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Microalgal biomass production and carbon dioxide sequestration from an integrated ethanol biorefinery in Iowa: A technical appraisal and economic feasibility evaluation

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ABSTRACT

Microalgae present some advantageous qualities for reducing carbon dioxide (CO_2) emissions from ethanol biorefineries. As photosynthetic organisms, microalgae utilize sunlight and CO_2 to generate biomass. By integrating large-scale microalgal cultivation with ethanol biorefineries, CO_2 sequestration can be coupled with the growth of algae, which can then be used as feedstock for biodiesel production. In this case study, a 50-mgy ethanol biorefinery in Iowa was evaluated as a candidate for this process. Theoretical projections for the amount of land needed to grow algae in raceway ponds and the oil yields of this operation were based on the amount of CO_2 from the ethanol plant. A practical algal productivity of 20 $g\,m^{-2}\,d^{-1}$ would require over 2,000 acres of ponds for complete CO_2 abatement, but with an aggressive productivity of 40–60 $g\,m^{-2}\,d^{-1}$, a significant portion of the CO_2 could be consumed using less than 1,000 acres. Due to the cold temperatures in Iowa, a greenhouse covering and a method to recover waste heat from the biorefinery were devised. While an algal strain, such as *Chlorella vulgaris*, would be able to withstand some temperature fluctuations, it was concluded that this process is limited by the amount of available heat, which could maintain only 41 acres at 73 °F. Additional heating requirements result in a cost of 10–40 USD per gallon of algal oil, which is prohibitively expensive for biodiesel production, but could be profitable with the incorporation of high-value algal coproducts.

1. Introduction

One of the major contributions to climate change comes from the increasing levels of carbon dioxide (CO_2) in the atmosphere. Our dependence on fossil fuels correlates strongly with this global problem. If left unresolved, it may pass a critical point, after which our efforts toward restoration will be ineffective [1]. As we move toward alternative sources of energy, there remains a necessity for high energy density fuels to replace petroleum. Liquid fuels derived from biomass

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represent one sustainable option and corn-based ethanol has led the way in providing a source of first-generation biofuel. However, in recent years corn-based ethanol has received criticism for its reliance on fossil fuel for production [2]. Life cycle assessments indicate that corn-based ethanol would not qualify as an advanced biofuel, but one viable route to decrease the amount of CO_2 emitted from an ethanol biorefinery is through the co-cultivation of microalgae. The possibility of decreasing the carbon footprint of corn-based ethanol while producing a second-generation biofuel is an appealing venture.

Microalgae are unicellular photosynthetic organisms that convert light energy into chemical energy. Algae have been typically grown in the Southwestern United States to produce edible biomass and nutraceuticals [3]. Depending on the species and growth conditions, algae can be selected to produce a diverse distribution and abundance of lipids, protein or carbohydrates. The National Renewable Energy Laboratory (NREL) has conducted extensive research on the capacity of algae to produce usable lipids (oil feedstock for biodiesel) [4]. The ability to generate large quantities of lipids without the use of fertile land has led to a renewed interest in microalgal-derived biofuels. In producing biomass, algae are capable of using CO_2 as their primary carbon source. They have also been used to sequester flue gas from power plants [5]. Microalgae can be continuously harvested for their lipids, which can be further processed into biodiesel.

Growing microalgae in conjunction with an ethanol biorefinery provides several benefits. The constant availability of CO_2 allows for microalgal production year-round. Furthermore, for widespread domestic bioenergy production, it will be important to develop distributed algal growth facilities that may be operated during colder seasons. Excess heat from an ethanol biorefinery can be used to maintain the algae at a constant temperature, particularly during winter months. The potential to sequester CO_2 while producing a second-generation biofuel and improve the viability of corn-ethanol has led us to investigate the implementation of this scenario.

The purpose of this study was to determine the feasibility of integrated algal cultivation in non-ideal Midwest climates using local resources. We herein propose a theoretical analysis of algal biomass production utilizing the excess heat and CO_2 of an Iowa ethanol biorefinery and define the necessary criteria that need to be met. Although some inherent biological limitations do exist for microalgal productivity, the aim of this study was to determine the engineering challenges that an integrated biorefinery may encounter and provide recommendations to ensure the success of such a project.

1.1. *Symbols and abbreviations*

A, surface area of raceway pond (ft^2)
ΔH_v, heat of vaporization (Btu lb^{-1})
gpm, gallons per minute
L, pond length (ft)
mgy, million gallons per year
ppm, parts per million
P_w, saturation pressure of pond water (psia)
P_a, saturation pressure of air at dew point (psia)
q_{ev}, evaporative heat loss (Btu h^{-1})
q_{cv}, convective heat loss (Btu h^{-1})
q_{rd}, radiative heat loss (Btu h^{-1})
Q_{X-Y}, heat transfer between material X &Y (Btu h^{-1})
SA, surface area of pond covering (ft^2)
T_a, ambient air temperature within greenhouse (°F)
T_e, external air temperature (°F)
T_w, pond water temperature (°F)
U, overall heat transfer coefficient (Btu h^{-1} ft^{-2} $°F^{-1}$)
W_p, rate of evaporation (lb h^{-1})

2. Background

Microalgae are diverse in habitation and exceptionally tolerant of extreme environmental conditions. They have also adapted to survive in conditions of low sunlight and minimal CO_2; however, if provided with sufficient nutrition, carbon dioxide, and light to drive photosynthesis, algae can be incredibly productive. The CO_2 concentration in the atmosphere is only 300–400 ppm [6]. For industrial purposes, relying only on diffusion of CO_2 through the surface of the pond limits the algal growth. A constant supply of additional CO_2 during daylight hours is necessary for maximum algal biomass production. Locating algal culture facilities in close proximity to an ethanol biorefinery allows for this ample source of carbon and can reduce the operating costs by as much as 20% [7].

