Low Cost Nutrients for Algae Cultivation

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Abstract Microalgae are aquatic microorganisms growing phototrophically using sunlight and inorganic nutrients viz. carbon, nitrogen, phosphorus and other micronutrients. Sustainable production of microalgae biomass as feedstock for renewable biofuels is facing important bottlenecks in nutrient and water requirements that may hinder commercial scale development of algal systems. Fertilizer nutrients and fresh water contribute up to 50 % of the total biomass production cost that eventually impact the economical feasibility of algal fuels. In the algae-biofuels industry, nutrients must be found in lower-value sources like wastewaters and other waste streams and for sustainable production, those nutrients be recycled within the system. Integration of algal wastewater treatment with biofuel production has been strongly promoted recently. Utilizing nutrient rich wastewaters and animal wastes like poultry litter can greatly reduce the water and fertilizer demands for alga culture. Additionally, producing algal feedstock from low-cost waste based nutrient media has multiple benefits including improved water quality, N and P recycling from animal waste, reduced environmental footprints, and economic efficiency. This approach appears very attractive, since the impacts of releasing N and P and greenhouse gases into the environment could be mitigated, while conserving nutrients and simultaneously producing a material that can replace crude oil as a fuel feedstock.

Keywords Algae · Wastewater · Nutrient recycling · Poultry litter · Anaerobic digestion

List of abbreviations

AD	Anaerobic Digestion
ADE	Anaerobic Digestion effluent
C	Carbon
CC	Carbonation Column

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CI	Carpet Industry
GHG	Green house gases
N	Nitrogen
P	Phosphorus
PL	Poultry Litter
PLE	Poultry litter extract
R&D	Research and Development
VTR	Vertical Tank Reactor

1 Introduction

Two of the most pressing current global issues are environmental sustainability and the energy crisis. About 87 % of global energy consumption is satisfied by fossil fuels (BP 2012). The availability of fossil-based energy may not be a threat for a considerable period of time; however, the more immediate concern is the potential threat of global climate change due to greenhouse gas (GHG) emissions from fossil fuel usage. Producing energy from renewable biological sources is critical to improved energy security and to establish an environmentally sustainable future. Significant self-reliance on alternative sources of energy protects the economy by eliminating uncertainties caused by fluctuations in fossil fuel prices. Reducing the buildup of GHG can be accomplished by using renewable and CO_2 neutral biofuels produced from biomass. Conventional biomass includes cultivation of energy crops, harvesting forestry residues and agricultural plant residues. Another emerging class of biomass source is microalgae, which have higher photosynthetic efficiency compared to terrestrial plants and grow rapidly. Efficient recovery of biofuel from microalgae can reduce our dependence on fossil fuels.

Microalgae use solar energy; consume nutrients such as nitrogen, phosphorus and other micronutrients from water, and CO_2 from the atmosphere to grow rapidly accumulating renewable biomass. Some species of microalgae produce high (>50 % of their dry weight) quantity of lipids that can be converted into biodiesel and jet fuels (Sivakumar et al. 2010). The unique potential of microalgae has therefore generated interest in the potential use of algae as a new source of renewable energy. Algae as a source of biomass for energy production are particularly attractive because of their higher photosynthetic efficiency (~5 %) than terrestrial plants (<1 %) resulting in higher growth rates (Posten and Schaub 2009). Microalgae can produce 15–300 times more oil for biodiesel production than land-based crops (Schenk et al. 2008). As microalgae can potentially be grown on non-arable land and using wastewater and seawater resources, they do not compete with food crops for land or water. Although algal production has been tested at large scale for several years, recent evaluations (e.g. Brennan and Owende 2010) indicate potential bottlenecks to wide-scale production in areas of nutrient and water requirements, algal productivity, and energy needed for downstream processing. According to Davis et al. (2011) under current open pond and photobioreactor technologies for commercial scale algae cultivation, the minimum selling price of algal biodiesel would be \$ 9.84 and \$ 20.53/gal respectively to achieve 10 % rate to return. This is however, 3–7 times more expensive than petroleum diesel given its current production cost of \$ 3.1/gal (EIA 2012). Therefore, the current economics of microalgal biofuels production is not competitive with traditional fossil fuels. Increasing the algae biomass productivity will provide economy-of-scale and reduce costs. Utilization of spent algal biomass after oil extraction for more valuable co-products using algae biorefinary technology could lead the algae industry into age of bio-based energy and economy (Das et al. 2010).

