture, and assembly of the pilot-scale system at the AWC is $1 million. A budget for the operational-scale system is to be estimated by the student team.

Scope of Work

Background and Literature Review

Given that this project involves emerging processes and technologies, one of the first orders of work for student teams will likely be literature review and orientation on the state of progress made by research foundations, relevant industry groups, and equipment vendors. A number of references are listed at the end of this document to help teams get started. Note that the listing intentionally excludes references to vendors with potentially suitable technologies. Key constraints that could impact the pilot-scale design as well as the operational-scale concept should be identified as part of this work. No specific deliverable is associated with this unit work.

Pilot-Scale Design

With a good portion of the background review done, ideas for a pilot-scale facility can begin. The pilot-scale facility is intended to provide a bridge from the laboratory setting (where a good part of NRC work has been to date) to the AWC, which is a more industrial setting. The pilot-scale facility will be used to examine parameters of optimization for each process unit to help inform the design for an operational-scale installation. The pilot-scale facility will be expected to batch produce algal biomass over durations of weeks and months. The facility must include the following:

- **Microalgae cultivation units**. Photobioreactors will be the choice for layouts with constrained footprints, and the design goal will be for a system to most efficiently grow microalgae biomass. Assume cultivation of Scenedesmus sp. AMDD and Chlorella Sorokiniana. Design considerations include, but are not limited to: size and shape of reactors, lighting design considerations (quantity, quality, intensity, LED bulb technology, light spectrum, and pulsing), handling of inputs and outputs, maintaining optimal temperatures, use of mixers, other requirements for batch processing, and parameters for monitoring and process control. The assessment of various CO_2 diffusers for efficient dissolution in the wastewater should be completed, as well as centrate feed mechanisms.

- **Microalgae harvesting and dewatering units**. Harvesting and dewatering may involve settling, flocculating, dissolved air floatation, and/or mechanical centrifuges. There have been reports of the successful use of industrial fruit juice or cornstarch processing equipment to separate microalgae from its aqueous growing media. The suitability of off-the-shelf designs should be considered when drafting designs for microalgae harvesting and dewatering. The use of flocculants will need to be evaluated with consideration of the impact on biomass quality. While specifications for the microalgae sludge is dependent on market demand, a good target would be to produce a 15% solids cake.

- **Deliverables:**
    - **Report describing:**
        i. The design basis;
        ii. Objectives, considerations, and selection of design;
        iii. Description of how the process chain works;
        iv. 11 x 17 process flow diagram;
        v. 11 x 17 site plan and relevant profiles for Pilot-Scale Process, demonstrating that the design can fit within the Annacis Wastewater Centre property; and
        vi. Demonstration that the design works within available inputs, stated budget, and capacity of industry to build.

Operational-Scale Concepts

Work on operational-scale concepts can start after gaining sufficient knowledge from background and literature review. Learned elements from the pilot-scale work can also feed into the operational-scale work (and vice versa) in parallel as it occurs. The focus of operational-scale concepts is to undertake a life-cycle analysis and develop a business case for the inclusion of a microalgae cultivation facility as part of the overall project definition for the new Iona Island WWTP design. The scope for operational-scale concepts is conceived as follows:

1. Identify the most promising value proposition. For example, should microalgae cultivation be designed to maximize its lipid, protein, or carbohydrate content to produce biochemicals, biofuels, cosmetics, nutraceuticals, or a combination of products? The operational-scale of algal processing should consider matching supply (production) with potential demand and within known constraints or price points (e.g. availability of inputs such as CO_2, nutrients, light, and energy). Identify the microalgae strain to be cultivated. If at this stage, the most promising value proposition cannot be identified, attempt to narrow the range of possible products. Consider quality and/or perception concerns associated with marketing products derived from algal cultures grown in municipal

wastewater effluent. Quantify all inputs and outputs to the proposed microalgae process units, then undertake a life cycle analysis using guidelines of the Algae Biomass Organization. Develop a high-level case for the selected algal biomass and subsequent product industries. Include economic and social elements in the case, with particular consideration to the environmental big-picture in terms of displacement of petroleum products and GHG emission reductions.