Iowa is one of the nation's largest ethanol-producing states, accounting for 26% of the total U.S. ethanol production [8,9]. With plans for plant expansions and new plant construction, Iowa's biofuel capacity is expected to increase by 25% [8]. This will result in a large increase in the emissions of carbon dioxide from the conversion of corn to ethanol. Based on a straightforward mass balance, this process produces 2.85 kg of CO_2 for every gallon of ethanol, on average.

Microalgae can achieve higher biomass productivities than terrestrial plants and are, accordingly, able to sequester more CO_2. On average, algae consume 1.83 g CO_2 to produce 1 g of biomass [10–12]. This enormous capacity to sequester CO_2 makes them an ideal candidate for CO_2 mitigation. Studies conducted on the ability of algae to fix flue gas CO_2 show that there is an overall 90% reduction in CO_2 [13].

Some of the major hurdles in commercially cultivating algae outdoors are low areal productivity and low culture density. Algae grow to 0.5–1.5 g L^{-1} in outdoor raceway ponds at a rate of 5–20 g m^{-2} d^{-1} [14]. This wide range of areal productivities is largely attributed to the variability in temperature and sunlight. The convenient supply of CO_2 in Iowa does come with a trade-off: the annual temperature variance is significant and can adversely affect the growth of algae. Fig. 1 shows the average temperatures for Sioux City, Iowa.

High areal productivities can be maintained by harvesting the culture on a daily basis. This promotes high growth rates by preventing nutrient depletion and mutual shading, caused by high-density cultures [15]. Two of the most common microalgal culturing systems are outdoor raceway ponds and closed photobioreactors (PBRs). These technologies are

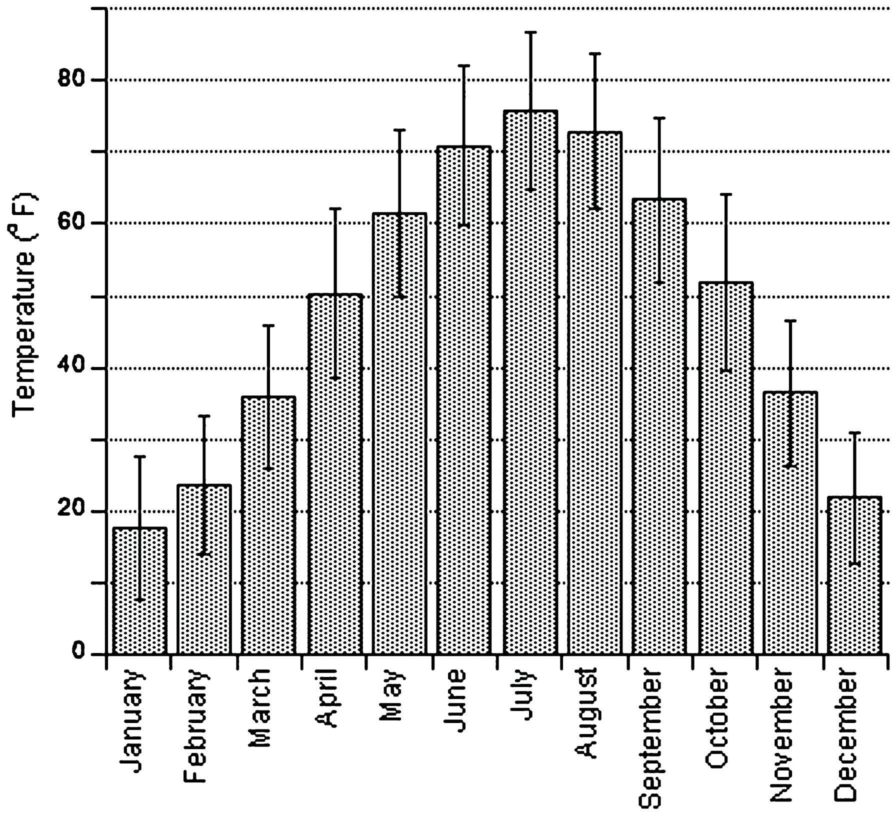

Fig. 1 – Monthly temperature data collected in Sioux City, Iowa in 2003 [17]. Each shaded bar represents the average temperature for each month with the associated lines denoting maximum and minimum temperatures.

routinely operated by different sectors of the algaculture industry [14,16].

The coupling of microalgal production facilities and CO_2 emission point sources has been promoted and investigated for decades [4,18,19]; yet, this application has only come to fruition within recent years and is still not entirely successful. For instance, one such venture carried out by the start-up, GreenFuel Technologies (previously of Boston, Massachusetts) aimed to adapt microalgal species to grow in closed PBRs aerated with unfiltered flue gas. Due to inconsistencies and unexpected consequences of large-scale growth in closed systems during pilot plant demonstrations, the company has discontinued this technology [20]. Since the climate of Israel is more amenable to outdoor cultivation in raceway ponds, a new partnership between the algal cultivation leader Seambiotic Inc. and the Israeli Electric Company plans to produce algal biomass inexpensively for use as biofuel using flue gas from coal-fired power plants (Dr. Ami Ben-Amotz, personal communication). However, unlike the impure CO_2 emissions from coal-fired power plants, biological production of CO_2 by fermentation is a clean feedstock for microalgal growth.

2.1. *Microalgal cultivation*

A number of microalgal species have been cultivated commercially; *Chlorella* and *Spirulina* have been grown as food supplements and *Dunaliella salina* has been grown to produce beta-carotene [21]. The success of these species is largely attributed to their low-cost culturing systems as well as their ability to grown in extreme conditions. *Spirulina* can grow in highly alkaline conditions, while *D. salina* can withstand saline conditions ten-fold greater than seawater [22].

Studies have been conducted to increase the oil producing capabilities of algae. Factors such as temperature, irradiance, and nutrient availability have been shown to affect both lipid composition and content [23]. When grown in nitrogen-deplete conditions, the lipid content in the cells nearly doubles; however, this is offset by a significant decrease in biomass generation [23,24]. Therefore, the optimal condition for producing large quantities of lipids is to grow algae in nutrient-sufficient conditions. The lack of available seawater in Iowa limits the use of marine algal strains. Table 1 lists the most promising freshwater algae species that can be cultivated for the production of biodiesel.

