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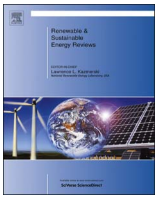

Algae production platforms for Canada's northern climate

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ABSTRACT

Large resources are being invested globally in algae research in the anticipation that these microorganisms will become the “silver bullets” that lead to economic bio-renewable fuels, new food sources, and a host of high value products and simultaneously mitigate rising atmospheric CO_2 levels. A great deal of research has been completed on strains of algae with the potential to produce high lipid yields that make the biomass suitable for biofuel production. Many production systems for algae cultivation continue to be developed for moderate and hot climates (e.g., USA, Europe, and Australia). The largest algae cultivation systems to date use open pond systems. These autotrophic systems, however, have limited applicability in Canada’s northern climatic conditions. There is consensus that closed photobioreactor systems are required to control environmental conditions (including temperature), minimize evaporation and contamination, and augment the limited sunlight available during winter to generate consistent biomass yields for economically sustainable crops. Given the high capital and operating costs, however, many are skeptical that meaningful and economically sustainable algae cultivation can take place in Canada. This paper identifies nine scalable algae photobioreactor cultivation technologies that may suit Canadian northern climates. The information provides insights related to the developing algae industry in Canada as well as highlighting opportunities for further technological development specific to cold climates. Although the review demonstrates that exciting headway has been made, significant technological challenges remain and require that further innovations be developed.

1. Introduction

Over the past relatively short period, there has been a renewed interest in growing and cultivating microalgae for commercial purposes. These single cell plants are extraordinary in their capacity to more than double biomass within a single day [1]. Research shows the plant’s ability to synthesize a host of highly valued compounds, including bio-oils for energy [2–10], hydrogen and isoprene production [11], food, livestock and fish feed [12,13], and coveted health and nutrition ingredients [14–18] while simultaneously improving water [19–21] and air quality [22–26]. It is for this reason that algae is seen to hold enormous potential for meeting a number of our world’s pressing challenges.

There are more than 40,000 species of algae [26,27], each with a unique composition and grown in micro-environments suitable for their existence. Considerable research has been conducted to isolate strains of algae with high growth yields and high lipid content [28]. Both qualities are important to building a business case for a sustainable renewable energy industry.

For commercial purposes, natural environmental growth conditions are weighed against artificial environments that can be tightly controlled and generally lead to much higher yields [26]. When considering artificial environments, emphasis shifts from working only with indigenous algae strains found in particular geographic locations to cultivating strains that offer the greatest yield potential for desired products and potential bi-products.

In Canada’s challenging northern climate, unless there is a specific environmental burden that can be improved through the cultivation of algae in situ, i.e., oil sand tailing ponds, control of algae blooms (or blue-green algae, also known as cyanobacteria, which can negatively affect habitats), it is generally necessary to create artificial environments to achieve meaningful commercial yields of algae biomass.

Each strain will have a unique composition and makeup and likewise require a tightly controlled growing environment to optimize yield. Photobioreactors are constructed to tightly monitor and control all aspects of the growth conditions including lighting, nutrients, temperature, pH, media composition, etc., and ensure optimal growth of a specific algae strain. The challenge in photobioreactor construction is to minimize capital and operating costs to the point where the cost of the biomass produced for industry is less than other competing renewable inputs to biofuel production [26] and/or other valued production endpoints.

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Table 1
Sample microalgae composition [29].

Parameter	NS	ND	Units
Ash	10.9	14.3	% w/w_{db}
C	52.1	53.9	% w/w_{db}
H	7.2	7.5	% w/w_{db}
N	7.8	3.8	% w/w_{db}
S	0.7	0.6	% w/w_{db}
O	21.3	19.6	% w/w_{db}
Total Lipid	23	45	% w/w_{db}
Heating Value (High)	25.8	25.5	MJ/kg_{db}
Heating Value (Low)	24.3	23.9	MJ/kg_{db}

NS = Nitrogen Surplus.
ND = Nitrogen Deprived.
db = dry basis.

An overarching goal of a series of studies by this research group is to develop a model that allows researchers to benchmark technology, performance evaluate and compare different technologies and processes to identify those technologies and processes that will support an economically viable and sustainable algae biomass industry.

2. Microalgae review

Generally, when considering microalgae for economic and commercial uses, it is important to first identify algae strains naturally growing in a region of interest, document the composition of the media and environmental conditions in which they naturally grow, characterize the composition makeup of the algae, and select those species that already demonstrate a natural capacity to synthesize compounds of interest.

By way of example, a recent study on the cultivation of *Nannochloropsis sp. F&M-M24* under altered media nitrogen availability demonstrates how cultivation conditions may alter the elemental composition of produced microalgae biomass [29] (see Table 1).

