Water and Energy Requirements for Outdoor Algal Cultivation in Panel and Raceway Photobioreactors

by

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ABSTRACT

Recognition of algae as a “Fit for Purpose” biomass and its potential as an energy and bio-product resource remains relatively obscure. This is due to the absence of tailored and unified production information necessary to overcome several barriers for commercial viability and environmental sustainability. The purpose of this research was to provide experimentally verifiable estimates for direct energy and water demand for the algal cultivation stage which yields algal biomass for biofuels and other bio-products. Algal biomass productivity was evaluated using different cultivation methods in conjunction with assessment for potential reduction in energy and water consumption for production of fuel and feed. Direct water and energy demands are the major focal sustainability metrics in hot and arid climates and are influenced by environmental and operational variables connected with selected algal cultivation technologies. Evaporation is a key component of direct water demand for algal cultivation and directly related to variations in temperature and relative humidity. Temperature control strategies relative to design and operational variables were necessary to mitigate overheating of the outdoor algae culture in panel photobioreactors and sub-optimal cultivation temperature in open pond raceways. Mixing in cultivation systems was a major component in direct energy demand that was provided by aeration in panel bioreactors and paddlewheels in open pond raceways. Management of aeration time to meet required biological interactions provides opportunities for reduced direct energy demand in panel photobioreactors. However, the potential for reduction in direct energy demand in raceway ponds is limited to hydraulics and head loss. Algal cultivation systems were reviewed for potential integration into dairy facilities in order to determine direct energy demand and nutrient requirements for algal biomass production for animal feed. The direct energy assessment was also evaluated for key components of related energy and design parameters for conventional raceway ponds and a gravity fed system. The results of this research provide a platform for selecting appropriate production scenarios with respect to resource use and to ensure a cost effective product with the least environmental burden.

DEDICATION

First and foremost, I dedicate this work to my wonderful parents Daruish and Faye, my brother Amir whome always fill my heart with love and faith despite distance and departure. To my sister, Sheida for her unconditional love and joy in my life, Ghazal and Kamelia for their valuable friendship.

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1. INTRODUCTION

Algae cultivation for biomass represents significant potential as an agricultural crop and an appealing carbon-neutral biofuel feedstock. Faster biomass production, ability to thrive on non-fertile land, and non-fresh water requirements qualifies algae as a leading biomass feedstock for energy, feed and food compared to other terrestrial crops.

The world energy market and fresh water resources have historically met the needs of rapid economic and population growth through unsustainable deployment of non-renewable resources. Exploitations of natural resources and the discharge of large quantities of waste is degrading the ecosystem (Rees & Wackernagel, 2008). The complex interrelationship between energy and water resources requires a holistic and integrated approach with energy and agriculture as focal points for future resource management and pollution control (Hoekstra, 2009). Sustainability and sustainable development requires resource management strategies that will improve current practices necessary to support the needs of future generations (Farley & Smith, 2013).

Energy sustainability entails providing energy security, mitigating climate change and reducing air pollution (McCollum et al., 2011). Over the last few decades, the fluctuating oil prices triggered research to explore non-conventional energy resources coupled with increasing awareness for global warming and environmental externalities. Raising concerns for climate change and global resources were supported by several assessment reports released by the Intergovernmental Panel on Climate Change (IPCC), Food and Agricultural Organization (FAO), and World Bank. The future shortage in fossil fuel supply and the projected higher prices will require energy markets to search for new sources of energy to meet the demands of a growing population.

Water sustainability is also critical as current practices have led to the depletion of fresh water resources. Water is a fundamental component in the world economy, specifically in the energy and agriculture sectors, where limitation of fresh water have led to increased production costs and energy associated with remediating wastewaters (Opara, 2003; Sato et al., 2013). Compared to terrestrial crops, algae are better suited to provide renewable energy, and reduce fresh water consumption, effectively increasing the sustainability of both the energy and agriculture sectors. However, further research efforts are needed to achieve the sustainability goals of using algal systems by improving cultivation performance (biology, biochemical composition, environmental conditions, system design, etc.) and efficient use of nutrients, energy, and water.

1.1. Algae: “Fit for Purpose” Biomass

Solar energy conversion to algal biomass allows for the production of different biomass compositions, which is affected by algal strain and cultivation parameters including production system, geographical location and resources (land, nutrients, water, and energy). This includes altering biochemical composition by selection of different algal strains or through genetic modification to yield different quantity and quality of biomass, including protein, carbohydrate and lipid content (Hu et al., 2008a). These macromolecule fractions enable algae to be utilized as a “fit for purpose” biomass to produce arrays of different food sources and animal feed with high protein, carbohydrate or lipid content. Additionally, production of biofuels such a bioethanol from carbohydrate fermentation and biodiesel and green diesel from lipids through transesterification and hydrotreating, respectively, represent sustainable renewable energy opportunities.

1.1.1. Biofuel and Energy Resource

Since the 1940's, algae have been studied for their biodiesel potential (Ludwig, 1938; Ludwig & Oswald, 1952). Renewable Fuel Standard (RFS) programs have been the main policy driver in the United States to achieve energy independence from fossil fuel sources in the transportation sector by promoting renewable biomass production for meeting GHG emission reduction targets. Algae demonstrate higher biomass productivity compared to conventional agricultural crops and have the ability to accumulate up to 60% triacylglycerol (TAG) with nutrient resource deprivation to stimulate lipid production (Hu et al., 2008a). Although biodiesel production via transesterification has been a major focus of algae production, direct combustion of biomass, thermochemical conversions and fermentation have also been considered for energy production pathways. However, energetics and financial viability of the majority of the current extraction/conversion processes are extremely high relative to the low value of algal biodiesel produced, which significantly reduces the viability and feasibility of algal biomass only as an energy source (Trentacoste et al., 2015). However, interest in production of biodiesel while recovering byproducts during the extraction processes such as hydrothermal liquefaction (HTL) provides promises for financial viability. Ultimately, better control of biochemical composition without focusing on a single product can provide better opportunities for financial viability, especially when considering environmental impacts, resources utilization and potential cultivation systems (Hulatt & Thomas, 2011a, 2011b; Soh et al., 2014; Wang et al., 2013).

1.1.2. Bioremediation and Ecosystem Services

Algae can utilize (and recycle) carbon, nitrogen and phosphorus in wastewater and flue gas emissions to produce biomass with the potential use for biofuels and other by-products. The application of algae in conjunction with wastewater treatment processes is not a new concept and has been researched since the 1950s (Oswald et al., 1957). The role of algae in secondary or tertiary treatment for wastewater includes toxic metals removal by providing required dissolved oxygen for activation of aerobic bacteria (Rawat et al., 2011). Furthermore, algae can utilize different types of wastewater including municipal and effluents from concentrated animal feeding operations (CAFOs) related to dairy, poultry, and swine production (Cai et al., 2013; Pittman et al., 2011).

1.1.3. Animal Feed

Algae have potential to be utilized as feed rations for ruminants and non-ruminants, but their wider application in livestock has been limited due to inadequate feeding experiments (Becker, 2013). The high protein content of algal biomass can provide nutritional supplements required for high quality animal feed and higher milk yield in lactating cows in dairies (Becker, 2013). This includes providing higher levels of omega-3 fatty acids in dietary supplements for improving the fatty acid profile of dairy cows' milk directly from algae biomass instead of using fish oil as a ration additive (Stamey et al., 2012). The potential of algal biomass for animal feed can minimize many sustainability issues resulting from farming practices.

1.1.4. Commercial Products

Traditionally large algae production systems have been devoted to production of food and feed (Benemann, 1996). Algae stains such as *Chlorella*, *Scenedesmus*, *Spirulina* and *Nanochloropsis* are commercially produced for specific health benefits, especially antioxidants, functional components in the food industry and biofertilizer to improve soil mineral and organic composition (Draaisma et al., 2013). However, production of high-value algal products requires controlled conditions for cultivation to maintain the desired strain and biochemical composition, which is energy intensive and is not considered sustainable. To improve commercialization potential for use of algal biomass, the energy costs of cultivation and processing must be reduced.

1.2. Challenges in Mass Algae Cultivation

1.2.1. Resource Constraints and Sustainability Concerns

Algal cultivation is evaluated based on environmental and economical inputs including sunlight, water, nutrients, land, infrastructure, and labor. Sustainability concerns arise related to multiple resource requirements for large-scale commercial production of algal biomass where resource availability, potential environmental impacts and siting requirements are crucial. Many scale-up scenarios indicate that there are significant resource supply challenges with current technologies. Acquisition of nutrients is one of the main factors that contributes to the challenge of large-scale production (Pate et al., 2011; Wigmosta et al., 2011).

1.2.2. Technology and Cost Bottlenecks

Commercialization of algae cultivation and production with a focus on specialty products with high market value has been practiced for decades (Spolaore et al., 2006). However, the viability of low value algal products including biofuels and animal feed are not considered feasible, but on-going research is exploring multiple pathways to improve the future of algal cultivation. The two major pathways focus on cultivation and downstream processing. Cultivation plays an important role in moving the industry toward commercial production and dictates equipment size and cost for downstream processing. Furthermore, the cultivation stage requires improvements with respect to water and energy consumption, capital and operation costs, through assessing resource inputs, design requirements, and algal strain and productivity (Hulatt & Thomas, 2011a; Molina Grima et al., 2003).

1.2.3. Absence of Defined Production Methodologies and Metrics

Providing accurate information and scientific data are crucial for outcomes generated by feasibility and environmental driven studies, including Life Cycle Assessment (LCA) and Techno-economic Assessment (TEA). Both methodologies are dependent on quantifying key environmental inputs (LCA) or technology elements (TEA) to assess environmental impact or overall feasibility of technology. However, lack of outdoor production data, and restricted access to privately owned data on large-scale algae production minimize reliability, quality and availability of information provided for TEA and LCA methodologies, which prevents an accurate assessment on the current state of algal cultivation.

1.3. Project Objectives

In order for a green technology such as algae production to thrive in the public's perception and in the global market, there is a need for more vigorous research to provide well-defined methodologies, standard metrics and credible production information for outdoor algal biomass production. These outcomes are critical for LCA and TEA studies to provide accurate information with reliable origin on resource flow from environmental systems (energy, water, nutrient, and land), climate and biological information. The three main objectives of this dissertation were to evaluate outdoor algal cultivation for feed and biofuel production as described below:

- Direct water demand is evaluated with respect to critical components, including evaporation, as an important step for estimating overall water input for large scale algal biomass production in flat-panel photobioreactors (panels) and open raceway ponds (raceways). Major questions are: What environmental and operational variables affect evaporation? How does increasing biomass productivity affect direct water estimates? Will reduction strategies for direct water demand make algal biomass requirements comparable with other crops?
- Cultivation is an energy input intensive process with respect to operational variables, including mixing in both panels and raceways. Panels consume more energy compared to raceways; however, both cultivation systems heavily rely on direct energy inputs to operate. Direct energy demand is highly dependent on optimal productivity and biochemical composition

for a higher net energy ratio (NER) close to unity. Major research questions addressed in this study are: What environmental and operational variables affect direct energy demand with respect to areal biomass productivity? What reduction strategies would be more beneficial for improving NER values in both panels and raceways? How are the higher and lower NER ratios at current technology for outdoor cultivation values set?

- Co-location of algal cultivation systems with dairy facilities, for example, can provide multiple positive externalities for improving sustainability. Relevant questions asked in this study include: What production system would be a better candidate for an algal farming system? How much nitrogen is available from a large dairy facility for algal biomass production? How can direct energy demand for a commercial scale algal farming system be estimated? How much animal feed is replaced by algal biomass production?

These first two objectives are intended to provide credible information for estimating water and energy demand as key limiting resource inputs associated with algal cultivation. The third objective focuses on assessing application of algal biomass production to produce a commodity for replacement of animal feed and improving sustainability by enhancing ecosystem services.

1.4. Scope of the Project:

This study focuses on the cultivation stage due to its major role in the algal production supply chain and potential for improvements that enhance the feasibility of commercialization. The following components were not considered in the scope of this dissertation:

- Micronutrients
- Harvesting methods
- Downstream processing
- Transport of potential biomass product
- Embedded energy and water for materials, operation and equipment
- Production and disposal of any wastes generated during the process

1.5. Organization of the Dissertation

The remainder of the dissertation is separated into 5 chapters that includes background, three manuscript chapters, and conclusions.

The background section provided information required for synthesizing the research design and the content of the three manuscripts. Water, energy and nutrients are major inputs that were both experimentally and theoretically estimated for assessing environmental sustainability of algal biomass production. However, each input is utilized differently in each cultivation systems which would determine the system’s performance-based input efficiency and thus, dictate their future viability in commercial algal production.

The first manuscript focused on determining direct fresh water demand as the critical step for site assessment and scale-up of algae production. Direct water demand is directly linked to the cultivation system's configuration and operational variables. Overall calculations indicate that panels have higher direct water demand due to high evaporative cooling water loss compared to raceways. Recycling and reducing water for cleaning would lower direct water demand to comparable values to direct water demand for terrestrial crops such as alfalfa in both cultivation systems and particularly in raceways. The purpose of the second manuscript was to assess seasonal direct energy demand and identify major environmental and operational variables by a side-by-side comparison of panels and raceways. Direct energy demand components are related to aeration and temperature control in panels. Despite the amount of energy use in panels compared to raceways, the overall NER can be increased by improving biomass productivity through semi-continuous cultivation. Ultimately, raceways showed poor performance and indicates that further research need to focus on improving biomass productivity.

The third manuscript used data from the peer-reviewed literature and results obtained in the previous manuscripts to evaluate algal biomass production systems to meet sustainability objectives using a dairy farm as a case study. Dairy production is an intensive agricultural practice associated with many environmental concerns, including volatile emissions, eutrophication of aquatic ecosystems and health risks to human communities. These concerns can be reduced by utilizing algal biomass production to remove the valuable nutrients found in dairy wastewaters which can, in turn, be used for animal feed. However, the feasibility of incorporating algal biomass for animal feed production requires achieving a higher energy balance for energy consumed per unit of biomass produced in cultivation stage. Therefore, paddlewheel driven raceways are compared to gravity fed bioreactors for comparing energy consumed per unit biomass produced.

The conclusion chapter summarized the results described in the previous chapters and identifies key steps required for future research in the algal biomass production field including TEA and LCA studies that would assist the industry by providing a pathway towards sustainability.

2. BACKGROUND

2.1. Water-Energy-Food Nexus and the Need for Algae

Water, energy and food are essential for providing economic progress, social welfare, and social equity to meet the core objectives of sustainable development. Fast approaching crises with respect to fossil fuel depletion, climate change, water, food shortages and a growing population require sustainable solutions which will prevent future environmental disasters.

Global water, energy, and food resources are intrinsically linked as water is an essential component for food and bioenergy feedstock in agriculture and the production processes for energy. The distribution of food and water relies on energy for transportation and power for agricultural and industrial processes (United Nations, 2015b). The complexity of dynamic interactions between water-energy-food has increased by using agricultural crops for energy, which transformed the dynamics and interrelationship of finite global resources (Food and Agriculture Organization of the United Nations, 2014).

Algae as versatile biomass resource can be used for energy, food, and animal feed production, along with providing bioremediation services for water and air. These capabilities can significantly reduce concerns for resources associated with the water-energy-food nexus.

2.2. Algal Biomass Yield

Algae rely on photosynthesis for biomass production using energy received from solar irradiance (Grobbelaar, 2013). Direct solar irradiance within the spectrum of 400-700 nm is approximately 40-45% of the total direct solar irradiance and is referred to as photosynthetic active radiation (PAR). This irradiance is utilized by autotrophic algae for converting carbon dioxide into biomass (Wilhelm & Jakob, 2011). Algae are very efficient in converting solar energy to chemical energy and achieving high biomass productivity with a Photosynthetic Conversion Efficiency (PCE) up to 8-10% obtained under the best case scenario and 4-5% achievable under fluctuating environmental conditions and in current cultivation systems (Masojidek et al., 2013; Melis, 2009). Light intensity is the major limiting factor for efficient photon conversion within algal cells and cultivation systems (Richmond, 2013). Thus, theoretical limits are reduced by 30-60% due to inefficiency in photon usage by algae cells, respiration, biochemical production pathways and type of cultivation systems (Melis, 2009; Williams & Laurens, 2010). This translates to a theoretical limit of 280 MT ha^{-1} year^{-1} for algae compared to corn 8-34 and alfalfa at 6-18 MT ha^{-1} year^{-1} (Williams & Laurens, 2010). However, the peak achievable levels of production have been limited to 182 and 60 MT ha^{-1} in panels and raceways, respectively (Williams & Laurens, 2010).

2.3. Algal Cultivation Systems

Cultivation is a major component of the algae production system and selected parameters influence the growth conditions, type of downstream processes and ultimately the energetics and financial viability of algal cultivation (Soh et al., 2014; Wang et al., 2013). Cultivation parameters can be categorized as: 1) algae strains; 2) environmental variables; 3) cultivation systems; and 4) cultivation methods which encompass gas exchange and transport for CO_2, oxygen removal, mixing for optimal light/dark cycles, temperature and pH control, nutrient supply, growth time, and harvesting rate (Grobbelaar, 2000).

Cultivation parameters influence the growth capacity for a given algal strain to yield biomass and desirable biochemical composition (Grobbelaar, 2000, 2012; Laurens et al., 2014). Thus, strain selection is an important biological component in cultivation, hence identifying strains with the desired attributes, including high growth rate; high lipid content, high cell density, ease of harvesting and extraction, ability to grow in a harsh environment, resistance to predation, and shear tolerance remain challenges for the algae industry to overcome (Borowitzka, 1992; Brennan & Owende, 2010; Griffiths et al., 2011; Grobbelaar, 2000; Kumar et al., 2010). Maintaining annual maximum biomass productivities and with a desired biomass composition are highly influenced by environmental conditions (Masojidek et al., 2013). Thus, the need to control environmental conditions in the selected cultivation system would increase cost of production beyond current engineering estimates that have been established using lab-scale data (Stephens et al., 2013). Determining the type of cultivation system is critical for assessing energy demand and cost requirements (Mata et al., 2010).

Historically, algal raceways (Figure 2.1) and panels (Figure 2.2) have been commonly used for algal biomass production for both research and food production. Raceways have been widely used due to their simplicity, ease of operation, scale-up ability and relatively low cost infrastructure when compared to panels. But the low biomass productivity in raceways ranging from 5-15 g m^{-2} d^{-1}, high evaporation rates, poor mixing, low CO_2 utilization efficiency and other operational difficulties related to pH control have been major drawbacks for their application (Slade & Bauen, 2013).

Conversely, higher biomass productivities achieved in panels (between 20-30 g m^{-2} d^{-1}) make them a better candidate for biomass production (Armandina et al., 2013; Hu et al., 1996) due to better control of culture conditions including temperature, light, pH and increased CO_2 utilization efficiency (Sierra et al., 2008; Ugwu et al., 2008).

Figure 2.1: Large scale raceway at AzCATI facility in Mesa, Az.

Figure 2.2: Flat-panel photobioreactors (panels) at AzCATI facility in Mesa, Az.

2.4. Reducing Resource Consumption

A production system can be evaluated using a system balance based on inputs (water, energy and nutrients) and outputs (biomass). The stochastic relationship between inputs and outputs can be translated into effective, quantifiable and verifiable water, energy metrics in terms of biomass productivity to evaluate viability and provide sustainability assessment tools for algal systems.

2.4.1. Energy

Growing interest in algae as the next generation agricultural crop for biofuel production has spurred many sustainability concerns regarding energy required for production of the algal biomass. Energy production from algae requires multiple steps including: 1) photosynthetic production of organic matter (biomass production); 2) collection and processing of biomass; and 3) conversion to biofuels (Goldman & Ryther, 1977). Energy as electricity and heat (non-renewable) are the major inputs for algal biomass production. Related energy efficiency metrics such as “net energy ratio” (NER) and “energy return of investment” (EROI) are established to measure “renewability” and performance of production systems with respect to the energy consumption (E_{in}) and energy produced (E_{out}) (Collet, 2013). As each metric is sensitive to changes, the selection of appropriate system boundaries are required to minimize error in calculations. NER assesses energy consumption at the point of the technology use, whereas EROI accounts for differences in energy quality, energy embedded in material (second-order EROI) along with actual energy production and consumption (first-order EROI) (Beal et al., 2012). EROI is often combined with economic metrics for providing further in-depth sustainability metrics (Zhang & Colosi, 2013). Yet, there is no firm consensus in mathematical approaches taken to calculate each of the metrics, which further adds to the uncertainty of the reported results (Zhang & Colosi, 2013). Ultimately, assessment of major direct energy demand components in each algal cultivation system is an important step in estimating the overall energy required for converting the algal biomass into a final product (Mata et al., 2010).

2.4.1.1. Raceways

Simple design and potential for scalability are the main advantages of raceways, with paddlewheels and mixing identified as the major components of capital and operating costs (Borowitzka, 2013; Borowitzka, 1999). Mixing accounts for the largest energy consumption, ranging from 22% to 79% for electricity, to avoid algae cell settling and temperature stratification between the top and bottom layers of the culture (Grobbelaar, 2013; Mata et al., 2010; Ras et al., 2013). Operating velocity in raceways may vary from as low as 5 cm s^{-1} up to 60 cm s^{-1}, although velocities greater than 30 cm s^{-1} result in higher energy consumption and can cause damage in unlined raceways and also reduce productivity (Weissman & Goebel, 1987b). A mixing velocity of 15 cm s^{-1} has been recommended in order to provide minimum velocity of 5 cm s^{-1} across the entire raceway (Moheimani & Borowitzka, 2007; Weissman & Goebel, 1987a). Conversely, lower velocities would not provide sufficient mixing and result in settling of the algae cells (Oswald, 1988; Weissman & Goebel, 1987b).

Low biomass productivity achieved for raceways (< 15 g m^{-2} d^{-1} annually) and dilute biomass concentrations have created bottlenecks in harvesting (Shen et al., 2009). However, control for temperature fluctuations in raceways would increase productivity by 20-50% depending on strain and desired optimal range (Béchet et al., 2011). Therefore, changes in operational parameters such as mixing, depth and temperature control may result in improved productivity and reduced energy input, but changes are restricted by the environmental conditions, technology and fluid dynamics.