The most cost-effective vessel for growing algae at large scales is an artificial outdoor pond. The predominant design for these ponds is a rectangular raceway made from two trenches dug in the ground with a separating barrier; this allows for water to flow in a circular motion around the pond, similar to a racetrack (Fig. 2a). Raceway ponds have been used since the 1970s and are currently being operated in Japan, Taiwan, Mexico, Israel, Thailand and the United States [25]. The bottom of the pond is compacted and lined with polyvinyl chloride (PVC) to prevent the loss of media and nutrients. The depth of the pond is between 0.1 and 0.3 m, which allows for maximum sunlight penetration [12,19].

Table 1 – Candidate algal strains for the production of biodiesel.

Species	Habitat	Oil Content (% dry weight)	Source
Chlorella vulgaris	Freshwater	26–32	[18,12]
Scenedesmus sp.	Freshwater	16–40	[5]
Neochloris oleabundans	Freshwater	29–54	[4,12]
Botryococcus braunii	Freshwater & Marine	25–75	[4,12]
Spirogyra sp.	Freshwater	22	[19]
Oedogonium sp.	Freshwater	27	[19]
Nannochloropsis sp.	Marine	29–68	[16]

A paddle wheel mixer is used to prevent the algae from settling. It also ensures that all the algae are equally exposed to sunlight and that there is no clumping. The paddle wheel has a low clearance with the sides and the bottom of the pond. This minimal clearance prevents backflow and allows all of the power of the paddle wheel to mix the pond. The nutrients and media are added to the pond behind the paddle wheel, and algae are harvested from behind the paddle wheel. The paddle wheel, along with the smooth PVC lining, also prevents regions of nutrient deprivation.

An added benefit of raceway ponds is their low construction costs. They are also simple to operate, requiring only a few parameters to be controlled, such as CO_2 and nutrient concentration. Their low capital cost and ease of scalability make them an ideal system for growing algae. Commercial scale production facilities as large as four hectares have been operated by Earthrise Farms (Irvine, CA) [26]. These operations utilize a multitude of ponds to cover the entire usable growth area. The standard size of each raceway pond unit is typically a fraction of an acre. The one drawback of growing algae in raceway ponds in the Midwest is the temperature fluctuation during the year and the shortened day/night cycles during the winter months. Both of these issues can significantly affect the growth rate and lipid accumulation in algae.

Evaporation and convection can account for a substantial amount of heat loss, especially in colder climates. To prevent the escape of heat from the algal culture medium, a greenhouse structure can be erected directly over each raceway pond (Fig. 2b). This physical barrier also serves to protect the pond from contamination. Several different types of greenhouse glazing materials are available including glass, polyethylene, polycarbonate, and acrylic. The key criteria for selecting a glazing material are cost, lifespan, strength, weight, and thermal conductance. While greenhouse enclosures represent an additional capital cost, they are absolutely necessary for microalgal cultivation in the Midwest.

3. Materials and methods

3.1. *Design of culture system*

The proposed model cultivation system is designed to maximize the use of available CO_2 and waste heat from a nearby ethanol biorefinery (Fig. 3). The CO_2 produced from fermentation will be mixed with air to create a 30–50% v/v mixture before it is filtered, injected into the culture system, and converted into biomass. The waste heat from the ethanol biorefinery will also be used to heat the liquid medium in the culture system during the winter months.

The proposed raceway pond will be 100 m × 10.1 m × 0.2 m and hold 200,000 L of water and nutrients with a quarter-acre footprint. The covering system will be constructed from greenhouse bays spaced 1.5 m apart and covered with a greenhouse glazing material. After analyzing several different glazing materials, the most suitable choice for the covered ponds was a double layer polyethylene film. This film consists of two layers of polyethylene inflated with a pocket of air between them. The presence of air between the two layers decreases condensation and provides further insulation to the greenhouse [27]. Polyethylene film has a light transmittance of 76% for a double layer [28]. This provides more than adequate sunlight for maximal photosynthetic efficiency. Polyethylene is also a lightweight material and does not require a strong reinforced structure to support it. Polyethylene has a low thermal conductance of 0.7 Btu h^{-1} ft^{-2} $°F^{-1}$ for a double layer film, which reduces the amount of heat lost from the structure [29,30]. The only downside to polyethylene is that it is susceptible to wear caused by dust and debris during high winds.

A two-stage cultivation system will establish a monoculture of microalgae within the ponds and ensure dominance of the desired species [31]. The first culturing system will be a flat-panel photobioreactor, which has been proven to be effective at growing algae at small scales [32]. Flat-panel PBRs are fabricated with transparent materials and allow for accelerated growth rates in relatively dense cultures due to high surface area to volume ratios [33]. PBRs routinely produce up to 20 g biomass L^{-1} compared to the 0.5–1.5 g L^{-1} observed in raceway ponds [34]. A high-density inoculum (grown in PBR) fed into the raceways coupled with daily harvesting is the

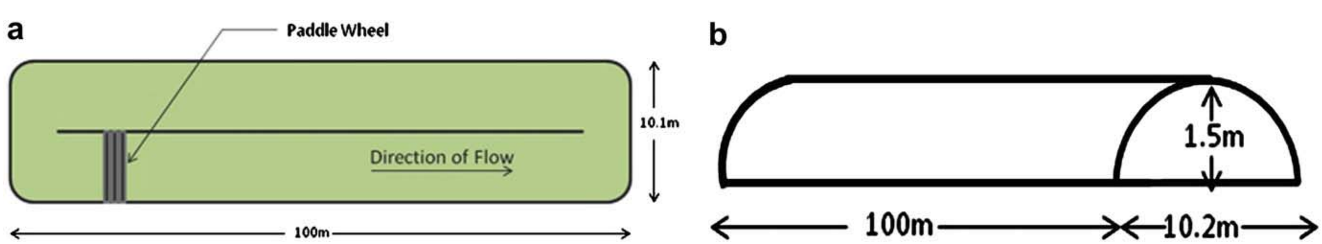

Fig. 2 – Schematic overview of the dimensions of the (a) quarter-acre raceway pond and (b) its corresponding greenhouse covering.

