Enhancing CO_2 mass transfer in large scale algal raceway ponds through wave generation

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Abstract

The commercial growth of algae in raceway ponds is limited by the availability of carbon, supplied as carbon dioxide (CO_2), resulting in a linear growth rate, also described as biomass productivity, determined by the mass transfer rate. This reduces the specific growth rate of the system, as the culture cannot achieve the maximum growth rate limiting the productivity of systems. A novel system for enhancing CO_2 mass transfer using slopes is being investigated by the Center for Bioprocess Engineering Research (CeBER) at the University of Cape Town. This contributes to the ongoing investigation into the use of carbon sequestering organisms as a means of producing valuable compounds. The growth rate of algae has presented a major constraint in its commercial applicability. Typically, raceway systems are limited by the available light and carbon in the system. The carbon source for autotrophic algal growth in raceways is typically atmospheric CO_2. The rate at which this enters the system is based on the concentration gradient at the gas/liquid interface. The addition of slopes aims to increase the turbulence in areas of the raceway systems with low CO_2 mass transfer to increase the concentration gradient across the gas/liquid interface, facilitating higher carbon input to the system. An increase in turbulence serves to both promote axial mixing in the raceway facilitating CO_2 transport to the lower liquid regions and at the microscale within the liquid medium, allowing the surface renewal of liquid with low CO_2 concentrations to interact with the gas/liquid interface.

The slopes were designed based on weirs, which create an impediment to flow, resulting in increased turbulence downstream of the slope. A number of slope gradients and heights were investigated in prior work done (Burke, 2016; Van Der Linde, 2022). The focus of this study was to validate these previous findings conducted at laboratory scale and investigate the applicability of the scale up of the slopes at larger scales. Two raceway scales were tested: the existing 62 L raceway ponds used in earlier studies and a 1000 L raceway pond designed and commissioned for this project. At constant paddlewheel rotation, a large reduction in fluid velocity was observed on introducing the slope. Higher fluid velocities result in more turbulent flow, better mixing and reduces algae settling in areas of low fluid velocity. The effect of the lower fluid velocity was evident as the increases in algal productivity were not proportional to the increases in mass transfer. It was found that the slopes performed better in the 1000 L raceway compared to the 62 L raceway. The average fluid velocity decreased by 13 – 20 cm/s and 4 – 15 cm/s in the 62 and 1000 L raceways, respectively with the utilization of slopes, indicating that the slopes had a proportionately smaller effect on fluid velocity at a larger scale. The mass transfer coefficients (k_La) improved by 0.02 – 0.18 h^{-1} and 0.34 – 0.63 h^{-1} in the 62 and 1000 L raceways, respectively. These indicate significant improvements in CO_2 mass transfer compared to the system without slopes. It was evident from the analysis that the increase in surface disturbance and therefore surface area for transfer as well as the increased turbulence in the system resulted in a net increase in CO_2 mass transfer rate in the raceway systems. The growth rates of a test strain, *Scenedesmus spp.,* was used as validation for the increased mass transfer rates, as where the carbon availability is the limiting factor during the linear growth phase, then an increase in CO_2 mass transfer rate will result in a proportional increase in the growth rate of the algae. However, no significant changes to the algal productivity were seen. This suggests that light is the limiting factor during the linear growth phase, but the results of these experiments were inconclusive and remain an area of interest to be investigated further.

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Acronyms and Abbreviations

CFD models	Computational Fluid Dynamic models
PIV	Particle Image Velocimetry
ADV	Acoustic Doppler Velocimetry
k_La	Mass transfer coefficient
TKE	Turbulent Kinetic Energy

1 Introduction

1.1 Context of project

Algal biotechnology is a growing sector of the industry with substantial potential to produce valuable products such as biofuels, animal feeds, high value chemicals, pigments, nutraceuticals, antioxidants and extracts for cosmetics, food and feed sectors (Borowitzka, 2013; Dragone et al., 2014), as well as for bioremediation of waste water(Chisti, 2016; Grobbelaar, 2009a; Khan et al., 2018; Mehta and Gaur, 2005); this is explored in greater detail in Section 2.2. The use of algal cultivation for the production of the above mentioned products is appealing to many sectors as it represents a means of production that is carbon negative i.e. it reduces atmospheric CO_2 during production. This is in line with many company and national goals to reduce the carbon footprint of industry. Traditionally, the production of fuel and chemicals has negative environmental impacts whereas the production of algae has potential to be a more environmentally friendly means of production.

The cost of production and the energy efficiency of production are core issues facing the production of algae on a commercial scale, the latter critical to achieve maximum carbon credit for the process. As algae are composed of a significant proportion of carbon, the availability of carbon in the system for assimilation into biomass is a key concern. The carbon source for algae grown autotrophically in an open raceway, pond or equivalent typically comes from atmospheric CO_2 which is available at relatively low concentrations for commercial growth. The typical means by which the mass transfer of CO_2 is increased in open raceway ponds is through the use of paddlewheels, which serve to circulate the culture to improve the mixing and to facilitate gas-liquid mass transfer and thereby CO_2 supply. The supply of CO_2 is insufficient for maximal algal production in these systems, necessitating investigation into methods of optimization in algal raceway ponds. The operation of these systems at sufficient velocity is a large cost to a commercial algal production facility while the provision of CO_2 and light are the most common limiting factors and are both impacted through the paddle wheel rotation. The supplementation of CO_2 to facilitate higher growth rates in the system contributes significantly to the cost of production and is not widely utilized in open systems such as raceway ponds owing to the short flow path of the gas added, leading to poor CO_2 assimilation (de Godos et al., 2014). To support maximum algal growth rates and final biomass concentrations (Stepan et al., 2002), the maximization of CO_2 mass transfer becomes a key concern for business. A novel method of increasing the CO_2 mass transfer rate was explored in Burke (2016) and a provisional patent filed, then extended by van der Linde (2022), where slopes were added into a raceway pond system. The slopes are designed to improve the mass transfer rate of CO_2 by increasing the surface area for transfer through surface disturbance, increasing the turbulence of the system, and by creating breaking waves that cause air entrainment. The methods of the proposed mass transfer increase are discussed further in Section 2.2.5.

Burke (2016) and van der Linde (2022) showed that the introduction of slopes into the 62-litre raceway increased the CO_2 mass transfer coefficient, as a result of the increased turbulence. This project aims to validate the work done by van der Linde (2022) and Burke (2016) in a 62-litre raceway pond system by repeating the same conditions used. Through conducting additional experiments, the mixing times, average fluid velocities, mass transfer rates and growth rates in the 62-litre system are examined before testing the scalability of these findings on a larger scale raceway pond with a working volume of 1000 liters. The information gleaned from the work done on the lab scale informed the design and operating parameters applied to the larger scale system. The results of the mass transfer experiments were validated by conducting growth rate experiments to determine the effectiveness of increasing mass transfer in achieving more efficient algal cultivation.

1.2 Typical algal cultivation systems and the rational for their improvement

Algae have been collected from natural sources and cultured in pond systems for hundreds of years. The use of high rate algal ponds (commonly referred to as raceways) began in the 1950s (Oswald and Golueke, 1960), along with the modern cultivation of algae for commercial use. Raceway systems are comprised of two long straight parallel sections through which the fluid can flow, with a typical depth maintained at 15 to 30 cm to enable light penetration. These sections are joined to each other by bends on either end. This makes the system resemble a race track, which is where the system derives its name. The partitioning of the pond enables a defined circulatory flow to be maintained. Various methods may be used to drive the circulation. Typically, the propulsion of the fluid is done with a partially submerged paddlewheel. The blades of the paddlewheel rotate through the fluid pushing the fluid along its long axis to move it, creating a constant circular flow. On leaving the liquid, the paddles are covered by a thin film of liquid which aids both expanded surface area for gas-liquid mass transfer and light penetration. The paddlewheel creates an area of turbulent flow through the channel on the side of the raceway that it is on, the other side of the raceway typically exhibits laminar flow. Introducing turbulence at discrete points in the flow allows for increased vertical mixing which is critical for the algal cells to enter the photic zone. The vertical mixing decreases the concentration gradient of CO_2 within the liquid, promoting a more constant CO_2 concentration with regard to depth and a higher concentration gradient across the interface. The vertical mixing keeps the algal cells in suspension, reducing the amount of settling that can occur.

The majority of algae production worldwide is done in raceway ponds (Benemann, 2013). Interest in algal industries is growing rapidly world-wide, particularly with regard to biofuel applications (Khan et al., 2018) due to the ever-increasing pressures to find cost effective and sustainable liquid renewable fuel, particularly for use as sustainable aviation fuel and in the markets where electrification is not practical, as well as to environmental concerns about the continuous use of fossil fuels. A major drawback of raceway cultivation of algae is the low mass transfer rate of CO_2 (Stepan et al., 2002) from both atmospheric and other CO_2 sources, such as flue gas and CO_2 gas supplementation following CO_2 capture. The supply of CO_2 from external sources can represent a large cost to a business (Caia et al., 2018). It has been estimated that the cost of using pure CO_2 gas to supplement growth may be between 8% and 28% of the production costs (de Godos et al., 2014). The use of CO_2 supplementation is limited in raceway systems due to the short gas retention times in the liquid, limiting the mass transfer into the liquid phase. This is primarily due to the relatively shallow operating conditions of raceways. The fluid heights are kept low to increase the proportion of the medium that is exposed to the photic zone owing to light penetration but this limits the gas/liquid contact time when sparging gas into the system to increase the carbon availability. Low CO_2 mass transfer rates limit the growth rate of the microalgal cultures, as CO_2 is the primary source of carbon for the algae. The volumetric growth rate of the system, equivalent to its biomass productivity, should be maximized to improve the efficiency and economic viability of algae as a source of environmentally friendly valuable commodities. A novel system utilizing slopes to influence fluid flow has been explored to increase the mass transfer rate of CO_2 from the atmosphere (Burke, 2016; van der Linde, 2022). The mass transfer of CO_2 into liquid via waves has been noted (Das and Hopfinger, 2009), this occurs via the entrainment of air bubbles and the increase in turbulence. The entrainment of air bubbles allows for areas of greater surface area to volume ratios within the fluid increasing the mass transfer across the interface, while increased turbulence increases the concentration gradient at the gas/liquid interface enabling increased mass transfer of gas. The use of slopes may mimic the wave formation allowing the same phenomenon to occur, allowing for greater CO_2 mass transfer.

The system studied in the 62-litre raceway, by van der Linde (2022) and Burke (2016), did not form breaking waves and rather formed standing or undulating waves. This is likely because the effects of surface tension dominated the effects of gravity on the scale investigated, as such the waves were unable to break (van der Linde, 2022). At small scales the effects of surface tension cause waves to dissipate rather than form the toppling, circular motion needed for breaking.

1.3 Project scope

The core focus of this project is to improve the mass transfer rate of CO_2 into a raceway system. The vast majority of commercial scale algal culture occurs in raceway ponds, therefore there are large potential gains to be had by improving the system. This project aims to improve the CO_2 mass transfer rate in the raceway pond by increasing both the pond surface area through its disturbance and the turbulence to facilitate vertical fluid mixing and thereby surface renewal at both the macro- and micro-scale. The increased vertical or axial mixing promotes the exchange of fluid found toward the bottom of the raceway with fluid at the gas/liquid interface, thereby enhancing the CO_2 driving force and allowing for a higher rate of CO_2 mass transfer. Further this aids algal exposure to light cycling. There is further potential to create entrainment of air bubbles in the system to further increase surface area for mass transfer as well as increasing the residence time of gas within the liquid.

This project is inspired by biomimicry, using the natural occurrence of waves as inspiration for improving CO_2 mass transfer.

The goal of the study is to test the effectiveness and practicality of the introduction of slopes into a raceway pond as a means of improving the CO_2 mass transfer. The use of simple slopes to improve the productivity of algal raceway ponds could represent a useful tool in increasing the economic viability and energy efficiency of raceway systems, the latter enhancing its carbon credit potential. Economic feasibility has been an issue in the development of algal technologies, particularly in the case of algae as a source for biofuels. Due to the low costs of the introduction of slopes, an increase in CO_2 mass transfer rate, which correlates with an increase in algal productivity, could improve the profitability of algal raceway ponds.

Due to the potential flexibility of the technique and the environmentally friendly nature of algae production through sequestering atmospheric CO_2, the research has the potential to contribute to several sustainable development goals. Where the technology is used for improving biofuel production, it has potential to contribute towards Goal 7, “Affordable and Clean Energy”. Where used in wastewater treatment it would contribute to Goal 6, “Clean Water and Sanitation” by improving the rate of algal growth which would improve the waste uptake rate. Due to the environmentally friendly nature of algal production of fine chemicals, platform chemicals and other compounds, Goals 11,12 and 13 are relevant: “Sustainable Cities and Communities”, ”Responsible Consumption and Production” and ”Climate Action” respectively.

The project has the potential to contribute towards sustainable development in South Africa and the world. While algal biotechnology is viewed as an important technology, the largest challenge to its large scale implementation is the improvement of its efficiency. Improvement of CO_2 mass transfer rates through the implementation of slopes could be a step towards large scale economic viability of energy-efficient algal raceway ponds.

1.4 Structure of dissertation

This dissertation has been divided into six sections: the introduction, literature review, definition of project, methodology along with materials and methods, results and discussion, and conclusions and recommendations. The introduction section above serves to provide the rationale and outline for the thesis. It is aimed at contextualizing the research scope and its underlying motivation.

In Chapter 2, the literature review, an overview of the current algal production techniques is provided with a focus on the advantages and disadvantages of algal culture systems as well as factors affecting algal productivity. The production techniques discussed include high-rate algal raceway ponds and an overview of closed photobioreactors. The latter was discussed in broad terms as there are vastly different set up conditions in photobioreactors. As this study focuses on the use of raceway systems, special attention is paid to the limiting factors of raceways and work done to mitigate these. Factors impacting algal growth and carbon dioxide mass transfer, within algal systems, are reviewed and synthesized to identify areas of improvement in raceway systems. The literature also informed by a review of slopes in wave formation to position the experimental design employed in this project. Synthesis of the above allowed the project objectives to be finalized and key hypotheses to be developed, as presented in Chapter 3.

Chapter 4 provides the research approach used, followed by the experimental procedure and analytical methods used, with rationale for their selection. The research methodology and approach are defined first to address the project objectives and test these hypotheses. The design of the raceways and slopes are provided, along with the methods used in the determination of the hydrodynamic characteristics of the systems. The methods used in testing the mass transfer and growth rates of the raceways under different conditions are provided.

Chapter 5 details the results obtained for the hydrodynamic study centered on mixing time and average fluid velocity, the CO_2 mass transfer analysis and volumetric growth rate measurements. The results for both the 62 and 1000 L raceways are given and the implications of the results are discussed. This chapter presents the results, investigates and interprets the findings of this study and addresses the limitations of the work. The results of the 62 and 1000 L raceway experiments are presented, analyzed and discussed here.

Chapter 6 provides the conclusions and recommendations. This section details the findings of the study, evaluates its elucidation of the hypotheses as well as constraints in interpretation. Finally, it provides recommendations for further research.

2 Literature Review

Raceway ponds have remained relatively unchanged since they were first used to cultivate *Chlorella* in Japan during the 1950's (Oswald and Golueke, 1960). These raceway ponds were designed as the first high-rate production system for algae. The system makes use of a paddlewheel to drive the circulation and mixing. The low depth of the ponds is designed to maximize the surface area to volume ratio, to maximise both light penetration and gas-liquid mass transfer for CO2 supply to increase productivity. Currently, raceway ponds have a maximum photosynthetic efficiency around 1.2%, in terms of the theoretical maximum production of organic carbon based on incoming solar radiation. However, research suggests that recent advances may improve this, particularly increases in vertical mixing is thought to be able to increase photosynthetic efficiency (Grobbelaar, 2012). The ultimate goal of microalgal culture is to produce the maximum amount of biomass at the highest concentration in the shortest possible time for the lowest costs (Gifuni et al., 2019; Grobbelaar, 2009b), making the most efficient use of resources and maximizing profits. This drives the necessity to improve cultivation techniques.

2.1 Classification of Algae

Algae is a term that refers to several large taxonomic groups, representing both prokaryotic and eukaryotic organisms, that are defined as thallophytes, meaning that they lack specialized regions such as roots or stems. These organisms are capable of photosynthesis, and unlike terrestrial plants, they contain photosynthetic apparatus in every location within the organism, whereas plant photosynthesis is limited to the leaves. This feature makes algae more efficient in terms of space, allowing for greater photosynthesis, and associated carbon assimilation and biomass formation, in a specific area. Algae are characterized by the presence of chlorophyll *a* as their main photosynthetic pigment (Lee, 2018). Many species of algae have additional light harvesting pigments, these pigments are often used to group algae taxonomically, as detailed below. All algae are capable of utilizing carbon dioxide and light for the synthesis of carbohydrates (Ansari et al., 2017; Khan et al., 2018), with many are also capable of hetero- or mixotrophy, meaning that they are able assimilate extracelluar organic carbon to fulfill the entirity of their carbon requirements or in conjunction with photoautotrophy in the case of mixotrophy. There are an estimated 350,000 to 1,000,000 species of algae in existence, with only around 30,000 of them studied (Packer et al., 2016). Microorganisms broadly classified as microalgae can be further classified as prokaryotic and eukaryotic. The main prokaryote taxonomic groups are strictly classified as bacteria (not algae) and include the cyanobacteria and the prochlorophytes. Notable the prokaryotic cyanobacteria that are commonly cultivated are the cyanobacteria *Arthrospira platensis, Arthrospira fusiformis,* and *Arthrospira maxima*, which are used as a health supplements and as sources of the antioxidant pigment phycocyanin, β-carotene and other useful compounds (Gumbo and Nesamvuni, 2017). These species are often included when discussing algae as functionally they are similar, in that they occur in water sources and photosynthesize**.** The main groups that make up the eukaryote groups are the Rhodophyta (red algae), Chlorophyta (green algae), Dinophyte, Chrysophyta (golden-brown algae), Prymnesiophyta or Haptophyta, Bacillariophyta (diatoms), Xanthophyta, Eustigmatophyta, Rhaphidophyta and Phaeophyta (brown algae) (Khan et al., 2018; Tomaselli, 2004). These algae have a multitude of different organizations, some having flagellum to aid in motility, being colonial, unicellular or filamentous (Tomaselli, 2004). Multicellular algae range from microscopic to around 60 meters long, as seen in the Phaeophyta; *Macrocystis pyrifera* species. The most commonly known multicellular algae are typically referred to as macroalgae, commonly called seaweeds, whereas the term microalgae does not refer to any specific taxonomic group but implies small (typically microscopic) uni- and multi-cellular organisms that can photosynthesize (Grobbelaar, 2012).

2.2 Microalgal uses

Algae are cultured in a multitude of environments and countries around the world (Packer et al., 2016), and used as food supplements, sources of fine chemicals, therapeutic agents, food, biofuel, bioremediation, hydrocolloids, cosmetics, fertilizers and more (Balboa et al., 2015; Cechinel et al., 2016; Monagail et al., 2017; Rasala and Mayfield, 2015; Sutherland et al., 2014; Wang et al., 2016). Microalgae can be rich in essential amino acids and essential fatty acids, such as omega-3 fatty acids, the yield of these products can be increased by utilizing specific growth conditions, specifically by inducing various nutrient limitations or environmental stresses (Ansari et al., 2017). A representation of the production of algae and the products that can be obtained from them is given below in Figure 1.

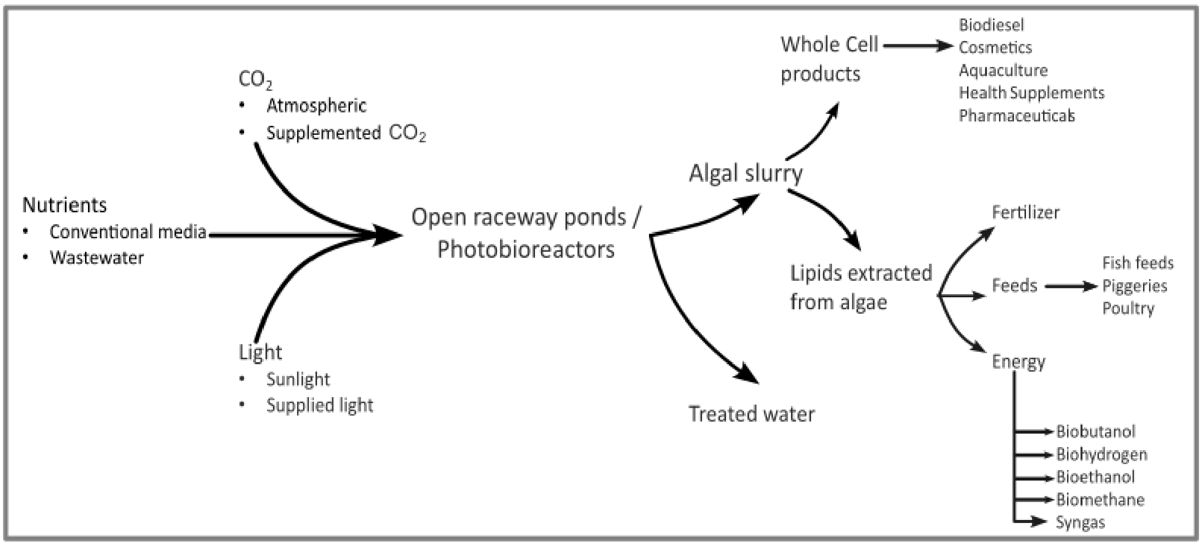


Figure 1 Redrawn from (Ansari et al., 2017) showing a simplified flow chart detailing the energy sources and products of algal systems.