2.4.1.2. Bioreactors

Photobioreactors (PBRs) demonstrate large illuminated surfaces and better biomass productivity by providing better control for gas-liquid hydrodynamics, including mass transfer (Sierra et al., 2008; Zemke et al., 2013). Energy and cost bottlenecks are related to 1) energy input for oxygen removal, CO_2 supply and nutrient utilization and 2) capital cost (material and infrastructure) and installation costs as limiting factors for large scale PBR production systems (Davis et al., 2011; Richardson et al., 2012). Mixing accounts for most of the total energy use to avoid sedimentation of algae cells and to provide light/dark cycles to maximize productivity. Aeration is a key operational variable in cultivation system for sufficient mass transfer, oxygen removal and CO_2 that would ultimately increase the daily energy consumption and operational cost (Slade & Bauen, 2013; Zhang et al., 2002). Among different designs, panels and tubular bioreactors are mostly preferred for their large illuminated surface area (Posten, 2009). Despite complex scalability, panels outperform tubular PBRs due to larger illumination surface area, less oxygen build-up, and less shear stress from mixing through aeration without pumping (Slade & Bauen, 2013; Ugwu et al., 2008). Sierra et al. (2008) evaluated system performance for energy input for panels at 53 Wm^{-3} compared to 2400-3200 $W\ m^{-3}$ in tubular bioreactors. PBRs provide opportunities for higher yield biomass under proper culture conditions where metabolic pathways in the cells can be enhanced for different biomass composition. However, that requires changing physiological, operational and even design of the reactors tailored for the specific strain including temperature control for providing optimal culture temperature as an additional energy input component that contributes to higher energy demand for panels compared to raceways (Béchet et al., 2010; Hulatt & Thomas, 2011b). Optimizing a PBR for cost and energy is complex requiring optimizing functional relationships between oxygen, carbon dioxide, irradiation and relationship between energy input and energy content of biomass expressed by NER ratio (Hulatt & Thomas, 2011a).

2.4.2. Water

As algae are aquatic species, water is essential for cultivation. Stress on water resources is a major challenge, especially in arid climates within the southwestern U.S., and an important issue due to interconnection with global water resources (U.S. Department of Energy, 2010). Algae can be cultivated using seawater, brackish water and wastewater, thereby removing the need for fresh water. However, cultivation is influenced by many variables that often dictate water requirements in a cultivation system and in many cases evaporation and maintenance forces the use of fresh water to balance salinity (Murphy & Allen, 2011; U.S. Department of Energy, 2010).

Guieysse et al. (2013) defines water footprint (WF) as a policy tool to assess fresh water depletion while water demand (WD) as an financial viability assessment tool to evaluate water required for a technology, production process and operations. Both tools have been subject to inconsistencies in applied methodologies. The wide spanned variabilities in assumptions are originated from different geographical locations and limitations in data extrapolated from laboratory experiments for production scale systems (Gerbens-Leenes et al., 2014; Wigmosta et al., 2011). Comparison of the two most commonly applied cultivation systems, raceways and panels, used in outdoor facilities improve the data used for determining water consumption during microalgal cultivation.

2.4.2.1. Raceways

Siting and evaluation of water availability is crucial when raceways are selected as the cultivation system to grow microalgal biomass mostly due to required temperature control strategies to maintain optimal temperature, evaporation and related critical environmental variables that determine biomass productivity and water requirements (Béchet et al., 2011). Temperature control in raceways mainly attempts to optimize sub-optimal morning temperature and seasonal overheating of cultures due to the higher volume to surface ratios in raceways (Ras et al., 2013; Vonshak et al., 2001). Unfavorable temperature fluctuations results in drop in pH, loss of nutrients, inefficient light utilization and ultimately reduction in biomass produced (Oswald, 1988).

Evaporation has been widely incorporated in culture temperature models in raceways in addition to solar radiation, air radiation for heat balance analysis and as a significant factor in determining the culture temperature with specificity to geographical locations. Thus, accuracy of temperature models for projecting productivity is significantly dependent on valid evaporation rates in raceways (Béchet et al., 2011). However, determining evaporation rates have been subject to a variety of empirically driven formulas that are not aimed at algal cultivation systems. However, recent studies list evaporation as a significant component of water demand for algal cultivation systems (Guieysse et al., 2013).

2.4.2.2. Bioreactors

Bioreactors are preferred cultivation systems compared to raceways for their comparatively minimal water use when water consumption is a major limiting factor in selection of a cultivation system. However, in arid climates, maintaining culture temperature close to the optimal range for a specific algal strain is critical to ensure culture stability. Thus, an evaporative cooling system becomes an essential element of a production system which significantly contributes to fresh water consumption to avoid overheating and ultimately larger water demand compared to raceways. Application of an evaporative cooling system is related to water and energy sustainability with respect to NER and profitability for large scale production. Utilizing brackish water to replace freshwater requirements for evaporative cooling system is financially viable due to the high cost of technologies used such as reverse osmosis (RO) (Béchet et al., 2014). Culture temperature resilience is a strain specific attribute which can vary among strains of algae and is a key factor to consider in algal cultivation and resource requirements. Overall, geometry of bioreactors significantly influence heat transfer despite emitting majority of the radiation as heat but the confined environment can rapidly increase the culture temperature. Presence of algae cells as a grey body effect would be negligible in small bulk culture but may be significant in the heat balance analysis in large biomass production (Morita et al., 2001).

2.4.3. Nutrients

Microalgal cultivation relies on nutrients and nutrient acquisition, but the high costs of nutrients create roadblocks to commercialization and large-scale production. The major nutrient requirements for algae are nitrogen and phosphorus, which are also the main nutrients found in agricultural fertilizers where nitrogen alone represents ca. 90% of the fertilizer composition (Food and Agriculture Organization of the United Nations, 2015).

The price of nutrients or fertilizers is influenced by fluctuating energy prices, transportation costs and supply and demand in the market. Comparison of nitrogen fertilizers such anhydrous ammonia shows a 211% increase since 1980 with a price increase from $277 to $706.77 per metric ton. This increase exceeds inflation due to a decline in the capacity of U.S. fertilizer industry, which resulted in increasing imports of nitrogen (50%) to meet domestic needs in agriculture (USDA-ERS, 2013). In addition to cost, production of agricultural grade fertilizers are very energy intensive. Approximately 80% of the cost of nitrogen can be allocated to fossil energy consumption (Food and Agriculture Organization of the United Nations, 2015).

Increasing the human population to approximately to 9.5 billion in 2050 will generate higher global demands for food and feed, and place escalating pressure on agriculture for increased yield and quality thus requiring more fertilizer, land, energy and fresh water resources for farming (FAO, 2014; Stephens et al., 2013; United Nations, 2015a). Focusing on the ability of algae to utilize wastewater for essential nutrients is a solution that can be used to overcome the cost and availability of nutrient sources for algal biomass production. Algae are considered to be both an agricultural crop and an energy source that can replace the cost of fertilizers by utilizing waste nutrients in concentrated animal feeding operations (CAFO’s) associated with dairy, poultry, and swine production. An algal biomass production system can improve water quality and be a potential source of animal feed containing proteins and essential nucleic acids that are typically obtained from alfalfa, soy and corn. Generally, there are no treatment facilities to remediate CAFO effluents; thus, environmental impacts arise from poor manure management including eutrophication of natural waters, odors from ammonia volatilization and GHG emissions (Erisman & Schaap, 2004; Tilman et al., 2002; von Keyserlingk et al., 2013b; Ward et al., 2005a).

Algae production should be able to provide sustainable environmental values by applying production scenarios which decrease dependence on fresh water resources, decrease energy demand, and replace requirements for fertilizers by utilization of wastewater with built-in nutrient recycling strategy. As a result, managed ecosystems can continue to provide goods and services that society values. However, selection of appropriate production scenarios requires evaluation of algal cultivation systems with respect to resource requirements including water, energy and nutrients. The aforementioned contributes to the core objectives and framework of the research design for the following manuscripts.

3. MANUSCRIPT 1: EVALUATING KEY OPERATIONAL AND ENVIRONMENTAL VARIABLES ON EVAPORATION AND DIRECT WATER DEMAND FOR ALGAE PRODUCTION IN HOT ARID CLIMATES

Manuscript Information Page

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3.1. Introduction:

Over the past several decades considerable research has focused on the use of algae as a renewable energy source. The higher productivity of algae compared to terrestrial crops is advantageous for biodiesel production, animal feed and high-value products (Schenk et al., 2008; Shen et al., 2009; Woertz, 2009). Although algae are able to utilize non-arable land and wastewaters for the main source of water and nutrients, major environmental impacts are associated with the cultivation stage (Clarens et al., 2011; Gerbens-Leenes et al., 2014). Water and energy demands are focal points for reducing environmental impacts of algal biomass production. Water demand, which is estimated to be ca. 5-10 kg for producing a kg of dry algae biomass, indicates that algae rely heavily on water during the cultivation process (Murphy & Allen, 2011). A majority of the water used is attributable to evaporation from open systems or loss during harvesting where algal biomass is separated from the cultivation water. An estimate of water use for biomass production in outdoor facilities is critical for estimating direct water demand for a large-scale algae production process when compared with other agricultural crops such as alfalfa. In central Arizona, alfalfa requires ca. 6.2 acre-ft acre^{-1} yr^{-1} of irrigation water (Ottman, 2009). Irrigation management strategies are attempting to reduce water consumption for major crops (Osteen et al., 2012); however, increasing demand for alfalfa as a major nutritional component in animal feed requires optimal cultivation conditions, including sufficient irrigation. The capability of algae to utilize wastewater resources more efficiently than alfalfa can reduce water demand creating a potential biomass replacement for alfalfa.

3.1.1. Evaporation

Evaporation is a complex meteorological process which supplies energy from solar radiation and accounts for approximately 50% of the heat loss from free water surfaces as a temperature control strategy (Sartori, 2000). The evaporation from crops or evapotranspiration (ET) which combines soil evaporation and plant transpiration is reported as depth of water loss over a given time period (Erickson et al., 2013). ET is an important parameter for irrigation management, and similar to evaporation from a water surface, is influenced by meteorological parameters such as solar irradiation, ambient temperature, relative humidity and wind speed. However, crop type, growth stage and soil characteristics are major determining factors for ET (Allen et al., 1998; Brown, 2014). Evaporation rates from the free water surface and ET have been estimated by theoretical and empirical methods, which require a detailed understanding of meteorology, latitude, seasons, physics, type or size of water body (Brown, 2014; Guieysse et al., 2013). Mass and energy balance approaches or combined methods use information including energy, air temperature, relative humidity and wind velocity to estimate evaporation rates (Doucha & Lívanský, 2009; Sartori, 2000).

During algal biomass production, water loss due to evaporation requires replenishing to maintain system volume and to stabilize salinity (Mata et al., 2010; Murphy & Allen, 2011). In algal cultivation, panels, due to higher surface area to volume ratios, temperature increases at a faster rate than in cultivation in raceways, and often require external cooling systems to help prevent extreme temperatures (Béchet et al., 2010; Mata et al., 2010; Morita et al., 2001; Murphy & Berberoglu, 2011). This can be both an energetic and economic issue since algae cultures usually have a limited temperature range with a maximum temperature tolerance of approximately 4°C above the optimal growth temperature (Ras et al., 2013). One desired method to minimize the cooling requirements is seasonal crop rotation that entails utilizing similar algae strains that have different optimal growth temperatures (Eustance et al., 2015a).

Previous approaches to estimate evaporation rates has been mainly limited to biomass production in raceway systems where pan evaporation, Penman equations and other empirical models have been widely used (Clarens et al., 2011; Cooney et al., 2011; Guieysse et al., 2013; Yang et al., 2011). A commonly used evaporation method in the U.S. is pan evaporation which applies a theoretical 0.70 coefficient for large bodies of water to account for the changes in microclimate conditions compared to the small pan evaporation measurement tool (Jensen, 2010; Kohler, 1954). In general, the applicability of these common formulas are limited in estimating evaporation rates for different cultivation systems due to differences in size, surface area, and temperature variations. These formulas have been developed for a clear or transparent water surface and not for cultivation systems with dense algae cell populations in suspension, and suggests that further research is needed to investigate the impact of the algae on evaporation in outdoor cultivation systems (Guieysse et al., 2013).

3.1.2. Direct Water Demand Assessment

Water demand in algal biomass production systems can vary based on geographical locations, environmental conditions, system configurations, surface/volume ratio, and operational variables, which also dictate biomass and lipid productivity.

Therefore, estimating water demand is a major step in assessing sustainability with respect to the technology used on a local or regional scale.

This study focuses on comparing evaporation water loss due to evaporation for both raceways and panels during different seasons at the outdoor cultivation facility located at the Arizona Center for Algae Technology and Innovation in Mesa, AZ. Evaporation rates were evaluated under 1) environmental conditions associated with changing seasons and 2) operational variables, including aeration rates in panels and different depths in raceways. Further direct water demand for algal biomass production was compared for both batch and semi-continuous cultivation of the algae. Evaporation water loss was determined and compared to literature values for a local agricultural crop, alfalfa.

3.2. Materials and Methods

3.2.1. Evaporation, Direct Water Demand and Metrics

Evaporation and water demand measurements were conducted in collaboration with algal biomass production (Eustance et al., 2015a; Eustance et al., 2015b). Cultivation occurred from April 2014 through May 2015 on the field site at the Arizona Center for Algae Technology and Innovation in Mesa, AZ. Experiments were completed in panels and raceways to assess direct water demand during batch cultivation for biofuel (biodiesel) production and semi-continuous cultivation for animal feed. The functional units for evaporation rate were cm d^{-1} and L d^{-1} of water evaporated for both systems. Direct water demand for both systems included water used for algae inoculum, maintenance, evaporation and water replenished or lost during harvesting. Water recycling after the harvesting process was also considered theoretically; however, the potential of using recycled water for algal cultivation was not experimentally explored in this study and requires future investigation.

3.2.2. Algal Biomass Cultivation and Process Model

Panels were arranged with North-South facing exposure and measured 46” (1.17 m) in width by 46” (1.17 m) in height and approximately 1.5” (3.8 cm) in depth (thickness) or path length. Aeration was provided through small drilled holes (~1/32” (0.8 mm) in 1/2” (1.3 cm) PVC located at the bottom of the reactor at a rate of approximately 0.5 volume/volume/minute (vvm). Raceways consisted of two channels 6.1 m long, 1.7 m wide with the two ends each with a radius of 1.78 m providing a total area of 30.37 m^2. Velocity of water movement in raceways was set to an average linear flow of 25 cm s^{-1}.

3.2.3. Monitoring and Daily Measurements

Temperature and pH were continuously monitored using a Neptune Apex controller (Neptune Systems, LLC.). Ambient weather conditions were measured with an Argus weather station capable of recording ambient temperature, relative humidity, wind velocity, and light intensity (Argus Control Systems, LLC.). Daily values were based on sampling at 3 pm.

3.2.3.1. Aeration Rates

Aeration in panels was adjusted to different rates by using a Flowmeter TS14000 (TSI Incorporated). The flowmeter outputs were in standard liters per minute (SLM) or in volumetric liters per minute (L min^{-1}). The experimental aeration rates were set to values

(L min^{-1}) based on 1 to 1.2, 0.5 and 0.2 (vvm) in duplicate panels. The aeration rate was typically set at 0.5 vvm for algae cultivation in panels.

3.2.3.2. Daily Evaporation and Direct Water Demand

Major components of the direct water demand investigated in this study were cultivation water, surface evaporation rates, maintenance water and evaporative cooling. The first three components were measured with a Sotera Flowmeter (Sotera Systems) attached to the water source to display the volume of water in liters. The evaporative cooling was measured by an inline DWYER Flowmeter (Dwyer Instruments Inc.) that measured volume of water in gallons (gallons values were converted to liters for the purpose of this study) to determine the net volume of water entering and leaving the system and to account for amount of water loss. Seasonal variations were mainly based on average ambient temperature ranges which categorized seasons into summer (early May to end of September), winter (early October to late March) and spring (late March and early May).

The following were the components of direct water demand evaluated:

- Surface Evaporation (L d^{-1}): This value represents evaporation rate at the surface of panels and raceways and is measured by the daily addition of water necessary to maintain constant operating volumes.
- Evaporative Cooling (L d^{-1}): This value represents daily evaporation water loss associated with the external evaporative chiller used for the panels.
- Maintenance Water (L): This value represents the water used for cleaning and sanitation of the cultivation systems.

- Cultivation Water (L): This value represents the water added at initial inoculation of algae and maintenance water

3.3. Results:

3.3.1. Effects of Environmental Variables on Evaporation in Panel and Raceways

The influence of average ambient temperature, solar irradiance, relative humidity, and wind velocity on surface evaporation for panels and raceways is illustrated in Figures 3.1 and 3.2, respectively, during different seasons. Raceways, compared to panels, showed a better relationship between surface evaporation rate and environmental parameters (R-squared of 0.87 for raceways compared to 0.2 for panels). Surface evaporation in panels was subject to parameters other than environmental conditions, in particular external cooling, desired culture temperature, and aeration rate.

Negative control experiments were completed to assess evaporation rate in the absence of algae cultivated in panels and raceways in order to determine the impact of algae on evaporation as a grey body. In raceways, no significant difference was observed in evaporation rate with or without the presence of algae (two-tailed P-value 0.06 for $\alpha < 0.05$). This means that the presence of the algal culture had minimal impact on the overall evaporation rate from raceways. In panels, the utilization of a centralized cooling system prevents evaluation of the presence of algae on evaporation. This occurs because the presence of algae increases temperature and absorbance as a grey body, which in a temperature controlled system masks the true differences in evaporation in panels with and without algae.

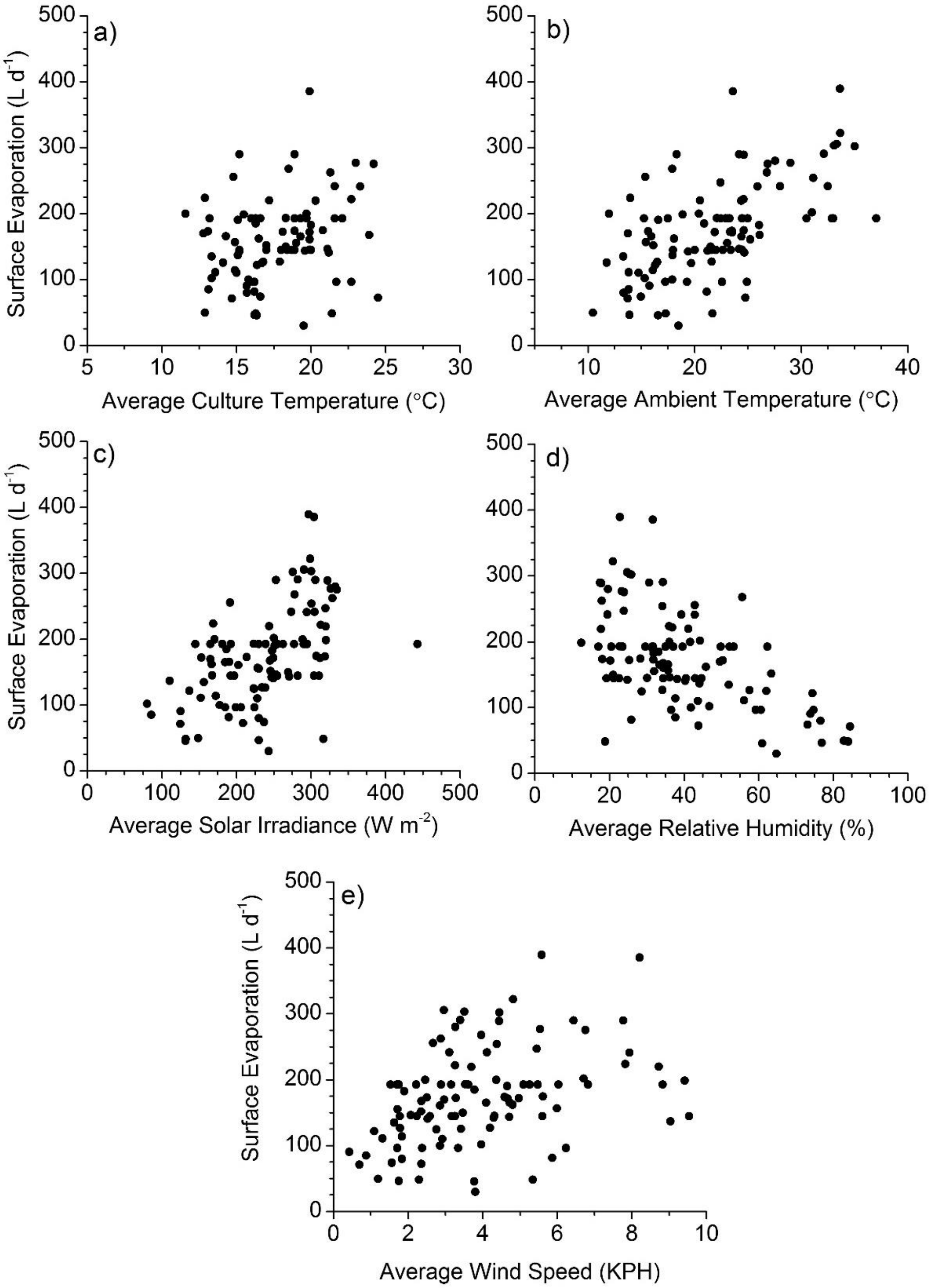


Figure 3.1: Influence of seasonal environmental variables on evaporation from raceways: average culture temperature (a); average ambient temperature (b); average solar irradiance (c); average relative humidity (d); and average wind velocity (e).

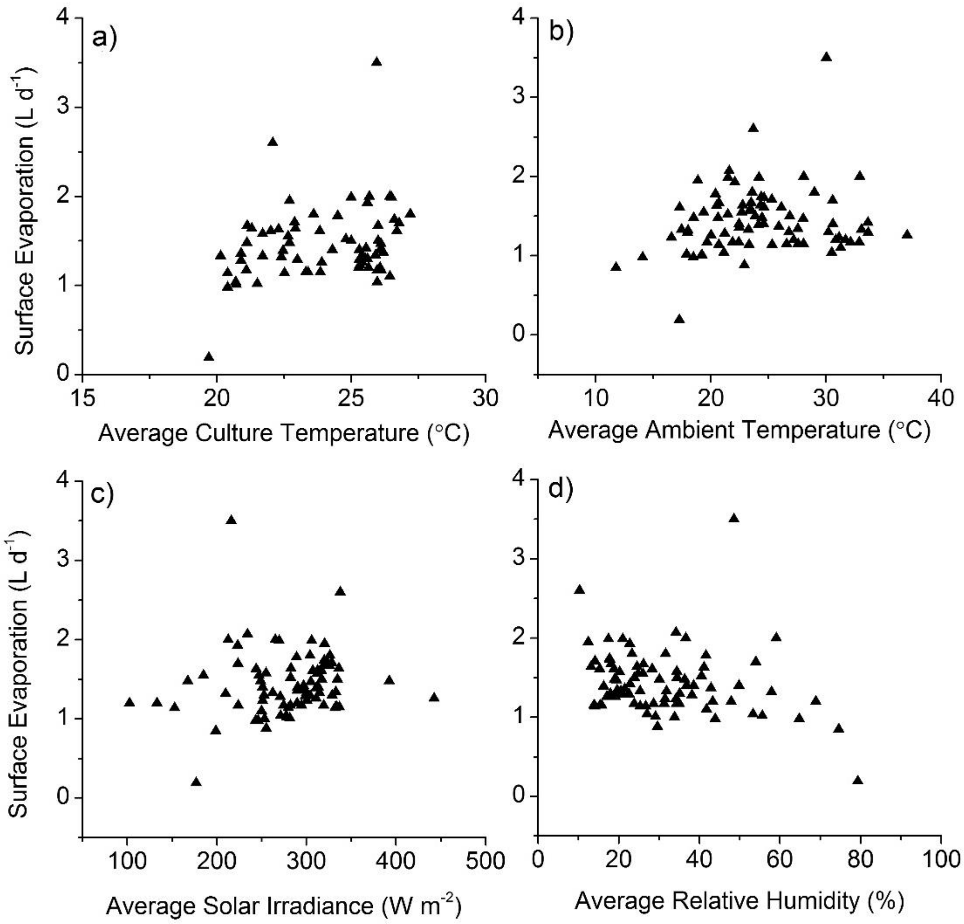


Figure 3.2: Influence of seasonal environmental variables on evaporation from panels: average culture temperature (a); average ambient temperature (b); average solar irradiance (c); average relative humidity (d).