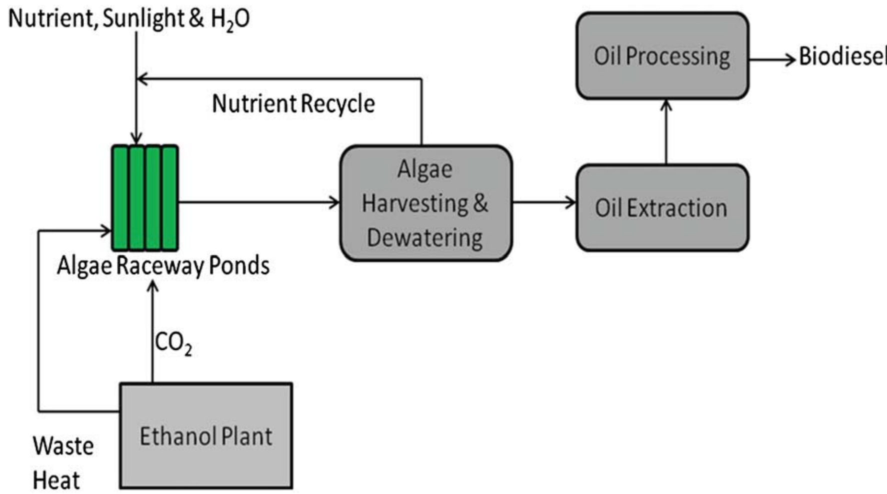

Fig. 3 – Process flow diagram of the integrated biodiesel–ethanol operation. Although this image is meant to illustrate the connections between each process, the model also eludes to the physical layout of the integrated biorefinery, as the raceway ponds must be located close to the ethanol plant.

most effective way to operate outdoor systems and encourages maximum utilization of available CO_2 and waste heat.

3.2. *Engineering principles and mathematical projections*

The land requirements to sequester CO_2 are based on a range of areal productivities – a currently attainable 20 g m^{-2} d^{-1} through an aggressive estimate of 60 g m^{-2} d^{-1}. A value of 1.83 g CO_2 g^{-1} biomass was used to determine the amount of CO_2 sequestered.

To estimate the theoretical amount of biodiesel produced, it was assumed that all of the CO_2 injected into the ponds is converted into algal biomass and the conversion of algal oil into biodiesel results in a 1:1 mass conversion ratio. A value of 0.864 kg L^{-1} was used for the density of biodiesel [35].

The peak heating requirements for the quarter-acre raceway pond were obtained using the convective, radiative and evaporative losses from the pond. Evaporative losses account for the largest percent of heat loss from the pond; this is due to evaporation taking energy away from the pond. Evaporative losses occur even when the temperature of the air is at the same temperature of the water. The evaporative losses were calculated using the following equation:

$$q_{ev} = \Delta H_v \times W_p \quad (1)$$

where W_p estimates the rate of evaporation and is modeled by [36]:

$$W_p = 0.204 \times A \times (P_w - P_a)$$

and $\Delta H_v = 1050$ Btu lb^{-1} for water.

The second major source of heat loss from the ponds occurs due to natural convection. This is a result of hot air near the pond rising and being replaced by cold air. The convective heat losses from the pond were obtained using [36]:

$$q_{cv} = 0.38(T_w - T_a)^{0.25} \times A \times (T_w - T_a) \quad (2)$$

The last source of heat loss that was accounted for in the model is radiative heat losses. These losses occur due to the temperature difference between the pond water and the water vapor present in the air near the pond surface. The water vapor temperature is assumed to be the same temperature as the air in the enclosure. Radiative heat losses were obtained using [37]:

$$q_{rd} = \varepsilon \times \sigma \times [(460 + T_w)^4 - (460 + T_a)^4] \times A \quad (3)$$

where, ε represents the emissivity of water (0.93), σ is the Boltzmann constant (0.174 × 10^{-8} Btu h^{-1} ft^{-2} °R^{-1}), and 460 is used to convert from Fahrenheit to Rankine.

The total heat loss from the water in the pond to the air inside the elliptical greenhouse was calculated by adding the three main significant modes of heat loss:

$$Q_{Water-Air} = q_{ev} + p_{cv} + q_{rd} \quad (4)$$

Next, the heat loss from the greenhouse to the outside air was accounted for in the model. It was assumed that the greenhouse covering was well sealed with negligible air infiltration. An overall heat transfer coefficient for double-layer polyethylene insulation was used to determine the heat lost from the greenhouse to the atmosphere [29,30]. The total heat loss from the surface of the enclosure was calculated with the following:

$$Q_{Air-Air} = U \times SA \times (T_a - T_e) \quad (5)$$

A steady state heat balance on the culturing system was carried out to determine the inside air temperature and the peak heat required.

The available heat for the microalgal culture was designed to come from the ethanol biorefinery cooling tower stream. During the coldest part of the winter, wastewater streams exit the ethanol biorefinery at an average temperature of 29 °C and are sent to a cooling tower where heat is removed. The flowrate into the cooling tower is 15,000 gpm. This ethanol wastewater stream can provide a potential 81 million Btu hr^{-1}. This data was obtained in 2009 from a 50-mgy ethanol biorefinery operating in Merrill, Iowa (CP Stremick, Plant Manager, personal communication).

4. Results

Based on the operating information available for a 50-mgy ethanol biorefinery, a detailed analysis was carried out to examine the feasibility of producing algal biofuels in the Midwest. An algal species with promising attributes for biodiesel production was selected and the land requirements were also determined. In addition, the maximum amount of CO_2 that could be used was determined and the capital and operational costs of the culturing system were calculated based on current data.