Algae require large quantities of carbon (C), nitrogen (N) and phosphorus (P) in addition to micronutrients such as iron (Fe). Additionally, raceway cultivation typically produces algal cell densities of 1 g/L (Pulz 2001). The biomass productivity in open raceways and closed photobioreactors is generally expressed as per unit area (g $m^{-2}d^{-1}$) and volumetrically (g $L^{-1}d^{-1}$) respectively. Most of the data assumptions reported in literature are based on extrapolations from laboratory experiments and are therefore misleading. The techno-economic analysis reported by Davis et al. (2011) assumed that currently achievable productivity in open ponds is 25 g m^{-2} d^{-1}. This can be translated into ~80 T ha^{-1} $year^{-1}$ with 330 days of operation. However, the freshwater requirements for algae cultivation in open ponds would be ~1.5 million L ha^{-1} $year^{-1}$ and the evaporation losses would be ~7–11 million L ha^{-1} $year^{-1}$ (Chinnasamy et al. 2010). The present state of the algal production industry (which predominantly targets high-value products such as protein supplements, nutraceuticals, and pigments) uses fertilizer grade nutrient inputs and fresh water for cultivation, a practice that cannot be carried over to the algae-biofuels industry. In the algae-biofuels industry, the sheer size of fuel demand requires that nutrients be found in lower-value sources like wastewaters (and other waste streams) and that those nutrients be recycled to the best of our abilities. In this chapter we first discuss important algal nutrients (presently derived from chemical fertilizers) and their contribution to the overall biomass production process, and thereafter we present the concept of utilizing low cost nutrients from sources such as municipal wastewater, animal wastes, and flue gases.

2 Algae Cultivation

Microalgae have long been used as a source of biomass and the most recent advances in systems biology, genetic engineering, and biorefining techniques suggest that microalgal biofuels could emerge as an economical and sustainable fuel source in the next 1–2 decades (Singh and Gu 2010). However, even with the newfound interest in microalgal biofuels, the technology has a long way to go to achieve cost competitiveness. As microalgal biofuel R&D moves forward, it will confront several key challenges including: finding suitable algal strains; acquiring sufficient low cost nutrients; developing better downstream processing to produce a variety of biofuels and value-added products, etc.

For high algal growth rate environmental conditions such as light, salinity (for marine microalgae), pH, and nutrient levels must fall within a preferred range (Pate et al. 2011). However, particular optimizations of physical factors that affect algal growth are strain specific. The most practical and economically feasible method of commercial scale algal cultivation is the photoautotrophic production in raceways under natural growth conditions using sun light as the energy source (Davis et al. 2011). Competing systems used for algal cultivation include outdoor raceways and outdoor closed photobioreactors. Both systems of cultivation have certain advantages and limitations. Raceways are a lower cost method of commercial scale algal cultivation with lower energy needs and maintenance costs and easy cleaning, resulting in large net energy production (Rodolfi et al. 2009). The inherent limitation of open raceway systems is the potential of contamination from other algae species and protozoa (common algal grazers). Open systems are less efficient than closed photobioreactors in terms of biomass productivity due to uncontrolled physical factors such as temperature fluctuations, evaporation losses and CO_2 deficiencies (Harun et al. 2010). Closed photobioreactors include tubular, flat panel and column reactors designed for advanced photoautotrophic algal cultivation. They are designed to provide greater control over temperature and nutrient delivery, prevent predators, enhance light penetration, and maintain an optimal growth environment thereby improving biomass productivities per unit area (Carvalho et al. 2006). However, the relatively high capital cost and limitations with ease of scaling up of closed photobioreactors put them under the less-preferred category for commercial scale algae production for biofuels (Benemann 2009; Davis et al. 2011).

3 Nutrients Requirements for Algae Cultivation

As aquatic organisms, microalgae need water for growth along with inorganic salts and CO_2. The major essential inorganic elements are nitrogen (N) and phosphorus (P) and for diatoms silicon (Si). Other nutrients required for favorable algal growth are iron, sulfur, potassium, magnesium and other micronutrients and cofactors (vitamins).