This shows the required inputs and products that can be obtained from algae. There are many other uses for algae that are not explored here, due to space limitations. Increasing research is being done to investigate novel uses for algae, with a substantial interest in bioprospecting for new compounds. Thus there is increasing interest in the cultivation of algal species which requires innovation in their culturing techniques.Factors affecting algal growth rate and total biomass accumulation

2.2.1 Productivity

Due to the need to produce algae as quickly and efficiently as possible, productivity of the system is of vital importance. Productivity (p) is defined as the product of the biomass concentration (C) and the specific growth rate (μ) as seen in Equation 2 (Borowitzka, 2013).

$$p = \mu C \qquad \text{Equation 2}$$

As such, both the specific growth rate and biomass concentration need to be optimized in order to achieve the maximum productivity. The factors that affect algal growth are represented below in Figure 2**Error! Reference source not found.**.

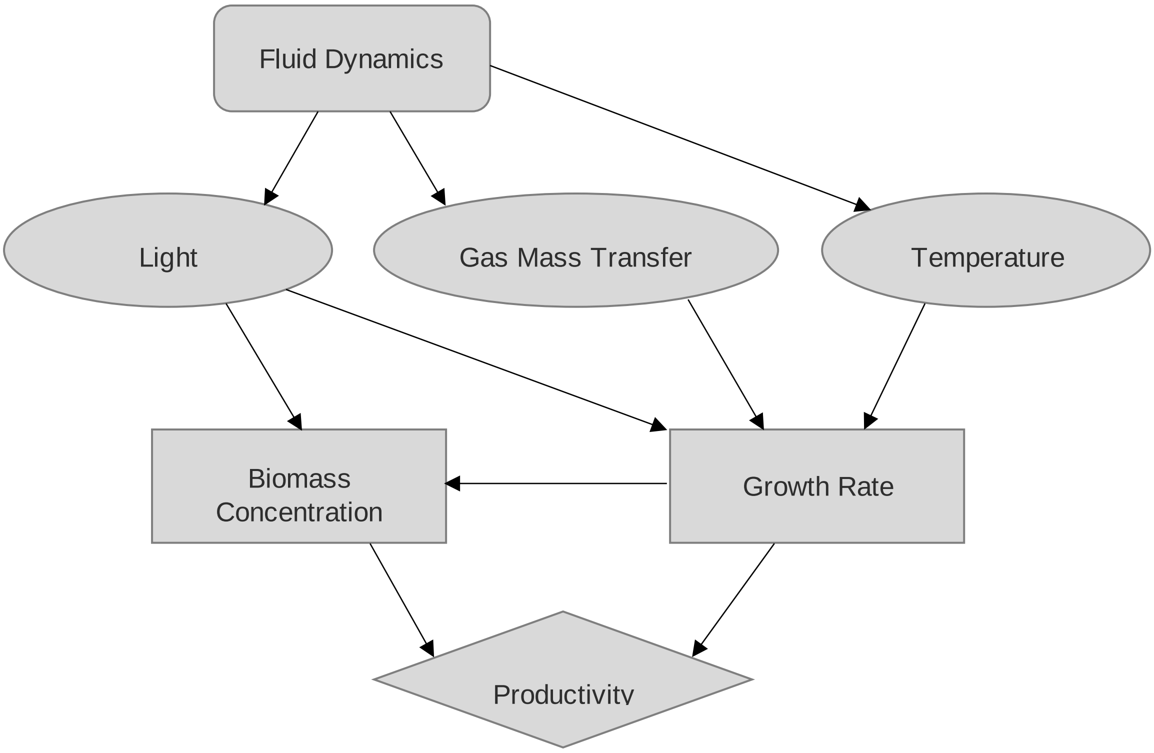


Figure 2 Simplified diagram of the factors affecting algal productivity. Adapted from Molina-Grima (1999).

The specific growth rate is affected by the temperature, the gas mass transfer (CO_2 into and O_2 out of the system) and the light conditions both in terms of intensity and wavelength. Naturally this assumes all nutrient requirements are met in the system and there is no limiting factor. The factors that affect growth are discussed in greater detail below.

2.2.2 Nutrient requirements

Although almost all algae require sunlight and CO_2 for growth, they are very diverse in the environmental conditions and nutrient requirements for growth (Borowitzka, 2005). While algae can be cultured all year-round, changes in temperature and light can affect their growth patterns. This can make businesses less efficient in colder climates or in areas with high rainfall, so, typically the cultivation of algae on a commercial scale is limited to tropical or sub-tropical regions (Borowitzka, 2005). While most algal cultures must be grown photoautotrophically, meaning that they require energy from the sun to produce the required organic compounds for life, some algae can be grown heterotrophically, where the energy required by the cell is obtained from external sources (Dragone et al., 2014). Certain algae can be grown using a mixture of photoautotrophic and heterotrophic means, making algae incredibly versatile in their uses. Algae can benefit from heterotrophic growth as light limitation is traditionally the principle determining factor for cell density (Lee, 2004). However, the maximum specific growth rate of algae cultured heterotrophically on simple sugars and organic acids is lower than that of photosynthetic cultures, this is due to algae cells typically having low affinity for the organic carbon substrates (Lee, 2004). When certain algae are grown heterotrophically they are unable to produce some commercial compounds, as light is needed to produce certain compounds in algae such as some pigments or fatty acids (Khan et al., 2018). Ideal conditions for growth are created by supplying the correct media/substrate, temperature, pH and mixing for the algae to grow. Photoautotrophic algae require light to grow, this facilitates photosynthesis to convert carbon dioxide into simple carbohydrates. The advantages of producing algae in a photoautotrophic manner are closely linked to sustainable development and environmentally friendly production (Stepan et al., 2002). Photoautotrophic algae require different optimal conditions depending on the strain and species of the algae as well as the desired outcome (Musgrove, 2016), however the basic requirements for photosynthetic growth are light, carbon dioxide, water, and inorganic salts, with temperatures remaining between 20 and 30 °C (Chisti, 2007a; Khan et al., 2018; Lee, 2016). Wastewater can provide suitable environments for certain algal species, as such organic effluents from food and agricultural industries can be used for cultivation (Khan et al., 2018).

Apart from the sunlight and carbon sources there are a number of other requirements for cultivation algae. There are two typical methods of algal cultivation, using a designed media with the necessary nutrients and minerals, or using wastewater to fulfil the nutritional requirements. Algal media are determined by analyzing the local conditions of the algae and investigating the nutritional requirements of the organisms (Watanabe, 2005). Photoautotrophic algae require inorganic mineral ions to grow, typically requiring very few organic compounds (such as vitamins) (Grobbelaar, 2003). The inorganic mineral ions concentrations are specific to the intended species, with the main ionic components being K^+, Mg^{2+}, Na^+, Ca^{2+}, SO_4^- and Cl^-, with a number of trace elements required in very small quantities (Grobbelaar, 2003). The trace elements added include aluminium, boron, manganese, zinc, copper, iron, cobalt and molybdenum, along with chelating agents such as citrate *a* (Lee, 2016). The three most commonly used vitamins are thiamine, cyanocobalamin and biotin, referring to vitamins B_1, B_{12} and B_7, respectively (Watanabe, 2005). Algal cultures also require a nitrogen source to facilitate growth, as most algae are not able to fix atmospheric nitrogen, this is provided in the form of urea, nitrates or ammonia (Lee, 2016). As nitrogen can comprise between 1 – 10 % of the biomass content, it is the second most abundant nutrient in the system (Grobbelaar, 2003). The form in which the nitrogen is supplied depends on the preference of the species and the intended pH of the medium, as nitrate addition tends to increase the pH while ammonia tends to decrease the pH (Lee, 2016).

Phosphorous is an essential element for algal growth, involved in energy transfer and biosynthesis of nucleic acids, although it constitutes less than 1% of the culture by mass (Grobbelaar, 2003). Phosphorous is typically taken up as orthophosphate (PO_4^{2-}) and is often a growth limiting factor in natural systems, however algae have the ability to store phosphorous in polyphosphate bodies during periods of scarcity (Grobbelaar, 2003) which enables the system to maintain growth for a period if there is no phosphorous in the system.

The balance of these nutrients must be maintained in the system with known concentrations added. There are multiple standard solutions used to culture algae, however it is crucial to investigate the optimal solution for the species of interest. Typically, the nutrients are supplied in a batch or fed batch manner depending on the intended usage.

2.2.3 Illumination

Illumination of the algal culture is one of the key considerations in the production of algal biomass as the maximal culture productivity of photoautotrophic organisms occurs when light is the sole limiting factor . The surface area to volume ratio determines the energy and distribution of the light available to the culture (Chisti, 2016). In general, the higher the surface area to volume ratio the higher the biomass concentration and volumetric productivity, resulting in more efficient systems in terms of media and harvesting costs (Pirt et al., 2007). Typically, the light needed for the system is provided in the visible light spectrum, 380 nm to 750 nm, which corresponds to the photosynthetically active radiation range (Posten, 2009; Richmond, 2004b). Most algae are low light adapted in natural environments, as such they cannot be subjected to ever increasing light intensities (Posten, 2009). High light intensities can lead to damage of the photosynthetic apparatus of the algal cell, this can cause a reduction in biomass production (Chisti, 2007b). The light saturation can be measured using a PI-curve which compares the specific growth rates at different light intensities. The saturation intensity is species dependent, and dependent on the acclimatization of the algae; for example, (Melis et al., 1999) found that *Dunaliella salina* grown in low light conditions (100 µmol photon/(m^2s^{-1})) reached saturation around 200 µmol photon/(m^2s^{-1}) however when grown under high light conditions (2000 µmol photon/(m^2s^{-1})) saturation was reached around 2500 µmol photon/(m^2s^{-1}). In general, higher light intensities result in lower light usage efficiency in the cells (Richmond, 2004b). The efficiency of light usage ranges from 0.1-8% of the total incoming irradiance (Grobbelaar, 2009b). With the theoretical maximum quantum efficiency of carbon fixation, a maximum productivity of 29.8 g(dw)m^{-2} which could theoretically improve with intermittent light of high frequency (Grobbelaar, 2009). The productivity and photosynthetic efficiencies can be up to 6.7 times higher in cultures grown in dynamic light fields compared to constant light fields (Grobbelaar, 2009).

A generalized growth curve (of biomass concentration over time) of an algae culture can typically be viewed in four phases. This general trend is because the amount and distribution of light energy absorbed by the culture is largely determined by the cell concentration. At low cell concentration only a portion of the photons are absorbed by the culture (the rest passing through the culture); thus, the cell concentration increases exponentially until all the photosynthetically available radiance is absorbed (Lee, 2016). The second phase shows a linear growth curve where the culture continues to grow utilizing the entirety of the photon flux. Once all the photons are absorbed by only the cells nearest to the surface the phenomenon of mutual shading occurs, where the cells under this photic zone receive no light, leading to a decrease in growth rate (Lee, 2016).The light attenuation due to mutual shading can cause the region where there is enough light for photosynthesis to be quite shallow. As such the turbulence of the system is very important to maintaining higher culture concentrations as it moves cells from the aphotic to photic zone to allow photosynthesis. Turbulence in a system can be seen as the mixing of the algae to create homogeneity in the culture, this is done to ensure that there is a uniform dispersion of microalgae, providing access to light as well as eliminating gradients of nutrient concentration, pH, dissolved gasses, and temperature (Carvalho et al., 2006). The light that each individual cell receives is related to the culture depth, biomass concentration and turbulence regime. The pond depth affects the proportion of the culture in the euphotic zone, the biomass concentration affects the degree of light attenuation, and the turbulence regime dictates the frequency at which the cell moves into and out of the photic region (Sutherland et al., 2014). Increasing the rate at which algal cells enter and exit the euphotic zone can increase the efficiency of light usage. As such the pond depth is kept around 20 cm and the fluid velocity is kept higher than 10 $cm.s^{-1}$ (Li et al., 2014a; Mendoza et al., 2013a), however these will be discussed in more depth later. Given that the concentration of the biomass is negatively correlated with light attenuation, it may seem advantageous to decrease the concentration of the cells, however this increases the harvesting cost as well as decreasing the total biomass productivity (Kumar et al., 2015). High biomass concentration is usually the aim of any economically viable cultivation due to low cell concentrations substantially increasing the costs of processing (Carvalho et al., 2006).

2.2.4 Mixing

Mixing is a crucial component in raceway operation as it is the means by which homogenity is promoted, the benefits of this having been discussed previously. The Reynolds number is used as an indication of the flow characteristics in the system, in particular the relative sizes of the turbulent eddies. The critical value of the Reynolds number where the dominant turbulence transitions from small to large scale eddies is around 100 (BIŃ, 1984), as such raceway ponds are always dominated by large scale eddies due to the higher Reynolds numbers and turbulent flow measured in the systems. Typically, the mixing in a raceway pond occurs in two regions, the paddlewheel and the two bends. The paddlewheel creates turbulence as the blade enters and moves through the fluid creating eddies and there when the paddlewheel leaves the fluid the upliftment of the fluid can cause air entrainment improving mass transfer of CO_2 in and O_2 out (Musgrove, 2016). Flows are typically sub-critical (Froude number < 1) thus the wave parameters can propagate upstream (Bai et al., 2019; van der Linde, 2022). This indicates that the bends play an important role on the secondary circulation and affect the inflow of water by upstream propagation of waves (Bai et al., 2019).

Flow through the straight channels tends to be approximately symmetrical, with the maximum flow velocity occurring towards the surface at the center of the raceway. The maximum flow moves towards the outer wall of the raceway as the flow goes around the bend, the flow returns to standard conditions a certain distance after the bend (depending on the configuration of the raceway) (Bai et al., 2019). As fluid enters the bends centrifugal force forces the fluid towards the outer wall of the raceway, this creates a tilt in the water surface causing pressure gradient towards the inner wall. This creates a secondary flow that has important implications on the mixing of a raceway system. The local imbalance of the inward pressure gradient and the outward centrifugal force creates a secondary circulation (Bai et al., 2019), this promotes mixing in the raceway, improving the mass transfer and light utilization of the microalgae, a depiction of this secondary flow is given in Figure 3. Turbulence in the bends can be five times that measured in the straight sections of the raceway (Hreiz et al., 2014). This is an important aspect as the bends make up a large area of the raceway, as such they provide a substantial amount of the total turbulence in the system. However the paddlewheel section has the largest mass transfer coefficient in the system (Mendoza et al., 2013b) due to the large amount of mechanical mixing at this point.

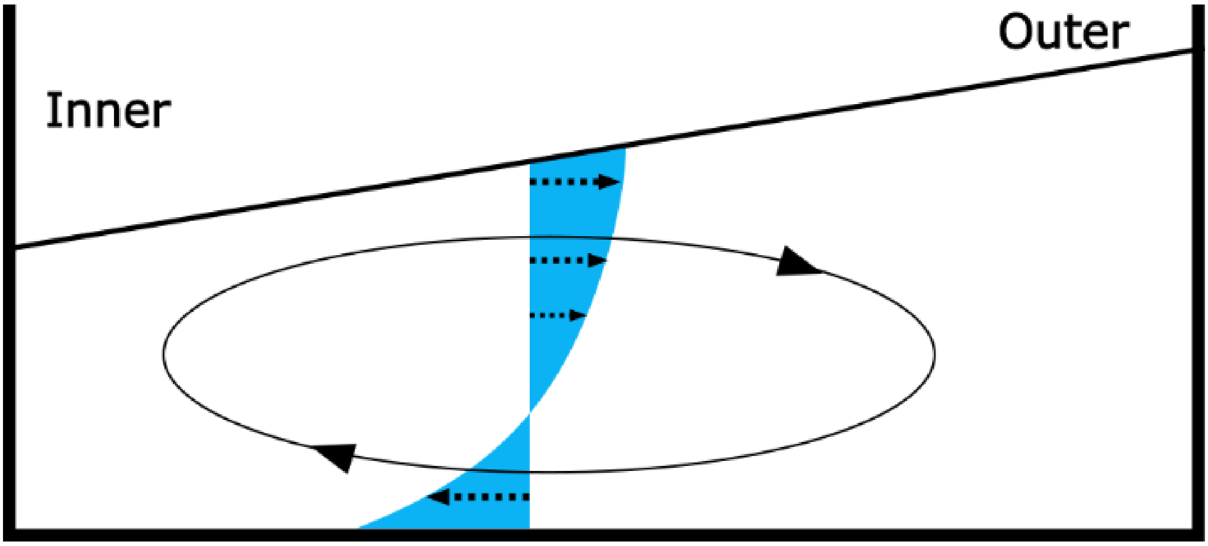


Figure 3 Redrawn from Bai et al. 2019 showing the circulation of the secondary flow caused by the centrifugal force at the top and the pressure differential flow at the bottom due to the difference in fluid height.

2.2.5 Mass Transfer of CO_2

The mass transfer of gases has great impact on the production of algae, as well as influencing our understanding of the role of CO_2 in climate change. It is estimated that 3 Pg of carbon are taken up by the oceans each year (Woolf et al., 2019). Mass transfer in raceway ponds typically centers around the movement of CO_2 into solution and O_2 out of solution. Both processes occur at the boundary of the liquid and the gas phase (air) above. The solubility of CO_2 in water is too low to sustain maximal microalgal growth, so it is essential to allow for the resupply through mass transfer from the atmosphere or some form of sparging (Chisti, 2007a). A number of models have been developed to describe gas transfer rates; for example, the Two Film Theory, the Penetration Theory and the Surface Renewal Theory. This paper will focus on the Two Film theory as it is the most common theory used (Clarke, 2013). It is assumed in the two-film theory that on either side of the gas/liquid interface there is a stagnant film, it is assumed that the bulk layers of each phase are well mixed (Clarke, 2013), it is also assumed that the resistance to mass transfer resides in the stagnant films and the gas/liquid interface provides no resistance to mass transfer (Chisti, 2007a; Clarke, 2013). This can be seen in Figure 4. Here mass transfer only takes place by diffusion across the phases (Chisti, 2007a).

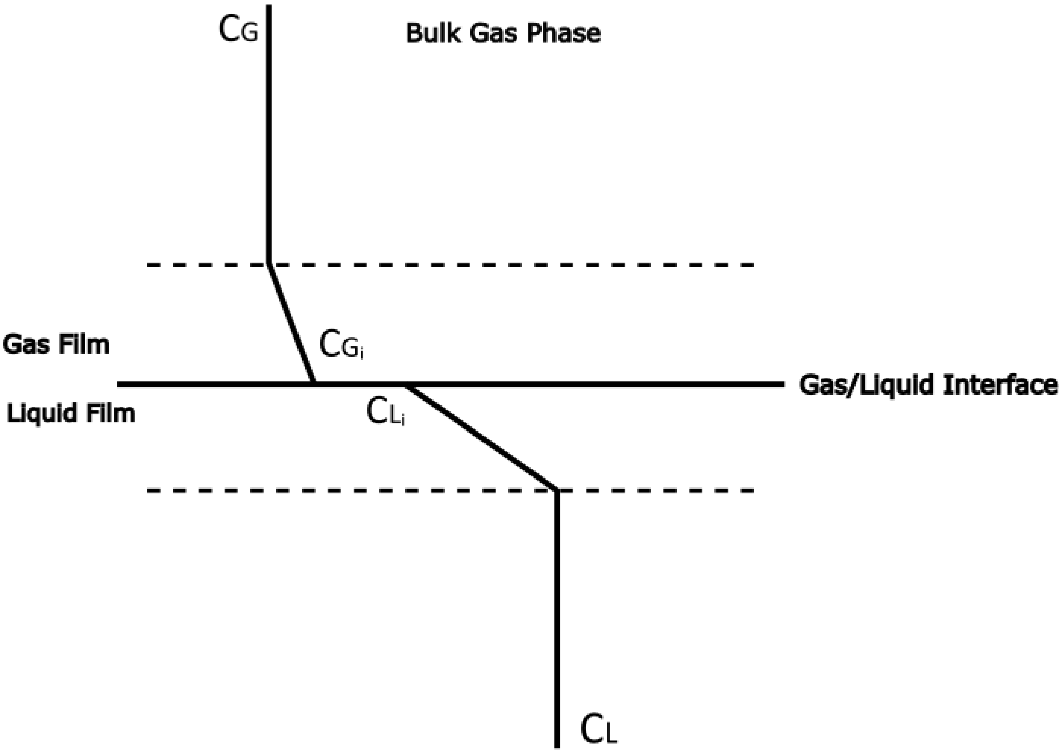


Figure 4 Gas mass transfer across the stagnant gas and liquid film on either side of the interface. Redrawn from (Chisti, 2007b).