4.1. *Algal species selection for Midwest climate*

In selecting a microalgal species for biomass production in Iowa, careful consideration was given to the following: (1) ability to grow in extreme environments; (2) rapid growth rate/doubling time; (3) cell characteristics which might reduce harvesting costs; (4) tolerance of temperature variations as well as changes in light intensity; (5) optimized growth for varying light/dark cycles and (6) high lipid content within cells. All these factors are important in producing a large quantity of biomass year-round and a high lipid content that can be converted to biofuel (Table 2).

Adding high amounts of CO_2 into the algal ponds will also make the culture medium somewhat acidic. Therefore, it is important that the species selected can tolerate pH shifts. This quality will also aid in preventing foreign species of algae from competing with the desired species. Taking into account the local climate and available resources, the optimal species for outdoor ponds in Iowa is *Chlorella vulgaris*. A significant amount of research has already been conducted on its ability to produce large quantities of lipids for biofuel production [42–47]. Despite *C. vulgaris*' proclivity for neutral pH, it is capable of growing within a wide range of temperatures and irradiance and has a rapid doubling rate. These desirable traits help to ensure a relative monoculture within the raceway ponds. Additionally, *Chlorella* has been successfully cultivated to produce up to 25 g m^{-2} d^{-1} in outdoor raceway ponds [48,49].

In addition to strain selection, genetic manipulation is another strategy to generate a microalgal strain that is dominant over competing species. Genetic engineering may also provide a mechanism of increasing lipid yield, but further research needs to be conducted to determine the stability of these species [42]. Two of the current foci of genetic manipulation for this purpose are to increase the areal productivity through altering photosynthetic antenna size and augment the lipid content through metabolic engineering.

4.2. *Land requirements and CO_2 sequestration*

For an ethanol biorefinery that produces 50 mgy, 143,000 tons of CO_2 are produced annually through the fermentation process. This allows for an abundance of reduced carbon feedstock for the algae to grow. In determining the land requirements, two criteria were analyzed: the average algal areal productivity and the percent of CO_2 to be sequestered. The areal productivity of microalgae is an important factor when determining the land requirement. Microalgae have been grown commercially with areal productivities of at least 10 g m^{-2} d^{-1}, but studies have shown that biomass productivities of up to 60 g m^2 d^{-1} are attainable [50]. The second factor critical to determining the land requirements is the percent of CO_2 to be sequestered.

Sequestering all of the biorefinery's CO_2 at 20 g m^{-2} d^{-1} will require 2,639 acres of continuous land – a large area that is not readily available. A more reasonable amount of land is 1,000 acres or about 1.56 square miles, where a potential 60% of CO_2 can be sequestered with an areal productivity of 30 g m^{-2} d^{-1} (Fig. 4). As the amount of land increases, the cost of pumping nutrients and harvesting the algae increases. Due to the shallow depth of raceway ponds, one of their inherent flaws is their dependence on large areas of land. Therefore, careful consideration should be given to the balance between biomass productivity and cost of transporting CO_2, nutrients and water. Proposals to provide nutrients for algae growth such as nitrogen, phosphates, and potassium with on-site anaerobic digestion of biomass are appealing [51–54].

The theoretical maximum amount of biodiesel that can be produced assuming a 1.83 g of CO_2 yields 1 g of biomass and

Table 2 – Optimal algal strains for the production of biodiesel in the Midwest.

Species	Advantages	Disadvantages	Source
Chlorella vulgaris	• Wide temperature tolerance range 5–30 °C • Capable of growing in 40% CO_2 • Rapid doubling time (8 h) • Substantial research already available	• Optimum pH between 7.5 and 8	[10,38,39]
Botryococcus braunii	• High lipid content • Tolerates wide range of light intensities	• Slow doubling time (2 days) • CO_2 & temperature tolerance unknown	[40]
Scenedesmus sp.	• Large, heavy cells; settle rapidly • Ease of availability	• Optimal temperature 30–35 °C • Low CO_2 tolerance	[10]
Neochloris oleoabundans	• Grows well in high CO_2 levels • High lipid content	• Slow doubling time (1.4 days)	[41]

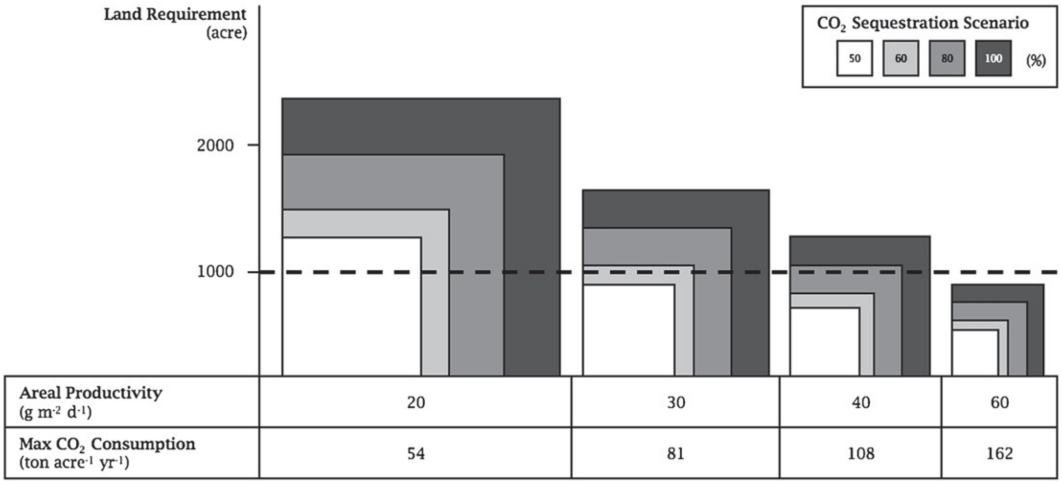

Fig. 4 – Estimated land requirements for various scenarios of areal microalgal productivity and carbon dioxide consumption (shaded regions). The dashed line at 1,000 acres represents a realistic amount of usable land in proximity to the ethanol plant. Shaded rectangles that fall within this region are deemed plausible cases; however, productivities greater than 30 g m^{-2} d^{-1} are considered extremely aggressive for raceway pond production.

a 1:1 mass conversion of algal oil to biodiesel was calculated for various percentages of potential oil accumulation. These data also assume that the oil present in the algae is all usable triacylglyceride (TAG). TAGs are an ideal feedstock for biodiesel production as they can easily undergo a transesterification reaction in the presence of an alcohol, such as methanol or ethanol, and a catalyst, such a sodium hydroxide or potassium hydroxide [6].