2. Consider issues and implications of: use of non-native species, species isolation, microalgae contaminant uptake and toxin production, cultivation robustness, competition from invasive organisms, availability of onsite resources, WWTP effluent quality, and other challenges. Develop ideas on how to address these potential issues.

3. At a conceptual level, suggest an appropriately-sized operational-scale algae facility connected to the new Iona Island WWTP. Show layouts of process units for: phototrophic cultivation, microalgae harvesting and/or dewatering, and handling and short-term storage of algal biomass (as required). For each process unit, provide supporting calculations on how the design capacity (and dimensions) were arrived at. For pump stations/pumping units, simplify your work by determining only the required hydraulic power. Exclude pump impeller selection. Identify points of interface between the algal process units and wastewater treatment processes.

4. Determine ball-park cost estimates for each major algal process unit, and expected benefits – monetary, environmental (including GHG impacts), and social aspects – of your concept.

- **Deliverables:**
    - A report describing the above items.

Supporting Information

Innovation on the topic of microalgae cultivation in wastewater is rapidly evolving, so student teams are encouraged to undertake their own research to uncover concepts applicable to their design. To help initiate your literature research, the following is provided:

1. On microalgae cultivation: http://en.wikipedia.org/wiki/Algaculture.

2. McGinn, Patrick (June 20, 2012). Intensive Cultivation of Microalgae in Wastewater Obtained from the Annacis Island Wastewater Treatment Plant. *National Research Council Canada*.

3. Other subject work by the National Research Council involving Patrick McGinn, Ph.D.

4. Subject work by Tryg J. Lundquist, Ph.D. P.E.

5. Pittman, Jon K.; Dean, Andrew P.; Osundeko, Olumayowa. "The potential of sustainable algal biofuel production using wastewater resources," Bioresource Technology, pp. 17-25, Vol. 102, Issue 1, (January 2011).

6. Andersen, Robert A. (2005). Algal Culturing Techniques, Elsevier/Academic Press.

7. Kunjapur, A. M., & Eldridge, R. B. (2010). Photobioreactor Design for Commercial Biofuel Production from Microalgae. *Industrial and Engineering Chemistry Research , 49*, 3516-3526.

8. Larsdotter, Karin, (2006). Wastewater Treatment with Microalgae – A Literature Review. VATTEN 62: 31 – 38. Lund.

9. Wang L.; Min, Min; Li, Yecong; Chen, Paul; et. al. (2009). Cultivation of Green Algae Chlorella sp. in Different Wastewaters from Municipal Wastewater Treatment Plant. *Applied Biochemistry and Biotechnology*. DOI 10.1007/s12010-009-8866-7.

10. U.S. Department of Energy on algae biofuels:
http://energy.gov/articles/energy-101-algae-fuel
w1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf

11. Factsheet on facultative lagoons:
http://water.epa.gov/scitech/wastetech/upload/2002_10_15_mtb_faclagon.pdf

12. Topic of pond treatment processes in: Wastewater engineering: treatment disposal and reuse. 3rd ed. / Tchobanoglous, George; Burton. / Metcalf & Eddy, Inc. New York: McGraw-Hill, 1991. [Note: newer 4th edition inadequate on this topic].

13. Topic of: high-rate algal ponds.

14. Sustainable Sanitation and Water Management: http://www.sswm.info/home.

15. Edwards, Mark (2008). Green Algae Strategy: End Oil Imports and Engineer Sustainable Food and Fuel. [Available from Food and Agriculture Organization of the United Nations website: www.fao.org/uploads/media/Green_Algae_Strategy.pdf]

16. Guidance to Evaluate Life Cycle Inputs and Outputs (October 2012, Version 5). Algae Biomass Organization – Technical Standards Committee.

Provided by Metro Vancouver:

17. Annacis Island Wastewater Treatment Plant algae cultivation trials.

18. Operational Certificate for the Annacis Island WWTP from the Ministry of Water, Land, and Air Protection.

19. Drawings of the Annacis Wastewater Centre, submitted for building permit.

Metro Vancouver does not guarantee the correctness, accuracy and completeness of any information, interpretation, deduction or conclusion shown and given in the relevant materials.