Molecular diffusion has been described by Fick's Law to be proportional to the concentration difference between the two phases (often referred to as the driving force) and inversely proportional to the thickness of the stagnant film (Clarke, 2013). The transport flux (J) of the diffusing species is related to the concentration gradient (ΔC) of the film, the film thickness (δ) and the diffusivity (D) of the transferring species according to Equation 2-1.

$$J = \frac{D}{\delta}\Delta C \qquad \text{Equation 2-1}$$

The ratio of $\frac{D}{\delta}$ is known as the mass transfer coefficient, denoted by k, (Chisti, 2007a). For an ideal gas, at steady state the transfer through the gas and liquid films is the same, represented by Equation 2-2 (Chisti, 2007a).

$$J = k_G\left(C_G - C_{G_i}\right) = k_L\left(C_{L_i} - C_L\right) \qquad \text{Equation 2-2}$$

Where k_G and k_L are the mass transfer coefficients for the gas and liquid films, respectively. Due to the low diffusion of most gases in water in comparison to gas, the liquid film is the limiting factor in the mass transfer of CO_2. As such the equation for transport flux can be re-written in terms of the saturation concentration (C^*), which represents the maximum possible value of the diffusing component in the liquid.

$$J = k_L(C^* - C_L) \qquad \text{Equation 2-3}$$

Here C^* is related to the gas phase concentration (C_G) by Henry's law (Chisti, 2007a) as seen below in Equation 2-4.

$$C_G = C_H C^{sat} \qquad \text{Equation 2-4}$$

Where c_H is Henry's constant, which represents a dimensionless number that is specific to each compound and dependant on temperature (Chisti, 2007a). k_L relates to both the mass transfer rates for the liquid and the gas as follows in Equation 2-5 (Chisti, 2007a).

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{c_H k_G} \qquad \text{Equation 2-5}$$

The liquid film phase is assumed to be the rate limiting step in the mass transfer of CO_2, thus the term $\frac{1}{c_H k_G}$ is taken to be negligible, so $K_L = k_L$.

The mass transport flux (J) is the rate of transfer per unit gas/liquid interfacial area, this area is difficult to measure so Equation 2-2 is re-written as follows:

$$\frac{dC_L}{dt} = k_L a_L (C^{sat} - C_L) \qquad \text{Equation 2-6}$$

Where C_L is the dissolved gas concentration at time t and a_L is the gas-liquid interfacial area per unit volume of the liquid. For simplicity the overall volumetric mass transfer coefficient ($k_L a_L$) is commonly referred to as the mass transfer coefficient ($k_L a$) and is used instead of calculating the interfacial area to separate the liquid mass transfer coefficient (k_L). The $k_L a$ depends on the fluid properties as well as the hydrodynamics of the flow, the full factors are given below in Table 1. The effects of fluid viscosity and surface tension are debated in literature (BIŃ, 1984) due to the changes in the viscosity and concentration of solids in a raceway pond during the growth cycle, due to growth of algae, it can be assumed that the mass transfer rate would change during the growth period. However, more work would have to be done to corroborate this.

Table 1 Factors influencing Gas/Liquid Mass Transfer, taken from (Chisti, 2007a).

Temperature	Concentration of solids
Pressure	Hydrophobicity of solids
Diffusivity	Morphology of solids
Viscosity	Shear rate or power input
Density	Aeration velocity
Surface tension	pH
Presence of surfactants and ions	Geometry of the gas/liquid contactor
Ionic strength	Flow parameters of non-Newtonian fluids

The mass transfer coefficient k_L is equal to the ratio of the diffusivity to thickness of the stagnant layer $\frac{D}{\delta}$ (Clarke, 2013), thus a decrease in the thickness of the stagnant layer would yield a higher mass transfer coefficient. This thickness is related to the turbulence of the system, the more turbulent the system, the smaller this thickness. However, one criticism of the two-film theory is that it assumes a linear relationship between the mass transfer coefficient k_L and the diffusivity (due to the assumption of a steady gradient in the stagnant film layers on either side of the interface), whereas experimental results have indicated a square-root relationship (Clarke, 2013). For the purposes of this study the two-film theory was used, as it is accurate enough for the purposes of this study as well as making the results more comparable to previous work done on the topic.

Unlike other macronutrients needed for algal culture such as nitrogen and phosphorous which have high solubility in water, carbon dioxide has low solubility and must be continually supplied to the culture to allow for growth (Weissman et al., 1989). Microalgae contain around 50% carbon (Li et al., 2013) as such a large amount of CO_2 is needed to produce large quantities of algae. This CO_2 can come from different sources; atmospheric CO_2, CO_2 gas or industrial waste such as flue gas. Supplementing atmospheric CO_2 can be a substantial cost to a business (Caia et al., 2018) and as such the low efficiency of uptake in a raceway system is of concern (Li et al., 2013). It has been estimated that the cost of using pure CO_2 gas to facilitate growth may be between 8% and 28% of the production costs (de Godos et al., 2014). In Grobbelaar, (2004) it is given that the CO_2 present in the atmosphere can sustain a maximum productivity of around 10 $g(dw)/m^2d$ whereas in Putt et al., (2011) it is stated that based on a productivity of $20g/m^2$day that the atmospheric CO_2 contributes only 5% of the CO_2 to the pond surface that is required to sustain the productivity. There are many things that affect the CO_2 uptake efficiency in the culture, including the microalgal strain, the design of the reactor, the light quality and intensity, the operating model, and the nutritional conditions (Li et al., 2013). For a raceway pond, the CO_2 limitations can be a major problem due to; the relatively low CO_2 concentrations present in the atmosphere (less than 400ppm), the shallow algal culture suspension (typically 15-30cm), the high areal productivity and the relatively low rate of CO_2 transfer from the air to the water (Putt et al., 2011). As such, many systems choose to supply CO_2 in response to pH sensors during daylight hours (Chisti, 2007b). The mass transfer rate of CO_2 is related to the surface area of the system and the driving force. The driving force can be improved by increasing mixing, increasing the concentration gradient across the gas/liquid boundary. For this reason, increasing the fluid velocity can improve the mass transfer (de Godos et al., 2014; Mendoza et al., 2013b). (Mendoza et al., 2013a) found that an increase in average fluid velocity from 0.17 m/s to 0.39 m/s improved the CO_2 mass transfer by 39%.

The addition of CO_2 to the system can also be useful for the stability of the system due to the bicarbonate-carbonate buffer system (Grobbelaar, 2004). In high density cultures photosynthetic fixation of CO_2 leads to an accumulation of OH^- in the solution causing the pH to rise (Grobbelaar, 2004). As such, the sparging of CO_2 can be used as a pH regulator as well as supplying CO_2 for the culture (Grobbelaar, 2004). Depending on the pH of the system, different species of inorganic carbon are selected for. As the pH increases the dominant species of inorganic carbon changes, following the trend of CO_2 - H_2CO_3 - HCO^-_3 - CO^{2-}_3. This is particularly important in freshwater systems to maintain specific pH levels for algal culture (Grobbelaar, 2004).Sparging of CO_2 can be an inefficient means to increase the CO_2 supply in the culture due to the typically shallow depths leading to short residence times of the bubbles (Becker, 1994) .This leads to an efficiency of carbon usage of 10 to 30% of the CO_2 supplied to the system (Becker, 1994; Xu et al., 2019). (Putt et al., 2011) found an uptake efficiency of 37% in a standard raceway set-up operated at 0.15 m depth sparging with air enriched with 10% CO_2.

In order to increase the efficiency of CO_2 uptake when sparged into the system, one can make use of a carbonation column in order to increase contact time with the culture, this can increase the transfer efficiency to 90% theoretically, however, an efficiency around 80% using air enriched with 10% CO_2 was found by (Putt et al., 2011). Weissman et al., (1989) found that the use of 0.91 m deep sump with CO_2 injected counter-current had an efficiency of 80–90% and found that the depth of the sparger did not significantly affect the mass transfer efficiency, suggesting that a shallower sump could be utilized for the same mass transfer efficiency. (de Godos et al., 2014) found a similar mass transfer efficiency of around 90% using a 1 m deep, 0.65 m wide sump in a 1 m wide channel. It has been found that the utilization of a sump does improve the mass transfer but has a negative effect on the energy consumption of the raceway system (Mendoza et al., 2013a; Weissman et al., 1989). However, it was found that there was a negligible effect on the fluid velocity due to the relative volumetric flow rates of the gas and the fluid (Weissman et al., 1989) .de Godos et al., (2014) found a that power consumption was up to six times higher using a sump with a baffle. The use of a baffle to guide flow through the sump improves the efficiency of carbon uptake especially when using a counter-current set up, as it improves contact time between the fluid and the bubbles (Musgrove, 2016). The matching of the counter-current downward flow to the rising velocity of the CO_2 bubbles maximizes the contact time between the CO_2 gas and the fluid, thereby improving the mass transfer efficiency (Weissman et al., 1989). The bubble velocity distribution is a function of bubble size (related to the sparger design, CO_2 flow rate and salinity (Weissman et al., 1989). The use of a co-current system can mitigate some of the increases to power consumption, as while the mass transfer efficiency is lower, the sparging of gas acts as an airlift pump (Musgrove, 2016). An alternative approach involves covering the raceway pond with a transparent, gas-tight film to form a closed system. This setup maximizes the contact time between the gas and liquid phases by preventing gas escape, through model investigation, it was found that this increased CO_2 fixation under intermittent gas sparging to 95% (Li et al., 2013).

Due to the costs and technical requirements of supplementing CO_2 into the algae system (specifically raceway ponds) it would be beneficial to improve the utilization of readily available atmospheric CO_2. Improving the mass transfer from the air to liquid would result in improved yields without the costs associated with additional CO_2 as well as allowing algal cultivation to occur at locations without ready access to affordable CO_2 access. The technique proposed is the addition of slopes in a raceway pond to increase turbulence and mimic ocean-breakers to allow air entrainment. This will be discussed in greater detail.

2.3 Slopes and waves

In the ocean, breaking waves serve to limit the height of surface waves, provide mixing, generate ocean currents, and enhance air-sea fluxes of energy, heat, mass, and momentum (Deike, 2021; Melville, 1996). The increases in gas transfer occurs through the introduction of turbulence and the entrainment of air (Melville, 1996). These fluxes have large impacts on the climate system, as they affect CO_2 and O_2 transfer, the transport of aerosols, cloud condensation nuclei and thermal regulation in the atmosphere (Deike, 2021). In the absence of waves, the direct transport of gasses from the atmosphere occurs through slow molecular diffusion and conduction processes (Deike et al., 2016). The structure of the turbulence introduced into the system by waves is directly tied to the characteristics of the breaking wave, particularly the rate of energy transfer from the breaking wave and the size of the breaking wave. The turbulence regime of the system influences the length and velocity scales of the eddies formed (Ting and Kirby, 1996). This alters the contact time of entrained bubbles as well as the CO_2 concentration gradient in the surface layer of the water column, as breaking waves serve to overturn the water column thus decreasing the concentration gradient in the liquid. Increased turbulence is also beneficial to raceway pond set ups as it increases vertical mixing, which improves light utilization as well as decreasing the concentration gradient of dissolved gasses in the fluid column, as discussed previously.

The entrainment of air bubbles primarily occurs through breaking waves, in particular plunging breakers which cause a plunging jet that entrains air when the front of the wave impacts the surface of the water (Lee, 1995). Air entrainment could potentially increase the CO_2 mass transfer by allowing bubbles to mix and interact with the fluid, providing higher surface area for gas exchange. The breaking of waves is a complex problem, as they may result from intrinsic instabilities of deep-water waves or through wave-wave, wave-current, and wave-wind interactions (Melville, 1996) as well as by the complications imposed by the unsteady nature of the flow in waves (Lee, 1995). Breaking waves are also important for gas diffusion through the medium (Ting and Kirby, 1996). The study of these interactions is made difficult by the strongly nonlinear nature of the process and that it occurs over a wide range of scales (Melville, 1996). A convenient measurement used to assess the nonlinearity is the wave steepness (ak), where a is the amplitude of the wave from half the crest to the trough, and k is the wave number which can be expressed as u/c where u is the horizontal fluid velocity at the surface and c is the phase speed of the waves (Melville, 1996). Previously Stokes' periodic wave of steepness $ak = 0.4432$ was considered the model for breaking (Melville, 1996). This is to satisfy the condition that the fluid velocity must match or exceed the phase velocity in order to break (Melville, 1996; Thorpe, 1995), it was found in Lee (1995) that the ratio of velocity at the wave crest to the phase velocity averaged 1.04 in breaking waves. However, wave fields of smaller slope are subject to intrinsic instabilities that can lead to breaking (Melville, 1996). The measured velocity of the peak of a wave has been seen to be up to 38% higher than the theoretical value predicted by the roller model of waves, which was 1.3 times the shallow water wave speed equation ($c = \sqrt{gh}$) (Mukaro et al., 2013), the equation is given below where c refers to the wave speed, g to the gravitational constant on the Earth or 9.81 m/s^2 and h to the depth of the water. It was seen in Melville, (1982), that breaking could occur at a wave steepness of 0.31. This can occur because the downward acceleration of a wave is limited by gravity, whereas the upward acceleration is not bounded by gravity, this means that the acceleration upward of the leading side is usually larger than the acceleration due to gravity (Thorpe, 1995). This can increase the instability of the breakers. The instability criteria for waves are estimated by Iribarren, (1949) to be when the amplitude of the wave is equal to twice the average depth of the water. This ratio has been the cut-off point when determining whether a wave is capable of breaking, however does not indicate a specific time when the wave will break. It assumes a shallow water trochoidal theory for uniform, progressive waves (Battjes, 1974). The Iribarren number was arrived at to predict the kind of breaking wave (Iribarren, 1949). This number is given as.

Equation 2-7

$$\xi = \frac{\tan(\alpha)}{\sqrt{H/L_0}}$$

Where α is the slope angle, H is the incident wave height and L_0 is the wavelength. As such the ratio of H/L_0 represents the wave steepness. This number can be used as an indication of whether a wave would break as well as of the type of breaking wave that can be expected (Battjes, 1974).The Iribarren numbers that are indicative of each type of breaking wave are given below in Table 2.

Table 2 Taken from Battjes, (1974) detailing the relation between the Iribarren number calculated and the expected type of breaking wave. Here ξ_b refers to the Iribarren number of the inshore zone.

Wave breaking type	**Iribarren number**
Surging or collapsing	$\xi_b > 2.0$
Plunging	$0.4 < \xi_b < 2.0$
Spilling	$\xi_b < 0.4$

The use of slopes in order to imitate the beach conditions that prompt the breaking of waves has been studied many times. Typically, these systems use a piston-like device to displace water and create a wave (Huang et al., 2009; Lee, 1995; Mukaro et al., 2013). The measured waves tend to be in the order of approximately 10 – 20 cm (Mukaro et al., 2013). Varied results have been obtained that indicate different wave types can be obtained with different systems on different slope heights, there is currently not a consensus on what wave type can be obtained on different slope angles as the wave characteristics play a large role, but for example plunging waves have been seen when propagating a 12 cm wave onto a 1:20 slope (Mukaro et al., 2013).

In raceway ponds specifically, the idea of using slopes to create breaking waves, in order to increase surface turbulence and increase CO_2 mass transfer, has been investigated (Burke, 2016; van der Linde, 2022). It was found in van der Linde, (2022), that the mass transfer rate (k_La) for CO_2 was increased by about 12% at a paddlewheel RPM of 19.8 and by around 16% at RPM of 28.9 using a 55° slope. However, Burke, (2016) saw improvements in k_La of between 56% and 80% using varied slopes. Although in these experiments breaking waves were not seen and the increased turbulence from the added slopes was due to the slopes acting at weirs in the raceway, the increase in turbulence was seen by a reduction in the mixing time for the culture of approximately 56%. However, these weir-like slopes caused a decrease in the fluid velocity (approximately 45% decrease). The introduction of slopes into the raceway increased the head loss in the system and the k_La per unit of theoretical energy was decreased by around 31% (van der Linde, 2022). An increase in algal productivity when using a slope of around 10% has been seen (van der Linde, 2022). The height of the slopes looked at by Burke, (2016) and van der Linde, (2022) had significant effects on the fluid velocity. The higher the slopes the lower the fluid velocity due to the slope being an impediment to flow. However, at lower slope heights there was less interaction between the wave propagating in the system, which leads to smaller wave heights, and consequently lower mass transfer of CO_2. Thus, there exists a trade-off between the increases in mass transfer due to larger wave heights (which is representative of the turbulence in the system) and the fluid velocity of the system. The waves studied by van der Linde (2022) and Burke (2016), did not break and rather formed standing or undulating waves. This is likely due to the effects of surface tension being of larger than the instabilities caused by the presence of the slopes (van der Linde, 2022).

A different means of increasing turbulence in the system is the introduction of foils, which act similarly to baffles. These are static plates or wings that impede flow through the system and create pressure differentials to create eddies within the fluid. The aim of these is not the replication of waves but to reduce laminar flow through the straight sections of the raceway ponds. Foil systems have been used to increase the turbulence in the system, these were introduced by Laws et al., (1983) in order to increase the frequency of the algae entering and exiting the photic zone which increased the photic efficiency by 2.2 to 2.4 times. This is due to the increase in vortices created by foil arrays that operate in a very similar way to that of an airplane wing. The wing or foil creates a pressure difference between the bottom and top sides of the foil which drives vortices in the vertical direction, thus facilitating greater vertical velocities and mixing. Voleti, (2012) found that the vertical velocity in the area after a foil was 0.1 ms^{-1} whereas after the area of the vortices the vertical velocity was 0 ms^{-1}, it was found that the vortices increased vertical velocities up to 3 m downstream. This has been shown to increase the biomass by nearly 30% using two side-by-side foils/delta wings (Vaughan, 2013). These delta wings need to be put in an array to be able to create mixing over the width of the channel, it is suggested that the optimal width for them to be apart is the width of the delta wing (Vaughan, 2013). These systems have not been widely adopted but there appears to be promising results from them as the relatively low volume of the foils has a smaller effect on the flow velocity while increasing the turbulence in the system. Foils were not investigated in this project, but are an interesting alternative to the use of weir-like slopes as they may address some of the drawbacks to the use of larger slopes.

3 Defining the Research Project and Limitations

Algae technology is a promising field with both financial and environmental benefits; however, algal biomass productivity is too low for many industrial applications. One of the major limiting factors is the availability of CO_2 to the algal cells in the cultivation system. The current methods of using natural atmospheric CO_2 or sparging gas into the system are not ideal due to low mass transfer and added cost, respectively. Improvements in the mass transfer of CO_2 would improve the economic viability of the major cultivation system currently used, the raceway pond. Any improvements would need to maintain low cost to the business and not negatively affect the growth conditions of the culture.

The aim of this project is to investigate a novel strategy to improve the mass transfer of CO_2 into open raceway ponds to facilitate higher productivity. The addition of slopes will be investigated as the means of increasing the mass transfer of CO_2. This continues from work previously done by Burke (2016) and van der Linde (2022).

To assess the air entrainment caused by waves, the void fraction is often measured. This may be done by using optical or conductivity probes among other techniques (Hoque and Aoki, 2005). This was deemed out of the scope of this project as there are issues with the removal of noise from the signals which makes the data processing a difficult task. The introduction of turbulence in the system and the dissipation of the turbulence were possible parameters of potential interest. These can be measured by determining the velocity fields in the area of wave turbulence. This can be done by using Particle Image Velocimetry (PIV) or Acoustic Doppler Velocimetry (ADV) (Garcia et al., 2005; Huang et al., 2009; Voulgaris and Trowbridge, 1998). However, these methods were outside the scope of this project in terms of funding and time allocation but represent possible future areas of study.

The average fluid velocity and mixing time were used as measures of the overall degree of mixing in the system. These were related to the changes to recirculation zones as well as dead zones were not investigated in this study as they were investigated by van der Linde (2022). The most efficient study of recirculation zones relies on imaging data that can view a dye tracer from the side of the raceway. While this was achieved in the 62 L raceway (van der Linde, 2022), the 1000 L raceways used in this study do not have transparent sides and as such the side-view imaging was not feasible.

The design of the paddlewheel that drives the raceway pond can influence the hydrodynamics of the system (Li et al., 2014b). In this study a single paddlewheel design and a single propeller system was investigated as the focus of the investigation was on the effects of the slope designs.

Large-scale 1000 L raceways were constructed for this research project. The dynamics of these are investigated with respect to mixing and mass transfer in the absence of and with the addition of slopes. Through testing the 62 and 1000 L raceways in the same manner, scale-up effects can be studied, allowing comparison between the scales. The systems were tested in terms of their hydrodynamic characteristics, mass transfer capacities and overall algal productivity, with and without the presence of slopes. These measurements were used to ascertain the effectiveness of the slopes on a larger scale to test the hypotheses given below. The same design of slopes used by van der Linde (2022) were scaled up for the size of the large-scale raceway ponds. Overall, this project aims to access the relative efficacy of slopes in improving CO_2 mass transfer and mixing in 62 and 1000 L raceway ponds. The study further extends the previous studies by assessing whether these improvements result in improved algal productivity.

3.1 Research Project Objectives

- Design and install 1000 L raceway ponds within the University of Cape Town’s greenhouse.

- Ascertain baseline measurements of hydrodynamics, CO_2 mass transfer and microalgal productivity in the 62 L and 1000 L raceway ponds.
- Determine the energy consumption demands imposed by the use of slopes in the 62 L raceways.
- Determine theoretical energy consumption for the operation of the 1000 L raceways with and without slopes.
- Create breaking waves in the 62 L raceway ponds using progressive wave slopes as described by van der Linde, (2022) by varying the depth and slope angle.
- Determine the effects of best design slopes from van der Linde (2022) on hydrodynamics, power consumption, mass transfer and microalgal productivity in the 62 L ponds and 1000 L ponds.
- Determine the potential for effective application of slopes in pilot scale raceway ponds.