3.1 Water

Algal biomass production utilizes large quantities of water that not only provide a growth environment for algae to live and multiply, but also serves as a medium for nutrients delivery, waste removal and temperature regulation. To generate a dry gram of algae biomass, more than a kilogram of non-cellular water is required (Murphy and Allen 2011). The volume of water required for algal cultivation depends on system type and geometry, natural losses from the system, and most importantly, the ability to retain, reclaim and reuse water within the system. This way, the volume of water necessary to grow algae is estimated from two key factors;

amount of water needed to be retained in the system to maintain target biomass productivity and amount required for replacing water losses due to evaporation and downstream processing. One approach to minimize freshwater footprints of algal cultivation is efficient water recycling. Life cycle analysis by (Yang et al. 2011) indicates that 3,276 kg of water is required to generate 1 kg of biodiesel if freshwater is used without recycling, and that a 55 % reduction potential exists if water is recycled. Microalgae have the potential to generate 220×10^9 L year^{-1} of oil which is equivalent to 48 % of current U.S. petroleum imports for transportation. However, the water footprints (312,079 GL year^{-1}) for this level of production would be nearly equivalent to three times of the 113,135 GL year^{-1} of fresh water used for irrigated agriculture in USA in 1995 (Wigmosta et al. 2011; Roy et al. 2005).

3.2 Carbon

Carbon (C) is the most abundant element in algae, contributing around 50 % of algal biomass by weight (Grobbelaar 2004). Under photoautotrophic conditions algae utilize atmospheric CO_2 as carbon source to synthesize organic compounds. Once dissolved in water, there are three principle interconvertible chemical forms of dissolved inorganic carbon viz. CO_2 (aq), HCO_3^- and CO_3^{2-} whose concentrations vary based on the pH of the aqueous environment (Goldman et al. 1981; Becker 1994). Although HCO_3^- is easily absorbed by algal cells, CO_2 is reported to be the most preferred source of inorganic carbon (Goldman et al. 1981). However, at $pH > 10.3$ the CO_3^{2-} form dominates which is generally an unusable form and not available for algal uptake (Knud-Hansen 2006).

CO_2 is often the limiting substrate for photosynthetic cultivation of algae in high rate algal ponds growing at specific productivity of 20 g m^{-2} d^{-1}. Atmospheric air provides to the pond surface only 5 % of the CO_2 required for photosynthesis (Stepan et al. 2002). Hence, CO_2 is usually provided via bubbling of concentrated CO_2-air mixture into the algal pond. Analyses indicate that CO_2 procurement is a significant cost and accounts for about 40 % of energy consumption and 30 % of GHG emissions in algal cultivation (Clarens et al. 2010). Therefore, targeting industrial C emissions as a source is attractive and can increase the overall sustainability of algal cultivation.

There are a number of algae that are facultatively heterotrophic and prefer, where available, an organic carbon substrate over fixing CO_2 (Shi et al. 2000). Some algae are mixotrophic and can simultaneously drive phototrophy and heterotrophy to utilize both inorganic (CO_2) and organic carbon substrates (Sun et al. 2008; Bhatnagar et al. 2011), thus leading to an additive or synergistic effect of the two processes that enhances the productivity and in turn capability of microalgae to grow in wastewaters. Under phototrophic growth, algae harvest radiant energy from sun and convert into valuable biomass at the expense of inorganic nutrients and natural resources (Carvalho et al. 2006). However, microalgae biomass production via this mode cannot reach maximum cell density since light penetration is inversely proportional to the cell concentration (Chen and John 1995). Light requirements increase as cell concentrations increase because mutual shading blocks the penetration of light to algae further in the culture vessel (Posten 2009). As a result deeper regions within algae cultivation system (e.g. ponds) will get deprived of light and net photosynthesis cannot occur (Richmond 2004). Shallow ponds are therefore preferred mode of phototrophic algae cultivation though it brings along several drawbacks such as, large footprints, high evaporation rate (Harun et al 2010). The light penetration limitation becomes more prominent when goal is autotrophic algae cultivation using dark colored industrial wastewater as light penetration inhibition effect become even more prominent. Mixotrophy could overcome problems associated with phototrophic algal growth, such as, light limitation at high cell densities and when using dark colored (opaque) wastewaters.