3.3.2. Comparison of Evaporation for Panels and Raceways with Penman and Local Weather Station

Daily measurement of evaporation in both cultivation systems provided the basis for seasonal and year-round evaporation loss and water use for algae cultivation systems.

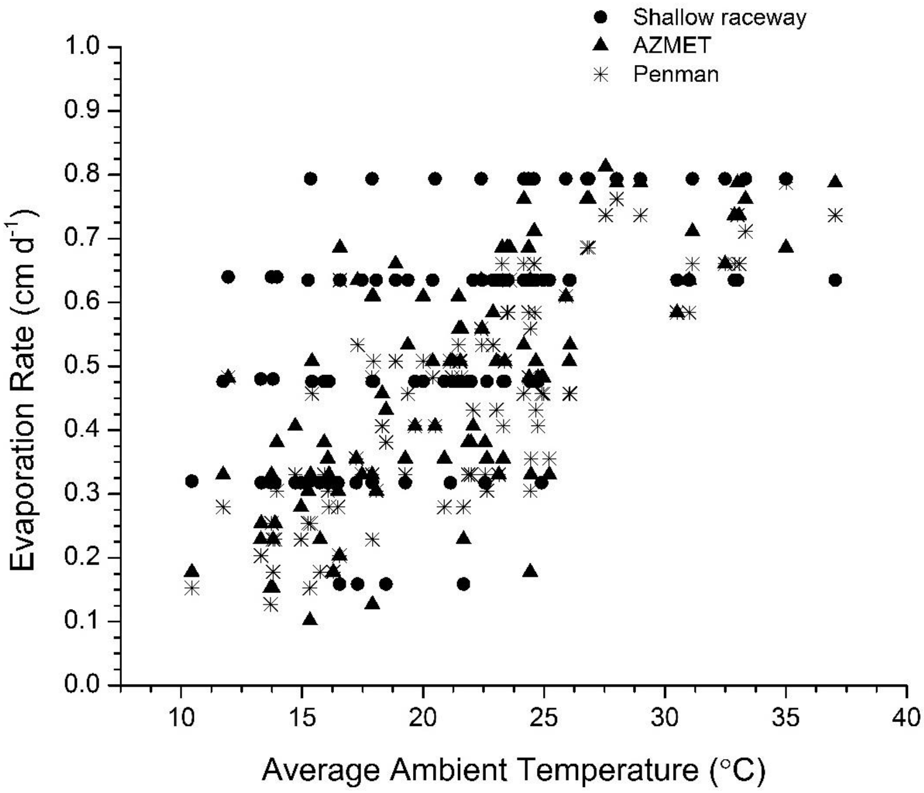


Figure 3.3: Evaporation rate in shallow raceways compared to evaporation rates based on Penman and a local weather station (AZMET) data.

Comparing evaporation rates of shallow raceways with Penman and the Arizona Meteorological Network (AZMET) is illustrated in Figure 3.3 which provides confirmation of these values for LCA studies and building large-scale facilities in the future. However, panels' evaporation rates were not comparable with these values due the complexity of the evaporation process associated with enhanced temperature control. Comparing environmental variables obtained from the field site weather station (Argus weather station) with the nearest local weather station AZMET showed higher relative humidity values at the field site, which suggests that the presence of algal cultivation systems may affect the local environment.

3.3.3. Effects of Operational Variables on Evaporation in Panels and Raceways

The influence on surface evaporation of different aeration rates and covering the panels with respect to average ambient temperature is illustrated in Figure 3.4 (b). The largest average surface evaporation rate of 2.8 ± 0.7 L d^{-1} $tank^{-1}$ was associated with the highest aeration rate of 1 to 1.2 vvm, while the lowest aeration at 0.2 vvm had an average surface evaporation rate of 1.1 ± 0.4 L d^{-1} $tank^{-1}$. At an aeration rate of 0.5 vvm, covering the panel surface effectively lowered the evaporation rate from 1.8 ± 0.5 L d^{-1} $tank^{-1}$ in uncovered panels to 1 ± 0.6 L d^{-1} $tank^{-1}$, which was comparable to 1.1 ± 0.4 L d^{-1} $tank^{-1}$ with aeration at 0.2 vvm.

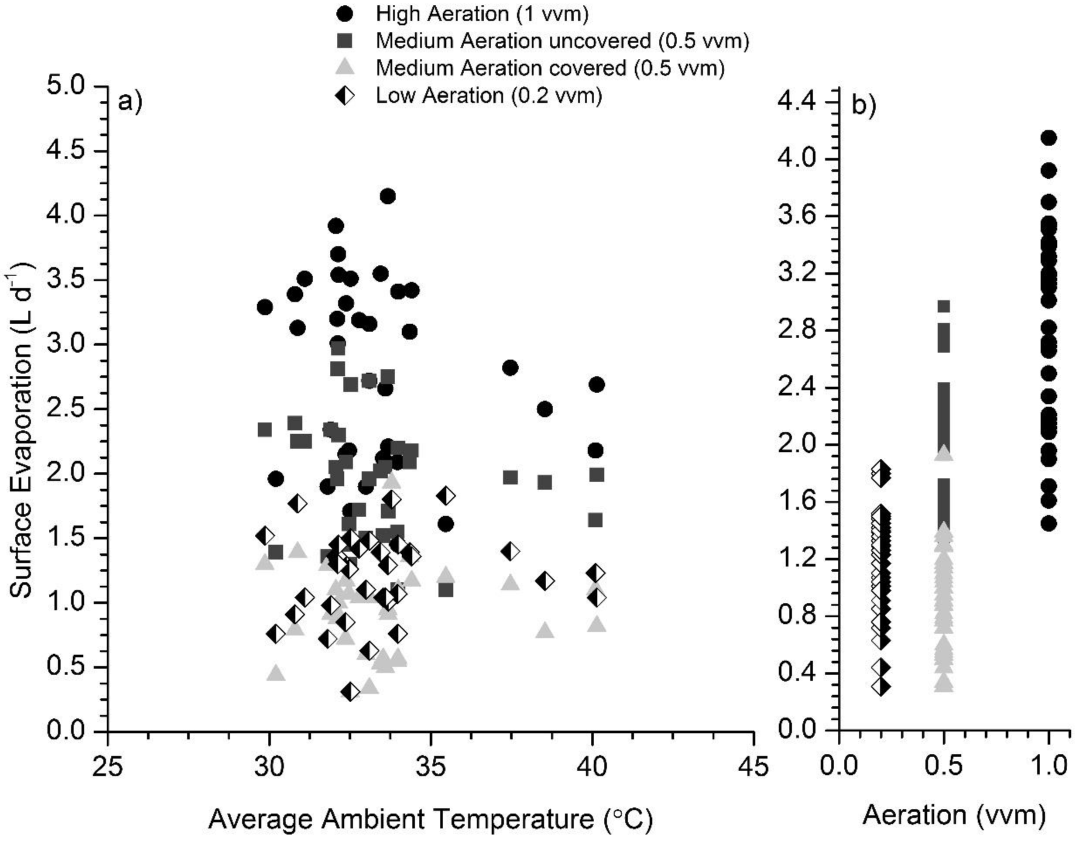


Figure 3.4: Influence of average ambient temperature (a) and, different aeration rates on surface evaporation from panels (b).

Figure 3.4 shows a side-by-side comparison of the effects of average ambient temperature and aeration rates on surface evaporation, which indicates that aeration is a major factor in evaporation at the surface of panels. However, this also does not consider the water consumption associated with the evaporative chiller, which is critical in maintaining lower culture temperatures as shown in Figure 3.5. Seasonal ambient temperature changes showed that increasing ambient temperatures above the desired algal culture temperature has a nearly exponential effect on evaporation rates in the evaporative chiller systems which also has a major impact on overall evaporation water loss. The four higher values for evaporation water loss of 103,105,116,133 L m^{-2} d^{-1} in Figure 3.5 are not considered in calculations for Table 3.1 as they occurred prior to installation of a second identical unit and was undersized for the desired temperature drop. This caused the system to operate inefficiently and caused the cooling water tower to flood, which resulted in using larger volumes of water.

However, as the culture temperature remains relatively constant, the evaporation water loss at the surface of the panels also remained relatively constant compared to that in the evaporative chiller. Figure 3.6 illustrates the higher temperature range for strain 0424 compared to 0414 which is a thermotolerant strain that could reduce the evaporative chiller requirements. This could be accomplished by increasing the desired culture temperature and as a result could increase the temperature set point of the evaporative chiller, thereby effectively shifting the evaporation data shown in Figure 3.5 to higher ambient temperatures.

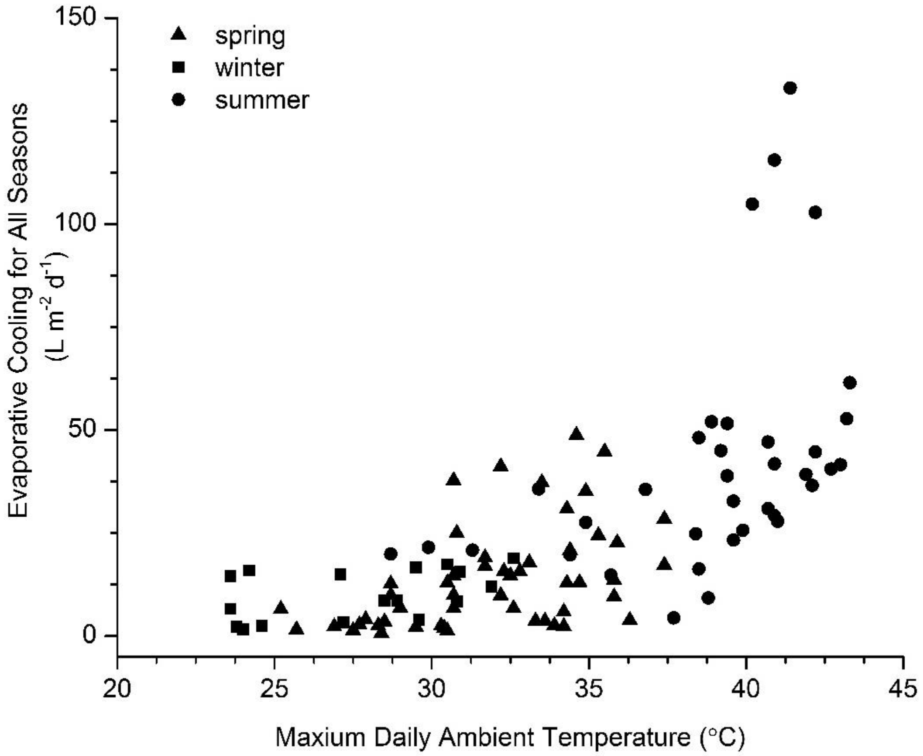


Figure 3.5: Influence of evaporative cooling and seasonal maximum daily ambient temperature on surface evaporation from panels.

Table 3.1 shows that the average evaporative cooling during the summer was 34.1± 13 L m^{-2} d^{-1} and occurred during a period with an average ambient temperature of approximately 30.6°C and average relative humidity of 41.1%. The highest value for evaporative cooling water loss was 61.5 L m^{-2} d^{-1} (summer) and lowest at 0.7 L m^{-2} d^{-1} (spring).

Table 3.1: Seasonal evaporative cooling water loss (L m^{-2} d^{-1}) for algal cultivation in panels.

Season Average (*Min, Max*)	Ambient Temperature [a] (°C)	Relative Humidity [a] (%)	Evaporative Cooling Water Loss (L m^{-2} d^{-1})
Summer	30.6 *(31.4 ; 33.5)* [b]	41.1 *(41.8 ; 20.9)*	34.1 *(9.2 ; 61.5)*
Winter	17.9 *(12.1 ; 23.4)*	34.5 *(20.9 ; 34.4)*	10.1 *(1.6 ;18.9)*
Spring	22.9 *(17.9 ; 23)*	25.2 *(55.6 ; 21.5)*	13.9 *(0.7 ; 48.8)*

[a] Relative humidity and temperature values are correlated to min and max evaporation values, excluding 4 high points in the graph due to the capacity of chillers

[b] Values reported as Average *(Min ; Max)*

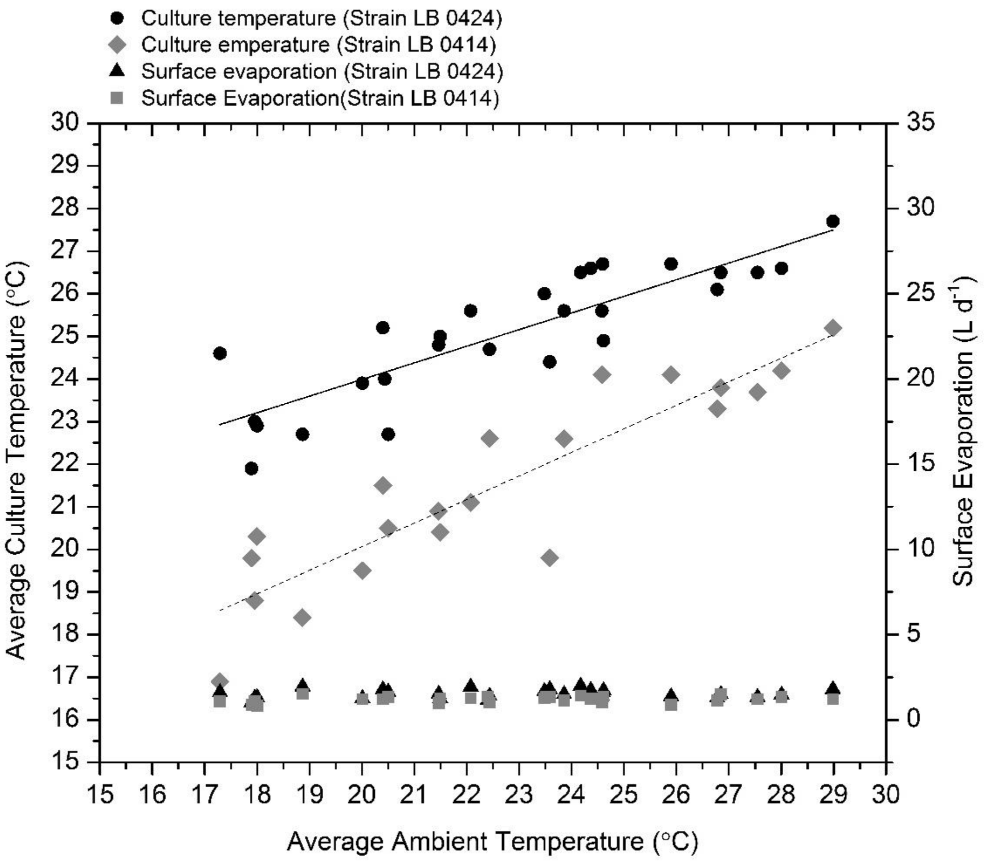


Figure 3.6: Evaporation related to cultivation of two different algal strains with different growth characteristics over different temperature ranges in panels.

Figure 3.5 also illustrates the highest and lowest evaporative cooling water loss with the highest evaporative cooling loss of 103,105,116,133 L m^{-2} d^{-1} attributed to summer days during suboptimal operation of the chiller (due to its capacity), which is approximately 250% to 340 % more that the culture volume of the 55 L per tank. The effect of depth on evaporation rates was investigated for a shallow raceway (7.5 cm) in comparison with a deeper raceway (24 cm). Surface evaporation rates from the shallow raceway was fairly similar to the deep raceway shown in Figure 3.7, suggesting that cultivation depth did not have a significant influence on evaporation rates. In raceways, there was a strong correlation between average ambient temperature and culture temperature.

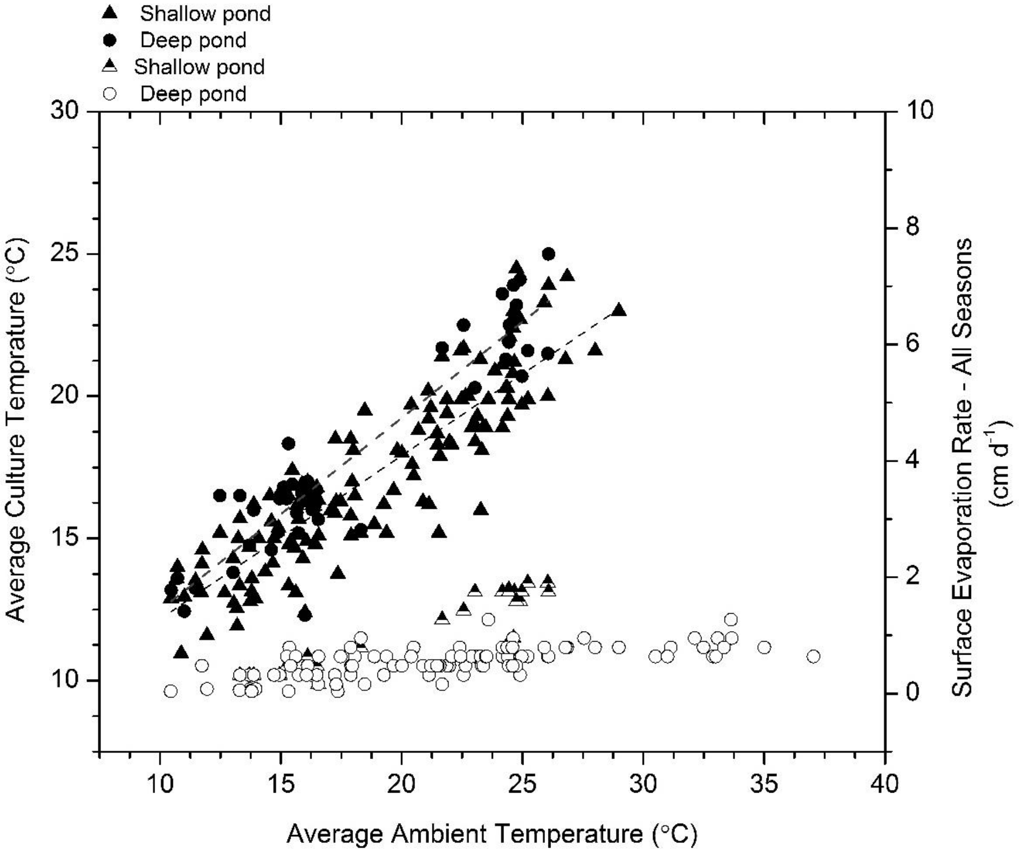


Figure 3.7: Relationship between average ambient temperature and average culture temperature on surface evaporation rate from shallow and deep raceways.

Figure 3.8 illustrates the influence of relative humidity on evaporation rates and culture temperatures in raceways. The figure shows two different but typical conditions: low ambient temperature and high relative humidity has a lower evaporation rate, while high ambient temperature with lower relative humidity has significantly a higher evaporation rate.

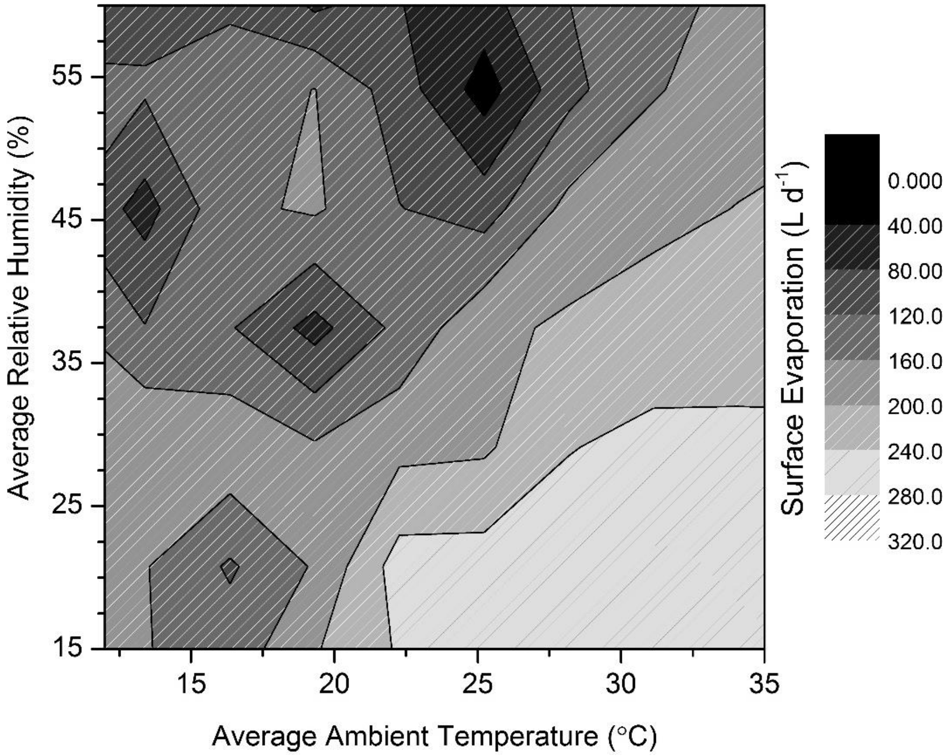


Figure 3.8: Relationship between average ambient temperature and average relative humidity on surface evaporation in shallow raceways.

3.3.4. Comparison of Direct Water Demand for Microalgal Cultivation Methods in Panels and Raceways

Direct water demand for both panel and raceway cultivation systems was evaluated by comparing water consumption for batch and semi-continuous cultivation methods. Figures 3.9 and 3.10 compare seasonal evaporation water loss in panels and raceways for both areal evaporation water loss (L m^{-2}) and volumetric evaporation water loss related to biomass productivity (L g^{-1}). Raw data collected were transformed and extrapolated into standardized metrics for comparison between the microalgal cultivation systems and other crops.