Based on the areal productivity of 20 g m^{-2} d^{-1}, a target goal of sequestering 50% of the available CO_2 is a possible option, producing 2.4 million gallons of biodiesel per year. If the algae are genetically engineered or selected to produce a higher lipid content a maximum of 7.2 million gallons of biodiesel can be produced annually (Table 3).

4.3. *Heating requirements*

Maintaining a constant culture temperature during the winter months, especially during periods of irradiance is critical to ensure algal viability and high productivity. To maintain a constant temperature within the raceway ponds, the waste heat streams from the ethanol biorefinery were analyzed for available heat. The available sources of usable heat from the ethanol biorefinery are from the distillation tower and evaporator effluent as well as the fermentors. These heat source streams are sent to a cooling tower, which removes the heat and then recycles the water back into the ethanol production process. The cooling tower operating in Merill, Iowa is rated at 108 million Btu h^{-1} and flows 15,000 gpm of process water. During the winter months the load on the cooling tower is lower due to a lower ambient temperature. Water enters the cooling tower at 84.2 °F and is reduced to 73.4 °F. A potential 81 million Btu h^{-1} of energy is available in this stream and could be used to heat the raceway ponds.

The peak heating requirements for the quarter-acre raceway pond were obtained using the convective, radiative and evaporative losses from the pond. The amount of heat required on a monthly basis was calculated using the assumption that the peak heating requirements were needed for a 12-h period during the night for the entire month (Fig. 5). To estimate the maximum peak-heating requirement for a quarter-acre raceway pond, January's minimum temperature of 7.7 °F was used to determine a heating requirement of 490,000 Btu h^{-1}. During the months of December and January,

Table 3 – Projections for the amount of biodiesel that can be produced annually over a range of lipid contents if a fraction of the CO_2 is sequestered, assuming an areal productivity of 20 g m^{-2} d^{-1}.

Percent of total CO_2 sequestered	CO_2 sequestered (metric tons)	Algal biomass produced (metric tons)	Biodiesel produced at percent oil (million gallons)		
			20%	40%	60%
100%	143,000	78,000	4.8	9.5	14.3
80%	114,000	62,000	3.8	7.6	11.5
60%	86,000	47,000	2.9	5.7	8.6
50%	71,000	39,000	2.4	4.8	7.2

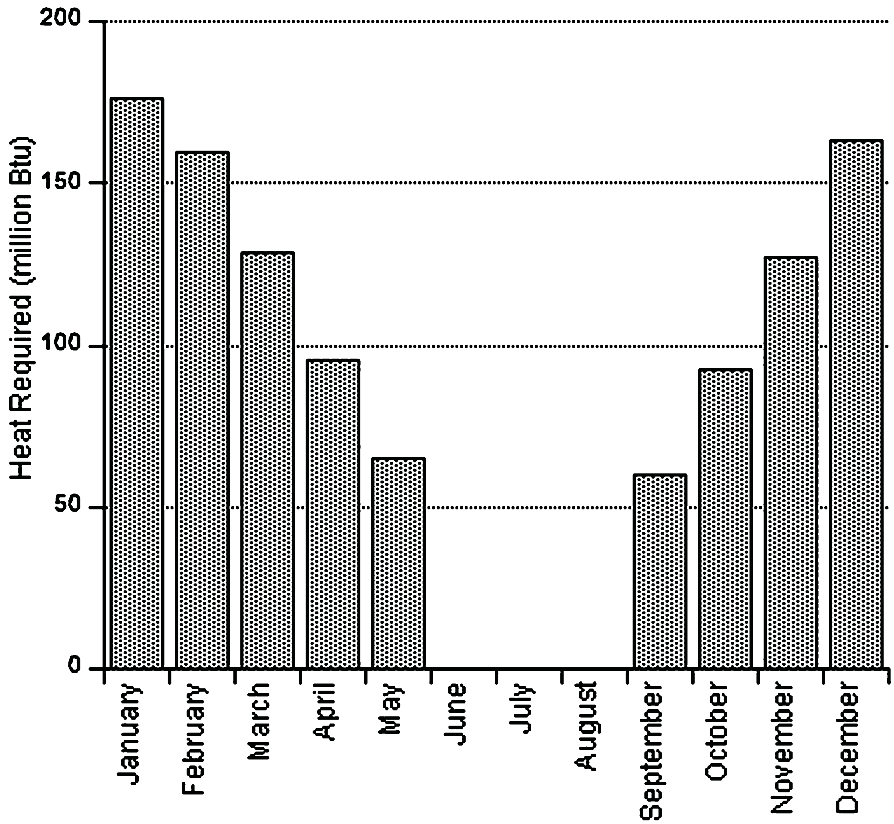

Fig. 5 – Monthly heating requirements for algal biomass production in raceway ponds in Iowa. Compared to Fig. 1, the additional heat necessary is precisely complementary to the temperature profiles for Sioux City and no supplementary heat is required during the summer months.

when the temperatures are the coldest, a theoretical maximum of 41 acres can be heated to a temperature of 73.4 °F.