3.3 Nitrogen

Nitrogen is a major component of cellular proteins and amino acids and comprises around 5–10 % of algal biomass by weight. Despite atmospheric abundance of nitrogen (78 % by volume), algae cannot directly utilize nitrogen gas. The primary N molecules that can be utilized by all algae are ammonia and nitrate, between which the former is the preferred form for algal growth. The biological nitrogen fixation by diazotrophic microbes such as *Rhizobia*, *Azospirillum*, *Anabaena* and *Nostoc,* via reduction of dinitrogen to ammonium was the only route where atmospheric nitrogen entered into living systems until 1909 when the Haber–Bosch process, which chemically converts nitrogen gas into ammonia (Smil 2001), was invented. Currently, algal cultivation predominantly uses nitrogen fertilizer produced from the Haber–Bosch process. Production of 227 billion L (60 billion gal) of algal-biodiesel, which is equivalent to 30 % of the U.S. transportation fuel consumption in 2010, requires 36 million T of nitrogen fertilizer (Huo et al. 2011). However, to produce this volume of biofuels 26 % of the energy in the final fuel product is spent in fertilizer production, adding to the overall cost of algal-biofuels production (Huo et al. 2011). Fertilizer-grade nutrient inputs and freshwater accounts for 50 % of energy inputs associated with algal cultivation (Clarens et al. 2010). Requirements of fertilizer nitrogen input can be minimized either by recycling algal-biomass nutrients via anaerobic digestion and/or thermochemical conversion techniques (Rösch et al. 2012) or by utilizing nutrient rich wastewater as culture medium (Clarens et al. 2010).

3.4 Phosphorus

Of the three primary nutrients (N, P and C) necessary for algal growth, phosphorus (P) is the scarcest nutrient in natural environments. Typically, microalgae contain 1 % P by weight in their biomass (Borchardt and Azad 1968). In some cases algae have higher concentrations resulting from luxury uptake of P, which is performed when this element is available is excess in the medium (Powell et al. 2008). The major source of P in natural environment is phosphate rock obtained through mining. World P reserves are being depleted and some believe that the reality of "peak phosphorus" could be reached in the next few decades (Cordell et al. 2009). Clearly, for sustainable implementation of algal biofuels on a large scale, P requirement has to be obtained from sources other than mineral rock phosphate. The only practical means of sustainable P supply for agriculture and algaculture is through recycling P from manure and other kinds of plant and animal waste. In principle, to close the P cycle, the P content of the algal-waste left after the oil-extraction or conversion process must be recycled into growing the next batch of algae. (Rösch et al. 2012) reported in a material flow modeling study that nutrient recycling rates in the range from 30 to 90 % for nitrogen and from 48 to 93 % for phosphorus can be achieved via anaerobic digestion (AD) and hydrothermal gasification of oil-extracted algal biomass. Biogas and biocrude oil would be the biofuel products from these processes respectively thereby adding economy to algae biofuels. The nutrient rich AD effluent can be used as growth medium for growing second batch of algae (Singh et al. 2011).

4 Integration of Algal Technology with Waste Recycling for Bioremediation and Biofuels

Open pond cultivation of microalgae require large quantities of water, which subjects algal cultivation to controversy, as world water resources are already depleting against exponentially increasing demand for agricultural and industrial use (IWMI 2009). Additionally, the global target for feedstock crops for biofuels production for 2030 itself would demand a staggering 180 km^3 of water (IWMI 2008). Consuming fresh water and fertilizers for algal cultivation will therefore not be environmentally sustainable or economically viable. To reduce this impact, nutrient rich wastewater should be used to offset such environmental and cost burdens associated with algal cultivation. Variations in the composition of wastewater and presence of several unknown constituents, however, could limit the growing of monoculture algal strains in wastewater. Therefore it is essential to select robust, mixotrophic algal consortia that are capable of growing in a variety of wastewaters (municipal, industrial, agricultural and aquaculture wastewaters), improving water quality and simultaneously producing feedstock for biofuels. Integration of biomass production with wastewater treatment will improve the economic feasibility of commercial scale algal cultivation.