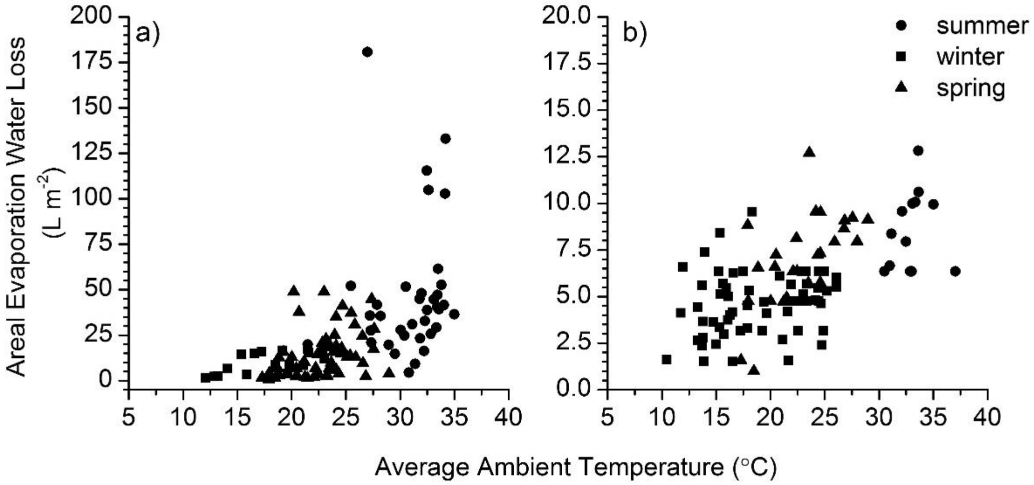


Figure 3.9: Comparison of seasonal areal evaporation water loss for panels (a) and shallow raceways (b).

Lower biomass productivity in raceways in winter resulted in higher evaporation water loss with respect to algal biomass produced (1.53 m^3 kg^{-1} d^{-1}) for both batch and semi-continuous culture, whereas higher productivity during the summer period reduced the evaporation rate for batch and semi-continuous cultivation methods to 1.07 and 0.71 m^3 kg^{-1} d^{-1}, respectively. However, the evaporation rate for panels was highest in summer for both batch and semi-continuous cultivation, reaching 11.13 and 5.51 m^3 kg^{-1} d^{-1}, respectively, compared to winter with 1.06 and 0.53 m^3 kg^{-1} d^{-1}. This is expected as the biomass productivity in panels is nearly constant throughout the year, but the need for evaporative cooling for temperature control significantly increases the water consumed per unit (kg) of biomass produced.

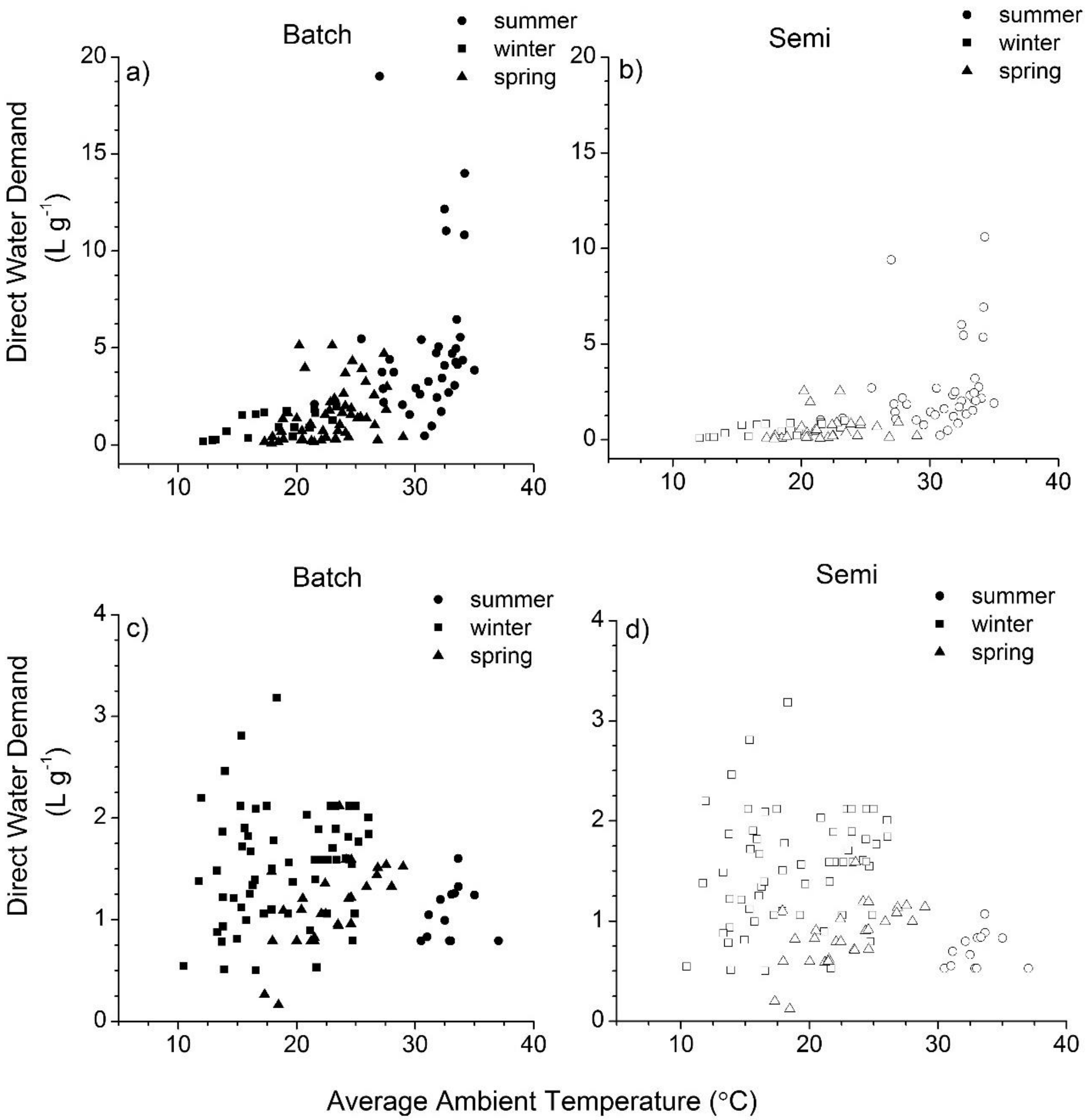
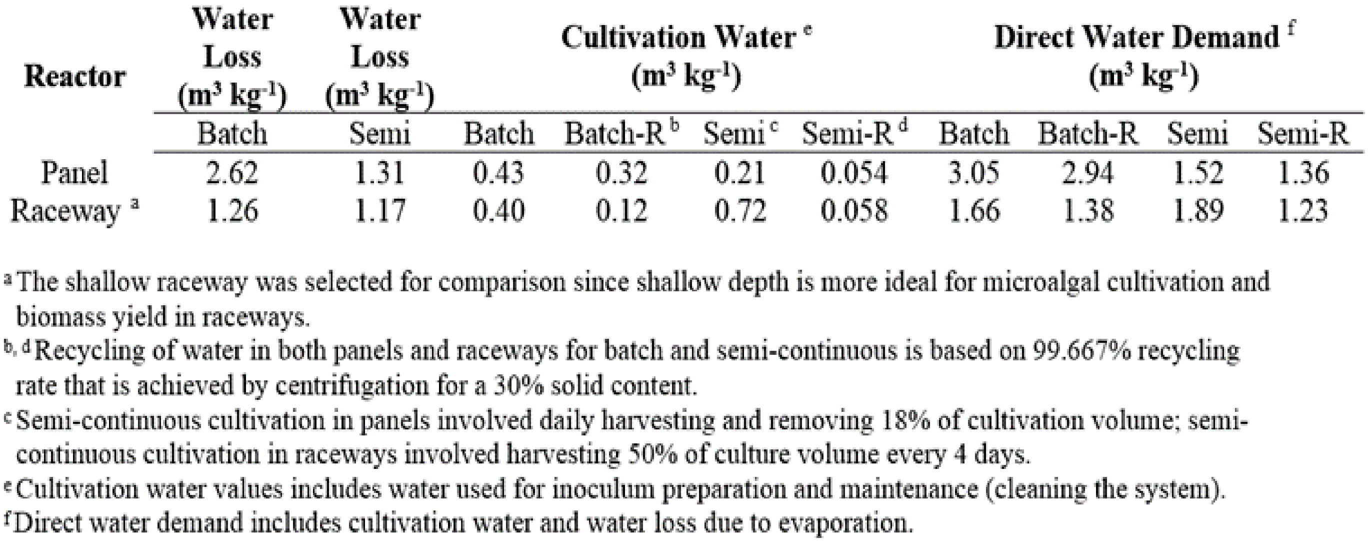


Figure 3.10: Comparison of seasonal direct water demand in batch (a) and semi-continuous cultivation in panels (b) and batch (c) and semi-continuous (d) cultivation in shallow raceways related to algal biomass productivity.

Table 3.2 shows estimates for annual evaporation water loss, cultivation water and direct water demand for biomass production in both cultivation systems and using batch and semi-continuous cultivation methods. Direct water demand takes into account seasonal variations for cultivation water, evaporation water loss and maintenance water. Evaporation water loss is the major contributor to water consumption in the direct water demand in batch cultivation (2.62 m^3 kg^{-1} in panels and 1.26 m^3 kg^{-1} in raceways) and in semi-continuous cultivation (1.31 m^3 kg^{-1} in panels and 1.17 m^3 kg^{-1} in raceways). Evaporation water loss in panels was higher in both cultivation methods. However, higher biomass productivity achieved in semi-continuous cultivation resulted in less cultivation water required for panels (0.21 m^3 kg^{-1}) compared to raceways (0.72 m^3 kg^{-1}) and ultimately, lower direct water demand in panels (1.52 m^3 kg^{-1}) compared to raceways (1.89 m^3 kg^{-1}). Recycling water in both batch and semi-continuous cultivation would result in further reduction; however, the reductions are marginally more for recycling in semi-continuous cultivation (35% in raceways and 10% in panels) compared to batch with (17% raceways and 3% in panels), respectively.

Reduction in use of maintenance water would also provide further opportunities for reduction in direct water demand. Maintenance water values are extremely high in research cultivation systems since reactors require extensive cleaning between experiments to prevent contamination and minimize the influence of the previous experiments. This suggests that large-scale facilities would use significantly less water for cleaning as systems would be shutdown less often, and cleaned to remove only when necessary.

Table 3.2: Direct water demand for batch and semi-cultivation methods for algal cultivation in panels and raceways.



Reactor	Water Loss (m^3 kg^{-1})	Water Loss (m^3 kg^{-1})	Cultivation Water[e] (m^3 kg^{-1})				Direct Water Demand[f] (m^3 kg^{-1})			
	Batch	Semi	Batch	Batch-R[b]	Semi[c]	Semi-R[d]	Batch	Batch-R	Semi	Semi-R
Panel	2.62	1.31	0.43	0.32	0.21	0.054	3.05	2.94	1.52	1.36
Raceway[a]	1.26	1.17	0.40	0.12	0.72	0.058	1.66	1.38	1.89	1.23

[a] The shallow raceway was selected for comparison since shallow depth is more ideal for microalgal cultivation and biomass yield in raceways.

[b, d] Recycling of water in both panels and raceways for batch and semi-continuous is based on 99.667% recycling rate that is achieved by centrifugation for a 30% solid content.

[c] Semi-continuous cultivation in panels involved daily harvesting and removing 18% of cultivation volume; semi-continuous cultivation in raceways involved harvesting 50% of culture volume every 4 days.

[e] Cultivation water values includes water used for inoculum preparation and maintenance (cleaning the system).

[f] Direct water demand includes cultivation water and water loss due to evaporation.

Table 3.4 summarizes different scenarios for reducing maintenance water by 20% and 90% for the cleaning of panels and raceways. The largest reduction in direct water demand values for each of the water maintenance reduction is allocated to the 90% reduction scenario for semi-continuous cultivation which reduces water use from 41 to 28 (acre-ft acre^{-1} yr^{-1}) in panels and from 21 to 7 (acre-ft acre^{-1} yr^{-1}) in raceways.

Table 3.3: Reduction of direct water demand for algal cultivation in panels and raceways by reducing water maintenance for cleaning the systems.

	Direct Water Demand (acre-ft acre^{-1} yr^{-1}) (20% Reduction)				Direct Water Demand (acre-ft acre^{-1} yr^{-1}) (90% Reduction)			
Reactor	Batch	Batch-R	Semi	Semi-R	Batch	Batch-R	Semi	Semi-R
Panel	43	38	44	31	33	29	41	28
Raceway	15	9	22	8	13	7	21	7

3.3.5. Comparison of Direct Water Demand for Algae Biomass with Another Agricultural Crop

Table 3.5 illustrates the direct water demand for algal biomass production compared to an agricultural crop such as alfalfa. With a semi-continuous cultivation mode and no water recycling, the estimated direct water demand for algae cultivation in panels and raceways is 45 and 22 acre-ft acre^{-1} yr^{-1}, respectively.

Water use can be significantly reduced for direct water demand by minimizing maintenance water (90% reduction) and recycling water after harvesting. Values for projected scenarios shows comparable and lower direct water demand for raceways (5 acre-ft acre^{-1} yr^{-1}) compared to direct water demand for alfalfa (6 acre-ft acre^{-1} yr^{-1}).

Raceways have a lower direct water demand of 353 kg-water kg-biomass^{-1} compared to alfalfa at 1020 kg-water kg-biomass^{-1} under projected scenario and reduction strategies.

Table 3.4: Direct water demand for algal cultivation in panels and raceways compared to a crop plant (Alfalfa).

Crop/Cultivation	Direct Water Demand (acre-ft acre^{-1} yr^{-1})		Direct Water Demand (kg-water kg-biomass^{-1})	
	Achieved [a]	Projected [b]	Achieved	Projected
Panel	45	10 [c]	2158	452
Raceway	22	5 [d]	2954	353
Alfalfa	6	-	1020	-

[a] Achieved case scenario indicates water loss and direct water demand under semi-continuous cultivation mode without accounting for recycling at harvesting and reduction of maintenance water

[b] Projected case scenario indicates water loss and direct water demand under semi-continuous cultivation mode and accounting for recycling at harvesting and reduction for maintenance water up to 90%

[c] Reduction achieved by crop rotation in panels to reduce water consumption was estimated to give a reduction up to 64%.

[d] Evaporation for larger scale raceways was considered to be 0.70 coefficient based on Pan evaporation for lakes.

3.4. Discussion:

3.4.1. Aeration Rates in Panels

The influence of operational variables on water evaporation rates were investigated for both raceways and panels with respect to culture depth, aeration rates and panel coverage. Aeration rate is the dominant factor in surface evaporation from panels. Covering the top surface of panels can significantly reduce evaporation rates (up to 44%±1) by providing a humid environment above the culture, which also retains additional water through condensation. However, the total evaporation from the surface of the reactor is minor compared to the evaporation associated with the evaporative chiller necessary to maintain culture temperature. Ambient temperature and desired culture temperatures determine the amount of evaporation associated with the evaporative chiller. Figure 3.5 showed a significant increase in water demand for the evaporative chiller with ambient temperatures above 30°. For experimentation purposes the chiller was set to maintain a culture temperature below 30°C for strain LB 0414, which has a maximum temperature tolerance of 29°C. Areal evaporation water loss can be reduced significantly (by 64%) when utilizing a thermo-tolerant algal strain (LB 0424), which can tolerate peak temperatures above 45°C. A strong correlation between culture temperature and average ambient temperature illustrate that the higher temperature range for strain LB 0424 compared to strain LB 0414 (Figure 3.6) could reduce the evaporative chiller requirements by increasing the evaporative chiller set point, which would reduce the runtime of the chiller and therefore reduce evaporation water loss. This provides strong support for the use of crop rotation in algal cultivation which can also increase overall annual biomass productivity. Creating new and sustainable algal systems require better resource utilization (water, energy, nutrients) by utilizing algal communities such as polycultures and thermophilic strains to provide better responses to diurnal temperature variation, culture stability and biomass productivity (Brennan & Owende, 2010; U.S. Department of Energy, 2014). Thermotolerant algal stains also provide resilience to high temperatures which are required for optimal growth during summer months in hot and arid climates (Jiménez et al., 2003).

3.4.2. Cultivation Depth in Raceways

This study evaluated evaporation rates at different raceway depths. Decreasing cultivation depth was critical for reducing the amount of water being used and processed. Previous research has shown that decreasing cultivation depth increased lipid productivity and culture density, which reduces the amount of water being used and removed, during cultivation (Eustance et al., 2015b). The results obtained from shallow raceways compared to deep raceways showed similar evaporation rates under the same environmental variables and conditions. Average culture temperatures in shallow and deep raceways were similar and highly correlated with average ambient temperature. The presence of algae, which is considered to have a black or grey body effect by increasing the amount of solar energy absorbed and not reflected was assessed by completing negative controls without algae present. Results showed that evaporation in raceways and panels with or without algae had no significant differences and that there was a strong correlation between the data obtained from raceways with evaporation rates from AZMET and Penman values. Thus, the values from these sources may be representative and useful for determining evaporation rates for assessment of future site locations.

Maintaining consistent depth in raceways during different seasons illustrated the significant effect of ambient temperature on productivity which varied from 3 g m^{-2} d^{-1} in winter to 6 g m^{-2} d^{-1} in spring when ambient temperature was more optimal for culture growth. Semi-continuous cultivation during an optimal ambient temperature also increased algal biomass productivity to 8 g m^{-2} d^{-1} in spring, which can potentially increase to 12 g m^{-2} d^{-1} in summer. These numbers are lower than those (30 g m^{-2} d^{-1}) reported for the summer by (Moheimani & Borowitzka, 2007). However, the use of 12 g m^{-2} d^{-1} as a maximum productivity provides a very conservative estimate for determining water consumption needs.

3.4.3. Strategies for Production of Algal Biomass Using Different Cultivation Systems (panels and raceways) in Hot Arid Climates

Direct water demand for cultivation comprises fresh water used during inoculum preparation, culture dilution when scaling up, water required to maintain volume due to evaporation, water loss during harvesting and cleaning of the cultivation systems. Both evaporation and water required during scale-up of cultivation are the main components of the total water footprint and life cycle water footprint estimates (Batan et al., 2013). Major approaches to minimize direct water demand in algal biomass production focused on reducing evaporation rates, providing optimal culture temperature regulation and higher biomass productivity. Many operational variables such as aeration rates and temperature control for panels would impact evaporation rates and lead to increased water consumption. Most of the literature has reported values on water demand in raceways rather than panels mainly due to the focus on raceways as the cultivation system for mass algal biomass production. Guieysse et al. (2013) reported evaporation rates and water demand values in arid climates of approximately 2.27 m^{-3} m^{-2} yr^{-1} and 5.19 m^{-3} m^{-2} yr^{-1}, respectively, which is lower than was measured in this study. When compared to values obtained at our location, the direct water demand for achieved scenarios was 13.7 m^{-3} m^{-2} yr^{-1} in panels and 6.7 m^{-3} m^{-2} yr^{-1} in raceways. These values decreased further under water reduction scenarios to 3 m^{-3} m^{-2} yr^{-1} in panels and 1.5 m^{-3} m^{-2} yr^{-1} in raceways.

Biomass production using crop rotation strategies to utilize different cultivation temperatures can also lead to a significant reduction in direct water demand. Removing the excess heat energy absorbed by the cultivation systems which occurs in panels is critical to maintain a desirable cultivation temperature range (25-35°C) appropriate for most algae species. Despite the efficiency of chillers, significant levels of energy and fresh water are necessary to operate an evaporative chiller. Therefore, chillers are not considered feasible for large-scale biomass production. Crop rotation becomes an important factor in the feasibility of algae cultivation when critical issues such as energy and water demand are considered. Cultivation of two different strains of algae, including Strain LB 0414 and Strain LB 0424, illustrated the differences in operating temperature ranges that would lead to major steps in energy reduction and evaporation water loss. By using the operating peak temperatures for LB 0414 (at 29°C) and LB 0424 (at 45°C) one could minimize the use of evaporative cooling in panels. With this crop rotation evaporation water loss and energy consumption for cooling could be significantly reduced during the summer (64% reduction in evaporation water loss and 37% reduction in energy consumption per day).

Large amounts of water loss can be attributed to harvesting the algal biomass. The volume of water loss is estimated based on achieving 30% solid content, which translates to water loss of 2.3 g of water per g of biomass at the point of harvest which would be permanently lost if the biomass was dried. The harvesting volume differs based on the cultivation mode and the cultivation system. Semi-continuous cultivation in 55 L panels equates to the removal of 10 L from panels daily or 18% of culture volume. For raceways the harvesting volumes are equal to removal of 1250 L or 50% every 4 days. This equates to 7 L m^{-2} in panels at harvesting compared to 41 L m^{-2} in raceways which represents nearly 80% more water at the processing step. The difference in volume of water is due to the lower biomass productivities in raceways (ca. 12 g m^{-2} d^{-1}) compared to panels (ca.19.2 g m^{-2} d^{-1}). Panels have a higher direct water demand in batch cultivation at 3.05 m^3 kg^{-1} compared to raceways 1.66 m^3 kg^{-1}.

Direct water demand reduction potential is higher for recycling in semi-continuous cultivation in panels (10%) and raceways (35%) compared to recycling in batch cultivation in panels (3%) and raceways (17%) respectively. However, potential for reduction in direct water demand is higher in recycling in both batch and semi-continuous cultivation in panels (54%) compared to raceways (11%) which is attributed to higher biomass productivity achieved in panels. The decrease in water consumption for semi-continuous cultivation compared to batch cultivation is attributed to the increase in biomass productivity, which is important for producing animal feed. However, if biodiesel was the desired final product, the water consumption per kg of biodiesel would favor batch cultivation, as results from Eustance et al. (2015b) showed lipid productivity was higher when lipids were allowed to accumulate compared to maintaining high growth with low lipid content. However, when accounting for the inefficiencies in water consumption when compared to large-scale cultivation, the achieved water consumption for panels is 2158 kg-water kg-$biomass^{-1}$ compared to raceways 2954 kg-water kg-$biomass^{-1}$. The projected water consumption for panels and raceways is closer to 452 and 353 kg-water kg-$biomass^{-1}$. This is higher than the 5-10 kg-water kg-$biomass^{-1}$ suggested by Murphy and Allen (2011), and is better than alfalfa at 1020 kg-water kg-$biomass^{-1}$.

Maintenance water also represents water that is required for cleaning and contributes to wastewater streams from cleaning panels and raceways. This volume of water represents water that is not recyclable back to the system. In addition, in most cases the volume must be diluted with the same quantity of water to allow release into the environment (Batan et al., 2013; Lundquist, 2010). However, in large-scale facilities there are a variety of opportunities available to reduce the amount of water for cleaning, whereas at a research scale this is usually limited, since inoculation requires pristine conditions.