Mostafa [30] reviewed metabolites as well as phytochemical and biologically active compounds including fatty acids, sterols, carotenoid pigments, antioxidants, anti-cancer, anti-microbial, anti-viral, nematicidal activity and molluscicidal activity. Microalgae can also be used for feed, fertilizer, CO_2 sequestration, wastewater treatment, biofuel production, and phytoremediation for heavy metals.

There is also an ongoing investigative task to determine ways to augment the growth media and environment to optimize both algae growth and the expression of the compounds of interest. Sustainable commercial viability is determined by the balance of capital and input costs versus revenues gained from saleable output products and avoided operating costs (i.e., GHG penalties). There are more exciting possibilities with the investigation of enhanced genetically modified organisms (GMOs) [31]. Acién et al., Norsker et al., and Chen et al. emphasize the importance of achieving biomass production yields that will support economic and commercial viability [32–34]. Abdelaziz et al. and Slade et al. point to the importance of reaching a net positive energy balance for all processes leading to the production of commercial end products [35,36].

Industry is looking for economically sustainable and scalable algae production platforms that will deliver algae biomass at costs that are lower than existing competing inputs. Recent literature provides a useful background on this topic [37–40]. It is the purpose of this research paper to determine the current ability of the algae industry to deliver algae biomass in Canada's northern climate by:

- reviewing cultivation technologies involving artificial environments that are currently being developed and are deployable in Canada;
- identifying a range of cultivation technologies with potential for Canada;
- identifying gaps in knowledge on algae cultivation in Canada.

3. Algae cultivation techniques

The algae cultivation method significantly influences growth characteristics, yield, and composition [41]. Algae growth generally depends on sufficient light and a carbon source for photosynthesis, but depending on the environmental conditions algae may assume a different metabolism approach [42]. The various cultivation methods include phototrophic, mixotrophic, heterotrophic, and photoheterotrophic [43,44]. Chen et al. summarized biomass productivity, lipid content, and productivity for different algae species under various cultivation methods [34]. Their review shows that the phototrophic approach is the most common, although biomass and lipid productivities were relatively low compared with the heterotrophic method when the same algae species were considered. The work by Liang et al. [45] showed that phototrophic cultivation provided higher cellular lipid content (38% for *Chlorella vulgaris*) but much lower lipid productivity compared with algae growth under heterotrophic conditions. Different algae strains can grow using different cultivation techniques. For example, while *Chlorella vulgaris*, *Arthrospira (Spirulina) platensis,* and *Haematococcus pluvialis* grow under phototrophic, heterotrophic, and mixotrophic conditions, strains such as *Selenastrum capricornutum* and *Scenedesmus acutus* grow favourably under phototrophic, heterotrophic, and photoheterotrophic conditions.

Bacterial contamination and infestation by predatory microorganisms, i.e., rotiphers, is a major concern in algae cultivation and addressing it may become even more challenging with high levels of organic substrates that support predator rapid growth. An infestation can rapidly destroy the culture. Great care is generally taken to ensure that the culture is anexic and is maintained in that way [46]. Given the challenges associated with maintaining anexic cultures, there has been a shift, especially over the past five years, toward exploring the benefits of maintaining a biodiverse polyculture [47]. Different cultivation methods are discussed briefly.

3.1. Phototrophic cultivation method

The phototrophic algae cultivation method involves the consumption of light and CO_2 as a source of energy and inorganic carbon [43]. The phototrophic, also known as photoautotrophic, culture method converts light into chemical energy via photosynthetic reactions [34,41,42]. This method of culturing algae is the most commonly used cultivation condition for algae growth; it generally results in media with low cell density but at relatively low cost. The method provides scalability with relative ease, although the low cell density leads to higher costs to concentrate the media [34]. The benefit of phototrophic cultivation is the potential use of CO_2 from flue gases emitted from power plants and heavy industries for its biological fixation [34,43].

3.2. Heterotrophic cultivation method

The heterotrophic cultivation method uses only organic compounds as sources of carbon and energy and therefore eliminates the requirement for light [41]. This method generally results in higher biomass concentration (cell densities of 50–100 g of dry biomass/L) and lipid productivity than autotrophic cultivation (cell densities of 30 g of dry biomass/L) [46]. Examples of organic carbon sources that can be assimilated by algae for growth include glucose, fructose, sucrose, galactose, acetate, glycerol, and mannose [45]. The cultivation method can be scaled up as a conventional fermenter, but there are issues associated with scaling up, such as contamination and competition with other microorganisms, limited number of microalgae species that may be grown heterotrophically, inhibition from excess organic substrate, the inability to produce light-induced metabolites, and high energy and substrate costs [34,46].