4.1 Wastewater as Algae Cultivation Medium

Based on nutrients available in the wastewaters from municipal sources, piggery, and dairy cattle worldwide, Harmelen and Oonk 2006 estimated that the production of 90 million T of algae $year^{-1}$ will be technically feasible in 2020 using municipal wastewater (~40 million T), dairy wastes (~30 million T) and pig wastes (20 million T). Also it was estimated that wastewaters from about 30,000 people or about 5,000 pigs or 1,200 dairy cattle are required for a minimum economically viable scale of about 10 ha of algal ponds. This study shows the biomass production potential of various waste streams (Harmelen and Oonk 2006).

In addition to municipal, agriculture and aquaculture wastewaters, industrial effluents also can be used for algal cultivation to produce bioenergy. In previous research in our group, we evaluated different cultivation systems, namely, raceways, vertical tank reactors (VTRs) and polybags for mass production of algal consortia using carpet industry (CI) untreated wastewaters (Chinnasamy et al. 2010). Overall areal biomass productivity of polybags (21.1 g m^{-2} d^{-1}) was found to be the highest, followed by VTRs (8.1 g m^{-2} d^{-1}) and raceways (5.9 g m^{-2} d^{-1}). We estimated biomass productivity of 51 and 77 Tons ha^{-1} $year^{-1}$ can be achieved using 20 and 30 L capacity polybags, respectively (Chinnasamy et al. 2010). Though the lipid content of the wastewater grown algae is low, the energy stored in other constituents of the biomass could also be recovered through thermochemical liquefaction where the algal biomass with less lipids and 80–85 % moisture could be converted directly to a biocrude with yield in the range of 30–44 % and a heating value of 34.7 kJ g^{-1} (Amin 2009) or into biogas through anaerobic digestion.

We also assessed the potential of carpet wastewater grown algae as energy crop for biomethane production and found that bioenergy recovery from algal consortia cultivated using the wastewater was better than yields estimated for cereals and sunflower (Chinnasamy et al. 2010). That study estimated that the consortium of algae cultivated in polybags using carpet industry untreated wastewater has the potential to produce ~134,144 kWh of renewable power ha^{-1} $year^{-1}$ compared to the estimated value of 97891, 42585 and 39543 kWh for maize, cereals and sunflower, respectively.

Our research group has been operating duplicate 100 m^2 raceways at a carpet wastewater treatment facility where treated wastewater is fed to raceways for algae cultivation. Over a one-year period of continuous operation, on average 200 mg/L biomass production was achieved in raceways. The most interesting result obtained was the 70–80 % removal of P from the wastewater which might be due to luxury uptake of P by algae as the algal biomass harvested was found to have around 3 % P by weight in contrast to the more typical 1 % P content in algae. Raceways were initially inoculated with a consortium of *Chlorella minutissima, Scenedesmus bijuga* and *Chlorella sorokiniana* strains. However, as was expected in open raceways system using wastewater, these strains could not maintain their dominance and were superseded by other locally dominant algae. Weekly samples collected from the two raceways were analyzed for microalgal diversity and biovolume ratio of various species that dominated in different seasons. The results revealed that cyanobacteria (blue green algae) dominated during summer, representing 95 % of the total microalgal population identified in the raceways. *Synechococcus elongates* was the most dominant cyanobacteria during summer and was on average 41 % of the total microalgal population throughout the duration of a batch run. Another dominant strain was *Synechocystis* spp. contributing up to 39 % of the total population. *Leptolyngbya breviarticulata* was also among the dominant cyanobacterial spp. In contrast, during winter green and blue green algae were almost in equal proportions, representing 47–53 % of the total microalgal populations, respectively. Among green microalgae, *Paulinella* was the most dominant with average biovolume of 53 % of the total green algae identified. *Chlorella vulgaris* (15 %) and *Trebouxia gelatinosa* (8 %) were also among the dominant green algal species seen. *Euhalothece sp.,* a salt tolerant cyanobacterium, was the most dominant blue green representing 14 % of the total microalgal population. We conclude from these experiences that for sustainable algal cultivation using wastewater, indigenous algae that are already adapted to the local environment will grow dominantly and is preferred. Further, the seasonal variation in environmental conditions will affect microalgal diversity and biomass quality and quantity from cultivation systems.