3.5. Conclusions:

- High aeration rates leads to high evaporation rates from the surface of panels. The optimal aeration rate in panels was 0.5 vvm.
- Covering the surface of panels minimized the evaporation rate by 44% at lower or optimal aeration rates.
- Ambient temperature and seasonal changes regulate the evaporation rate when using an evaporative cooling system for algal cultivation in panels.
- Utilization of thermo-tolerant algae strains resulted in more efficient use of the water resource and can minimize evaporation water loss up to 64%.
- Raceway's depth did not have a significant effect on evaporation rate.
- With an optimal raceway depth (7.5 cm) for biomass production evaporation rate was similar using Penman and local weather station.
- Higher algal biomass productivities in raceways and water reduction strategies result in a reduced direct water demand of 353 kg-water kg-biomass^{-1} and is comparable to the agriculture crop-alfalfa with 1020 kg-water kg-biomass^{-1}.

- Reduction in water demand requires recycling of cultivation water and 90% reduction in maintenance water.

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4. MANUSCRIPT 2: EVALUATING KEY OPERATIONAL AND ENVIRONMENTAL VARIABLES ON DIRECT ENERGY DEMAND FOR ALGAL BIOMASS PRODUCTION IN PANELS AND RACEWAYS

Manuscript Information Page

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4.1. Introduction

Growing interest in algae as the next generation agricultural crop for biofuel production has encountered many sustainability concerns regarding energy requirements. Algal production for biofuels requires multiple steps: 1) photosynthetic production of organic matter (biomass production); 2) collection and processing of biomass; and 3) conversion of biomass to biofuels (Goldman & Ryther, 1977). Currently, each step of production consumes large amounts of energy which has prevented algal derived biofuels from achieving a net energy ratio close to current biofuel crops. The system design and cultivation process, as the first step in biofuel production, has a significant impact on downstream processing and equipment which is determined by the culture density, volume of water being processed, and the biochemical composition of the biomass (Eustance et al., 2015a; Eustance et al., 2015b; Eustance et al., 2015c). Therefore, the efficiency and type of equipment required for downstream processes are strongly affected by upstream cultivation decisions. This creates major uncertainty in feasibility assessments for algal biofuel production and is therefore considered a main limitation in advancing the commercialization of algae.

4.1.1. Energy for Biomass Production

4.1.1.1. Cultivation

Determining the best method for algal cultivation is critical for biomass and biofuel production. The cultivation of algae can consume significant amounts of energy and, thereby contributing the majority of the total cost and energy requirements for production of biofuels (Mata et al., 2010). Energy consumption in algal cultivation/biomass production is used primarily for regulating culture temperature and providing sufficient culture mixing to minimize limiting factors such as light (Hulatt & Thomas, 2011b). When panels are used for biomass cultivation, mechanical energy is required for aeration to create adequate mixing for mass transfer and efficient light utilization. The energy consumption for algae cultivation and biomass production in panels is higher than for raceways due to enhanced mixing provided by aeration and temperature control from external cooling sources (Chiu et al., 2008). Aeration is a critical operational component relative to mixing that also directly influences fluid-dynamics, mixing efficiency and energy consumption (Morweiser et al., 2010; Posten, 2009; Reyna-Velarde et al., 2010; Sierra et al., 2008; Ugwu et al., 2008). Energy consumption for different photobioreactors can vary depending on configuration and engineering characteristics but culture circulation or mixing can account for up to 92% of the total energy use. However, higher aeration rates do not necessarily increase the biomass productivity and, in some cases, may lead to cell damage and shear stress (Quinn et al., 2012a; Zhang et al., 2002). Previous studies regarding different aeration regimes indicated that considerable energy savings could occur (up to 23%) by minimizing the aeration rate with minimal changes to growth rate (Quinn et al., 2012b).

Outdoor cultivation in panels is subject to overheating due to confinement of the algae in a closed or nearly closed system which requires a temperature control component. The utilization of an external cooling system alleviates overheating of the outdoor culture due to absorption of infrared light received by the algae cells, especially in hot and arid climates (Mata et al., 2010). With an evaporative cooling system to maintain desirable culture temperatures, the total energy consumption attributed to aeration and cooling can escalate beyond 92% (Slade & Bauen, 2013).

When raceways are used for biomass cultivation, the majority of the energy (from 22% to 79%) is consumed by the mechanically driven paddlewheel used to mix and circulate the culture for better light utilization and to prevent algae settling (Mata et al., 2010; Rogers et al., 2014). Establishing and setting the optimum mixing velocity and depth are among critical design and operational parameters which influence light availability, temperature control and energy use (Grobbelaar, 2013; Ras et al., 2013). The operating velocity of paddlewheels in raceways varies from as low as 5 cm s^{-1} to up to 60 cm s^{-1}. Greater velocities result in higher energy consumption requiring a higher operational cost without providing a corresponding increase in biomass productivity. Furthermore, velocities above 30 cm s^{-1} can cause higher levels of shear stress, which reduces biomass productivity and occasional disruption of unlined raceways (Weissman & Goebel, 1987b). Cultivation depth dictates the volume of culture that is circulated, algal productivity and eventually harvest volume. Therefore, methods to reduce cultivation depth may significantly decrease operating and capital costs (Chiaramonti et al., 2013; Lundquist, 2010).

The cultivation of algae is a critical step that influences and dictates biomass productivity, biochemical composition and culture density, which ultimately defines the requirements for downstream processing. Theoretical algal biomass production is estimated to be 280 MT ha^{-1} $year^{-1}$ which is based on a photosynthetic efficiency range of 8-10%; however, sub-optimal growth conditions decrease this maximum value to ca.182

MT ha^{-1} $year^{-1}$ and 60 MT ha^{-1} $year^{-1}$ in photobioreactors (PBR) and raceways, respectively (Melis, 2009; Williams & Laurens, 2010). These are high values, which are currently not achievable in large-scale cultivation systems. Higher biomass productivities in panels (20-30 g m^{-2} d^{-1}), compared to raceway ponds (5-15 g m^{-2} d^{-1}), is attributable to better surface area to volume ratio, better mixing, and temperature control.

4.1.1.2. Downstream Processing

Harvesting is an energy bottleneck in algae production processes. Selection of lower cost harvesting methods is important for large-scale algal biomass production (Shen et al., 2009). Downstream processes contribute up to 60% of the total biodiesel production cost and harvesting alone contributes 20-30% of the total production cost (Kim et al., 2013). The major energy expenditure in harvesting is the capture of algae cells, which as dilute suspended solids, account for less than 1% of the total mass of the water being processed. By improving cultivation variables that increase productivity and algal culture density, the amount of water being processed per kg of biomass or kg biodiesel significantly decreases (Chiaramonti et al., 2013).

4.1.2. Strain and Cultivation Mode Selection

Long-term interest in algal lipid content has been the main driver in altering cultivation to meet the goal of increasing algal lipid/oil production for biofuels. This has traditionally been accomplished through nutrient depletion and high light intensity. Nitrogen starvation can effectively influence lipid content and alteration of the metabolic pathway (Chisti, 2007; Hu et al., 2008b; Illman et al., 2000; Khotimchenko & Yakovleva, 2005). Biomass and lipid productivity are strongly correlated with nitrogen concentration, where the effect of nutrient addition can be further altered by selection of different cultivation methods. Variation in nutrient dosing and harvesting time can be used to control for rate of lipid accumulation and overall biomass composition (Eustance et al., 2015a; Fábregas et al., 1998). Different nitrogen sources such as ammonia, nitrate and urea have also been investigated for their influence on growth rate, lipid and fatty acid content in different algal strains. Growth on ammonia as a nitrogen source, in general, provides for a higher algal growth rate compared to nitrate as a nitrogen source (Williams & Laurens, 2010).

The batch cultivation method has been extensively explored as a preferred cultivation method leading to nutrient depletion to achieve higher lipid content compared to semi-continuous cultivation in raceways and panels (Brennan & Owende, 2010). Different nutrient feeding rates in semi-continuous cultivation at stationary growth stages have shown different rates of lipid production (Eustance et al., 2015a; Hsieh & Wu, 2009). However, higher biomass productivity can be achieved by semi-continuous cultivation when logarithmic growth is maintained (Eustance et al., 2015a; Eustance et al., 2015b; Rodolfi et al., 2009).

In algal production, biomass and lipid yield are critical parameters in determining large scale production viability (Davis et al., 2012). In panels, a substantial increase in growth may be achievable, but the level of aeration (mixing) and energy required create process conditions that are not energetically feasible (Hu & Amos, 1996; Quinn et al., 2012a). It is important to investigate empirically the changes in operational parameters including energy-related cultivation parameters and cultivation methods with respect to biomass and/or lipid productivity and to monitor environmental variables that influence energy consumption and productivity in outdoor cultivation. Consequential decreases in energy consumption when accompanied with a preferred cultivation method could favor the overall net energy ratio (NER) for each individual cultivation system. In the absence of reliable energy data at each step of production, including cultivation, harvesting and extraction, estimating total energy is subject to a wide range of uncertainties (Chiaramonti et al., 2013). The purpose of this research was to investigate energy consumption and factors that are important in reducing energy consumption in outdoor panels and raceways on the Arizona Center for Algae Technology and Innovation (AzCATI) field site in Mesa, Arizona.

4.2. Materials and Methods

4.2.1. Direct Energy Demand and Metrics

Energy demand measurements were conducted in collaboration with on-going experiments on algal biomass production (Eustance et al., 2015a; Eustance et al., 2015b). Cultivation occurred from April 2014 through May 2015 on the AzCATI field site. Experiments were completed in panels and raceways to assess energy demand during batch cultivation for biofuel (biodiesel) production and semi-continuous cultivation for animal feed. The functional units for energy demand were kilowatt hours (kWh) of energy used daily for both cultivation systems used for algal biomass production.

4.2.2. Algal Biomass Cultivation and Process Model

Panels were positioned to provide a North-South facing exposure and measured 46” (1.17 m) in width by 46” (1.17 m) in height and approximately 1.5” (3.8 cm) in depth (thickness) or path length. The panels contained approximately 55 L of algal culture. Aeration was provided by small drilled holes (~1/32” (0.8 mm) in 1/2” (1.3 cm) PVC located at the bottom of the reactor at a rate of approximately 0.5 volume/volume/minute (vvm). CO_2 was added to the aeration line to provide a concentration of 1.5% CO_2 (v/v) during the day. The reactors contained an internal 1/2" (1.3 cm) stainless steel cooling line connected to an evaporative cooling system. Raceways consisted of two polypropylene channels 6.1 m long and 1.7 m wide with the two ends each with a radius of 1.78 m, providing a total cultivation area of 30.37 m^2. Water velocity in raceways was set to an average linear flow of 25 cm s^{-1}.

4.2.3. Monitoring and Daily Measurements

Temperature and pH were continuously monitored using a Neptune Apex controller (Neptune Systems, LLC.). Ambient conditions were measured with an Argus weather station capable of recording ambient temperature, relative humidity, wind velocity, and light intensity (Argus Control Systems, LLC.). Energy measurements in panels and raceways were based on daily readings from the auxiliary mechanical and electrical equipment located on the AzCATI field site.

4.2.3.1. Aeration Rates

Aeration in panels was adjusted at different rates by using a Flowmeter TS14000 (TSI Incorporated). The flowmeter outputs were in standard liters per minute (SLM) or in volumetric liters per minute (L min^{-1}). The aeration rate was typically set at 0.5 vvm for algae cultivation in panels as this was the standard rate required for operating the panels. The aeration experiments included: 1) continuous aeration at (0.5 vvm); 2) no aeration; 3) intermittent sparging at different operational times, including 1 min per 60 min , 1 min per 30 min, 0.5 min per 5 min, 0.5 min per 10 min and 0.5 min per 20 min throughout the experiment.

4.2.3.2. Daily Energy Use and Direct Energy Demand

Major components of the investigation of direct energy demand were energy values for aeration (blower) and maintaining culture temperature (fan for evaporative chiller and cooling water circulation pump) were recorded and reported in kilowatt hours (kWh). Data and information were based on daily and seasonal readings from electric meters (EKM-OmniMeter I v.3 single phase or 3 phase, 120 to 208 Volt) and samplings at daily intervals (3 pm to the next day at 3 pm). Seasonal variations were based on average ambient temperature ranges which categorized seasons into summer (early May to end of September), winter (early October to late March) and spring (late March and early May).

The following were the components of direct energy demand evaluated:

- Energy use for aeration (E_{aerate}): This value represents electricity used to aerate panels using a large blower (Pentair Aquatic Eco-Systems Sweetwater Regenerative Blower, Model number: S453-AQ, 3 Phase).

- Energy use for cooling (E_{chill}): The electricity required to prevent overheating of panels: 1) energy consumption at the circulation pump (E_{pump}) for circulating chilled water throughout cooling lines and evaporative chiller (Flotec model Model AT251001-01, 1 HP,208 V, 3 PH); and 2) fan utilized for forced air convection within the evaporative chiller (E_{fan}).
- Specific energy (E_{areal}): Total auxiliary energy or total direct energy demand, which is sum of energy used for aeration and cooling in both panels per unit area (m^2) of production system (energy density). This value also represents the total energy consumption in raceways with different depths per unit area (m^2) of production system. Plugged-in Kilowatt meters (Kill a watt ez electricity cost usage meter P4460) were installed and plugged directly to the motor at each raceway for daily cumulative energy measurements.
- Total energy content ($E_{biomass}$): energy content of biomass based on different lipid, carbohydrate and protein contents obtained in panels and raceways estimated in kWh kg^{-1} of biomass produced.
- Energy ratio for cultivation (ER): The total auxiliary energy versus energy content of biomass based on different lipid, carbohydrate and protein content. Based on previous work by (Illman et al., 2000) the approximate energy content for biomass was estimated to be 6.5 kwh for stressed phase biomass in panels and 6 kwh for raceways and 5.5 kWh for log phase biomass.

4.3. Results

4.3.1. Effects of Environmental Variables on Direct Energy Demand in Panels and Raceways

Seasonal variations in average ambient temperature and relative humidity impose a burden on auxiliary energy demand required for algal biomass production for different cultivation systems, and panels in particular.

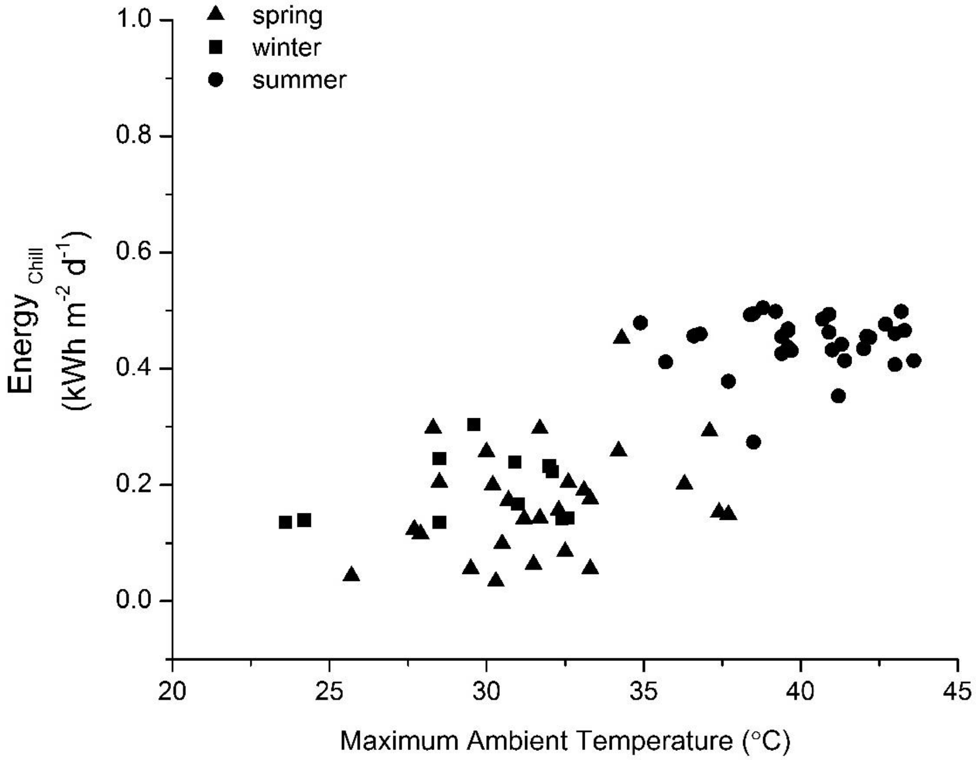

Figure 4.1: Maximum ambient daily temperature and seasonal energy required for temperature control in panels.

E_{chill} values at maximum ambient temperature during different cultivation seasons is illustrated in Figure 4.1. E_{chill} is mainly attributable to E_{pump} and E_{fan}. According to

Figure 4.1 energy consumption is highest for maximum daily ambient temperatures (above 40°C) that occurred during the summer season. Ambient temperature clearly dictates the rate of energy consumption required for temperature control. However, the high energy consumption during winter, despite the lower average ambient temperature, can be attributed to the change in the angle of incidence of sunlight, which was more direct to the surface of panels. As cooling was accomplished utilizing evaporative chillers, higher relative humidity increased E_{fan} as chiller efficiency dropped. This is due to the nature of evaporative chillers, which require dry air to effectively remove heat from the chiller water.

Table 4.1 shows the largest value for E_{chill} which was 0.6 kWh m^{-2} d^{-1} and attributed to an ambient temperature of 31 °C and a relative humidity of 69% during summer while the lowest value for E_{chill} was 0.4 kWh m^{-2} d^{-1} at an average ambient temperature of 20°C and a relative humidity of 35% during winter.

Table 4.1: Seasonal and average values for E_{chill} in panels (aeration constant at 0.5 vvm).

Season Average (*Min, Max*)	Average Ambient Temperature [a] (°C)	Average Relative Humidity [a] (%)	E_{Chill} kWh m^{-2} d^{-1}
Summer	32 *(27 ; 31)*	38 *(49 ; 69)*	0.5 *(0.3 ; 0.6)* [b]
Winter	20 *(19; 20)*	35 *(36; 35)*	0.2 *(0.1; 0.4)*
Spring	22 *(21 ; 18)*	29 *(27; 58)*	0.2 (*0.03; 0.5)*

[a] Relative humidity and temperature values are correlated to min and max evaporation values
[b] Values reported as Average *(Min; Max)*

Table 4.2 shows that the highest E_{areal} was associated with aeration as illustrated by E_{aerate} 0.71 kWh m^{-2} d^{-1} compared to E_{chill} 0.57 kWh m^{-2} d^{-1} during the summer with average ambient temperatures of 27 °C and relative humidity of 69%. Comparing average aeration rates E_{aerate} between different seasons, including summer (0.71 kWh m^{-2} d^{-1}), winter (0.65 kWh m^{-2} d^{-1}) and spring (0.63 kWh m^{-2} d^{-1}), did not show a significant difference which indicates that aeration values were fairly constant throughout the year, but remained the major component of E_{areal}.

Table 4.2: Comparison of maximum values for E_{areal} in panels during different seasons.

Season	Average Ambient Temperature °C	Relative Humidity (%)	E_{aerate} kWh m^{-2} d^{-1}	E_{chill} kWh m^{-2} d^{-1}	E_{areal} kWh m^{-2} d^{-1}	E_{areal} W m^{-2}
Summer	27	69	0.71	0.57	1.28	53.35
Winter	19	34	0.65	0.42	1.07	44.58
Spring	18	58	0.63	0.46	1.08	45.10

Therefore, attempts to reduce energy consumption in panels focused on the influence of different aeration rates and operational times for E_{aerate} and overall E_{areal}. Maximum values E_{areal} in panels were 1.28 kWh m^{-2} d^{-1} (summer) compared to 1.07 kWh m^{-2} d^{-1} (winter) and 1.08 kWh m^{-2} d^{-1} (spring). The fairly high E_{areal} values during winter compared to spring is attributed to the direct angle of the sun in winter during which the panels receive more sunlight energy.

4.3.2. Effects of Operational Variables on Direct Energy Demand in Panels and Raceways

Decreasing direct energy demand for cultivation was accomplished through different approaches such as 1) reducing aeration in panels; 2) decreasing raceway cultivation depth; and 3) producing different biomass quantities by modifying the cultivation methods, including batch and semi-continuous cultivation.

Table 4.3 illustrates E_{aerate} where values for different aeration strategies with respect to seasonal changes were normalized to land use for cultivation. Average values for E_{aerate} for different aeration strategies were compared in percentage reduction from base case or with continuous aeration in panels. The reduced aeration strategy (1 min on per 60 minutes, at night only) shows the highest reduction in energy use next to absence of aeration at night. For different operational seasons, absence of aeration at night would reduce the average energy use (from 0.614 kWh m^{-2} $d^{-1}$to 0.307 kWh m^{-2} d^{-1}) during summer by approximately 50%.

Table 4.3: Comparison of average values for E_{aerate} used for different aeration strategies (percentage reduction compared to base case: no aeration at night) in panels (aeration rate constant at 0.5 vvm).

Aeration Strategy (min-min)	Reduction in Aeration (%)	E_{aerate} Summer kWh m^{-2} d^{-1}	E_{aerate} Winter kWh m^{-2} d^{-1}	E_{aerate} Spring kWh m^{-2} d^{-1}
No aeration at night	50	0.307	0.318	0.306
1-60	49.2	0.312	0.323	0.311
0.5-20	48.8	0.315	0.326	0.313
1-30	48.3	0.317	0.328	0.316
0.5-10	47.5	0.323	0.334	0.321
0.5-5	45.0	0.338	0.349	0.337

Table 4.4 compares paddlewheel average energy use in raceways with respect to different depths and illustrates that no significance difference in energy consumption occurred with the different depths (p= 0.0560>). Average energy consumption for shallow raceways (7.5 cm), medium raceways (18 cm), and deep raceways (24 cm) are 0.051±0.016 kWh m^{-2} d^{-1}, 0.047±0.011 kWh m^{-2} d^{-1} and 0.059±0.011 kWh m^{-2} d^{-1}, respectively, with an operating velocity of ~ 25 cm s^{-1}. The lack of observable differences in energy consumption at different depths may be explained by the scale of

the raceways which may not be large enough to account for the friction losses associated with Manning Equations. Thus, the difference in energy consumption at different depths, with respect to biomass and lipid productivity, were not investigated further due to no detectable changes in energy consumption and no design changes to raceways. However, shallow raceways demonstrated significantly better energy use compared to panels where the average seasonal E_{areal} was estimated to be 0.057±0.02 kWh m^{-2} d^{-1} (summer), 0.053±0.02 kWh m^{-2} d^{-1} (winter) and 0.057±0.02 kWh m^{-2} d^{-1} (spring).

Table 4.4: E_{areal} for raceways at different depths (velocity ~ 25 cm s^{-1}).

Average Ambient Temperature °C	E_{areal} kWh m^{-2} d^{-1} Shallow (7.5 cm)	E_{areal} kWh m^{-2} d^{-1} Medium (18 cm)	E_{areal} kWh m^{-2} d^{-1} Deep (24 cm)	E_{areal} W m^{-2} Shallow (7.5 cm)
15± 2.14	0.051±0.016	0.047±0.011	0.059±0.011	2.11±0.66

In panels, the average seasonal E_{areal} was 1.07±0.08 kWh m^{-2} d^{-1} (summer), 0.86±0.10 kWh m^{-2} d^{-1} (winter) and 0.79±0.11 kWh m^{-2} d^{-1} (spring). However, since the two cultivation systems tended to have different biomass productivities, it was important to determine energy consumption based on the amount of algal biomass produced during the different seasons.