3.2 Research hypothesis and key questions

Hypothesis 1

Current productivity in raceways is often too low for industrial feasibility. One of the limiting factors is the supply of CO_2 to the culture. Current uses of atmospheric CO_2 leads to insufficient mass transfer rates, and the additional sparging of compressed CO_2, flue gas or air adds cost and reduces contribution to carbon neutrality. The use of slopes to generate waves may increase mass transfer through the entrainment of air and decrease the concentration gradient of CO_2 (by increasing vertical mixing) within the culture, thereby increasing the CO_2 driving force at the air-liquid interface.

Hypothesis 2

The entrainment of air by ocean breakers is seen as an important factor in the mass transfer of CO_2 in the ocean. The use of slopes was shown by van der Linde (2022) to improve CO_2 mass transfer; however, it negatively affected energy input to achieve specific liquid velocities. Larger scale systems will provide better mass transfer relative to energy usage. At larger scales the head loss due to the slopes will be smaller relative to the whole system. The signal created by the larger paddlewheel and larger volume will create larger waves, increasing the entrainment and turbulence, thus increasing CO_2 mass transfer.

Key research questions

In order to validate the above hypotheses a number of questions need to be addressed:

- What is the optimal trade-off between energy usage and CO_2 mass transfer?
- How does slope design affect hydrodynamics and mass transfer?
- Are there significant decreases in fluid velocity on introduction of the slope when slopes are used at larger scales?
- Are the effects of the slopes proportional to the volume they occupy in the raceway?
- Does the increase in turbulence caused by the slopes increase the mixing and mass transfer in the system?

4 Approach to Project and Methodology

4.1 Research methodology

These experiments included hydrodynamic characterizations, mass transfer quantifications, productivity experiments, and power consumption measurements (these methods are discussed in Section 4.2). The mass transfer coefficient of CO_2 is the primary concern of this project as it is hypothesized to be the limiting factor for carbon assimilation and algal growth.

Measurements of fluid velocity, mixing time and wave height all form part of the hydrodynamic evaluation. These methods are described in Section 4.2.3. The changes in hydrodynamic conditions were also characterized when slopes were placed in the system. From previous studies (Burke, 2016; van der Linde, 2022) the addition of slopes increased overall turbulence by improving mixing time and creating waves, but decreased the average fluid velocity. The average fluid velocity and mixing time were measured by means of a sodium chloride tracer. A conductivity sensor was used to measure the tracer in the system. The conductivity peak represents the bulk of the tracer. The time taken between the peaks of the tracer are representative of the circulation time within the raceway and so is impacted by the average velocity of the fluid. As the tracer disperses in the fluid the relative height of the peaks decrease and their breadth increases. At some point the conductivity measurement is equal at all points in the fluid, the mixing time is taken as the time taken to reach 95% of the final conductivity value.

The K_La of CO_2 was quantified by the changes in pH in the fluid, as detailed in Section 2.2.5. This allows for the quantification of the K_La of CO_2 more directly than measuring the K_La of O_2 and using a conversion factor for CO_2. The latter method has limitations owing to the reactivity of CO_2 in the system which must be accounted for should the latter method be used. This pH method was also deemed to be more suitable than the dynamic outgassing method which would require the system to be enclosed which could affect the mass transfer dynamics of the slopes in particular. The pH method used assumes that any changes in the pH of the system are due to the changes in CO_2 concentration of the system. The reactions and protocol used are further explained in Section 4.2.4.

The power consumption of the system was measured in two methods: theoretical power consumption and actual power consumption. The theoretical power consumption is related to the frictional head losses, bend head losses and losses due to any slope present. The equations for these head losses and theoretical power requirement are detailed in Section 4.2.7. The actual power consumption was measured directly using a Topward 1310 digital watt meter. It is assumed that the slopes increase the head losses in the system due to the increase in fluid depth upstream by limiting the area of flow over the slope, this increases the hydrostatic pressure pressing against the paddlewheel. The calculations for the theoretical power requirements require the fluid velocity and fluid depth at different locations. As such the tracer experiments are used.

The algal productivity is assumed to be related to the CO_2 gas-liquid mass transfer rate. The large-scale raceway ponds used were placed in a greenhouse. As light and temperature were not constant, as such light and temperature were monitored continuously. These parameters were taken into account when assessing the growth rate and productivity of the algal system. A simplified schematic of the work conducted can be seen in Figure 5. Each step in the workflow informs the next, such that the best performing conditions are used in the next stage of experiments.

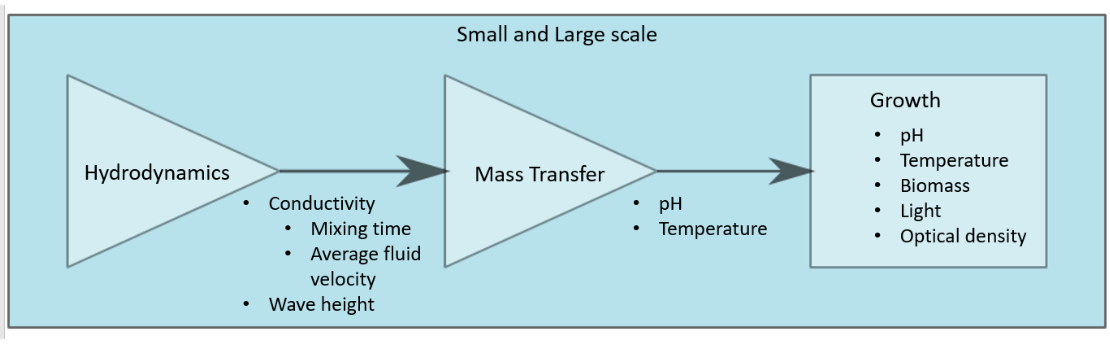


Figure 5 Simplified workflow of the experiments run.

4.2 Materials & methods

4.2.1 Raceway setup

Investigations into dynamics, mass transfer and growth were conducted in small-scale 62 L raceway ponds. These were the same ponds used by van der Linde (2022) and Burke (2016). The dimensions of these ponds are given in Figure 6. The working depth of these raceways was 12 cm, and circulation was maintained using 6 bladed paddlewheels, with each blade having a length and width of 11.5 cm and 13.5 cm, respectively. The power for these paddlewheels was supplied by a 0.37 kW Bonfiglioli motor with a S2U Bonfiglioli variable frequency drive. Light requirements for these reactors were provided by a series of cool White Osram 58 W bulbs, as these raceways were operated within the laboratory. Three 0.6 m bulbs were placed in the central island area to illuminate both channels of the ponds from the inside, two 1.5 m bulbs were placed on the outer side of each long section and an additional two 1.5 m bulbs were attached below the long section opposite the paddlewheel to provide light from below. These lights provided 24-hour illumination for the entire growth period.

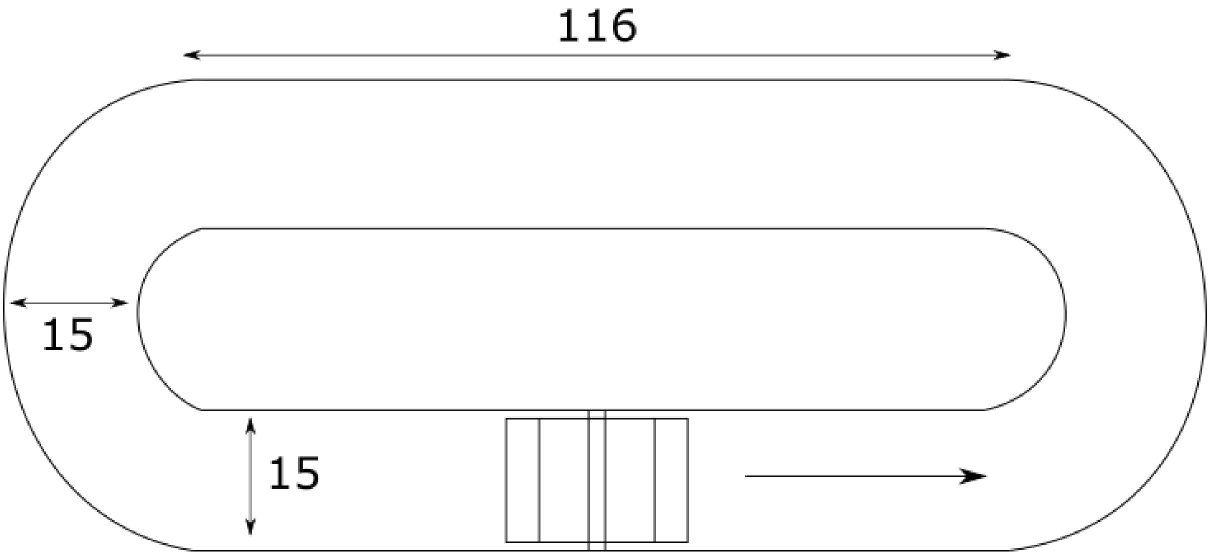


Figure 6 Dimensions of the small-scale raceways used in this study. All measurements are reported in centimeters.

The dimensions of the large-scale 1000 L raceway pond are seen below in Figure 7 below. Two raceways of the same design were used in this experiment. The fluid depth was maintained at 20 cm. A single Bonfiglioli 2.2 KW (BX 100LA 4) motor was used to power the paddlewheel for both raceways. Eight bladed paddlewheels were used to power the circulation in the raceways, the length from the impeller to the blade edge and width of the blades were 36 cm and 62cm respectively. This gave an approximate clearance of 1 cm from the bottom and 0.5 cm on either side. The position of the paddlewheel was set in the center of the long section as indicated by an X in Figure 7.

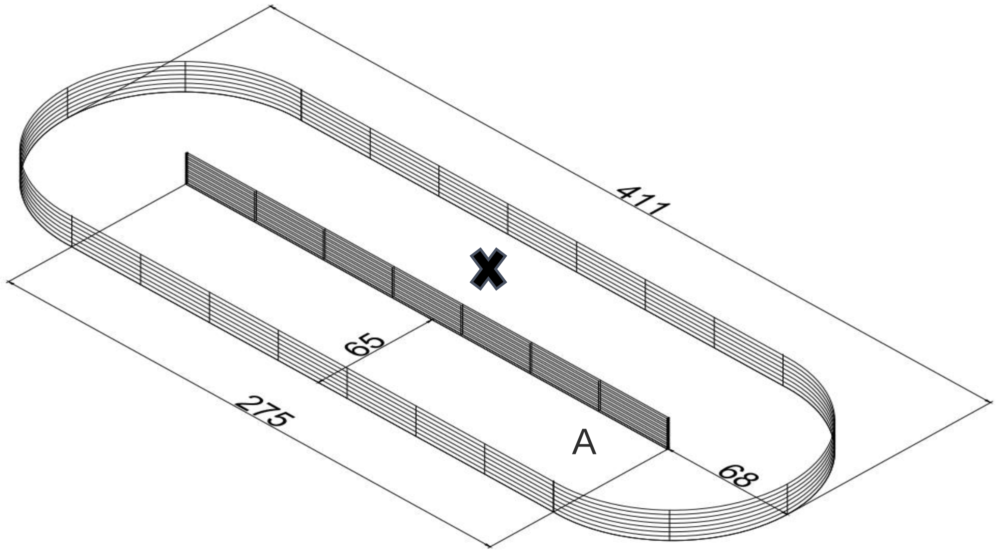


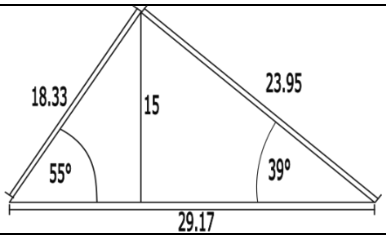
Figure 7 Schematic of the large-scale raceway to be used in this project. The working volume is around 1000 liters. All measurements given in centimeters. The symbols X and A represent the locations of the paddlewheel and location used for measurements (pH and conductivity), respectively.

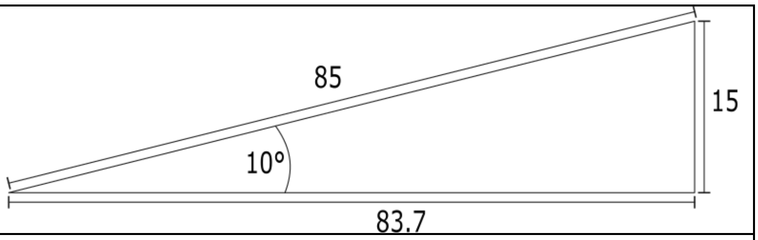
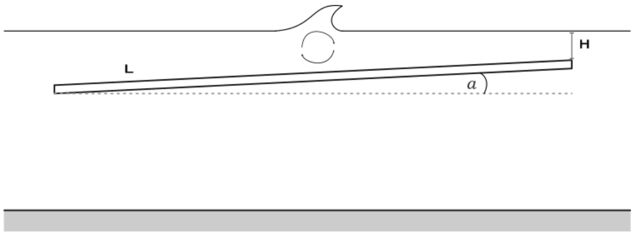
The illumination for the raceway ponds was provided by natural light. The solar irradiation was obtained from research groups within the University of Cape Town. No additional light was provided during the night to better simulate commercial raceway systems.

4.2.2 Slope design

Three slopes, denoted as HHL, UL and the progressive wave slopes as seen below in Table 3, were used in this experiment. Weir-like slopes, HHL and UL, were used to create hydraulic jumps. The impediment created by the slopes causes a standing wave to form that oscillates with the pulse driven by the paddlewheel. These represent the two best slopes found by van der Linde, (2022) , they were selected based on hydrodynamics, k_La and the k_La per unit of energy requirement. The design of the selected weir-like slopes is shown below in Table 3. The dimensions used in the 62 L raceway pond experiments, of this study, were identical to those used in van der Linde, (2022), however the weir-like slopes used in the 1000 L raceway had a height of 15 cm as opposed to the 10 cm due to the relative depths of the fluids. The scale up was done to allow a similar proportion of water to be able to flow over the slopes based on the fluid depth. The slope height was approximately 80% of the fluid depth in the 62 L raceways, as conducted by van der Linde, (2022) and 75% in the large-scale raceways. The change in the proportionate height of the slope was made to allow slightly more flow over the slope, as it was found in van der Linde, (2022) that the height of the slopes was the largest factor in reducing the fluid velocity in the system.

Table 3 Dimensions of the slopes used in the experiment seen from the side. All measurements are in cm.

HHL	

UL	
Progressive wave (PW)	

To create breaking waves that imitate the actions of natural waves, progressive wave slopes were implemented. A schematic of this slope can be seen above. These slopes were first introduced in the 62 L raceway ponds by van der Linde, (2022). They were intended to improve upon the weir-like slopes by allowing higher average fluid velocities in the system and creating breaking waves to allow air entrainment. The fluid velocity is a large concern in the weir-like slope implementation, as seen in previous studies (Burke, 2016; van der Linde, 2022), the progressive wave slopes would allow the flow of fluid under the slope to improve average fluid velocity. The second way that the progressive wave slopes proposed to improve upon the weir-like slopes is that they better mimic beach profiles. This serves to mimic shoaling waves that naturally break on beaches. The pulse from the paddlewheel, when a blade leaves the fluid, generates a wave that would propagate along the raceway. The pulse progresses along the slope and interacts with the slope, this causes the wave to increase in height and steepness until the signal breaks down and the wave breaks. The progressive wave slope used in the small-scale raceway system was approximately 60 cm in length. The depth of the slope (H) and the angle (α) were varied to test the performance of the system in creating breaking waves. However, as discussed below in Section 5.2, no breaking waves were noted and as such this system was not scaled up for the larger system.

4.2.3 Hydrodynamics assessment

All experiments to assess the hydrodynamics of the 1000 L raceway ponds were done using municipal city of Cape Town water with a depth of 20 cm. The pond was exposed to ambient temperatures which ranged between 8 and 58 degrees Celsius in the greenhouse, the monthly averages are provided below in Figure 8 with the grey bar representing the absolute range of temperatures (maximum and minimum temperature during the month), the raceway temperature was recorded with a Hanna HI98194 multiparameter. The hydrodynamic parameters assessed were the mixing times and average fluid velocity (indicated by the circulation time). It was assumed for this project that a larger wave height was proportional to the turbulence in the area following the slope, as the larger the wave height the greater the potential energy given to the fluid which would then be transferred to the eddies formed following the slope. This assumption was validated by the mixing times measured in the conductivity tracers.

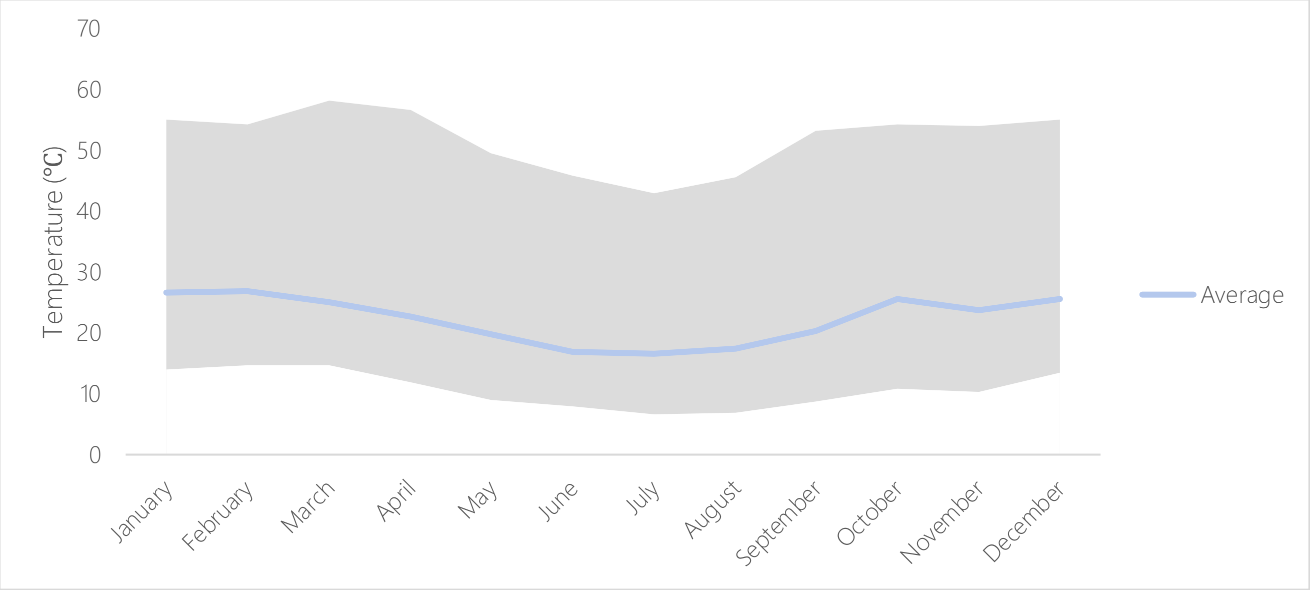


Figure 8 Average temperatures in the University of Cape Town greenhouse shown with the range of the maximum and minimum temperatures experienced each month. These averages, maxima and minima were measured from January 2017 until April 2022. The monthly temperatures were averaged during this time period to identify the mean conditions while the maximum and minimum temperatures were investigated to determine the potential hazards to work in the greenhouse and potential negative impacts on algal growth that could be expected.

Mixing and circulation times

A conductivity tracer experiment using 5 M NaCl was used to calculate the mixing and circulation times. An 80 ml pulse of 5M NaCl was added in the area after the paddlewheel to ensure the most turbulent flow, for accurate results. The pulse was measured using a Hanna HI98194 portable multiparameter meter positioned before the slope after the first bend (position A in Figure 7) at a depth of 6 cm. The conductivity data was logged at a frequency of 1 s^{-1}. An example of this data is given below in Figure 9. The average time taken between peaks for the first three peaks was used to calculate the circulation time and therefore the average fluid velocity. The average velocity was taken as the length along the center of the raceway (764 cm) divided by the circulation time. The mixing time was calculated by the time from the first peak to the time that the pulses stabilize to within 95% of the steady state value. These experiments were conducted in triplicate using the same water after the system reached equilibrium.

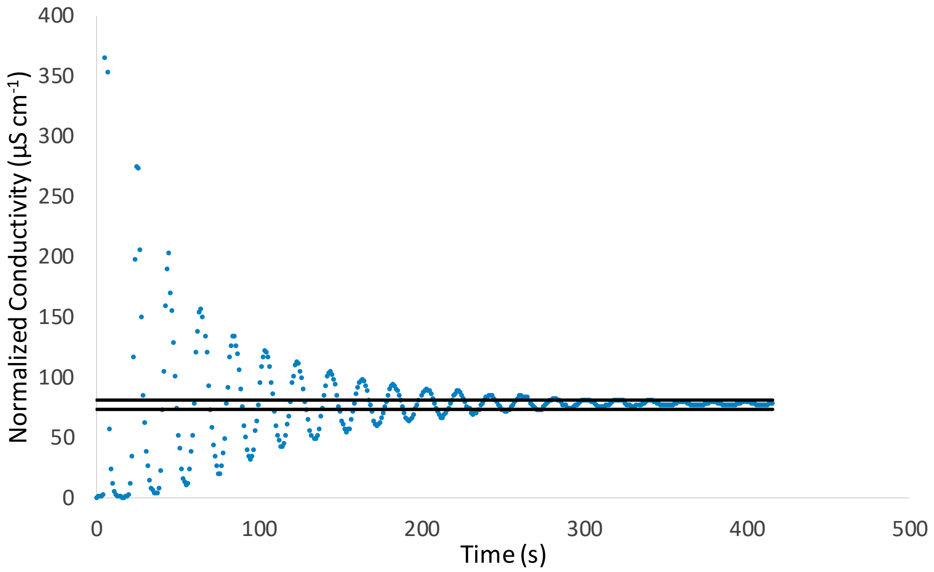


Figure 9 : Example of the conductivity tracer response over time for the raceway control. The two black lines indicate the zone where the conductivity reaches 95 % of its final steady state value. Taken from (van der Linde, 2022).