4.2 Nutrient Delivery From Animal Waste

Poultry production is the number one agricultural business in the state of Georgia (USA). With more than 5,000 poultry farms in the state, approximately two million tons of poultry litter (PL) is generated annually in Georgia which is ~20 % of the national annual PL generation. The PL from broilers contains approximately 11.3 kg-P and 32.6 kg-N per ton of litter. An estimated amount of nutrients equivalent to 108 T of urea and 85 T of Di-ammonium phosphate can be recovered from PL (Lory and Fulhage 1999). Authors earlier reported isolation of several mixotrophic microalgae belonging to *Chlorella* and *Scenedesmus* genera capable of preferably growing on wastewater and poultry litter extract (PLE) and producing biomass as much as typically achieved from freshwater-based enriched growth media (Bhatnagar et al. 2011). In comparative open pond algal cultivation studies, it was observed that PLE media promoted better growth than standard synthetic fertilizer media. The average growth rate of algae over 18 days operation of ponds was >200 mg L^{-1} and the biomass productivity was 7 g m^{-2} d^{-1} which represents approximately 21 T ha^{-1} $year^{-1}$ with 300 days of cultivation in raceways. Further, an efficient method was developed for extracting nutrients from PL and used those nutrients as growth medium for algal cultivation. This in-situ extraction technique was further optimized in pre-pilot raceways. The insoluble residue from extracted PL was anaerobically digested and was found to have no significant difference in biogas yield when compared to un-extracted PL.

4.3 Nutrient Recycling via Anaerobic Digestion of Algae Biomass

Recently, anaerobic digestion (AD) has seen a resurgence of interest due to its potential for biogas production using high moisture substrates like algae. Methane (CH_4, the principal component of biogas) is one of the cleanest and most energy efficient transportation fuel. Interest is growing in use of CH_4 as a transportation fuel in Europe and Asia where natural gas vehicles are widely driven. Also, biogas generated biopower can be used in electric vehicles. Campbell et al. (2009) noted that biopower pathways deliver more transportation GHG offsets than liquid biofuels. A key advantage of AD is the mineralization of organic N and P into ammonium and phosphate, which can then be recycled to satisfy N and P requirements of algal cultivation making algal production environmentally and economically sustainable.

Although AD of algal biomass has not been reported widely, AD as a technology is well established and commercial scale operations are economically viable. Major challenges in AD of algal biomass include its low C/N ratio due to high protein content of algae and the inability of AD bacteria to degrade intact algal cells, because of cell wall recalcitrance, resulting in low conversion efficiencies (Ehimen et al. 2010). A literature review has shown that there are several researchers who have mentioned the potential for effluent recycling, but we could not find any that have provided experimental data. Our laboratory has had a 1,000 L digester consistently generating biogas with average CH_4 content of 50–80 %(v/v) for the last several months. Effluent from the digester typically is dark in color, which can be centrifuged to obtain a supernatant rich in dissolved nutrients. A representative composition of the AD effluent (ADE) supernatant from our 1000 L digester is given in Table 1.

The reactor was fed an algal slurry at 2 % solids and since algae have about 0.76 % P (Rösch et al. 2012), a total of 152 mg-P/L was fed to reactors. Of this, 100 mg/L (66 % of input P) was recovered as soluble *o*-phosphate suitable for algal cultivation. The ADE supernatant has almost all the nutrients required in a balanced algal growth medium at about tenfold the required concentration. In previous work, we have demonstrated significant algal growth using diluted (6 %) effluents from poultry litter anaerobic digesters without supplementation of any nutrients (Singh et al. 2011). Results showed that all organisms evaluated reached cell densities greater than 0.55 g/L, with *Scenedesmus bijuga* reaching the highest concentration of just below 0.70 g/L in eight days. Biomass productivity of 76 mg L^{-1} d^{-1} was recorded for microalgae grown in PLDE with concomitant nitrogen (60 %) and phosphorus (80 %) removal from effluent in 8 days. The algal biomass was rich in proteins and low in lipids and could be used as an animal feed supplement. Although wastewater grown algae may not have a high lipid content, AD of algal biomass can produce as much energy as can be recovered from extraction of lipids (Sialve et al. 2009). Several researchers have concluded that bioenergy pathways that include wastewater use and biogas production may be the most practical processes for converting algae into energy (Costa et al. 2008; Campbell et al. 2009; Wiley et al. 2011).