4.3.3. Comparison of Energy Balance for Cultivation Methods in Panels and Raceways

A comparison of specific energy and energy ratio for cultivation (ER) for the two different cultivation systems was further evaluated using different cultivation methods and summarized in Table 4.5. E_{areal} values compared seasonal changes of energy consumption in panels and raceways, independent of biomass productivity (Figure 4.2). In panels the E_{areal} value is higher and varied more over the seasons during the year, whereas in raceways, energy consumption was slightly less throughout the year.

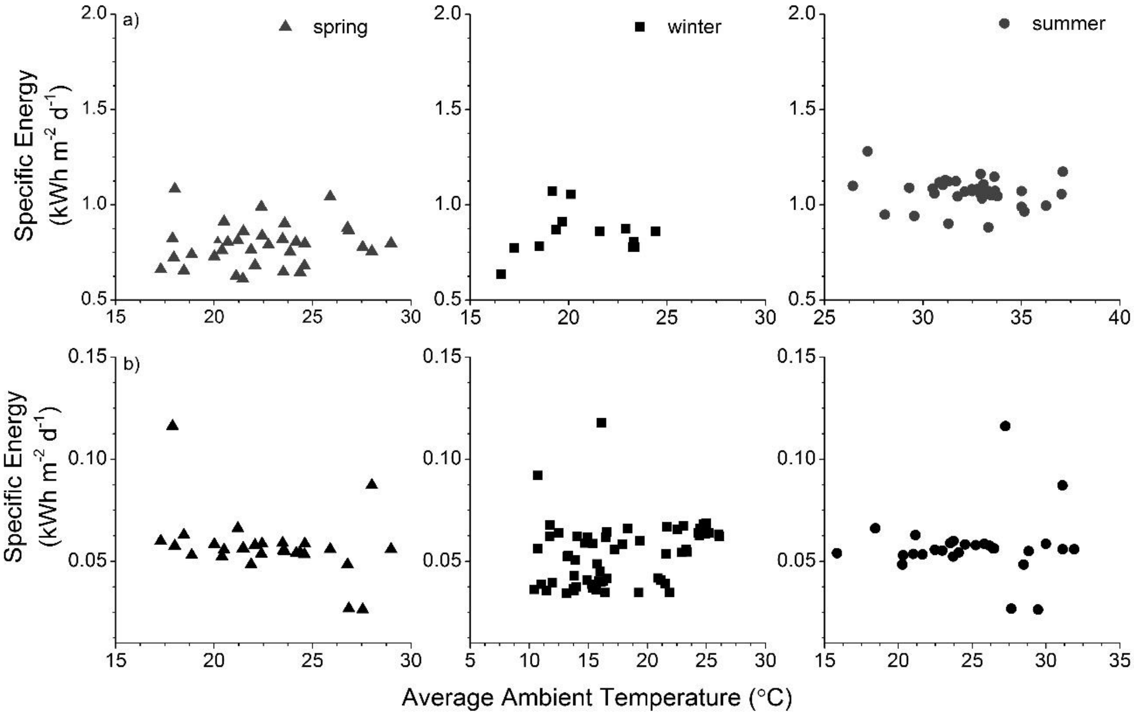

Figure 4.2: Comparison of seasonal specific energy consumption, E_{areal} (kWh m^{-2} d^{-1}) in panels (a), and comparison of seasonal specific energy consumption, E_{areal} (kWh m^{-2} d^{-1}) in raceways (b).

The highest value for E_{areal} in panels occurred during the summer (1.28 kWh m^{-2} d^{-1}) compared to winter (1.07 kWh m^{-2} d^{-1}) and spring (1.08 kWh m^{-2} d^{-1}) as illustrated in (Figure 4.2.a). Overall, higher E_{areal} in panels was related to E_{chill} for auxiliary energy demand required for cooling or lowering the culture temperature.

The ER obtained was based on energy content of the biomass ($E_{biomass}$) measured in kWh kg^{-1}-biomass and the areal energy consumed (E_{areal}) measured in kWh m^{-2} d^{-1} and was further compared with the cultivation systems based on biomass productivity obtained. ER values below 1 indicate the system utilized more energy than what can be produced in algal biomass, while values above 1 indicate the system produces more energy in the biomass than it consumes. It is critical to note that the ER is based on the overall energy available in the biomass and not what is necessarily utilizable only for biofuels (Figure 4.3). This suggests that the ER for the cultivation stage should be well above a value of 1, so that the NER of the entire process is also above 1.

Overall higher biomass productivity achieved in a semi-continuous cultivation in panels yielded an ER of 0.0052 ± 0.0007 kWh-biomass kWh-$consumed^{-1}$ compared to 0.0031 ± 0.0004 kWh-biomass kWh-$consumed^{-1}$ for batch cultivation as illustrated in Figure 4.3 (a). Lower ER for batch cultivation is related to the higher E_{areal} required for longer cultivation times and lower overall biomass productivities required to increase the lipid content and biomass energy content. Thus, semi-continuous cultivation provides a higher ER with increased biomass productivity of 19.0 ± 0.6 g m^{-2} d^{-1}, which is consistent year round, compared to a biomass productivity of 9.5 g m^{-2} d^{-1} obtained in batch cultivation.

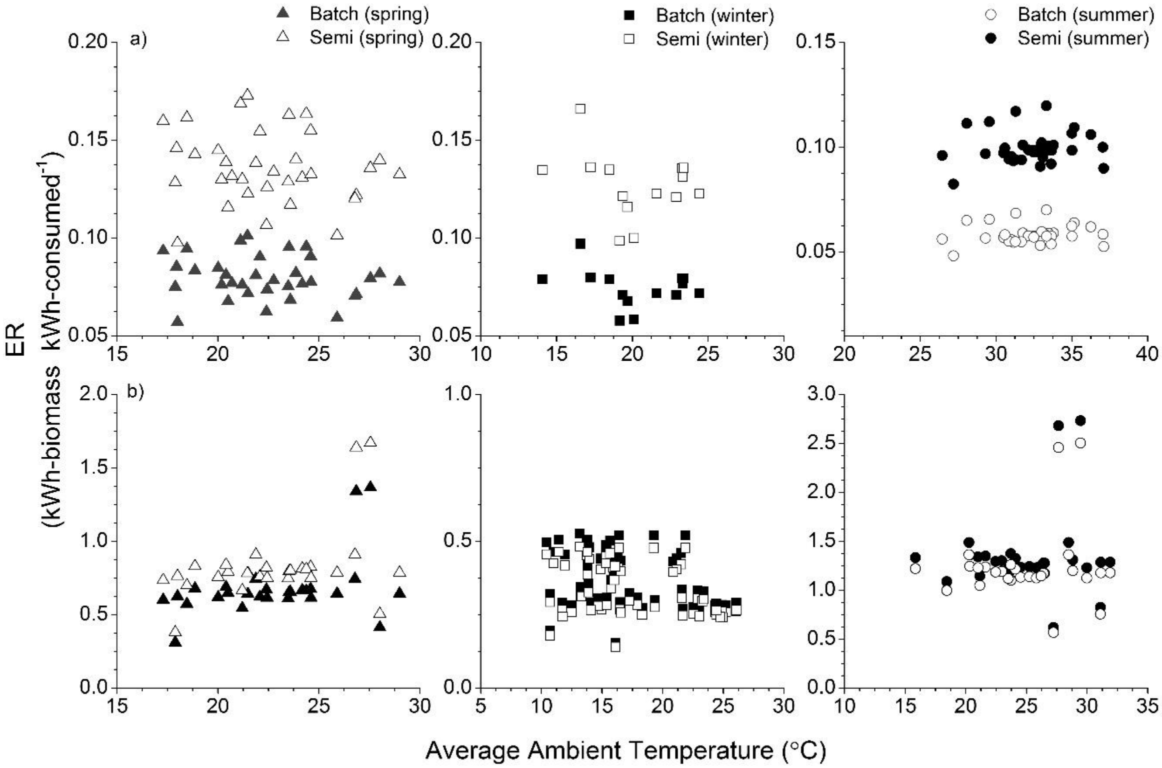

Figure 4.3: Comparison of seasonal ER (kWh-biomass kWh-consumed^{-1}) for batch and semi-continuous cultivation methods in panels (a), and comparison of seasonal ER (kWh-biomass kWh-consumed^{-1}) for batch and semi-continuous cultivation methods in raceways (b).

Figure 4.3 (b) indicates that in raceways, ER values obtained are higher for both cultivation methods compared to panels, which indicates a lower E_{areal} for raceway cultivation. However, comparing ER values over different seasons indicated that ER values were similar for both batch and semi-continuous cultivation and was related to the overall lower biomass productivity in raceways. Biomass productivity was approximately 3 g m^{-2} d^{-1} for both cultivation methods in winter, whereas the ER obtained in batch cultivation was slightly higher (0.4±0.10 kWh-biomass kWh-consumed^{-1}) compared to semi-continuous cultivation (0.3±0.09 kWh-biomass kWh-consumed^{-1}). Although optimal average ambient temperature and higher sun angles in the spring improved growth in raceways for both batch and semi-continuous cultivation (with approximately 8 g m^{-2} d^{-1} compared to batch cultivation with 6 g m^{-2} d^{-1}) and yielded average ER values of 0.7±21 kWh-biomass kWh-$consumed^{-1}$ and 0.8±0.26 kWh-biomass kWh-$consumed^{-1}$, respectively. Along with low productivity values, lipid accumulation in raceways was relatively low, which resulted in only slight changes in ER values between batch and semi-continuous cultivation, compared to a larger change in ER when cultivating in panels. The average ER in raceways was 1.4±0.44 kWh-biomass kWh-$consumed^{-1}$ in batch cultivation compared to 1.3±0.40 kWh-biomass kWh-$consumed^{-1}$ for semi-continuous cultivation achieved in summer with a biomass productivity of approximately 12 g m^{-2} d^{-1}. The overall ER values obtained indicates the importance of biomass productivity to achieving a desirable NER.

4.4. Discussion

4.4.1. Different Operational Aeration and Sparging Times in Panels

Lower biological activity of algae cells during night or dark period provides opportunities for reducing auxiliary energy demand, ammonia volatility and toxicity. However, both absence of aeration at night and intermittent sparging increased anoxic conditions and anaerobic respiration that can reduce the final lipid content and biodiesel potential of the algal biomass (Eustance et al., 2015c). The aeration reduction strategies could achieve between 45 and 50% reduction in energy as shown in Table 4.3. This is an important factor in improving the feasibility of large-scale production.

Table 4.5: Comparison of average values for E_{areal} and ER in panels and raceways.

Reactor	E_{areal} kWh m^{-2} d^{-1}			ER-Batch kWh-biomass kWh-consumed^{-1}			ER-Semi-continuous kWh-biomass kWh-consumed^{-1}		
	Summer	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring
Panel	1.07±0.08	0.86±0.10	0.79±0.11	0.0022±0.0002	0.0029±0.0004	0.0031±0.0004	0.0038±0.0003	0.0049±0.0006	0.0052±0.0007
Raceway	0.057±0.02	0.053±0.02	0.057±0.02	1.4±0.44	0.4±0.10	0.7±21	1.3±0.40	0.3±0.09	0.8±0.26

4.4.2. Different Depths in Raceways

Culture depth and culture temperature determines biomass and lipid productivity with respect to seasonal changes, where overheating during peak sun exposure in the summer or low culture temperatures during winter nights significantly influences algal growth and biomass production. In raceways, depths greater than 15 cm are preferred based on the Manning Equation to maximize distance between paddlewheels and for improved thermal stability associated with the increased heat capacity of the system (Béchet et al., 2011; Oswald, 1988). Deeper raceways have shown the capability for greater heat storage, which can be an important factor in hot arid climates such as experienced in Central Arizona by reducing the maximum temperature of algal cultures during the day and by minimizing night-time temperature drops (Chiaramonti et al., 2013; Grobbelaar, 2013; Lundquist, 2010; Oswald, 1988). In the literature hydraulic power consumption is estimated using the Manning Equation for head loss in straight channels and kinetic energy with a bend coefficient to account for head loss in curves (Chiaramonti et al., 2013), and a range greater than 0.25 - 1.12 Wm^{-2} based on theoretical values related to power input into raceways. However, energy consumption values estimated in the current project are vastly greater than reported values in the literature. An absence of changes in energy consumption at different depths can be explained by size or scale of the raceways in which friction loss is negligible. Energy analysis of the raceways operated in this study suggests an energy consumption of 2.11 Wm^{-2}, which may be in part due to the shallower depth utilized for cultivation, and older equipment that reduces the shaft efficiency of the motors driving the paddlewheels.

Limitations related to decreasing cultivation depth is associated with unfavorable temperature gradients, CO_2 off-gassing, light attenuation and increase in total head loss, which corresponds to reduced efficiency of the paddlewheel (Béchet et al., 2011; Grobbelaar, 2013; Oswald, 1988). However, there are advantages in cultivating in raceways with decreased depths as it reduces the amount of water required for cultivation, harvesting and processing along with a possible energy reduction (up to 50%), with refined design (Chiaramonti et al., 2013).

(Moheimani & Borowitzka, 2007) showed that areal productivity in raceways can reach up to 40 g m^{-2} d^{-1} or higher under optimal temperatures during summer in raceways with a 20 cm depth. The same study also showed a decrease in areal productivity to less than 3 g m^{-2} d^{-1} in colder seasons when suboptimal morning temperatures were observed, thus, these results indicate that temperature is a critical factor. Previous research on algal lipid productivity indicated that by decreasing the cultivation depth (9 cm compared to 24 cm in December 2014 and a depth of 7.5 cm compared to 20 cm in February 2015) areal biodiesel productivity was increased by 62% (0.36 to 0.58 g-FAME m^{-2} d^{-1}) and 38% (0.59 to 0.82 g-FAME m^{-2} d^{-1}), respectively (Eustance et al., 2015b) . Hence, increased lipid productivity was achieved while biomass productivity remained constant (3-4 g m^{-2} d^{-1}). However, reducing operating depth can ultimately result in greater energy consumption (Oswald, 1988). However, density of algal cells and overall culture volume are among the critical parameters that can influence energy consumption which can translate to light path length in panels and raceway depths (Grobbelaar, 2013).

4.4.3. Comparison of Batch and Semi-continuous Cultivation Methods in Panels and Raceways

Areal productivity is a good indicator for comparing the efficiency of cultivation systems regardless of different operating depths and path lengths. Higher ER achieved in both cultivation systems using semi-cultivation methods indicates the critical importance of biomass productivity in achieving a better energy yield. Biomass productivity in vertically orientated panels was consistent at 19.2 g m^{-2} day^{-1} with semi-continuous cultivation. However, higher direct energy demand in panel cultivation lowered the ER to 0.0052 kWh-biomass kWh-$consumed^{-1}$ compared to raceways at 0.8 kWh-biomass kWh-$consumed^{-1}$. Higher biomass productivity obtained in semi-continuous cultivation yielded better ER in both raceways and panels compared to batch cultivation. Better energy yield during spring compared to other seasons indicated the influence of temperature on productivity in panels and raceways. Improvement of productivity in raceways during the summer decreased the energy per unit of biomass produced, but did not affect the energy yield per unit area of production as the average specific energy use in raceways remained consistent (ca.0.6 kWh m^{-2} d^{-1}) during different seasons. Improving the algal growth rate by semi-continuous cultivation will increase the ER in panels, and improve feasibility of algal production. Despite the higher areal productivity in panels, the potential for scalability, high capital cost and lower energy ratio may not make them desirable as a future candidate for mass cultivation systems. However, new designs and materials should be considered.

4.4.4. Upper and Lower limits of Direct Energy Demand for Biofuel and Feed Production from algae in Hot Arid Climates

The cultivation process for algae is considered to be the most energy intensive stage for production of biofuels or bio-products in both panel and raceway systems. Majority of studies show a lower energy balance in panels compared to raceways, which is mostly due to the auxiliary energy demand by equipment, design efficiency, and reactor materials. Common values for energy demand for panels (mostly gas-sparged reactors) are reported to be 50-70 Wm^{-3} as function of aeration rate and liquid density; however, these are based on an aeration rate of 0.05 vvm and do not include cooling requirements (Hulatt & Thomas, 2011a; Sierra et al., 2008). The values obtained in this study (53.35 Wm^{-2} or 1200 Wm^{-3}) were based on the use of 0.5 vvm and accounting for cooling. However, this value is still lower than those reported for tubular reactors of 2400 to 3000 Wm^{-3} (Sierra et al., 2008).

Net energy ratio (NER) is an indicator which assesses the energy performance of a technology with respect to ratio of produced energy to consumed energy within the boundary of a production system such as biomass production (Collet, 2013). Given the obtained results on ER, NER is projected to be much lower value due to harvesting and extraction. Semi-continuous cultivation in panels demonstrated a higher ER at 0.0052 kWh-biomass $kWh\text{-consumed}^{-1}$ compared to 1.4 kWh-biomass $kWh\text{-consumed}^{-1}$ for semi-continuous cultivation in raceways. The influence of seasonal changes with respect to ambient temperature and relative humidity on algal biomass productivity can affect the ER achieved in both panels and raceways.

The NER reported by Lehr and Posten for panels and air-lift reactors is a third of the possible chemical energy harvested (Stephenson et al., 2010). Jorquera et al. (2010) showed an NER of 4.51 in a flat plate bioreactor compared to 0.20 estimated for tubular photobioreactors, with the highest net energy ratio reported for raceways at 8.34. . However, panels outperform tubular reactor designs for mixing, less oxygen build-up and outperform raceways due to the increased surface/volume ratio, and increased biomass productivity (Lehr & Posten, 2009; Slade & Bauen, 2013). Overall, the observed ER is much lower in panels in this study due to the use of an evaporative cooling system and seasonal changes. The ER for raceways is also often over estimated due to lack of accounting for friction head loss. The high capital cost and energy consumption have prevented large-scale production using panels but the higher productivity levels in panels can provide a baseline of achievable algal biomass productivity and thus could be used to further improve cultivation in raceways (Eustance et al., 2015c).

Energy savings in raceways can be achieved with better designs to overcome frictional head loss and temperature fluctuations in open cultivation systems (Doucha & Lívanský, 2014). Thus, further research should focus on evaluation of the direct energy demand with respect to biomass productivity. Other strategies such as algal crop rotation in both cultivation systems could reduce energy consumption due to different temperature tolerances of algal strains.

4.5. Conclusions

- Highest direct energy demand in panels occurred in summer of 1.28 kWh m^{-2} d^{-1} with an auxiliary energy demand of 0.71 kWh m^{-2} d^{-1} for aeration and temperature control compared to average specific energy for raceways which was constant at ca.0.6 kWh m^{-2} d^{-1} over different seasons.

- Aeration was the largest component of direct energy demand in panels (0.71 kWh m^{-2} d^{-1}) and in energy required for temperature control (0.57 kWh m^{-2} d^{-1})
- Environmental variables such as ambient temperature and relative humidity are important factors in determining direct energy demand in algal cultivation systems. Using algal strains with different temperature tolerances can result in reduced auxiliary energy demand (by 37 % in panels).
- Better strategies for reduced aeration in panels result in significant changes (by 90%) in overall reduction in energy consumption without significant changes to biodiesel potential and biomass productivity.
- Semi-continuous cultivation method provides better ER for biomass production due to higher biomass productivity compared to the batch cultivation method. ER obtained in semi-continuous cultivation in panels was 0.0052 kWh-biomass kWh-consumed^{-1} compared to 1.4 kWh-biomass kWh-consumed^{-1} for semi-continuous cultivation in raceways.
- Overall poor performance in raceways results in similar ER values for both batch and semi-continuous cultivation methods.

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5. MANUSCRIPT 3: ENERGY AND NUTRIENT ASSESSMENTS FOR FEED PRODUCTION USING DAIRY WASTEWATER WITH ALGAL CULTIVATION

Manuscript Information Page

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5.1. Introduction:

The increasing human population and demand for food is imposing pressure on water, land and energy resources. This affects many different economic sectors, especially agriculture. Recently, the Arizona State legislature has recognized the potential of algae and has designated algaculture as agriculture based on the ability of algae cultivation to provide biomass that has potential for use for biofuels, animal feed, and for environmental bioremediation (Trentacoste et al., 2015). Current agricultural processes used for producing animal feed are considered to be inefficient because of the over application of fertilizer and low nutrient utilization efficiency resulting from volatilization into the atmosphere and leaching into the groundwater. In addition, concentrated animal feed operations (CAFO) produce large volumes of wastewaters, which are highly valuable due to the high nutrient concentrations. However, poor management often results in large losses of nitrogen as ammonia through emissions thereby losing potential fertilizer that could be recycled to crops (Rotz et al., 2010). In 2013, agriculture accounted for 9% of total U.S. Greenhouse Gas (GHG) emissions including emissions from CAFOs (U.S. Environmental Protection Agency, 2015). As it meets the existing demand for major dairy products, the dairy industry is increasing the size of CAFOs, which increases the production of concentrated wastewaters and emissions (MacDonald et al., 2007; Von Keyserlingk et al., 2013a).

Algae have the potential to utilize these wastewaters, provide animal feed, and minimize most of the environmental impacts associated with upstream energy use for fertilizer production and direct energy use for harvesting and transportation on the farm for feed production (Gallego et al., 2011). Algae can utilize wastewater and provide high nutrient removal efficiency (up to 90- 99%) depending on type of wastewater and strain of algae (Chinnasamy et al., 2010; McGinn et al., 2012). Different types of wastewater can be utilized for algal biomass production. Compared to municipal wastewater with a low nitrogen and phosphorus content, the higher concentration of nitrogen and phosphorus found in wastewater from livestock farming like dairy effluents suggest that they are a better candidate for algal biomass production (Cai et al., 2013). To exploit the ecosystem services that algae offer in terms of bioremediation and biomass for feed production when integrated with CAFOs wastewater collection and treatment, it is important to consider the types of cultivation system that can be used since they represent the majority of the total cost and energy requirements for algal biomass production (Mata et al., 2010). The high biomass productivity achieved in an optimized cultivation system should be used as a baseline for achievable growth rate for algal biomass potential for animal feed production. The notion of integrating algae production with CAFOs wastewater pretreatment facilities require careful energy and resource assessments, including nutrient concentrations of the wastewaters and land availability.