The same steps as above were conducted when determining the mixing and circulation times of the 62 L raceway system, however a smaller pulse of 5 ml 5M NaCl was used to account for the smaller volume.

4.2.4 Mass transfer

The core focus of the project is to assess the improvements that can be made to the CO_2 mass transfer into the raceway system. As such the mass transfer coefficient (k_La) measurements for CO_2 were of great importance for this study. The k_La was measured using a pH-alkalinity method as used by Burke, (2016) and van der Linde, (2022). This method allows the quantification of the CO_2 mass transfer rate into the fluid. Simultaneous reactions take place between the carbon species occurring in these conditions. The relative concentrations of each are determined iteratively to solve the simultaneous equations detailed from Equation 4-1 to Equation 4-4.

$$CO_{2\,(g)} \leftrightarrow CO_{2\,(aq)}$$ Equation 4-1

$$CO_{2\,(aq)} + H_2O \leftrightarrow H_2CO_3$$ Equation 4-2

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$ Equation 4-3

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$ Equation 4-4

Aqueous $CO_{2(g)}$ and H_2CO_3 are chemically inseparable and as such these two species are put into a single term of CO_2^*. Equation 4-1 to Equation 4-4 each have their own reaction constants given below.

$$K_0 = \frac{CO_2^*}{p_{CO2}}$$ Equation 4-5

$$K_1 = \frac{H^+ \cdot HCO_3^-}{CO_2^*}$$ Equation 4-6

$$K_2 = \frac{H^+ \cdot CO_3^-}{HCO_3^-}$$ Equation 4-7

$$K_w = OH^- \cdot H^+$$ Equation 4-8

Here Equation 4-5 describes the equilibrium between $CO_{2(g)}$ and CO_2^* and Equation 4-8 describes the self-ionization of water. The equilibrium constants can be calculated empirically and are functions of temperature and salinity, these were calculated according to the CeBER protocol that can be found at https://uctcloud.sharepoint.com/. k_La can then be determined using Equation 4-9 (which is a derivative of Fick's Law of molecular diffusion), where $\left(\frac{dC_T}{dt}\right)$ is the change in total inorganic carbon (CO_2^*, HCO_3^- and CO_3^-) and CO_2^{sat} is the saturation point for CO_2 in the system which can be calculated from Equation 4-6 using the known partial pressure of CO_2 in the air and the calculated equilibrium constants.

$$\frac{dC_T}{dt} = k_L a(CO_2^{sat} - CO_2^*)$$ Equation 4-9

To quantify the concentrations of the different inorganic carbon species, present in C_T, the pH, temperature and alkalinity of the fluid must be understood. As such these were measured using a Hanna HI98194 multiparameter in the 62 and 1000 L raceways. For each time point, the concentrations of the different carbon species are simultaneously solved using the equilibrium equations (Equation 4-5 to Equation 4-8), pH data, temperature and total alkalinity. The total alkalinity (described in Equation 4-10) was used to evaluate the change in total inorganic carbon over time (dC_T/dt). dC_T/dt is the slope for Equation 4-9, which is graphically represented below in Figure 10.

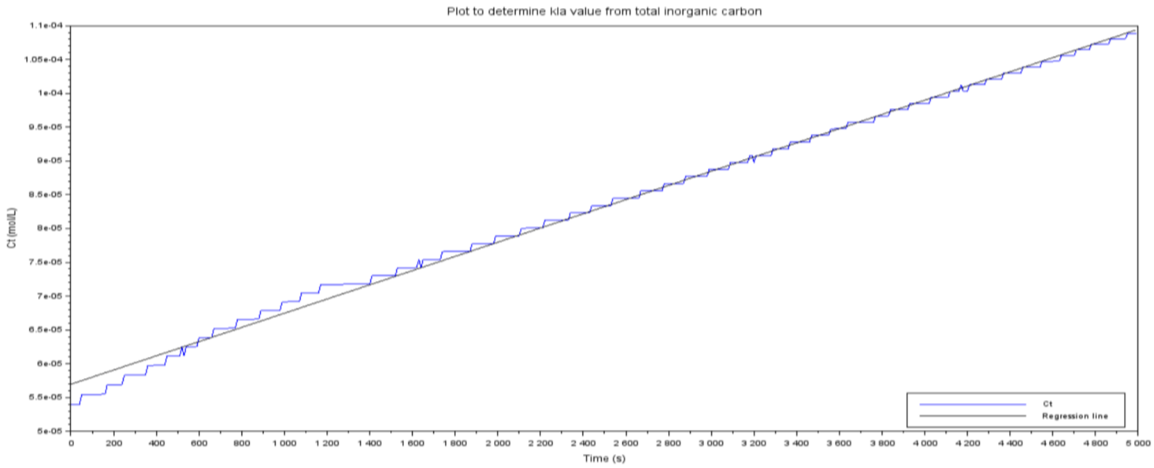


Figure 10 An example of the calculated total carbon species in solution over time during a mass transfer experiment. This was conducted in the 62 L raceway with no slope at a paddlewheel speed of 15.5 RPM.

$$A_T = HCO_3^- + 2CO_3^- + OH^- - H^+$$ Equation 4-10

The total alkalinity was measured using a sample taken from the fluid post sodium hydroxide addition. The time at which the sample is taken is unimportant as the carbon dioxide entering the system creates an equal number of positively and negatively charged ions, and as such does not affect the calculation of total alkalinity.

Scilab code to solve the simultaneous equations and calculate the k_La is provided and documented in the CeBER Methods Manual (https://uctcloud.sharepoint.com/). The Scilab code in the CeBER manual was detailed for CO_2, mass transfer using media. As such the calculations for total alkalinity and pH included other ionic species that are assumed to be negligible in tap water. As such, Equation 4-10 was used instead.

This experiment was conducted on tap water to reduce the wastage of media chemicals as the same media cannot be used for a growth experiment once the mass transfer experiment is concluded. The raceway was filled with standard tap water to a depth of 20cm and left to run for approximately 18 hours. This is to degas the water of chlorine and equilibrate with local atmospheric conditions. Before each run the water's total alkalinity, salinity, conductivity, and pH were analyzed. The fluid temperature was not controlled, as such it was recorded and used in the calculation of the mass transfer coefficient.

A Sodium Hydroxide solution with a concentration of 5M was added to the raceway until the pH was just above 10. After the pH stabilized the data logging began, where pH was logged every 10 sec using a Hanna HI98194 multiparameter in the 1000 L raceways, and a Mettler Toledo InPro 3250/120/PI1000 pH probe with a built-in temperature sensor was used in the 62 L raceways. The probes were immersed to a depth of 6 cm in the center of the channel. For the 62 L raceways, a Mettler Toledo M300 Transmitter, with the accompanying software, was used to log the pH. The decrease in pH from 10 to 9.5 was measured while at the same time conductivity and alkalinity were measured. This pH range was chosen to simulate a developed algae cultivation system as the process of photosynthesis increases the pH.

4.2.5 Algal preparation

All algal growth experiments were conducted using an indigenous strain of *Scenedesmus spp.* grown in 3N BBM media. The contents of which are outlined in Table 4. The strain was isolated by the CeBER research group as is used as an test species as it has a high growth rate and is tolerant to changes in conditions.

Table 4 Composition of 3N-BBM used in the cultivation of Scenedesmus spp.

Component	**Concentration (g L^{-1})**
$NaNO_3$	0.75
$CaCl_2 3H_2O$	0.025
$MgSO_4 7H_2O$	0.075
$K_2HPO_4 3H_2O$	0.075
KH_2PO_4	0.175
NaCl	0.025
Na_2EDTA	0.0045
$FeCl_3 6H_2O$	5.82×10^{-5}
$MnCl_2 4H_2O$	2.46×10^{-5}
$ZnCl_2$	3.00×10^{-5}
$CoCl_2 6H_2O$	1.20×10^{-5}
$Na_2MoO_4 2H_2O$	2.40×10^{-5}
Vitamin B1	1.20×10^{-3}
Vitamin B12	1.00×10^{-6}

The pre-inoculum was generated by transferring individual colonies, from streak plated 3N BBM agar plates, into 500 ml bottles, with a working volume of 300 ml containing 3N BBM media. This was scaled up to 1L Schott bottles with a working volume of 700 ml. From there a 10 L hanging bag with a working volume of 7.5 L was inoculated. The stages from the 500 ml bottle to the 10 L hanging bag were continuously supplied with air via an air tube with suitable aeration rate and light via artificial lighting in the CeBER laboratory.

The 10 L hanging bag served as the inoculum for the 62 L raceways, however if growth experiments were to be conducted on the 1000 L raceways the hanging bag was used to inoculate 100 L raceways in the greenhouse. This served dual functions; it allowed for an increase in the total biomass to be used as inoculum in the 1000 L raceways, as well as allowing the culture to acclimatize to conditions in the greenhouse. This was crucial as the greenhouse was not temperature controlled and did not have constant lighting, which the laboratory had. A total of 200 L of inoculum was cultured for the two 1000 L raceways. It was noted that the growth in the 100 L raceways was slower than the previous steps, and there was a significant lag period that occurred during the acclimatization.

The 1000 L raceways are located in the University of Cape Town greenhouse, on the Southwest corner of the campus, and as such used natural light. The light intensity during the growth periods was taken as the solar irradiation that was experienced on the University Campus, this information was obtained from ongoing university studies.

4.2.6 Cultivation experiments

To validate the results of the mass transfer experiments, the microalgal growth performance was tested. It is assumed in this experiment that the limiting factor during the linear algal growth phase is CO_2 and as such any change in the k_La should directly affect the productivity of the culture. As such the final microalgal concentration was not investigated, as at high algal densities the limiting factor rapidly becomes light, which would confound the effect of changes in CO_2 mass transfer.

Prior to growth experiments, the 1000 L raceways were filled with water and Black n Go (active ingredient: didecyldimetylammonium chloride). This was run at approximately 10cm/s for approximately 24 hours. This was done to ensure that no unwanted microbes remained in the raceway. The presence of additional algal or predatory species within the system would alter the growth rate of the system, giving inaccurate data. The system was then cleaned thoroughly by rinsing the raceway and draining the water to ensure no contamination remained. Fresh tap water was added to the raceways and left to equilibrate with atmospheric conditions for approximately 12 hours, prior to use. Media components were added to the raceway, according to the concentrations for 3N BBM seen in Table 4. The raceways were set to the appropriate fluid velocity for the experiment and algae culture from the 100 L raceways were used to inoculate the 1000 L ponds. A starting OD of 0.1 was intended but due to light limitations during the period of cultivation this was not possible. During the experiment the culture was maintained at 20 cm depth by adding additional water to account for evaporation losses.

Productivity is measured as the rate of change of biomass during the linear growth phase of the culture before the stationary phase. For this dry cell weights were calculated using pre-dried 0.45 µm cellulose nitrile filter papers. These pre-dried filters were weighed, thereafter 20ml of the culture was filtered through the paper and then rinsed with approximately 10ml of deionized water to remove excess salts from the filter paper. The filter papers were then dried for approximately 24 hours at 80°C then their mass with the algae was compared to the mass before. All filters were placed in a desiccator for a period of 1.5 hours before their weight was taken in order to cool. These measurements were taken in triplicate.

In addition to the algal dry weights, pH, temperature and OD_{750} were measured in triplicate. The algae were cultured in raceway ponds for a period of 16 days. After the run the raceway ponds were sterilized with a biocide (BIOCIDE D 500, Diversey South Africa) to give a concentration of 300 mg/L free chlorine in the culture.

The same procedure was followed when conducting growth experiments for the 62 L raceways, however the temperature was maintained at 25 degrees using heaters to ensure consistency of results.

Since the growth trials in 1000 L raceways were conducted in an outdoor greenhouse, the temperature and conditions are of importance as they influence the growth kinetics of the algal culture. Therefore, temperature and relative humidity were measured prior to this experiment from February 2020 until August 2021. The temperature and humidity were logged each hour for the period. This provided an understanding of the conditions that could be expected in the greenhouse and assess the suitability of the grow site. It was deemed that the extreme temperatures experienced in the greenhouse, Figure 29, did not have a duration that would affect the growth of the algae owing to the thermal conductivity of water.

4.2.7 Power consumption

The power consumption was calculated as a theoretical energy consumption and a measured power consumption using a Topward 1310 digital Watt meter. This followed the same protocol used in van der Linde, (2022) .

The theoretical energy was calculated using the following equation (Chiaramonti et al., 2013):

$$P_{Theo} = \rho Q g \Delta H \qquad \text{Equation 4-11}$$

In this equation ρ is the fluid density (kg m^{-3}), Q is the volumetric flow rate (m^3 s^{-1}), g is the gravitational acceleration constant (m s^{-2}) and ΔH is the total head loss throughout the raceway (m). The total head loss is comprised of the concentrated and distributed head losses, which correspond to the head loss due to the bends in the raceway and the head loss experienced in the straight channels due to friction respectively. If a slope is present in the raceway during the experiment, then the head loss due to the slope also needed to be added into the calculation of ΔH.

The concentrated head loss (H_c) occurs as a result of obstacles to fluid flow, this is the dominant head loss in the curves of a raceway. Although slopes constitute an obstruction to flow they were treated as an additional factor in the head loss calculation as they require a different calculation. The concentrated head loss (H_c) is dependant on the average fluid velocity and the bend loss coefficient (k_b). This can be seen below, where v is the velocity of the fluid (m s^{-1}) and:

$$H_c = k_b \frac{v^2}{2g} \qquad \text{Equation 4-12}$$

The value of k_b typically lies between 1.5 and 4 (Chiaramonti et al., 2013), this variation is due to differences in the bend geometry and fluid velocity in the raceway. A k_b value of 3 was used for the 1000 L raceways after consulting literature of similar systems. There was no consensus within the literature and perhaps this could be investigated more in future works to determine a more accurate k_b value for this specific system.

The distributed head losses (H_d) are a function of L the length of the straight channel (m), D_h the hydraulic diameter (m) and λ the friction coefficient as seen below:

$$H_d = \lambda \frac{L}{D_h} \frac{v^2}{2g} \qquad \text{Equation 4-13}$$

The friction coefficient was calculated iteratively using the Colebrook-White formula seen below:

$$\frac{1}{\sqrt{\lambda}} = -2 \log\left(\frac{2.51}{Re\sqrt{\lambda}} + \frac{\varepsilon/D_h}{3.7}\right) \qquad \text{Equation 4-14}$$

Where, ε is the roughness coefficient (m) and Re is the Reynolds number. The roughness coefficient was calculated based on the material used in the construction of the raceway pond. For fiberglass it is typically a value of 5×10^{-6} meters.

Hydraulic diameter (D_h) is a function of A, y and w. These being the cross-sectional area of the channel (m^2), the fluid depth (m) and the width of the channel (m) respectively.

$$D_h = \frac{4A}{2y+w} \qquad \text{Equation 4-15}$$

Energy loss due to the slope can be estimated using the principle of mechanical energy conservation. A version of the Bernoulli equation is used below in Equation 4-16 (which relates to Figure 11).

$$(h_s + h_1) + \frac{v_1}{2g} = h_2 + \frac{v_2}{2g} + \Delta H_s$$ Equation 4-16

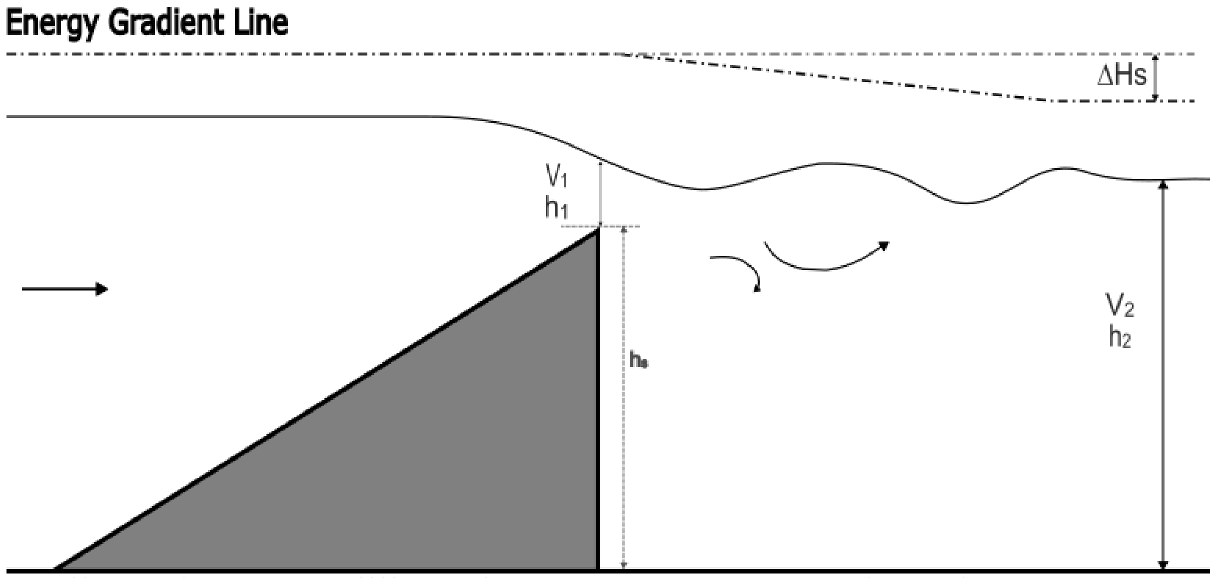


Figure 11 Redrawn from van der Linde, 2022 showing flow over the slope, depicting the head loss from point 1 at the slope crest and point 2 after the hydraulic jump.

Equation 4-16 was applied from point 1 at the top of the slope to point 2, just after the hydraulic jump. This is shown above in Figure 11. The non-uniformity in flow (specifically for the velocity terms) was assumed to be negligible for the calculation of Equation 4-16.

To estimate the flow rates at points 1 and 2 the volumetric flow rates were used with the cross-sectional areas of the two locations. The volumetric flow rate was calculated by Equation 4-17.

$$volumetric\ flow\ rate (m^3/s) = \frac{volume\ of\ raceway\ (m^3)}{circulation\ time\ (s)}$$ Equation 4-17

From this the flow rates can be calculated using Equation 4-18

$$average\ flow\ rate\ \left(\frac{m}{s}\right) = \frac{volumetric\ flow\ rate (m^3/s)}{cross\text{−}sectional\ area\ (m^2)}$$ Equation 4-18

5 Results and Discussion

This project focused on assessing the viability of introducing slopes as a means of improving CO_2 mass transfer and hence autotrophic algal productivity in the raceway, particularly as a raceway system was scaled up from 62 to 1000 litres. The scale up was achieved by moving from a lab scale raceway to an larger outdoor raceway system of 1000 litres. The results obtained seek to improve the Technology Readiness Level (TRL) of the proof of concept to inform industrial enterprises to consider the addition of slopes as a means of improving algal productivity while maintaining or improving energy efficiency. As such the investigation was designed to have each step inform the following, with the results of the laboratory scale raceways (62 L) guiding the testing for the pilot scale raceways (1000 L). The same is true of the experiments covered.

The experiments followed a predetermined path of examining the hydrodynamic characteristics of the systems in response to varying key factors to determine the best conditions for mass transfer experiments. The algal growth experiments used the conditions providing the best mass transfer results in the hydrodynamic experiments to validate their findings. The system should still be geared towards the production of algae rather than purely focused on mass transfer improvements as the intended use of these systems remains algal growth for commercial purposes.

The hydrodynamic flow patterns, mixing, mass transfer rates and growth rates were tested in the 62 L raceway used in the previous studies of Burke (2016) and van der Linde (2022), described in Section 4.2.1. The raceway design is illustrated schematically in Figure 5, This entailed re-examining the work done by van der Linde, (2022) to determine the optimal conditions in the 62 L raceway; these were re-evaluated experimentally. This included the selection of the slopes used in this investigation, as the two best performing slopes form van der Linde, (2022) were used. Namely, the HHL and UL slopes as discussed previously. Further investigation into the effects of fluid velocity on mass transfer rates was conducted and the use of an alternate slope design, the progressive wave slope, was studied to attempt to form shoaling waves rather than the standing waves observed using the weir-like slopes investigated by van der Linde (2022).

Figure 12 A picture of the 1000 L raceways used inside the University of Cape Town greenhouse. The ponds that were manufactured are identical and the paddlewheels are powered by a single motor as shown above.

The accumulated insight from studies in the 62 L raceway was applied to the 1000 L raceway pond through a scaling study. The 1000 L raceway was designed as described in Section 4.2.1. A photograph of these raceways is shown in Figure 12.

5.1 Baseline hydrodynamic study of the 62 and 1000 L raceways

To determine the base line effects of the addition of slopes, the average fluid velocities and mixing times were investigated for the 62 and 1000 L raceway ponds. This was conducted according to the methods described in Section 4.2.3. An example of this can be seen below in Figure 13. The average fluid velocity was taken as the average of the time between the peaks in conductivity, shown below as the points in red. The mixing time was taken as the time taken from the first peak to where the conductivity reading was within 5% of the final value, the range is indicated below by the dark blue lines. These tests were done in triplicated to ensure that a representative average fluid velocity and mixing time was achieved. The results showed good replicability, typically less than 5% variance between individual runs. However, if greater than 5% variance was seen between the runs, then the experiment was repeated again in triplicate.