Since 41 acres only accounts for a small fraction of the 1,000 acres required to sequester 60% of the CO_2, the temperature change in the raceway ponds was examined if only one-fourth of the required heat was delivered to each raceway pond. The large quantity of water in the ponds retains substantial thermal energy, which can be exploited if additional heat is lacking. With 122,500 Btu h^{-1} supplied to each quarter-acre pond, the total heat loss from the raceways would be 2.94 million Btu over an 8 h period. This directly correlates to a 6.6 °F change in the culture temperature overnight for 165 acres, which is still only one-sixth of the desired acreage. The sun's irradiance during the day is capable of heating the pond back to 73.4 °F. In certain cases, a lower nighttime temperature can be beneficial by slowing down the aerobic respiration rate of the algae and can prevent the loss of up to 30% of the daily biomass production [55].

4.4. *Economic evaluation*

In order to determine the financial viability of this integrated biorefinery, the capital and operational costs were analyzed for 1,000 acres. The capital costs include costs that are incurred during the construction of the raceway ponds and the algal facilities. These include the raceway construction,

Table 4 – Capital cost for the construction of a quarter-acre covered raceway pond.

Materials for a quarter-acre raceway pond	Cost
Low grade land	$750
Excavation	$500
Pond lining	$5,000
Double layer polyethylene glazing	$1,500
Paddle wheel motor	$2,600
Greenhouse structure	$5,000
CO_2 supply system	$5,000
Total	$20,350

Table 5 – Expected annual operating costs for a quarter-acre covered raceway pond.

Productivity ($g\,m^{-2}\,d^{-1}$)	20	30	40	60
Electricity	$370	$660	$1,130	$2,310
Labor	$750	$750	$750	$750
Nutrients	$880	$1,330	$1,770	$2,650
Flocculant	$260	$390	$520	$770
Heating	$14,850	$14,850	$14,850	$14,850
Total cost	$17,100	$17,970	$19,010	$21,330

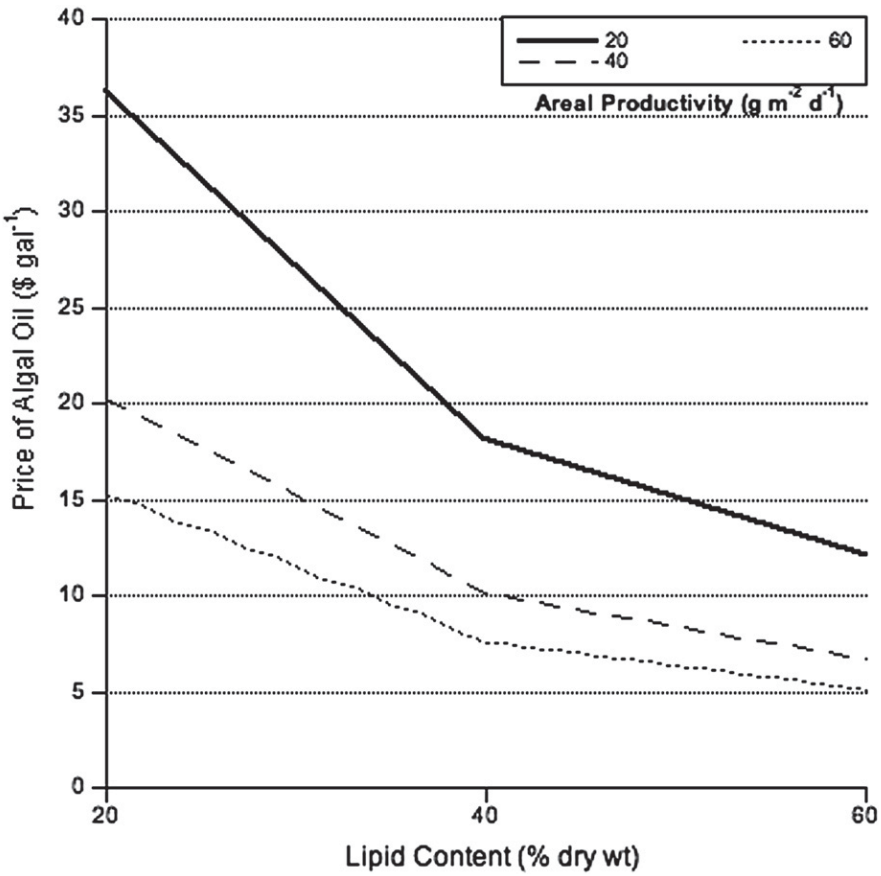

Fig. 6 – Price of microalgal oil over a range of areal productivities and lipid contents. These prices are relatively intangible because they account for only the cost to produce lipids within the algal cells, discounting any extraction or downstream processing costs; however, they provide a good benchmark when moving forward with the evaluation of biodiesel production.

greenhouse structure and glazing material and the CO_2 transfer system (Table 4).

Next, the operating costs of sequestering CO_2 to produce biomass and harvest it were analyzed. The operational costs of the raceways include the maintenance of the ponds, harvesting and de-watering, algal nutrient costs as well as electricity and supplementary heating costs. Flocculant costs were determined based on the use of ferric chloride as the primary flocculant, which has a working concentration of 100 ppm to induce algal flocculation and settling [56]. Electricity costs include the pumps, paddle wheel motors, blowers to deliver CO_2 into the ponds as well as blowers to keep the double layer polyethylene film inflated. It was also assumed that electricity would be used to heat the raceway ponds, at a cost of 4.95 cents kWh^{-1} [57]. Finally, the heating costs were also adjusted to account for the 41 acres that could be supported through the heat from the ethanol biorefinery. The operational costs were calculated on a per acre basis. Table 5 lists the expected annual operating costs for a quarter-acre covered raceway pond operating in Iowa. A large fraction of the operational cost (70–90%) is due to the heat required for the raceway ponds.