5.1.1. Environmental and Economic Concerns for Use of Dairy Wastewater and Current Manure Management Practices

Dairy wastewater produced by CAFOs is considered to be both a significant resource and a large burden due to environmental concerns associated with emissions and leaching of nutrients (MacDonald et al., 2007). CAFOs generate more waste than that collected by municipal wastewater treatment facilities in the U.S. Manure produced daily by a dairy cow generates 20-40 times of feces the amount generated by a human (Agency, 2015; Hribar, 2010; U.S. Environmental Protection Agency, 2005a). However, facilities specialized for manure treatment are not usually available. Thus, the primary utilization of manure is geared towards land application to enhance crop growth and soil stability. Land application has been limited as result of nutrient runoff, leaching into the water column, noxious emissions, and inefficient manure deployment procedures (Bock & Hergert, 1991).

The physical and chemical characteristics of manure are site specific depending on operational parameters of the dairy facility, which means that each location has different concentrations of nitrogen, phosphorus and potassium in the manure (Davis et al., 2002; Lorimor, 2004). Based on the type of feed, nutrition and the cows' metabolism, ruminants typically excrete 65-75% of the nitrogen as feces and urine; however, major nutrients are excreted differently, as urine contains high concentrations of potassium and nitrogen, while a majority of the phosphorus is excreted in feces (Ishler; Lorimor, 2004).

Overall, regulating nitrogen plays a major role in manure management since control for ammonia volatilization and adjustment of adequate nitrogen for proper crop application remains an obstacle. This includes the production of soluble nitrate under aerobic conditions with the application of manure to soils, which can result in leaching into the local aquifer and/or runoff into nearby surface waters. Ammonia volatilization contributes to most of the nitrogen loss and release into the environment, which occurs rapidly (within 24-48 hours) with excretion of urine (Hristov et al., 2011). Ammonia volatilization from manure is a slower process and occurs during anaerobic digestion when the wastewater is stored in large open-pit lagoons (U.S. Environmental Protection Agency, 2005b).

5.1.1.1. Ammonia Emissions

Ammonia (NH_3) is an important air pollutant and a main precursor of particulate matter ($PM_{2.5}$), which results from interactions with sulfuric and nitric acids to form ammonium nitrate and ammonium sulfate (Aillery et al., 2005). In addition, ammonia plays a role in increasing soil acidity and is considered a major pollutant in the eutrophication of aquatic ecosystems (Hristov et al., 2011). NH_3 emissions from dairy farms vary in total ammonia nitrogen concentration (TAN), which includes both NH_4^+ and NH_3 , seasonal temperature variations and ultimately manure management practices. The formation of TAN occurs as the concentration of ammonium (NH_4) increases by hydrolysis of the urea in urine and can increase volatilization up to 50% during manure handling and management (Laubach et al., 2015; Pinder et al., 2003).

Traditional storage and treatment of manure in anaerobic lagoons does not control or prevent ammonia emissions. Nutrients including nitrogen and phosphorus remain relatively high in the lagoons and can also lead to surface and groundwater contamination (Aillery et al., 2005; U.S. Environmental Protection Agency, 2005b). To overcome emissions and nutrient loss, application of Anaerobic Digesters (AD) to abate GHG emissions, stabilize and recover nutrients, control odor and generate electricity and heat has slowly increased in popularity (Key & Sneeringer, 2011). AD reduces the amount of organic matter while maintaining high levels of nutrients. However, it increases the NH_4^+

concentration which is readily available for use by crops and algae for biomass production (Möller et al., 2008).

Elimination of the TAN content from dairy wastewater can be successfully achieved in conjunction with algal biomass production since algae have demonstrated the ability to efficiently and quickly remove nutrients from highly concentrated wastewaters (Buchanan et al., 2013a; Woertz et al., 2009). Wang et al. (2010) demonstrated a nutrient removal efficiency of up to 100% for anaerobic digested dairy manure. Based on U.S. estimated NH_3 emissions of approximately 3 MMT and the fact that algae contain 4.5-8.8% N during log-phase growth, it is estimated that 32 to 62 MMT of algal biomass can be produced and used for animal feed with a protein concentration between 25 and 60% (Eustance, 2015 Submitted).

5.1.1.2. The Need for Anaerobic Digestion

Key and Sneeringer (2011) estimated that the potential offsets achieved by anaerobic digestion (AD) application would provide up to 62% GHG reduction for manure management in both dairy and swine industries. Additionally, the AD process, by digesting the manure, unlocks a significant amount of nitrogen and phosphorus from the degraded manure, which provides a highly concentrated nutrient source that can be utilized as a nutrient source for algal cultivation. However, widespread application of AD in CAFOs is hindered by financial limitations including cost-effectiveness, absence of a carbon market and surplus electricity pricing. Additionally, high capital and operational costs limit AD usage on smaller dairies, but ultimately may be justified for use on large dairies.

5.1.1.3. Fresh Water Consumption in Dairy Facilities

In addition to air emissions, dairy production consumes more than 33 L d^{-1} of fresh water per cow resulting in large volumes of wastewater being generated (Ward et al., 2005b). In addition, the geographical locations of dairy facilities in the arid and semi-arid Southwestern U.S and the proximity to nearby highly populated areas have increased the demand for water resources (MacDonald et al., 2007). With fresh water being a scarce resource, utilizing algae for removal of nutrients by bioremediation of dairy wastewater and production of high protein algal biomass for animal feed may provide a useful solution.

5.1.2. Animal Feed Production

Since the 1940’s, algae have been recognized for their ability to produce an array of valuable products. This includes the three major biomacromolecules—carbohydrate, protein and lipid—as well an array of specialty compounds such as essential fatty acids, DHA and EPA, and carotenoids such as lutein, beta-carotene and astaxanthin (Markou & Nerantzis, 2013). *Chlorella*, *Scenedesmus*, *Spirulina* and *Nanochloropsis* are well known commercial microalgal strains with specific characteristics, including potential for biofuels production, bioremediation, animal and fish feed, food and health products for human consumption. Moderately growing, but robust species such as *Scenedesmus spp.* are promising and have been intensively studied for use as animal feed, specifically as a dairy ration (Boeckaert et al., 2008; Franklin et al., 1999; Moate et al., 2013). *Scenedesmus* has a favorable amino acid profile, as well a relatively high protein content of up to 45% (Moo-Young & Gregory, 1986) and a fatty acid profile (Ahlgren et al., 1990; Becker, 2007) with an appropriate omega-6 to omega-3 ratio that is similar to flax. These profiles can be tailored by controlling the nutrients in the algae growth media (Moo-Young & Gregory, 1986). This species has been used primarily as a supplement to the high protein grain or alfalfa portions of the diets of dairy cows with favorable results (Chowdhury et al., 1995).

For optimal milk yield, the dairy industry is highly interested in specific characteristics in feed for optimal nutritional value such as protein content. Among animal feeds, alfalfa has the desired protein quality for lactating cows and with a peak protein content of 22% at the pre-bloom stage when it is harvested (Orloff, 2007). Interestingly, the average protein content of log phase algal biomass is 25% to 60%, which indicates that algae may provide an alternative feed (protein) source to alfalfa. This is further emphasized by the fact that alfalfa has a lower protein content which requires additional high quality forage as part of the feeding regime in order to maintain high milk production (Higginbotham et al., 2008). One benefit that algae provide is the opportunity for continuous harvesting for high protein content compared to bulk harvesting of traditional crops, which could reduce time from harvest to consumption and perhaps reduce protein degradation.

Animal feed production is a large component of the cost in dairy milk production. Therefore, exploring other highly qualified sources of animal feed with a lower cost is highly desirable for the future of dairy industries. Over the years, the price of daily feed has increased thereby influencing the milk to feed price ratio, an indicator used to measure the economic well-being of the dairy industry (Wolf, 2010). Sub-optimal price ratios (below 2) have been predominately observed since 2009, which illustrates the continuing high costs of animal feed (USDA-ERS, 2014).

5.1.3. Algae Cultivation Systems

Energy demand is among the ultimate criteria in selecting algal biomass cultivation systems. Algae have been traditionally cultured in raceways to minimize energy input. However, many desired strains of algae require enclosed Photobioreactors (PBR) for stricter environmental control. Raceways operate on a level surface require sufficient depth—15-30 cm—to provide adequate mixing for the culture (Weissman, 1987). This depth reduces the culture's exposure to light and reduces photosynthetic efficiency, which limits biomass yields to below 5-15 g m^{-2} d^{-1} (Moheimani & Borowitzka, 2007). Over the past few decades attempts have been made to match the productivity of PBR systems with the economy of a raceway by making a hybrid cultivation system. An innovative design that crosses the boundary between raceways and PBRs have been investigated since the 1960s in the Czech Republic and is referred to as a cascade reactor (Doucha & Lívanský, 1995). The cascade reactor system provides financial viability that are closer to raceways with productivity levels similar to PBRs; however, the system is still used only in research settings and has yet to be integrated into mainstream agriculture. Another example is a system designed by at the University of Arizona's Agricultural Research Facility. The system, dubbed A.R.I.D. for "Arid Raceway Integrated Design" uses a basin to store algal culture to maintain higher nighttime temperatures in desert environments; however, the system operates like traditional raceways, using a deeper culture, which limits productivity and photosynthetic efficiency (Waller et al., 2012).

In raceways the two major energy losses are due to friction and bends. To account for loss in bends, baffles are incorporated to reduce the energy loss and reduce dead zones (Weissman & Goebel, 1987a). Gravity fed systems like the cascade reactor overcome energy loss by utilizing the force of gravity, which as a consistent force provides homogenous mixing throughout the reactor and minimizes the dead zones. This system and other gravity fed systems are among potential designs for improving biomass productivity and operational parameters to increase the net energy ratio (NER). Both the ARID system and the cascade reactor circulate the algae culture and store the culture in basins, where biomass is collected and pumped back up into the system (Doucha & Lívanský, 2009; Waller et al., 2012).

Panels can produce optimal biomass yields around 20-30 g m^{-2} d^{-1} and can reach up to 55 g m^{-2} d^{-1} with a 1-10 cm light path; however, they are not currently energetically and financially viable to be integrated with agriculture (Armandina et al., 2013; Eustance et al., 2015a; Qiang et al., 1996). Raceways average 5-15 g m^{-2} d^{-1} for biomass productivity, whereas higher biomass productivity (above 40 g m^{-2} d^{-1}) has been achievable in outdoor cultivation in raceways (Moheimani & Borowitzka, 2007). The production potential of algae represents a significant increase over alfalfa, which produces around 5.4 g m^{-2} d^{-1} when grown in good soils (U.S. Department of Agriculture-NASS, 2013). The purpose of this study was to evaluate the energetic feasibility of utilizing either gravity fed or raceway reactors for the cultivation of algal biomass with the goal to replace alfalfa for a dairy containing 4,400 cows. This was accomplished through multiple steps, including: 1) Calculation of energy required for gravity fed and raceway systems; and 2) Assessment of average wastewater production by a CAFO dairy. The information and assumptions utilized for calculations focus on some critical unknowns in algae biomass production for dairy application.

5.2. Materials and Methods

5.2.1. Design and Calculations of Energy Requirements

5.2.1.1. Gravity Fed Reactors

Attempts have been made to increase the productivity of open raceway systems by reducing cultivation depth and improving mixing by utilizing a slope design and allowing gravity to drive flow. This innovative design, known as a cascade reactor, was developed in the Czech Republic (Doucha & Lívanský, 1995). The design consists of algae flowing down a sloped glass surface to allow the culture to flow at shallow depths less than 1 cm. This allows the system to operate at very high culture densities and maximizes exposure to sunlight allowing for production rates to reach above 40 g m^{-2} d^{-1} and lower harvesting costs through processing less water (Doucha & Lívanský, 2014). The gravity fed system can provide financial viability closer to raceways with productivity levels similar to panels; however, limited research has been conducted to estimate the energetics and practicality of utilizing cascade reactors over raceways (Buchanan et al., 2013b). This is due in part to its precise construction requirements including smooth grading to achieve the desired slope with minimal roughness or the use of concrete infrastructure to ensure proper grading, which is more feasible than utilizing glass as was done in the cascade system (Borowitzka, 1999). Table 5.1 presents assumptions that were used for each major energy and design parameters for a module gravity fed system to evaluate the energy balance for producing algal biomass.

Table 5.1: Assumptions for different design and energy related parameters for a module gravity fed system (0.8 Ha).

Design and Energy Parameters /Unit	Value	Description of Values
Slope (%)	1	Assumption, 0.6% required for minimum slope calculated from manning equations
Area (m^2)	1.59	Calculated based on width and depth selected for the design
Width (m)	63.6	Assumption
Depth (m)	0.025	Assumption
Linear Flowrate ($m\ s^{-1}$)	0.20	Less energy use compared to 0.25 Based on mean velocity in traditional raceways
Total Head (m)	2.8	Calculated (includes head for basin, piping and slope)
Volumetric Flowrate ($m^3\ s^{-1}$)	0.318	Calculated based on linear flowrate and area
Manning Number (n)	0.05	Assumed for a smooth pipe
Hydraulic Radius (m)	0.025	Calculated based on wetted perimeter and area
Distance Traveled (m)	127.2	Assumed based on 2 acre size module production unit
Volumetric flowrate per pump ($m^3\ s^{-1}$)	0.159	Calculated per pump based on volumetric flowrate
Density ($kg\ m^{-3}$)	1000	Alga biomass has similar density to density of water
Accelerated Gravity ($m\ s^{-2}$)	9.81	
Pump Efficiency (%)	0.6	Assumption
Number of Pumps	2	Assumed based on 2 acre size module production unit
Operational Time (hours)	14	Assumption (daylight hours)

The design of the system is based on information derived from the cascade reactors developed in the Czech Republic, the ARID system designed at the University of Arizona, USA, and mathematical equations for calculating flow in an open channel (Doucha & Lívanský, 1995; Waller et al., 2012).

Based on Manning's equation (Eq. 5.1) for cultivation at a depth of 2.5 cm and a velocity of 20 cm s^{-1}, along with physical design parameters shown in Table 5.1, the critical slope for the system is 0.6%; however, to account for unexpected frictional losses associated with settling biomass and/or biofilm development, the slope of the is set at 1% for further calculation.

$$S_0 = \frac{n^2 V^2}{{R_h}^{4/3}} \quad \text{Eq. 5.1}$$

Where S_0 is the slope of the channel (m m^{-1}), n is Manning's roughness factor, V is the mean velocity (m s^{-1}), and R_h is the hydraulic radius (m).

The selection of a 1% slope is less than of 1.5% that selected by Doucha and Lívanský (1995); however, Duocha and Livansky selected a slope that would provide a depth closer to 1 cm and not 2.5 cm. The main reason for the system depth at 2.5 cm is the feasibility of creating a smooth grade over large distances that could handle a shallower depth than 2.5 cm. It is still uncertain whether the desired depth of 2.5 cm could be obtained in a full-scale reactor.

One of the main advantages of this system is the development of a constant Reynolds number (Re) (Eq.5.2), which indicates the culture would maintain high levels of mixing.

$$Re = \frac{Vd_h}{v} \qquad \text{Eq. 5.2}$$

Where d_h is the hydraulic diameter (m), V is the mean velocity (m s^{-1}), and v is the kinematic viscosity (m^2 s^{-1}).

In a sloped reactor system, centralized centrifugal pumps in a basin are used to lift the culture to the required height. The total head that the pump needs to be rated is the change in height from the beginning to end of the channel, the head loss in the piping from the pump, and the depth of the basin. The basin is designed to hold the total volume of the sloped section plus an extra amount to ensure that the pump is successfully submerged at all times to prevent cavitation. The purpose of the basin is to hold the algal culture at night so that the system does not require continuous pumping, and to prevent heat loss from the cultures, which significantly reduces culture productivity (Crowe et al., 2012; Waller et al., 2012). In this system, the depth of the basin is assumed to be 1.5 m with an accommodating width to hold the volume of water being circulated during the day. The length and width of the system were arbitrarily set at 127 m and 63 m, respectively, creating a unit area of 2 acres (0.8 ha). The design is intended for use in large-scale agriculture with multiple units combined to form a larger system. However the design principles for a larger system would be based on linking several small units in a side-by-side production scenario.

Selection of size, type and number of pipes and pumps are based on energy consumption and biology of algal cells. Pumping provides a significant amount of shear stress to algal cultures. This can be minimized by ensuring low shear pumps and the low R_e of the piping. In addition, the length chosen for the system reduces the recirculation rate, which dictates the total time the culture is experiencing the high shear conditions on a daily basis. Based on the design length of 127 m, the culture will be recirculated every 11-12 minutes. The hydraulic pump power is a function of volumetric flow rate and total head loss (Eq.5.3).

$$P_{h_{kW}} = q\rho g h/(3.6 \times 10^6) \qquad \text{Eq.5.3}$$

Where $P_{h_{kW}}$ is the hydraulic power (kW), q is the flow capacity (m^3 h^{-1}), ρ is the density of the fluid (kg m^{-3}), g is acceleration of gravity (m s^{-2}), and h is the differential head (m). The shaft power which relates to the power provided by the motor to the shaft of the pump accounts for the efficiency of the pump assumed to be 0.6. (Eq.5.4)

$$P_{s_{kW}} = P_{h_{kW}}/\eta \qquad \text{Eq.5.4}$$

Where $P_{s_{kW}}$ is the shaft power (kW) and η is the pump efficiency. Total power requirement accounts for the total of 2 pumps, 14 hours daily operational time, and hydraulic pump power.

5.2.1.2. Raceways

For comparison with the gravity fed system, energy consumption in raceways was also assessed. In Weissman et al. (1989), the suggested length to width ratio for cultivation in algal cultures was 15. This value was used to determine the length of each channel based on the set width of 150 m creating a unit area of 1.24 acres (0.5 ha), as is shown in Table 5.2.

Additional parameters were average velocity of 20 cm s^{-1} and a depth of 20 cm, as was similarly done by Chiaramonti et al. (2013). Total head loss in raceways is composed of frictional loss and loss associated with bends. Head loss due to friction can be estimated by utilizing either the Manning equation or the Darcy-Weisbach equation (Eq.5.6), which has been referenced to be more accurate than Manning's equation, but requires the use of values that are not easy to measure (Barnard et al., 2002).

$$S_f = \frac{fV^2}{8gR_h} \qquad \text{Eq.5.6}$$

Where S_f is the slope of the surface of the raceway (m m^{-1}), V is the mean velocity (m s^{-1}), g is gravity (9.81 m s^{-2}), Rh is hydraulic radius (m), and f is Darcy-Weisbach friction factor, which can be estimated based on the Moody chart. The evaluation of head loss in bends is based on the kinetic energy associated with the fluid flow, and has an empirical coefficient k_b, which ranges from 1.5 to 4 depending on the design of the bend and the presence of baffles (Eq.5.7).

$$h_b = k_b \frac{V^2}{2g} \qquad \text{Eq. 5.7}$$

Oswald (1988) estimated the length between paddlewheels and assumed that the maximum head loss that should be achieved is half the value of the initial cultivation depth. This was considered in estimating the number of paddlewheels each raceway would require. Oswald (1988) estimated that the length between paddlewheels, assuming that the maximum head loss that should be achieved is half the value of the initial cultivation depth.

Table 5.2: Assumptions for different design and energy related parameters for a module raceway (0.5 Ha).

Design and Energy Parameters /Unit	Value	Description of Values
Area (m^2)	3	Calculated based on width and depth selected for the design
Width (m)	15	Assumed based on L/W at 10 and the optimal is 15 based on Weismann 1989 to require less bends
Depth (m)	0.2	Assumption
Length (m)	150	Assumed based on L/W at 10 and the optimal is 15 based on Weismann 1989 to require less bends
Linear Flowrate ($m\ s^{-1}$)	0.20	Less energy use compared to 0.25 Based on velocity in traditional raceways
Total Head (m)	0.102	Calculated (includes head for 2 channels and 2 bends)
Volumetric Flowrate ($m^3\ s^{-1}$)	0.6	Calculated based on linear flowrate and area
Darcy-Weisbach friction factor (f)	0.03	Smooth pipe
Hydraulic Diameter (m)	0.195	Calculated based on width and depth
Density ($kg\ m^{-3}$)	1000	Alga biomass similar to density of water
Accelerated Gravity ($m\ s^{-2}$)	9.81	
Paddle Wheel Efficiency (%)	0.3	Assumption
Shaft Efficiency	0.6	Assumption
Number of Paddle Wheel	1	
Operational Time (hours)	24	Assumption

This was considered in estimating the number of paddlewheels each raceway would require. By increasing the width of the system to 12 m, the corresponding increase in length increased the head loss to greater than half to initial depth, indicating that the system would require two paddlewheels to ensure proper flow. The change in depth and velocity of raceways associated with friction and bend losses also mean that the algal cultures would experience a decrease in R_e with distance from the paddlewheel (Raes et al., 2014). This means that the culture will have decreased mixing thereby reducing exposure to light and CO_2 gas transfer, which may reduce culture productivity (Oswald, 1988). The reason for this concern is the utilization of an energy point source in an open system (not a closed pipe), which creates a gradually varied flow (GVF) system rather than a uniform and constant flow system as is found with a sloped design. However, calculations for GVF are based on a step function and is an iterative process. The equation used for GVF, Equation 8, can account for changes in height (potential energy of the system) and velocity (kinetic energy of the system). However, because the method can account for two different energy losses, the equation requires experimental data to determine the energy lost to height or decreased velocity.

$$\frac{dh}{dx} = \frac{S_0 - S_f}{1 - Fr^2} \qquad \text{Eq.5.8:}$$

Where S_0 is Bottom slope (zero in raceways), S_f Friction slope (slope of the culture surface), and Fr is Froude's number found by solving Equation 5.9.

$$Fr = \frac{V}{\sqrt{gh}} \qquad \text{Eq.5.9:}$$

Where h is culture depth (m), g is gravity (m s^{-2}), and V is mean velocity (m s^{-1})

The hydraulic pump power is a function of volumetric flow rate at the pumps (q) and total head loss which accounts for total head loss at the channels and bends (Eq. 5.10).

$$P_{h_{kW}} = q\rho gh/(3.6 \times 10^6) \qquad \text{Eq.5.10}$$

Where $P_{h_{kW}}$the hydraulic power (kW) is, q is the flow capacity (m^3 h^{-1}), ρ is the density of the fluid (kg m^{-3}), g is acceleration of gravity (m s^{-2}), h is large scale total head loss (m)

The shaft power which relates to the power provided by the motor to the shaft of the paddlewheel accounts for total power input efficiency. The value is calculated as the sum of paddlewheel efficiency and shaft efficiency of 0.18 (Eq.5.11)

$$\eta_{total} = \eta_{paddlewheel} * \eta_{shaft} \qquad \text{Eq.5.11}$$

$$P_{s_{kW}} = P_{h_{kW}} / \eta_{total} \qquad \text{Eq.5.12}$$

Where $P_{s_{kW}}$ is the shaft power (kW) and η is the total power input efficiency. Total power requirement accounts for a total of 1 paddlewheel per raceway, 24 hours operational time and hydraulic pump power with respect to total efficiency calculated as above (Eq.5.12)

5.3. Results and Discussion

5.3.1. Energy Assessment and Comparison of Raceways and Gravity Driven Channels

Calculation of head loss (h) and volumetric flow rate (q) in both systems are important criteria for energy assessments. In a gravity fed system, the total head loss of 2.8 m is calculated based on the depth at the basin, head loss in the piping system and head loss as a function of nearly 1% slope. Thus, total areal power requirement for 2 pumps is estimated to be approximately 1.78 W m^{-2} which takes into account a pump efficiency of 0.6 and total operational time of 14 hours during the day.