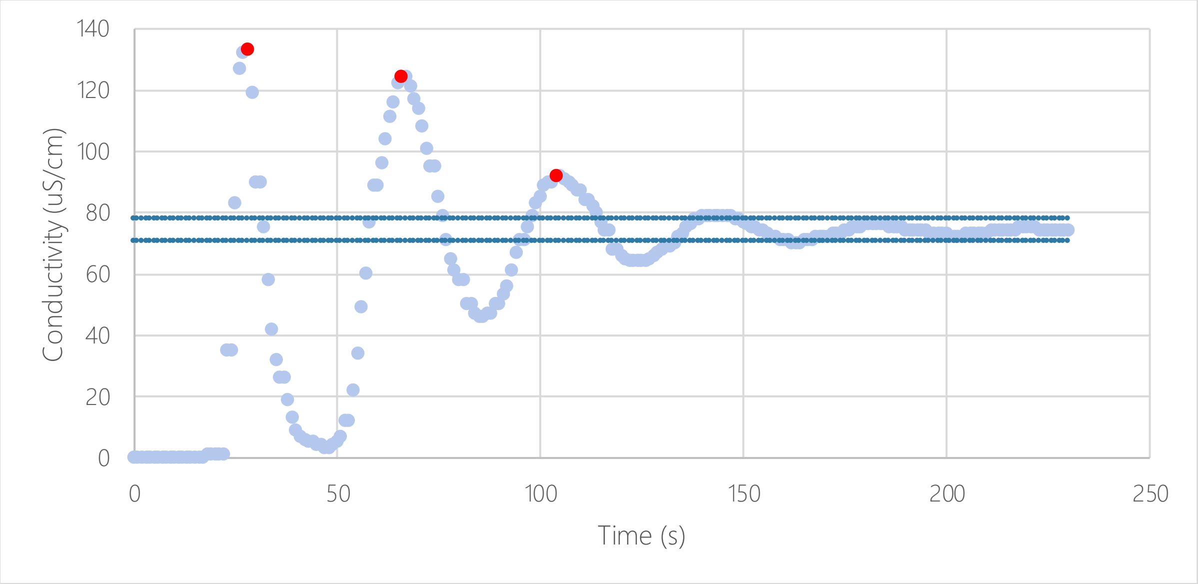


Figure 13 An example of the data used to calculate average fluid velocity and mixing time in the 62 L raceway. The paddlewheel velocity used was 28.9 RPM.

The hydrodynamic results are presented in Figure 14.The lines in dark green represent the baseline hydrodynamics without the slope addition while those in light green and blue indicate the results for two different slopes. For both the 62 and 1000 L systems, fluid velocity and mixing time are strongly affected by the addition of slopes.

Figure 14 A and B show the average fluid velocities at differing paddlewheel speeds in the 62 L and 1000 L systems, respectively. As would be expected, increased paddlewheel speed resulted in higher average fluid velocities. The relationship observed between the two followed a linear trend, however the same trend was not seen with and without slopes. The introduction of slopes into the system decreased the average fluid velocity across all paddlewheel speeds. In the 62 L raceway, increasing divergence with and without slopes is observed as the paddlewheel speed increases. At a paddlewheel speed of 40 RPM, an average fluid velocity of 35 cm/s is maintained in the absence of the slope whereas when the slopes were added the average fluid velocity decreased to approximately 15 cm/s. Standard operating velocities reported for raceway ponds are around 30 cm/s (Hadiyanto et al., 2013; Liffman et al., 2012; Lima et al., 2021; Sompech et al., 2014) and it is recognized that at velocities of less than 10 cm/s, dead zones may form, particularly in the bends (Mendoza et al., 2013a; Sompech et al., 2014). As such the addition of slopes to the 62 L raceway decreased the average fluid velocity into the range 9 to 24 cm/s across paddle wheel rotational speeds of 20 to 40 RPM; increasing the likelihood of dead zone formation. The increased likelihood of dead zones could limit both the mass transfer rate and productivity of the system. This is discussed in further detail in Sections 5.3 and 5.4. The expected fluid velocities with slopes at higher paddlewheel speeds can be inferred from the data presented owing to the linearity of the relationship between paddle wheel speed and linear velocity in the presence or absence of slopes; however, splashing and water loss on operation at a paddlewheel speed of 50 RPM did not allow accurate measurement.

Figure 14 B also shows a linear relationship between paddle wheel rotational speed and linear velocity in the 1000 L raceway pond. Again, the differences in average fluid velocities in the system with and without slopes are larger at higher paddlewheel speeds. The fluid velocities varied between 12.44 and 38.05 cm/s without slope present and between 8.72 and 24.57 cm/s with a slope, across a rotational speed range of 3.33 to 9.23 rpm. Hence, the differences between the systems with and without slopes at higher paddlewheel speeds was not as large as in the 62 L system which aligns with the hypothesized outcomes (Section 3.2). It was hypothesized that at a larger scale the slopes would make up a smaller area proportional to the overall size of the system, hence reduce the average fluid velocity less. At a paddlewheel speed of approximately 9 RPM, the system without a slope had an average fluid velocity of approximately 38 cm/s whereas the system with slopes had an average fluid velocity of approximately

23 cm/s. Therefore, the addition of slopes in the 1000 L system had a lesser effect on the average fluid velocity than in the 62 L system.

The mixing time of the systems, presented in Figures 11C and 11D, showed that as the paddlewheel speed and average fluid velocity increased the mixing time decreased in both the 62 and 1000 L systems. This did not follow the same pattern as the average fluid velocity. This follows the expected outcome as higher paddlewheel speeds increase the turbulence in the system, allowing for more rapid mixing. However in the 62 L system, the mixing times with the slopes were consistently lower than without slopes when operated at the same paddlewheel speed and this was not seen in the 1000 L system. It would be expected that a higher average fluid velocity, seen in the 1000 L raceway with slopes compared to the 62 L raceway, would result in improved mixing times. Prior to the tests it was hypothesized that there would be a larger decrease in mixing times in the 1000 L than in the 62 L raceways. This was not seen, as demonstrated in Figure 14 C and D. The mixing times for the 1000 L raceway at higher paddlewheel speeds were not statistically different when operated with and without slopes. This is likely due to the method used to determine the mixing times, as discussed further below.

62 L raceway average fluid velocity and mixing time	1000 L raceway average fluid velocity and mixing time

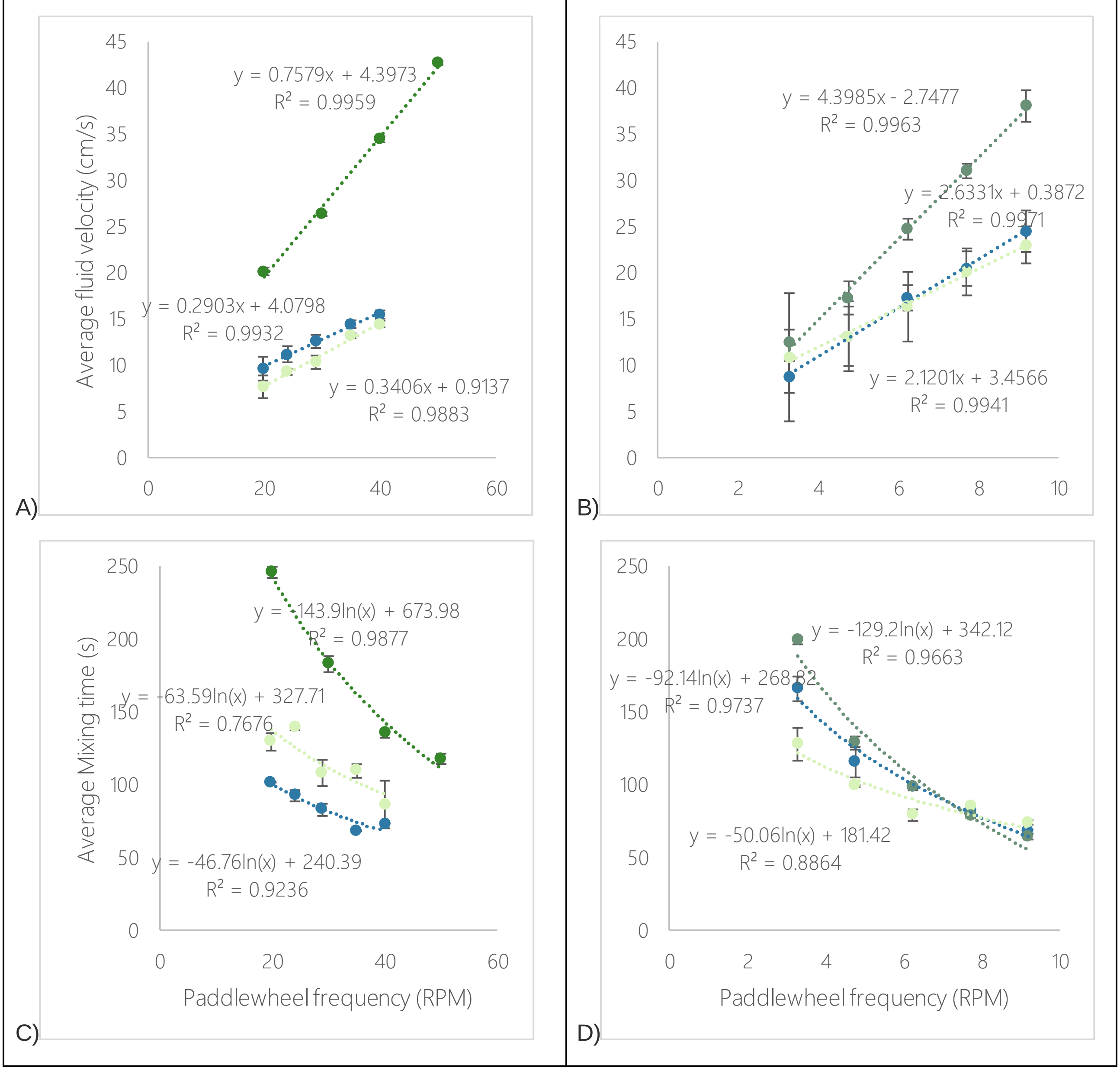


Figure 14 The effects of paddlewheel rotational rate on the hydrodynamic characteristics. Figure A and B show the average fluid velocities for the 62 l and 1000 l raceways, respectively. Figure C and D show the mixing times for the 62 l and 1000 l raceways, respectively. Blue, light green and dark green refer to UL, HHL and no slope conditions, respectively.

Figure 14 A above shows that the weir-like slopes dramatically influence the average fluid velocity seen in the raceway. This is a confounding factor when determining the influence of the slopes on mass transfer, as fluid velocity and mass transfer are positively correlated (Caia et al., 2018) . Typically, as the fluid velocity increases so does mass transfer as the turbulence in the system increases. However, experiments conducted with and without a slope cannot be directly compared, as to achieve the same fluid velocity different paddlewheel speeds must be used, this is discussed in greater detail in Section 5.3. As can be seen in Figure 14 A and B, at the 1000 L scale the effects of using single weir-like slopes on the average fluid velocity were not as significant as when they were placed in the 62 L raceway. There were no substantial differences in the fluid velocity for the different slopes. The HHL slope had slightly lower average fluid velocity than the UL slope, however this difference was not significant.

It is particularly noticeable that in the 62 L system it was not possible to achieve average fluid velocities higher than 20 cm/s, whereas in the 1000 L system it was easily achieved. The limiting factor for the fluid velocity had to do with the paddlewheel speed, as at very high speeds there was a large amount of splashing and water loss. This was deemed unlikely to provide reproducible results if the volume of fluid was decreasing at variable rates. The fluid velocity is viewed as an important factor in algal growth as the average fluid velocity has an effect on the settling of algae, which in turn has a large effect on the growth of the culture as discussed in Section 2.2.3 and 2.2.4.

The smaller decrease in fluid velocity with the addition of slopes in the 1000 L raceway when compared to the 62 L raceway was likely due to the slopes representing a smaller obstacle in relation to the size of the system. In the 62 L system the slope represented a larger obstacle volumetrically than in the 1000 L system. Although the slopes were scaled up to account for the increased depth of the 1000 L system, the width along the plane of circulation was not proportionally as large as in the 62 L system. This was to preserve the angles of the slope. Therefore, it can be hypothesized that on larger scales (greater than 1000 L) the introduction of slopes would have less of an effect on the average fluid velocity in the system. This would need to be verified in a larger system as perhaps an increase in localized mass transfer around the slope would not be discernable given the size of the system. This would have to be investigated as the use of slopes for improved mass transfer of CO_2 has not been studied. There likely exists a tradeoff between the improvement of mass transfer and the reduction in the fluid velocity that would need to be managed in order to facilitate maximum productivity. The relative importance of each based on the application would need to be determined according to the system in operation.

The mixing times were significantly reduced with the addition of slopes in the 62 L raceway ($P = 0.003$). The same trend was seen in the 1000 L raceway however the difference was not statistically significant ($P = 0.188$). In particular at paddlewheel rotational velocities above 6 RPM no clear difference could be seen. The mixing times are taken as an indicator of the total turbulence in the system, with the mixing time and total turbulence being inversely proportional. As discussed in Section 2.2.4, increased turbulence allows for higher growth rates as the algal cells are allowed to enter the photic region of the culture with greater frequency. This is supported by previous work done that investigated the surface renewal rate and found that it was proportional to the overall mixing and mass transfer of gasses, this surface renewal rate was determined by the large scale eddies generated by the upward motion driven by obstacles to flow (Komori et al., 1989). The increased turbulence also serves to decrease the concentration gradient of carbon dioxide in the system as explained in Section 2.2.5. It can be seen in Figure 14 C that the UL slope provided the fastest mixing times, with the HHL slope providing improved mixing times compared to the control but not as large an improvement as the UL slope. This is in line with the average fluid velocities seen, as the size of the impediment is proportional to the increase in turbulence to a certain extent. However, this same trend was not seen in the 1000 L system, as seen in Figure 14 D. In the 1000 L system no significant differences were seen between the slopes and control. This is unlikely to be a true indication of the relative mixing conditions in the systems but rather related to issues with the measurement technique. The same technique was used in the large and 62 L systems for comparison, however the large volume of water and distance around the raceway in the 1000 L raceway meant that the diffusion of the salt tracer was too rapid to get an accurate measurement of the mixing time. An example of the data collected while running the conductivity tracer experiment is given below in Figure 15. Here it can be seen that the tracer very quickly became diffuse in the system, making accurate conclusions problematic. The average fluid velocity calculated for this set of experiments was 20.09 cm/s, which means that the mixing time would be 2.23 revolutions of the salt tracer, as such the bulk of the tracer passed the sensor only twice in the time it took for the solution to fully mix indicating that it is not a suitable technique in larger scale systems. As such the use of a salt tracer in the 1000 L raceway proved to be inaccurate in determining the mixing time in the system. It can be seen from the figure above that at higher fluid velocities there was no decrease in mixing time when using slopes in the system, but it is not possible to draw conclusions on any changes in turbulence with these results. Further investigations into the changes in turbulence may be beneficial to understand the effects of paddlewheel speed and slopes, particularly in specific areas of the raceway system, such as the long channels which are typically regions of low turbulence.

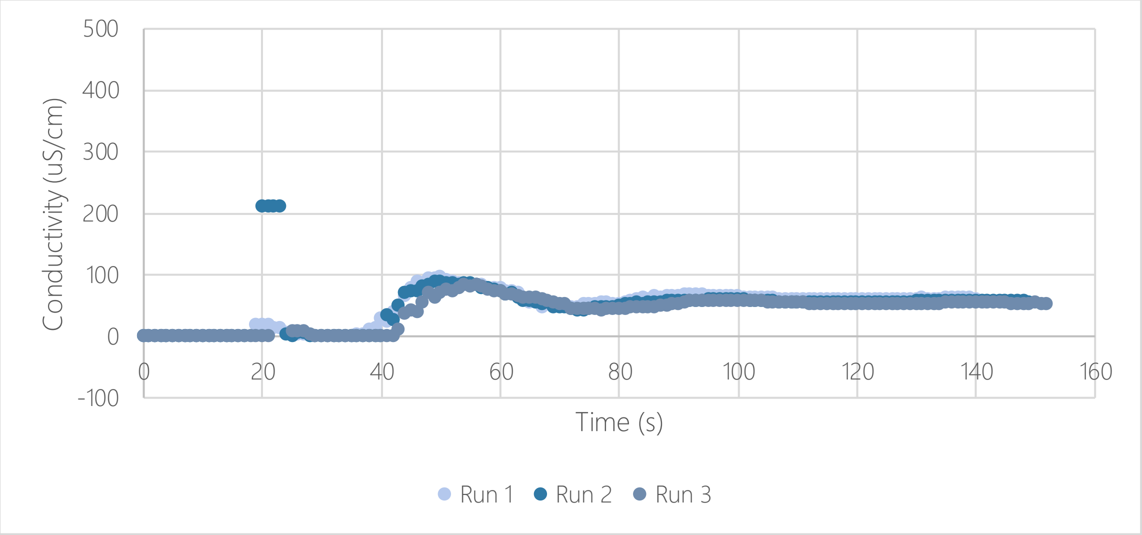


Figure 15 Conductivity data measured in the 1000 L raceway pond using a 5M NaCl tracer while operating the raceway with a paddlewheel rotational velocity of 7.7 RPM with the HHL slope.

5.2 Investigation into the creation of breaking waves using a progressive wave slope in the 62 L raceway

The progressive wave slope (as described in Section 4.2.2 was installed into the 62 L raceway using hanging strings as illustrated below in Figure 16. This allowed for the height and angle of the slope to be adjusted. The angle of the slope was tested from 1 to 5 degrees and the depth of the slope closest to the surface was tested from 0.25 cm to 1.5 cm in increments of 0.25 cm. The combinations of these variables did not yield any breaking wave formations. It was hypothesized that the signal from the 62 L raceway paddlewheel was not sufficient to overcome the surface tension forces, as surface tension can be strong enough to prevent the formation of surface waves (Longo, 2010).

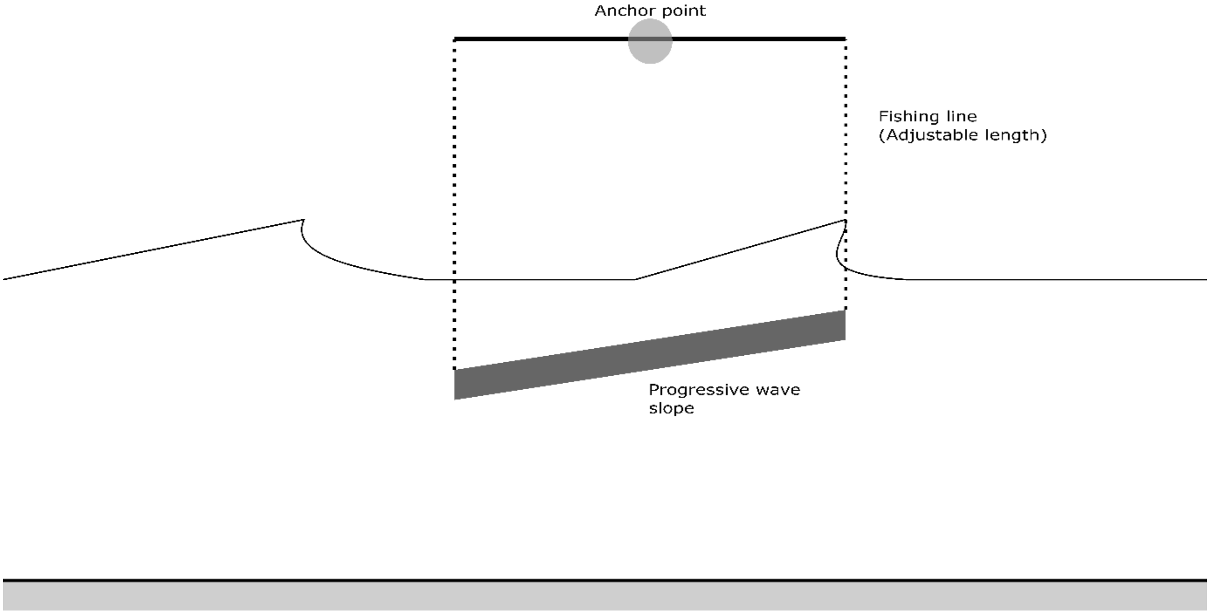


Figure 16 Representative diagram of the setup of the progressive wave slope. The adjustable fishing line was used to alter the depth and angle of the slope.

Further study would benefit from examining the effect of paddlewheel location relative to the slope as there is likely a great deal of signal deterioration that occurs as the wave signal moves around the bend of the raceway. If the paddlewheel and slope were on the same side of the raceway there would likely be less deterioration of the signal, which may result in wave formation. The locations of paddlewheel relative to the slopes are shown below in Figure 17. However, the use of a slope and paddlewheel on the same side may not have a large effect on the overall mass transfer of the system as the lane opposite the paddlewheel is the location with the lowest turbulence in the system. The paddlewheel introduces a large amount of turbulence and therefore increases the mass transfer in the system on the side that it is on, hence the slope was placed on the opposite side in this study to increase turbulence on the turbulence limited side. The lane opposite the paddlewheel was identified as the most important zone of increasing mass transfer therefore this zone would be addressed by techniques in increasing mass transfer.