Based on the capital investment and operational costs at these various levels of areal productivity, the cost to produce wet algal biomass is estimated to be between $0.95 and $2.30 per kg, with values less than $1.25 kg^{-1} considered as highly optimistic cases. These calculations include de-watering and harvesting costs, but not the energy-intensive step of drying. The corresponding price of algal oil within these cells would be anywhere between $5.10 and $36.25 per gallon, again, with prices below $20.00 gal^{-1} for aggressive cases of high areal productivity and oil content – not including the costs to extract and reclaim the lipids for transesterification to biodiesel. The dependence of algal oil cost on both areal productivity and lipid content is shown in Fig. 6. Even for the lowest estimate of just over $5.00 gal^{-1} for an extremely aggressive case, algal biodiesel could not be produced economically at current market prices.

5. Discussion and conclusions

The ultimate feasibility of algal production systems with ethanol biorefineries depends on several factors that were taken into account in this analysis: (1) algal growth rate; (2) lipid content of the algae; (3) algal concentration in growth system; (4) cost of the growth system and, most importantly for Iowa, (5) the available heat. Based on current algal productivities alone, a large fraction of the CO_2 from the ethanol biorefinery could potentially be sequestered. Albeit technically feasible, the project is not currently economically viable for the purpose of producing biofuels. This conclusion is based principally on the large heating requirements well in excess of heat energy available from the ethanol biorefinery as a byproduct.

With current growth systems, supporting reasonably attainable algal productivities and lipid contents, the cost of producing biodiesel from algae in conjunction with an ethanol biorefinery would be in the range of $10.00 to $40.00 per gallon. For calculating the price of actual biodiesel we have assumed a price of approximately $5.00 gal^{-1} for extraction and downstream processing based on current publicly available technology. While $10.00 would be the price for a somewhat impractical case of 60 g m^{-2} d^{-1}, a more probable estimate would be at least above $30.00 per gallon. Although this figure is currently too high for the biodiesel market, these costs are likely to decrease with technological advancements that are currently underway.

The high heating cost incurred by maintaining a constant temperature within the ponds is prohibitive for producing biofuels in Iowa. For practical implementation in close proximity to a biorefinery, a land requirement of 1,000 acres may also be unattainable. Since evaporative losses appear to be the most significant source of heat dissipation, one possible solution would be to maintain the interior of the greenhouse at a high humidity by using the saturated water vapor from evaporative processes (distillation, cooling) of the refinery. This preemptive mechanism of using water vapor to reduce evaporation could minimize the amount of heat provided to the culture medium.

The small fraction of land sustainable by the available heat demonstrates that raceway ponds may not the best method to cultivate algae in the Midwest. Other intrinsic weaknesses of open ponds are the low and inconsistent cell densities and large areal footprint. Alternative culturing systems, including enclosed PBRs such as low-cost flat panel reactors, need to be investigated for this installation. While such enclosed growth systems represent higher initial capital costs, this will rapidly be compensated for by improved efficiencies and lower ongoing heating costs. High-performance PBRs will also enhance the transfer of CO_2 to the culture medium. Photobioreactors can begin to address some of these problems, but improvements in manufacturing costs and design must be achieved for these PBRs to be a viable option. Higher culture densities achieved in PBRs can also reduce the harvesting costs. An alternative approach to addressing heating costs, areal productivity, and harvesting is to develop immobilized algal growth systems, such as biofilm-based PBRs.

The findings of this study suggest that two suitable options to mitigate the CO_2 emissions of bioethanol production in the Midwest are (1) to operate the algal production ponds for a 6-month period during the warmer months or (2) produce algal biomass for high-value products, such as nutraceuticals or premium aquaculture feed, rather than biofuel. The high market value of specialty chemicals and protein-rich biomass can compensate for the current operating costs.

The significant seasonal variation in average temperatures in Iowa may suggest that emphasis on developing at least two strains of algae, one for summer and one for winter somewhat akin to summer crops and winter wheat, is necessary. It is noteworthy that perhaps the most productive body of water on Earth for algal biomass is the Southern Ocean during the southern hemispheric summer. Even in summer months, such bodies of water are still relatively cool and capable of supporting very high algal productivities.

Downstream of the growth process, some of the excess CO_2 can be used to extract the products produced by the algae with various CO_2-based extraction methods. This environmentally-conscious solution circumvents the use of toxic solvents, such as hexane, to isolate the lipids. By taking advantage of other naturally available resources in Iowa, additional mechanisms of reducing the overhead of this process may include solar and wind power generation to help reduce the carbon footprint of this process [58]. Additionally, the cultivation of algal species tolerant of wastewater may also reduce the operating costs of this process; however, these amendments would likely improve the economic viability only marginally, as the major bottleneck remains as the high cost of supplementary heat during the winter months.

It is important to note that the heating requirements for the algal growth systems described in this analysis are based on covered raceway ponds. This represents a very heat intensive growth mechanism. The assumptions made for this analysis are based on *current* techniques, productivities, and processes for mass algal cultivation. We believe that this analysis is best applied as a guide for areas of research and improvement required to allow algal biofuels production in conjunction with bioethanol biorefineries to become fully viable. These areas include heat efficient, low-cost, high performance PBRs as well as high-productivity (potentially genetically engineered) algal organisms with perhaps different strains for different seasons. For downstream processing, the recovery and utilization of a range of metabolites by lower cost extraction mechanisms, such as secretion, will undoubtedly improve the process.

The recommendations revealed by this assessment are corroborated by the fact that, presently, nearly all algal biomass production facilities are operated in temperate or tropical locations. Despite the fact that algal biofuels may not yet be economically achievable in Iowa, algae show great promise for the remediation of CO_2 point sources. Integrated ethanol biorefineries will, nonetheless, be an important step toward positive publicity of both ethanol and microalgal biomass production. Although biofuel production from microalgae in Iowa is currently economically unfavorable, algae cultivation remains a very realistic goal provided certain key barriers to commercialization can be overcome. This important mechanism for the Midwest to sequester carbon dioxide biologically can begin immediately with smaller-scale demonstration systems, which take advantage of high-value algal coproducts.

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