4.4 Carbon Supplementation

Algal biomass contains about 50 % C and it has long been known that supplementing C in algal cultivation will increase productivity significantly. Growing algae at high productivities (>20 g m^{-2} d^{-1}) is typically done by bubbling air (or 5 % CO_2)

Table 1 Elemental composition of clear Algae-AD Effluent (ADE)

Elemental analysis	ADE (mg/L)
Total Phosphorus (TP)	103
o-phosphate P (PO_4-P)	100
Potassium (K)	100
Calcium (Ca)	94.8
Sodium (Na)	160
Magnesium (Mg)	53.7
Sulfur (S)	13.3
Iron (Fe)	4.78
Total Nitrogen (TN)	322
Nitrate-N (NO_3-N)	0.6
Ammonium-N (NH_3-N)	281
Total organic carbon (TOC)	300
COD	973

through the culture liquid. Targeting industrial C emissions as a source is attractive and can increase the overall sustainability of algal cultivation.

An important challenge with using exhaust gases from fixed sources is the geographical disconnect between the source and algal farms. Pumping CO_2 gas distances over a mile is cost prohibitive (Sheehan et al. 1998), and such pumped gas is only usable during daylight hours for photosynthesis, thus requiring a capture and storage method. Typically, CO_2 is separated from a mixed gas stream (e.g. flue gas), compressed to 150 atm and transported off site in containers, which are energy intensive processes. Kadam (1997) estimated delivered CO_2 cost for the standard process with monoethanloamine (MEA) extraction as US$40.5/MT for a 500 MW power plant. This cost included $ 28.72 for CO_2 capture via MEA extraction, $ 8.48/MT CO_2 for compression and drying, and $ 3.30/MT CO_2 for transportation.

It is known that bubbling a gas stream through the algal culture medium results in only a fraction of the CO_2 taken up by the algae and as much as 80–90 % of the CO_2 is simply lost to the atmosphere (Becker 1994; Richmond and Becker 1986). We have developed and used a carbonation column (CC) system to increase the interfacial area of contact available for gas exchange to liquid and propose it as an efficient alternative (Putt et al. 2011). The CC performance recorded was 83 % CO_2 transfer efficiency. This CC design is an example of a hybrid system combining a column bioreactor and open pond. The proposed device can be used with any exhaust gas stream with higher concentrations of CO_2 in conjunction with raceways for optimizing algal production. The use of the CC for CO_2 mass transfer into microalgal culture ponds not only offers enhanced efficiency of gas transfer but also meets the CO_2 demand of high-rate algae outdoor ponds. The CC performance is twice the transfer rate compared to direct bubbling, and thus offers the opportunity to significantly reduce the cost of algae pond carbonation. For less than a 1 % increase in the installed cost of the farm, the cost of the carbon dioxide when a CC pit is used is nearly half that of the deepest in-pond carbonation well reported in the literature (Putt et al. 2011). The ease to design and construct the CC makes it an economical device for carbon recycling and can be used with various CO_2 rich air streams for optimizing algae production.

Overall, microalgae have the potential to curb emerging environmental problems, by fixing CO_2 released from industries and treating industrial wastewaters. Such technology meets the priorities of developing countries handling wastewater from different sources in a sustainable, cost-effective, and environmentally sound manner. Future work should focus on evaluating the economics of integrated waste treatment processes for commercial-scale production of algae biodiesel, biomethane, bioethanol and biocrude through biochemical and thermal conversion processes.

5 Conclusion

Production of bioenergy from waste streams conserves natural resources. Integrated waste management coupled with bioenergy production, can be a near term solution. Apart from treating wastes, this microalgae technology also produces renewable algal biomass for conversion into value added products such as biomethane, biocrude, biodiesel, bioethanol and protein supplements. Coupling microalgae cultivation with nutrient removal from animal wastes (e.g. poultry litter) will be an attractive option for minimizing fertilizer requirements and eventually the energy costs of biofuel generation from microalgae. Successful implementation of microalgae technologies for wastewater treatment and CO_2 cycling would help to establish advanced integrated waste management facilities for production of bioenergy and bioproducts in the future. Producing energy locally from renewable biomass sources is critical for achieving energy independence and these pathways described here show great promise. Future work should focus on large-scale microalgae technologies for waste treatment coupled with bioenergy production.

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