Additionally, due to time constraints, this project was unable to investigate the use of progressive wave slopes on the 1000 L scale. It is thought that with the larger signal occurring, owing to a larger water displacement by the paddlewheel, there may be better wave propagation. The design and depth of the progressive wave slope would need to be examined in order to optimize the conditions for breaking waves. Further work is likely needed to determine the strength of the wave signal as it propagates around the raceway, as well as optimization of the paddlewheel and raceway design to allow for a larger signal and less deterioration of the signal.

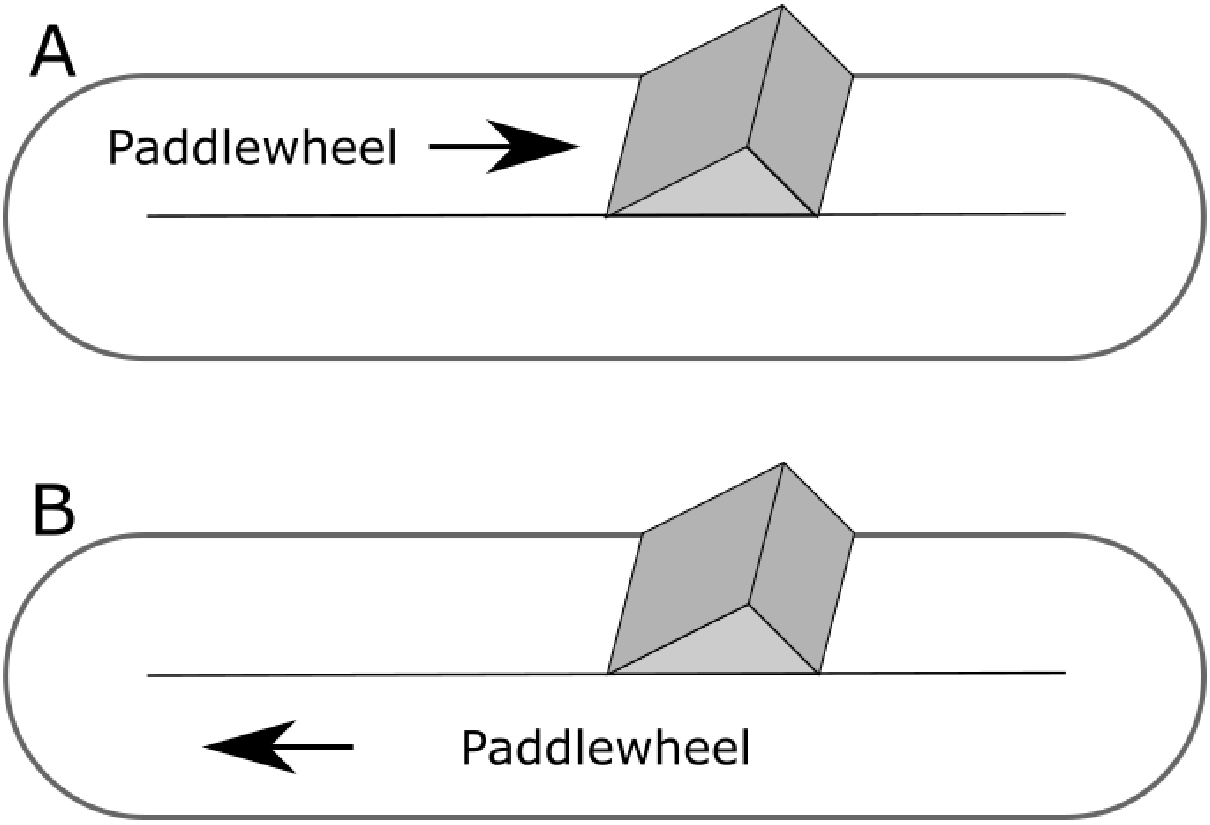


Figure 17 Representative diagram of the location of the slope relative to the location of the paddlewheel. A shows the paddlewheel and slope being located in the same lane of the raceway. B shows the standard set up used in this project, where the slope and paddlewheel are in different lanes of the raceway.

5.3 Mass transfer and power consumption

5.3.1 62-liter raceway system

The mass transfer of CO_2 in a raceway pond is related to temperature, CO_2 concentration gradient across the phase interface, paddlewheel type, paddlewheel speed and type of slope used. The decoupling of these factors proved a challenge, particularly as the fluid velocity is a product of paddlewheel speed. The movement of the paddlewheel through the fluid causes a certain amount of splashing and air entrainment (resulting in CO_2 mass transfer) that has not been accurately quantified in literature or in this study. Paddlewheels and the fluid velocity that they impart in the culture increase the turbulence of the system which is of importance as turbulence has been identified as a cause of increased mass transfer into fluid systems (Battjes and Sakai, 1980; Longo, 2010b) as such they are typically preferred over other means of circulation (such as pumps or jets) as they have increased turbulence and lower operating costs. There is a great deal of difficulty in determining the exact mass transfer implications of paddlewheels given the differences between paddlewheels. It is also difficult to create similar flow conditions in a raceway pond without the use of a paddlewheel. Mass transfer increases with fluid velocity, and as such the effects of fluid velocity were investigated. Below, in Figure 18 and Figure 19 the mass transfer at constant paddlewheel velocity and at constant fluid velocity are given in order to assess the relative effects.

Figure 18 and Figure 19 show that the while the differences, in terms of mass transfer rate, between the slopes used and the control are minor when the system is used at the same paddlewheel speed, the difference increased when the fluid velocity was kept constant. Further work would need to be done to separate the effects of the increased paddle wheel speed from the increases in fluid velocity, as the paddle wheel turning faster would increase the mass transfer that takes place at the liquid/gas interface, via the mechanisms discussed in Section 2.2.5. The utilization of slopes did increase the mass transfer rate at all conditions, with larger increases at higher paddlewheel velocities. This suggests that an increase in the size of the weir created improves the functioning of the slope in improving the mass transfer.

The low fluid velocities seen with the use of slopes in the 62 L system may cause settling related issues that would hamper the production of algae. Therefore, higher fluid velocities were experimented with to determine the mass transfer that would occur at equal fluid velocities. It was found that the slopes improved the mass transfer as seen below in Figure 18. The slopes at fluid velocities just over 15 cm/s had higher mass transfer rates than the system without a slope operated at a fluid velocity of over 25 cm/s. In order to compare the system with and without slopes operated under the same fluid velocity conditions, the paddlewheel speed needed to be altered. To achieve the same fluid velocity in the system with slopes placed in the raceway had to be operated at a much higher paddlewheel speed, thus increasing the power consumption of the system significantly. The higher paddlewheel speed can be seen in Figure 19, where the system with slopes needed to be operated at nearly 50% higher paddlewheel rotational velocity in order to achieve the same fluid velocity. The paddlewheel speeds required are listed below in Table 5. However, as seen in Figure 20 there was a large increase in the power consumption associated with the increased paddlewheel speeds. Further economic analysis would need to be conducted to determine the relative trade-off between the increase in algal productivity and the increased power consumption.

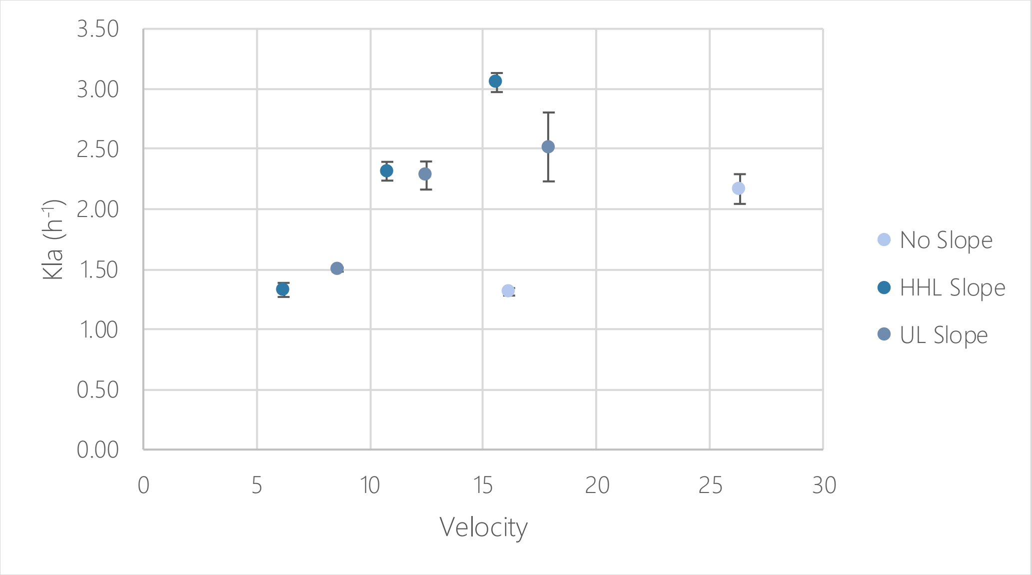


Figure 18 The effects of changing the fluid velocity on the mass transfer rate of CO_2. The lower velocity values for the HHL and UL slopes used the same paddlewheel speed as the No slope conditions (15.5 RPM). As such a comparison between the mass transfer rates at a constant speed and at constant paddlewheel velocity can be seen. The average fluid velocities were calculated based on the fluid velocity equations calculated in Figure 14.

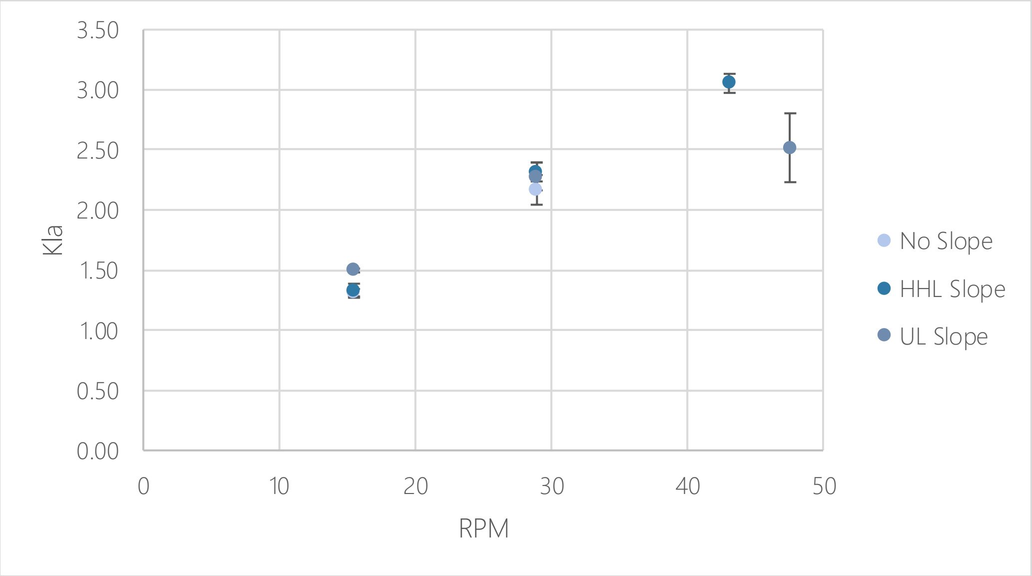


Figure 19 The effects of changing paddle wheel speed on the mass transfer rate of CO_2. These results are the same as those shown above in Figure 18, however the x-axis is shown as the paddle wheel speed (RPM) rather than as the corresponding fluid velocity.

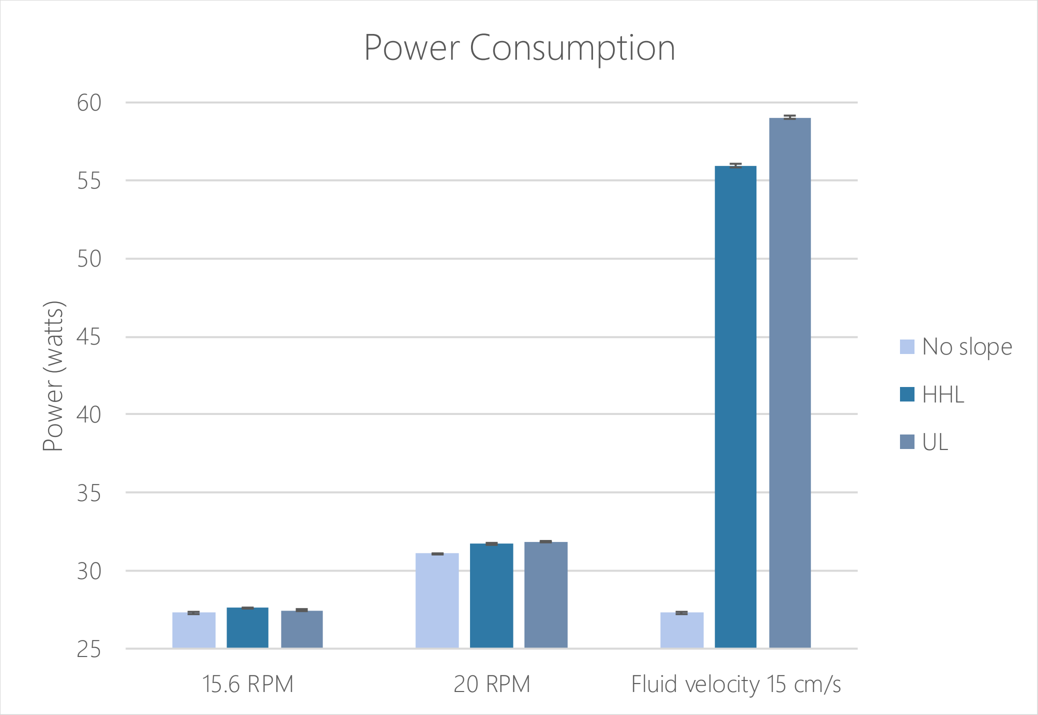


Figure 20 Indicates the power consumption (watts) at varied paddlewheel speeds. The fluid velocity of 15 cm/s refers to the power consumption at the paddlewheel speed required to reach that fluid velocity. The paddlewheel velocities required to reach 15cm/s are shown below in Table 5.

Table 5 Indicating the required paddlewheel speed for each condition to reach an average fluid velocity of 15cm/s in the 62 L raceways.

Slope used	**RPM required to reach 15cm/s average fluid velocity**
HHL	43.4
UL	47.8
No slope	15.6

Figure 20 shows that to achieve the same fluid velocity when using weir-like slopes in the 62 L raceway, far higher energy inputs are required. This increased energy requirement could make the operation of a raceway pond under these conditions economically unviable. However as seen below in Figure 21 the mass transfer coefficient achieved per unit of energy required remained fairly constant, this suggests that in carbon limited systems it may be beneficial to operate at higher paddlewheel speeds in order to increase the productivity of the system. The power costs would need to be compared to the profitability of the increased algal production to maximize the profits. From the work done in this project and in previous work from CeBER (Burke, 2016; van der Linde, 2022), it is suggested that the effect that the slopes have on the system is dependent on the system itself. It can be seen from comparing the 62 and 1000 L (shown below), that the systems behaved differently in terms of proportional increases in mass transfer and in the efficacy of the slope types. Further investigation into the best designs of raceways, to maximize the effectiveness of slopes could likely be beneficial rather than solely investigating better slopes for existing raceway designs.

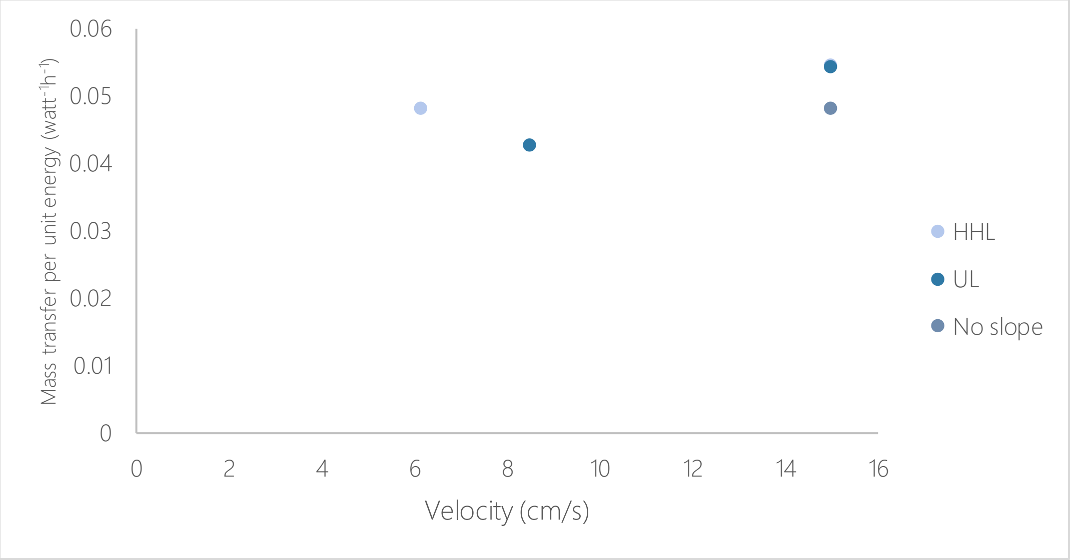
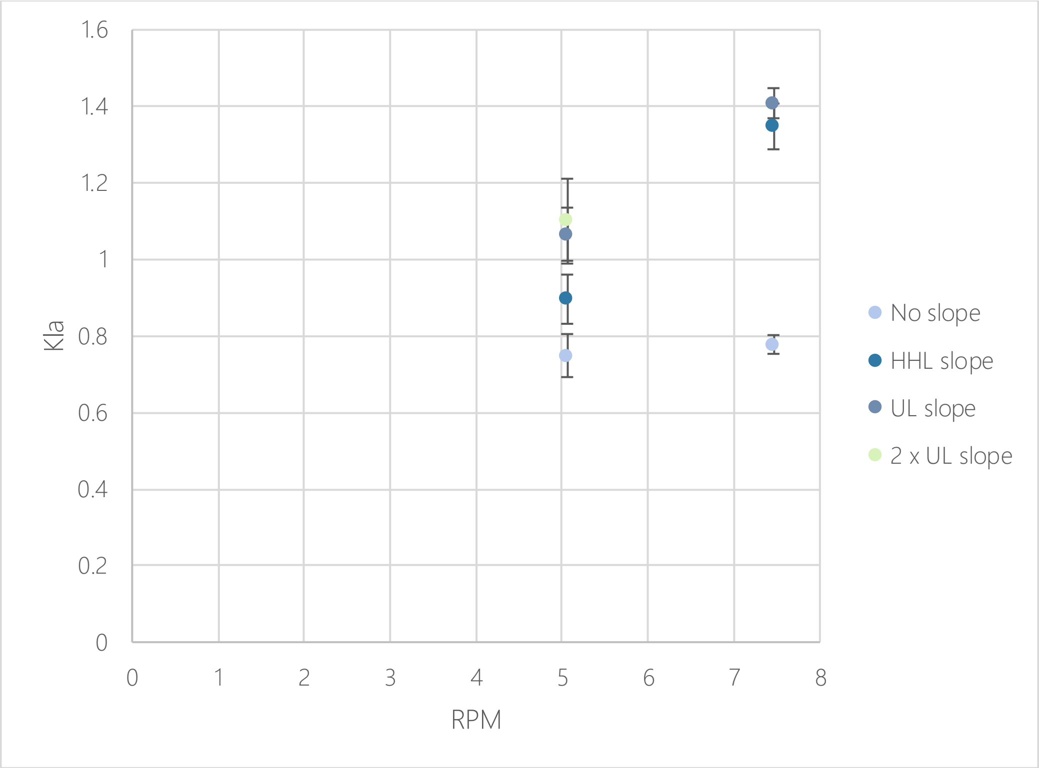


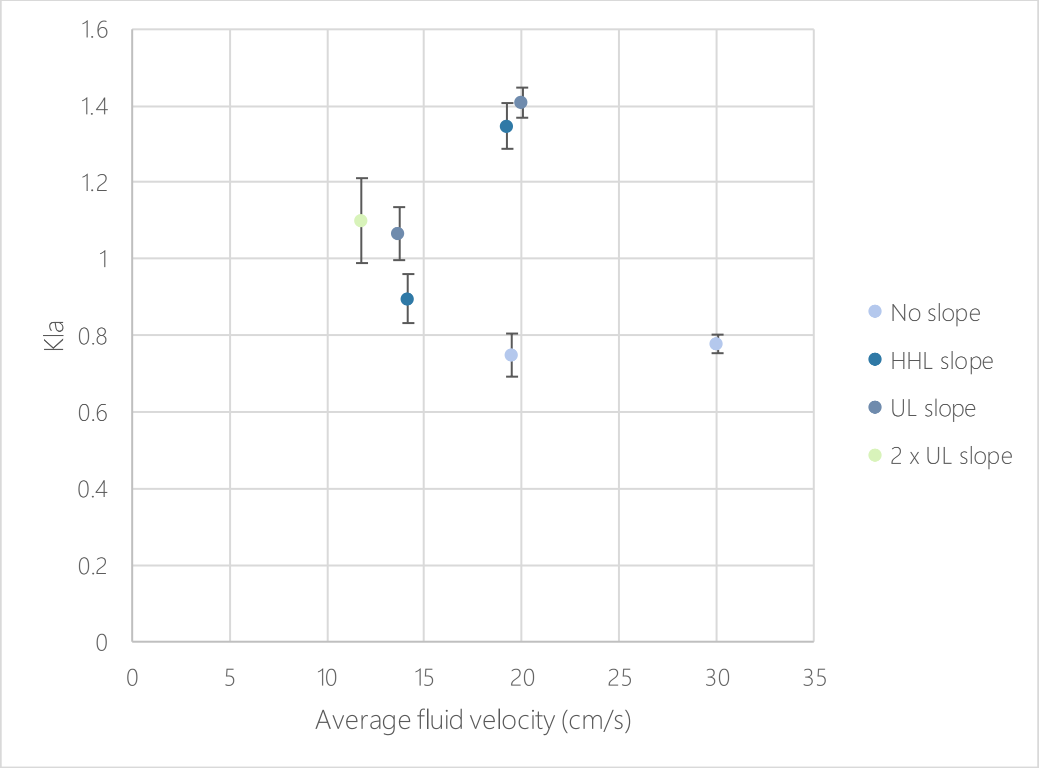
Figure 21 showing the mass transfer coefficient (kla) per unit energy (watt.hr) in the 62 L raceways.