Energy assessment in raceways accounts for the bend head loss coefficient k_b which is assumed at 2 associated with baffles in design for improvements in energy efficiency (Lundquist, 2010). Thus, head loss is estimated at 0.102 m which accounts for total head loss when two channels and two bends are considered in the system design. Estimated total areal power requirement of approximately 0.64 W m^{-2} takes into account total power input efficiency (around 0.18) which consists of paddlewheel efficiency at 0.3, shaft efficiency at 0.6 and 24 hours of operational time for paddlewheel and mixing.

Chiaramonti et al. (2013) estimated the total areal energy consumption at 1.1 W m^{-2} at 20 cm depth and 20 cm s^{-1} flow velocity for 500 m^{2} which was further reduced to 0.47 W m^{-2} with decreasing depth to 5 cm and installation of a propeller pump replacing a paddlewheel. The previous values are fairly comparable when accounting for the bend and friction head loss, whereas total energy consumption of 0.25 W m^{-2} reported by Weissman and Goebel (1987b), 0.24 W m^{-2} by Lundquist (2010) and 1.12 W m^{-2} by Jorquera et al. (2010) did not account for components of total head loss such as bends (Chiaramonti et al., 2013). Rogers et al. (2014) estimated the lowest energy consumption for a paddlewheel at 0.22 W m^{-2} compared 0.73 W m^{-2} for Waterwheel Inc., and 8.16 W m^{-2} for the NMSU testbed (Rogers et al., 2014). These values can be compared to values previously obtained in Chapter 4 (2.11 W m^{-2}), which are due to old motors with lower shaft efficiency. Improvements in energy consumption can be achieved by other modifications in mixing such as only day time mixing, which can decrease energy consumption by 37% (Cuello et al., 2014).

Table 5.3 summarizes energy balance values obtained from raceways compared with values obtained from gravity fed systems. Despite the higher specific energy in gravity fed system (25 Wh m^{-2} d^{-1}) compared to a raceway (15.4 Wh m^{-2} d^{-1}), the expected higher annual productivity achieved in gravity fed system compared to the highest annual productivity achieved in raceways would provide a better energy ratio (ER) of 1.41 kWh-consumed kg -$biomass^{-1}$ compared to 2.01 kWh-consumed kg^{-1} -biomass obtained in paddlewheel raceways.

Table 5.3: Comparison of average energy assessment values in gravity fed and raceway systems.

Cultivation System	E_{areal} Wh m^{-2} d^{-1}	ER kWh-consumed kg-$biomass^{-1}$
Gravity fed	25	1.41
Raceway	15.4	2.01

5.3.2. Incorporation of an Algae Cultivation System within a Dairy Facility

This research assumes the presence of a dairy pretreatment facility including separation of solids and liquids, and Anaerobic Digestion (AD) for biogas recovery. The pretreatment stage would ultimately determine available inoculum composition which dictates the biomass production potential with respect to areal biomass productivity; however, energy consumption by pretreatment stage and AD are not considered as part of energy balance calculation in section 5.2.1

Availability of nutrients, mostly nitrogen, is strongly dependent on storage, separation and treatment methods selected for dairy effluents. Table 5.4 shows the quantity of nutrients including nitrogen, phosphorous and potassium in dairy cow excretion. Average values of the quantities presented in the Table 5.4 were selected to present a generic characteristics of manure (as excreted), including nutrient composition and total manure production, in a large dairy (4,400 lactating cows) for this research project.

Table 5.4: Assumptions for manure characteristics at a dairy facility.

Dairy Facility Size and Manure Characteristics	Assumptions and Units	References
Facility size	4,400 lactating cows	Assumed for a local dairy with 10,000 cow
Cow body weight (kg)	544	MWPS (2004)
Total Manure (kg d^{-1})	60	MWPS (2004)
TS (kg d^{-1})	7.78	MWPS (2004)
VS (kg d^{-1})	6.60	MWPS (2004)
N (kg d^{-1})	0.39	MWPS (2004)
P (kg d^{-1})	0.20	MWPS (2004)
K (kg d^{-1})	0.22	MWPS (2004)
Urine- as excreted	N (52%), P (3%), K (70%)	Meyer et al (2007)
Feces - as excreted	N (48%), P (97%), K (30%)	Meyer et al (2007)

The total amount of manure and water, approximately 1,200 m^3 d^{-1} (3% TS), is collected from different parts of the dairy facility for the pretreatment stage located on the dairy site for solid-liquid separation. After a thickening system process, the flow is separated into two main streams where 640 m^3 of effluents with lower solid content (1.5% TS) is transferred to lagoons for additional settling. The remaining approximately 570 m^3 of effluents with higher solid (4.6% TS) is pumped to AD for the digestion process. Nutrient analysis for both effluents, including lagoon (635 m^3) and AD centrate

($500\ m^3$), shows 300 mg-N L^{-1} and 700 mg-N L^{-1} nitrogen content at each collection point, respectively, which contributes to total nitrogen (540 kg d^{-1}-N) available for algal biomass production. However, 53.5% of nitrogen is in the form of ammonia that is assumed to volatilize by ca. 20% before capture. Therefore, the available nitrogen for algae is reduced to 481 kg d^{-1}-N. Nitrogen content of algae at 5% dry weight for higher protein content production and areal productivity of 12 g $m^{-2}\ d^{-1}$ at log phase is translated to an annual biomass production of 3,500 MT-biomass. Total land required to produce algal biomass is ca. 220 acre for an algae facility to utilize the daily nitrogen content in the dairy effluents. This system can replace either 20% of the alfalfa based on biomass produced or 36% of the protein produced from alfalfa assuming 40% protein content in algae and 22% for alfalfa.

Biomass downstream processes, including harvesting and drying, contribute to obstacles moving forward with this approach because it has been stated that the algae biomass for feed use will have to be relatively dry for storage. This can be problematic since many strains of algae cannot be easily separated from water and the process can be very costly. *Scenedesmus*, however, shows the ability to be settled at 15 to 20% solids within a 24 hour period. This may be reduced by optimizing settling conditions. Further experimentation should be conducted to investigate settling rates for both warm and cool climate strains in order to design an appropriate settling system.

Silage for feed is stored wet and fed to livestock, unlike alfalfa which is dried to use as animal feed. Algal biomass may also be utilized in the form of wet biomass as animal feed without the need to be dried. This would not only influence the energetics and profitability of unit cost of biomass produced but also provide a significant opportunity to reduce overall production cost for animal feed for dairies.

The economic structure of Arizona is heavily dependent on farming, and mostly focused on providing forage for animal feed, cotton and vegetables. The State allocates nearly 324,562 acres land for forage production. In 2014, nearly 260,000 acres of alfalfa were harvested representing nearly 2 MMT, which is higher than cotton and all other vegetable crops individually. However, alfalfa production is highly dependent on irrigation water and fertilizers for growth (U.S. Department of Agriculture-NASS, 2014) which confirms that this animal feed is a resource intensive crop with unilateral application for feed. The financial viability related to system design is associated with capital costs for algal cultivation system including land preparation, construction, pond liner, water pumps and installation in both gravity fed systems and raceways, although paddlewheels in raceways would be the major equipment requirement in addition to the liner. The projected operational costs are allocated to labor and utilities, with electricity being the highest cost component. Economics of scale might apply to capital cost components, including site preparation and infrastructure, to lower the unit cost of production. However, financial viability of feed production from algal biomass is subject to many variables (some of which are unknown or assumed) that are required for operating and maintaining a production facility; however, in the absence of existing facilities, uncertainties with quantifying these variables contributes to ambiguity in the financial viability assessment.

5.4. Conclusions

- Nitrogen loss due to ammonia volatilization from dairy waste waters results in negative environmental externalities.
- Algal biomass production systems can utilize the high nutrient concentrations in dairy wastewater and minimize ammonia volatilization into the atmosphere.
- Previous research indicates significant variability in calculating the total energy consumption by raceways, which results in underestimated values for energy requirements.
- Energy consumption for algal biomass cultivation in a gravity fed system is estimated to be 25 Wh m^{-2} d^{-1} compared to raceways at 15.4 Wh m^{-2} d^{-1}. The potential for significantly higher areal biomass productivity in a gravity fed system provides a better ER (1.41 kWh-consumed kg -biomass^{-1}) compared to raceways (2.01 kWh-consumed kg -biomass^{-1}).
- Algal biomass produced by an algal cultivation system of 220 acres utilizing wastewater from a dairy with 4,400 lactating cows, could replace 20% of the alfalfa based on estimated biomass produced or 36% of the protein produced from alfalfa required by the facility. Use of microalgae allows for remediation of wastewater over a short time period and reduces ammonia volatilization compared to application of manure for crops (alfalfa) or collection in lagoons.

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6. SUMMARY CONCLUSION AND FUTURE RESEARCH

6.1. Strain and Site Specific Sustainability Measures

In the absence of large-scale production formulating a set of metrics which best represents algal biomass production remains a challenge. Few studies have evaluated the impact of regional environmental conditions and cultivation systems for achieving maximum biomass productivity. However, there are also significant components within the technology selected that have a greater impact on productivity that need further evaluation. This should be accompanied by well-defined operational data, advanced knowledge in biomass production and appropriate cultivation parameters.

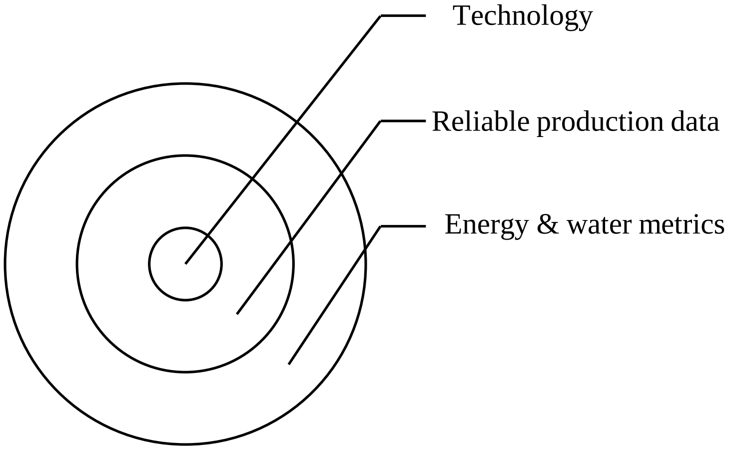

Figure 6.1: Components for algal sustainability assessment.

The key result of this study highlighted the strong impact of biomass productivities on the viability of commercial algal biomass production. The importance of outdoor cultivation, environmental conditions and role of biomass productivity in determining environmental and financial viability of algal biomass production have been recognized in previous research. Recent publications of the DOE (2012) provided the

“Harmonization model” which integrated the results from TEA, LCA and previous resource assessment (RA) reports for models that incorporated several key variables including productivity, lipid content and nutrient recycling for producing 5 billion gallons per year of renewable diesel in raceways. The RA model was used to estimate seasonal and spatial distributions of biomass production on locations where fresh water supply is available. The results emphasized that profitability, emissions reduction potential, and resource consumption were highly sensitive to assumptions for algae productivity and lipid content, including seasonal variability.

This research carried out for this dissertation was performed at an outdoor algae facility in Arizona (AzCATI) to monitor and assess seasonal variability of algal biomass productivity in the outdoor environment. The outcome provides information for input resource consumption including energy and water demand for modeling scale-up scenarios. The results of this research have shown the impact of environmental and operational variables in outdoor cultivation can be extrapolated from obtained baseline values at research scale to larger production systems. Limitations related to resource inputs including water, energy and nutrients were introduced and interconnected with environmental and engineering variables for improving future technologies adapted for biomass production. Crop rotation and application of thermotolerant algae compared to other strains introduced a significant difference in resource demand requirements with the same biomass cultivation technology.

6.2. Appropriate Technology and Production Scenarios

Algal biomass production is a developing field and therefore lacks infrastructure, policy interventions, and the low and fluctuating market values for algal biofuels represent hurdles to commercialization (Stephens et al., 2013). Currently, the algae industry is at its infancy and heavily relies on technologies stemmed from other sectors such as wastewater treatment, aquaculture and other agricultural practices (Slegers et al., 2011). Therefore the algae technology should define the connection between engineering (design and process) and biological parameters to provide appropriate methodologies and well-defined metrics to evaluate key input and output variables for production systems.

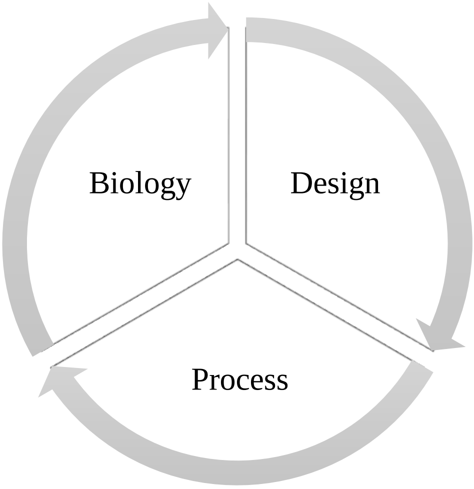

Figure 6.2: Algal technology components

For development of new technologies including algal biomass production, decisions not only rely on the technology to be cost affordable but also be able to utilize alternative input resources to determine related trade-offs based on environmental and social benefits. This research incorporated empirical information obtained from outdoor cultivation to evaluate hypothetical algae cultivation technology for utilizing dairy wastewater, provide biomass for feed and to minimize negative environmental impacts as a result of untreated dairy effluents.

6.3. Key Findings from the Research Chapters

Evaporation is a major contributor to direct water demand for producing potential algal biofuels and bio-products and an important step for estimating water consumption for large scale algal biomass production in panels and raceways. Assessment of water resources is a critical issue for determining suitable sites for algal biomass production, including Arizona and the arid Southwest climates. While water is considered to be a major bottleneck for both panels and raceways, water loss is highly dependent on local meteorological conditions and system's operational parameters. The major conclusions from this chapter were:

- High aeration rates leads to high evaporation rates from the surface of panels. The optimal aeration rate in panels is 0.5 vvm.
- Covering the surface of panels can minimize the evaporation rate by 44% at optimal or lower aeration rates.
- Ambient temperature and seasonal changes regulate the evaporation rate when using an evaporative cooling system for biomass cultivation in panels.
- Utilization of thermo-tolerant algae strains can result in more efficient use of the water resource and can minimize evaporation water loss up to 64%.
- Raceways depth does not have a significant effect on evaporation rate.

- With an optimal raceway depth (7.5 cm) for biomass production the evaporation rate was similar using measurements from Penman and a local weather station.
- Higher algal biomass productivities in raceways and water reduction strategies results in a reduced direct water demand of 353 kg-water kg-biomass^{-1} and is comparable to the agriculture crop-alfalfa with 1020 kg-water kg-biomass^{-1}.
- Reduction in water demand requires recycling of cultivation water and 90% reduction in maintenance water.

Chapter 4 assessed algal biomass cultivation with respect to operational variables (mixing and aeration) and environmental variables (ambient temperature and relative humidity) in panels and raceways. Direct energy demand is highly dependent on optimal productivity achieved under scenarios for biomass for biofuel (biodiesel) and biomass for animal feed in panels and raceways. However, obtaining better biomass productivities in panels compared to raceways did not offset the higher direct energy demand. Upper limit for the energy ratio for cultivation (ER) can be obtained by considering the major energy inputs and production outputs of the system based on the biomass composition and seasonal variations. Conversely, lower limits can be established by optimizing operational parameters for outdoor biomass production, including operational time for aeration. The key conclusions from this chapter were:

- Highest direct energy demand in panels occurred in summer at 1.28 kWh m^{-2} d^{-1} with an auxiliary energy demand at 0.71 kWh m^{-2} d^{-1} for aeration and temperature control compared to average specific energy in raceways which was constant at ca.0.6 kWh m^{-2} d^{-1} over different seasons.

- Aeration is the largest component of direct energy demand in panels (0.71 kWh m^{-2} d^{-1}) with additional energy (0.57 kWh m^{-2} d^{-1}) required for temperature control.
- Environmental variables such as ambient temperature and relative humidity are important factors in determining direct energy demand in algal cultivation systems. Using algal strains with different temperature tolerances resulted in reduced auxiliary energy demand (by 37 % in panels).
- Better strategies for reduced aeration in panels resulted in significant changes (by 90%) in overall reduction in energy consumption without significant changes to biofuel potential and biomass productivity.
- Semi-continuous cultivation method provided better ER for biomass production due to higher biomass productivity compared to the batch cultivation method. ER obtained in semi-continuous cultivation in panels was 0.0052 kWh-biomass kWh-consumed^{-1} compared to 1.4 kWh-biomass kWh-consumed^{-1} for semi-continuous cultivation in raceways.
- Overall poor performance in raceways resulted in similar ER values for both batch and semi-continuous cultivation methods.

Chapter 5 reviewed the main environmental burdens associated with dairy facilities which can be reduced by incorporating algal cultivation systems for bioremediation and animal feed production. However, energy bottlenecks associated with cultivation systems require a better assessment of related energy and design parameters. Based on information provided in the previous chapters, panels can provide greater biomass productivity but their high direct energy demand may restrict their application to smaller or research scale production. Despite lower direct energy demand compared to panels, raceways are criticized for lower productivity as result of poor hydraulics and unfavorable temperature control. However, modifications to raceways including application of gravity fed systems may be beneficial to the field and provide multiple positive externalities for improving sustainability. The main conclusions from this chapter were:

- Nitrogen loss due to ammonia volatilization from dairy waste waters results in negative environmental externalities.
- Algal biomass production systems can utilize the high nutrient concentrations in dairy wastewater and minimize ammonia volatilization into the atmosphere.
- Previous research indicated significant variability in calculating the total energy consumption by raceways, which may result in underestimated values for energy requirements.
- Energy consumption for algal biomass cultivation in a gravity fed system is estimated to be 25 Wh m^{-2} d^{-1} compared to raceways at 15.4 Wh m^{-2} d^{-1}. The potential for significantly higher areal biomass productivity in a gravity fed system provides a better ER (1.41 kWh-consumed kg -biomass^{-1}) compared to raceways (2.01 kWh-consumed kg -biomass^{-1}).

- Algal biomass produced by an algal cultivation system of 220 acres utilizing wastewater from a dairy with 4,400 lactating cows, could replace 20% of the alfalfa based on estimated biomass produced or 36% of the protein produced from alfalfa. Use of algae allows for remediation of wastewater over a short time period and reduces ammonia volatilization compared to application of manure for crops (alfalfa) or collection in lagoons.

6.4. Future Research Recommendations

6.4.1. Future Generation of TEA and LCA Studies for Sustainable Algal Industry

Sustainability is a multidisciplinary concept where despite its widespread application among ecologists, economists and environmentalists, it remains complex in practice (Stavins et al., 2003). Three pillars of sustainability encompass environment, economic and social aspects. In general, environmental sustainability ensures natural systems (land, water, and air) continue to provide goods and services that society values such as clean water. Thus, algal biomass production should provide environmental benefits by applying production scenarios that decrease dependence on fresh water resources or utilize wastewater, and recycle nutrient resources (N, P, and CO_2). Economic sustainability focuses on principles beyond market based profits and takes into account social well-being for maximizing welfare (Downes, 2013).

However, thorough assessment of benefits and trade-offs can be evaluated in a cost benefit analysis (CBA) study where the impacts of an algal system are quantified for environmental and economic impacts and further combined with a social cost benefit analysis (SCBA) that evaluates how efficiently the resources for algae production are utilized and allocated to obtain desired social benefits. Thus, outcomes of studies including CBA and SCBA are critical for setting clear abatement costs, energy credit benefits and transaction costs. Sustainability tools including Life Cycle Assessment (LCA) and Technoeconomic Assessment (TEA) studies provide background information for sustainable choices that includes selecting appropriate production scenarios to ensure the long-term provision of products in a cost effective manner while taking environmental impacts and social benefits into consideration. Thus, both LCA and TEA should incorporate robust outdoor algal biomass cultivation information based on different biomass compositions and cultivation methods. However, in the absence of commercial scale algae facilities, variability in production assumptions and limited operational data beyond laboratory scale production have contributed to uncertainties in production data obtained. In addition, the cultivation methods and associated parameters would vary based on the type of products, available technology and the geographical conditions at the specific location which emphasizes the importance of research on outdoor cultivation.

Overall, the following research questions should be answered in future LCA and TEA studies: 1) how to evaluate and select the most appropriate cultivation parameters for optimal biomass composition for potential products; and 2) what is the optimal biomass biochemical composition for sustainable algal commodities with the least environmental impact. This should be coupled with selection of assessment methodologies for setting future production targets and scenarios. Thus, a better evaluation of social benefits requires metrics beyond conventional measures such as GDP that only focuses on measuring efficiency and not equity (Downes, 2013; Stavins et al., 2003). Both LCA and TEA results can be applied for CBA and to estimate social benefits in SCBA.

The concept of a sustainable algal production system, in terms of co-locating with other industries, including dairies was theoretically evaluated as a win-win scenario to minimize environmental impacts including GHG emissions and wastes, while providing bioremediation services and generating by-products with potential for use as animal feed. Despite the vigorous task of quantifying social aspects, it is important that future studies represent the services that the algal industry can provide in terms of social benefits and environmental benefits.

6.4.2. Current Policy Limitation and Regional Planning Opportunities

The potential of algal biomass is recognized in isolation and typically regarded separately by decision-makers. This includes current policy approaches in the algal field for setting mandatory requirements for utilizing renewable energy in the transportation sector. However, the current energy market and petroleum prices will limit the viability of algal biofuel production in the short run. This requires development of processes to maximize biomass production for other valuable co-products and ecosystem services. Recent legislation in the State of Arizona has designated algae as a crop, indicating that “algaculture” is agriculture which provides tax and land access benefits. Despite recent localized policy development at the state level, future directions in algaculture requires stronger and continuing support from federal agencies other than research-based programs and contracts limited to biofuel production (Trentacoste et al., 2015). Promoting algal biomass for products, including feed, requires feed trials and generating critical data for investors and companies who wish to look at the possibilities of cultivating algae for feed. Feed trials require large quantities of biomass to be processed for experimentation, which dictates the need for pilot-scale facilities for biomass production for feed trials and beyond. Agricultural products benefit from various market analyses conducted by governmental entities which illuminates the future direction of R&D. However, in the case of algae there is limited background data available (Trentacoste et al., 2015). Therefore, continued efforts are required to validate the value propositions of algal biomass that can provide a product of equal quality to animal feed and also benefit ecosystems services.

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