5.3.2 1000 Liter raceway system

The mass transfer coefficients for the 1000 L systems were determined in the same manner as for the 62 L raceways discussed above. Representative paddlewheel velocities were chosen to give a similar range of average fluid velocities as in the 62 L system. The mass transfer coefficients as functions of both paddlewheel speed and average fluid velocity can be seen below in Figure 22.



A)



B)

Figure 22 Showing the effects of changing the paddle wheel speed (a) and fluid velocity (b) on the mass transfer rate of CO_2 in the 1000 L raceways. The average fluid velocities were calculated based on the fluid velocity equations calculated in Figure 14.

As can be seen in Figure 22, the improvements in mass transfer by using slopes at lower paddlewheel speeds and fluid velocities are not as significant as when at higher speeds. This aligns with what was predicted based on the hydrodynamic assessments, as seen in Figure 14. The addition of slopes did not have as large an effect on the fluid velocity in the 1000 L raceway as in the 62 L raceway. As such, the reduction of the mass transfer due to a decrease in fluid velocity would not have been as large. This may provide a more accurate indication of the effects of the slopes on the mass transfer of CO_2, as the fluid velocity is more similar.

From the above figures indicate that the HHL and UL slopes performed similarly, the mass transfer differences were not statistically significant ($P = 0.26$). However, the difference between the UL slope case and the system without a slope was statistically significant ($P = 1.213 \times 10^{-5}$). This was more significant than between the HHL slope and the system without a slope, however there is an indication that the HHL slope did improve the mass transfer in the system ($P = 0.003$). It was interesting to note the higher levels of variability seen in the 1000 L system when compared to the 62 L raceway. The variability in the measured mass transfer coefficient values was much higher than in the 62 L raceways, this is likely due to there being less environmental control as the 1000 L raceways were situated in a greenhouse. There was no temperature control, varying lighting conditions and changes in the wind patterns that were experienced by the ponds that may have affected the mass transfer occurring in the system.

The power consumption of the 1000 L raceway was not accurately quantified as the meter for measuring the actual power consumption could not be used with the 1000 L raceway setup. As such only the theoretical power consumption is shown below in Figure 23. This took into account the concentrated head loss due to the bends, the distributed head loss due to friction and in the case of the slopes, the head loss due to the obstruction to flow caused by the slopes. The wave heights could not be accurately measured during the course of the experiment, however approximate values were used based off measured values using a tape measure. The height of the wave could be of further investigation but it would require a fairly sophisticated set up in order to achieve a reliable result as the waves undulate a great deal during the flow. As such the slopes are shown together below. The slopes had identical vertical heights and as such result in a very similar theoretical power consumption. The difference between the theoretical power consumption with slopes and without is primarily related to the impediment to flow caused by the obstruction. This results in the volumetric flow needing to pass through a smaller area, defined above in Figure 11 as h_1. This restriction in in the area of flow results in a pressure increase in that area. The area of the flow is limited by the gravitational forces and the surface tension of the fluid, which decrease the weir height. As such the increase in theoretical power consumption is relative to this decrease in the area through which the fluid can flow. As the wave height did not increase exponentially with flow rate, as is the case with the head loss due to friction, the increase in power consumption due to the slope is larger at higher flow rates. At a flow rate of 30 cm/s, the power consumption with a slope was 24.3 watts higher than that of the system without a slope. Whereas, at a flow rate of 10 cm/s the difference was only 3.6 watts.

It is clear that the addition of slopes presents a substantial increase in the power required to maintain flow rate. With an increase in the difference in power consumption between systems with and without slopes increasing with the average fluid velocity. This theoretical power consumption serves as an indicator of the power requirements for operating the raceway, however these values are purely indicative. An accurate quantification of the power requirements would need to be conducted in the system to determine the actual difference in power consumption.

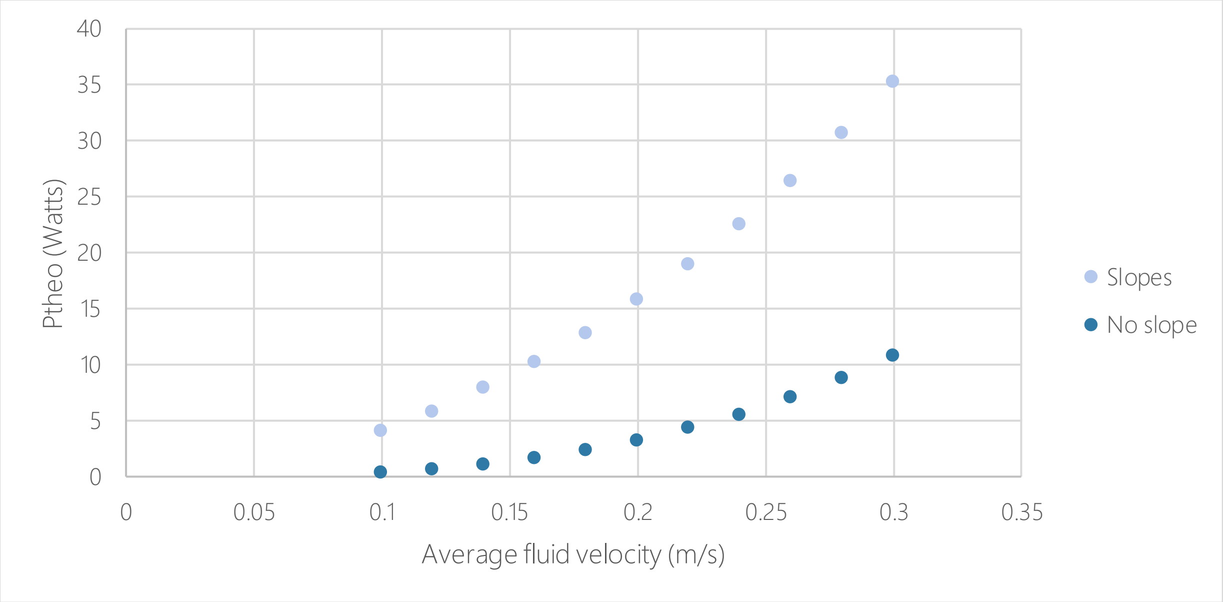


Figure 23 Showing the theoretical power consumption in the 1000 L raceway system in relation to the average fluid velocity.

5.3.3 Temperature effect on mass transfer

The effect of temperature on the mass transfer coefficient can be significant. In the 62 L raceway mass transfer experiments this was not an issue as the CeBER laboratory space is climate controlled to approximately 25 ℃. However, the 1000 L raceways were placed in a greenhouse without climate control. The mass transfer coefficients presented above were calculated by measuring the temperature in the system for each recording of the pH values in order to give the most accurate mass transfer measurement. This makes the measurement for each experiment accurate but causes difficulties in making comparisons between different experiments as they may have occurred at different temperatures. To determine the effect that temperature could have had on the outcomes of the mass transfer experiments, various temperature conditions were simulated as seen below in Figure 24. Here the same data that was measured had the temperature values set artificially (0 – 35 ℃) in order to assess the effects. As can be seen below, the differences in mass transfer increase as the temperature increases. This would make comparisons between the different conditions more challenging, particularly as it is noted that the different slopes do not appear to have the same response with regard to temperature. The fluid temperatures observed during the mass transfer experiments were deemed to be acceptable for comparison as the fluid temperatures remained at approximately 16 – 20 ℃. For the purposes of this study this was deemed to be acceptable due to constraints that would have made it impossible to control the temperature within the greenhouse.

The effect of temperature on mass transfer of CO_2 may be of interest to investigate further as according to the theoretical results, seen below in Figure 24, there was greater divergence in the expected mass transfer coefficient at higher temperatures. The effect of temperature would have to be controlled in the raceways but could provide better insight into the effect of temperature on algal cultivation by looking at the changes that occur with temperature. The solubility of CO_2 in water is inversely proportional to the temperature of the solution, if perhaps the addition of slopes could improve the mass transfer of CO_2 at higher temperatures it could be of benefit to commercial applications.

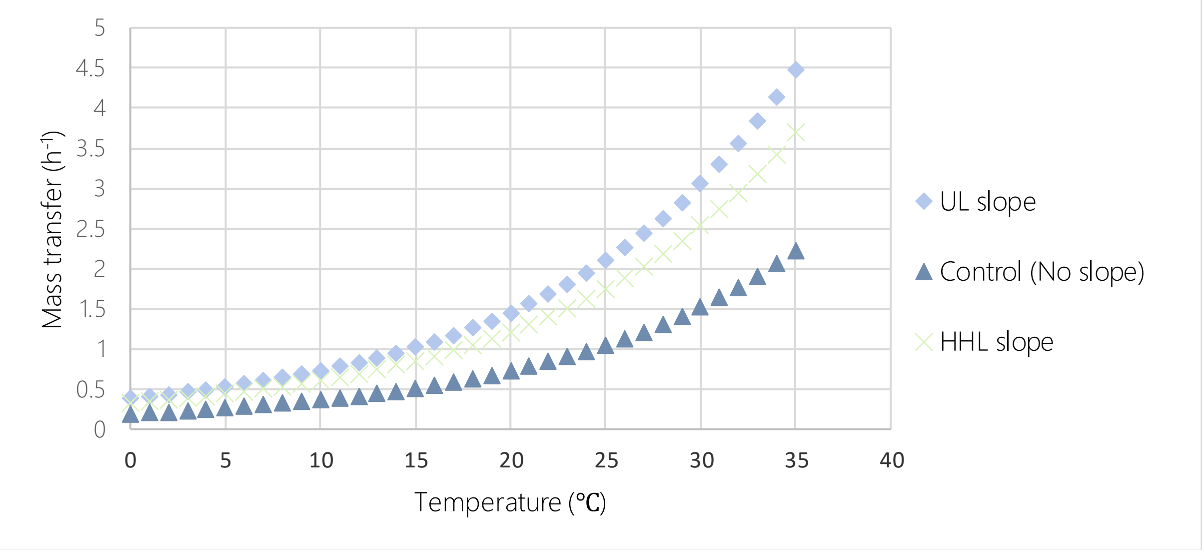


Figure 24 Showing the effect of temperature on the mass transfer calculation used. Each set of experimental data was conducted in the 1000 L raceway at 7.45 RPM. The temperature of each experiment was artificially set, and the mass transfer calculated.

5.4 Growth

As the raceway systems are primarily designed for algal cultivation, the changes in mass transfer needed to be validated against changes to the productivity of algae. This was primarily to ensure that the addition of the slopes did not cause unforeseen growth inhibition of algae. These may be related to insufficient overall mixing, resulting in settling or the formation of dead zones which would result in localized areas of low productivity. Areas of low productivity can in extreme cases result in additional issues for the system, as the unmixed algae can die releasing unwanted compounds in the water and create anoxic areas which would decrease the algal cultures viability during periods without light.

The productivity was calculated based on the change in algal concentration over time. The slope of the algal concentration from when the system reached a pH of 8 until when the pH began to drop was used in accordance with the procedure used in previous work (van der Linde, 2022). An example of how this was applied is shown below in Figure 25 and Figure 26. The rate of biomass concentration increase from when the pH of the culture went above 8 until when the pH decreased was taken as the productivity of the system for the specific operating conditions. These experiments were conducted in triplicate to provide an average productivity and ensure accuracy.

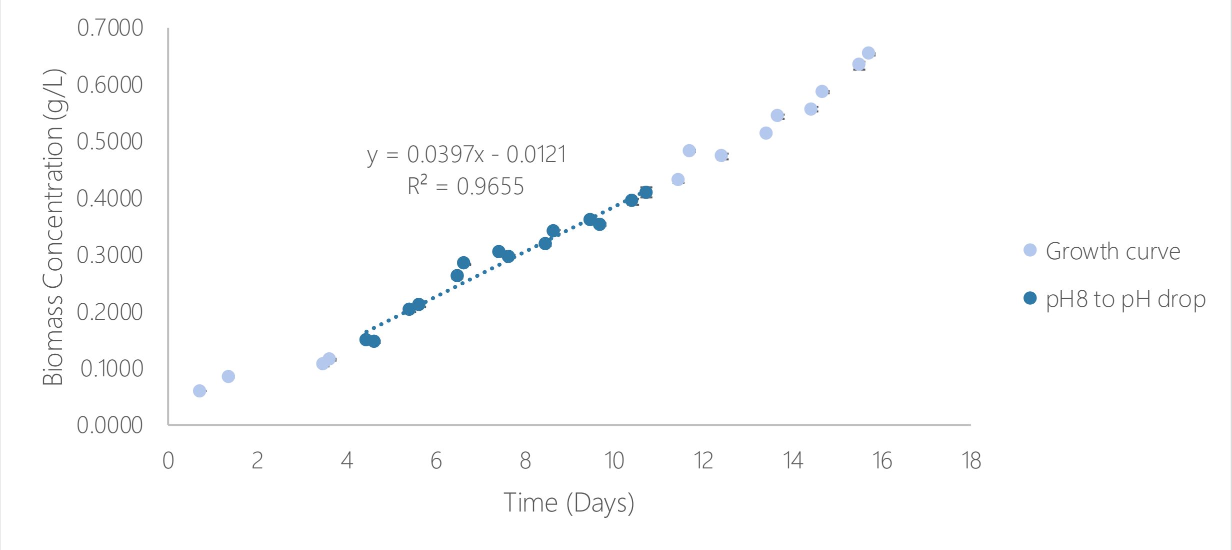


Figure 25 Growth curve experiment conducted in the 62 L raceway pond operated 28.9 RPM with no slope. The trend line and dark blue points indicate the growth points on the curve when the pH was above 8 and before the pH decreased again.

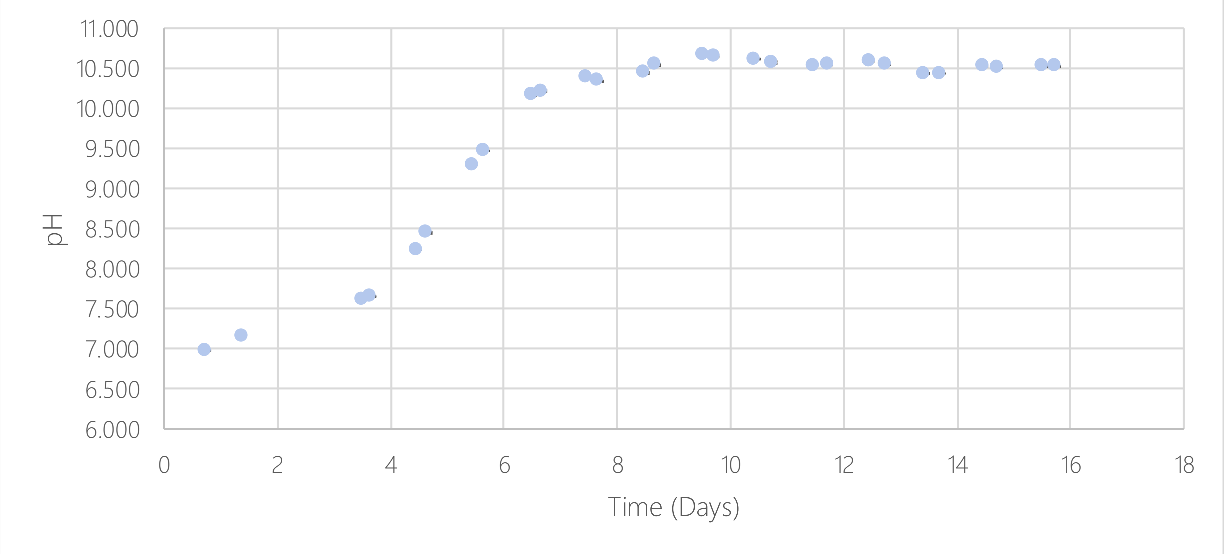


Figure 26 The pH values for the above growth curve experiment conducted in the 62 L raceway pond operated 28.9 RPM with no slope.

These growth experiments were conducted in both the 62 and 1000 L raceways. The rational for testing growth in the 62 L raceways was primarily to validate the results of van der Linde (2022), as this work focused on the 62 L raceways. The results of van der Linde (2022) needed to be validated to ensure that any findings used to inform testing on the 1000 L raceways was accurate and reliable. It was of note in van der Linde (2022) that there was a discrepancy between the increases in CO_2 mass transfer and improvements in algal growth. It was seen that there was a large improvement in the mass transfer coefficient, which theoretically should result in a directly proportional increase in productivity if the only limiting factor in the system is the availability of CO_2. This proportional increase in productivity was not noted in van der Linde (2022) and as such the same conditions were created to assess the validity of these findings. These findings as well as the growth experiments conducted in the 1000 L raceways are shown below.

5.4.1 Small Scale (62 L)

Figure 27 and Figure 28 show the algal concentrations over the course of a growth experiment calculated by van der Linde (2022) compared with those measured in this project. These were used to calculate the productivity, a summary of which is shown below in Table 6. These results show that the measurements obtained in van der Linde (2022) are reproducible. It was noted that in both the work conducted by van der Linde (2022) and in this study the use of a slope (in this case the HHL slope) reduced the productivity of the system compared to when the system was run at the same conditions without a slope. The difference in the productivity was not statistically significant (P = 0.98) but a slight reduction was noted in both studies. Given that the difference between the productivities (with and without a slope) was not statistically significant and was not as large as that seen in van der Linde (2022), it was concluded that there is no difference between the two conditions. However, the lack of improvement in the productivity, given that there was an improvement in mass transfer, is thought to be due to an increase in the amount of settling. Large amounts of settled algae were noted on the downstream side of the slope while the productivity experiments were being conducted. The algae were resuspended prior to measurements; however, this would have still had a negative effect on the productivity as the settled algae was not continually resuspended. In the control condition, without a slope, settling was noted on the straight section opposite the paddlewheel but it was not as large an amount.

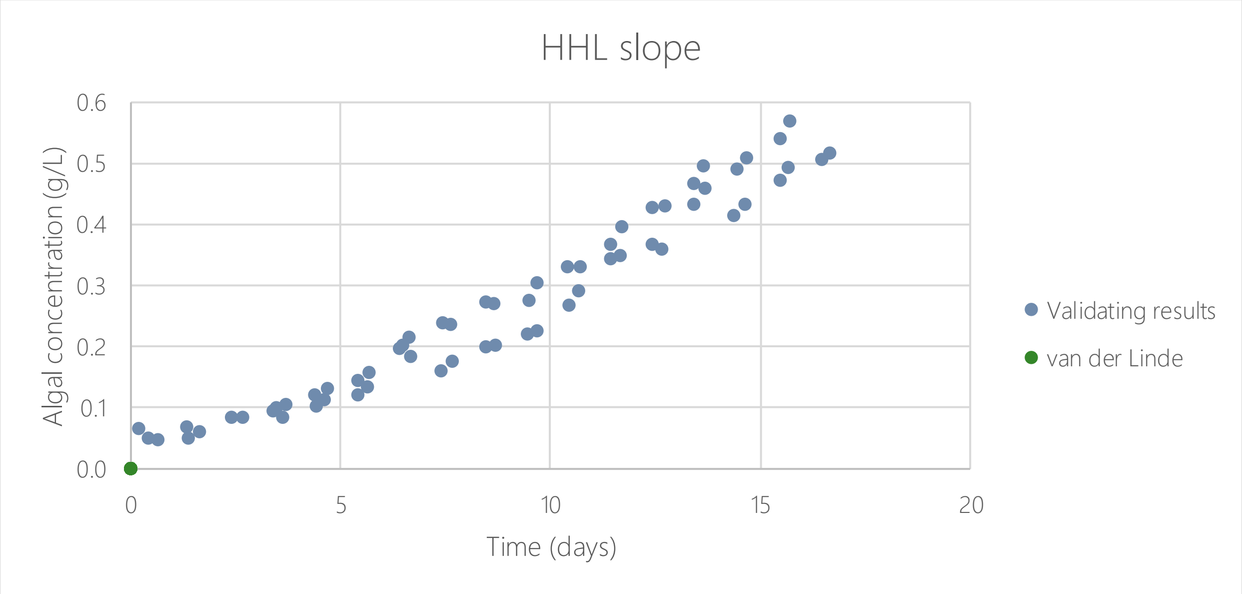


Figure 27 Comparison of the results obtained, for the HHL slope operated at 19.8 rpm, in van der Linde (2022) and the results that were obtained prior to this study.

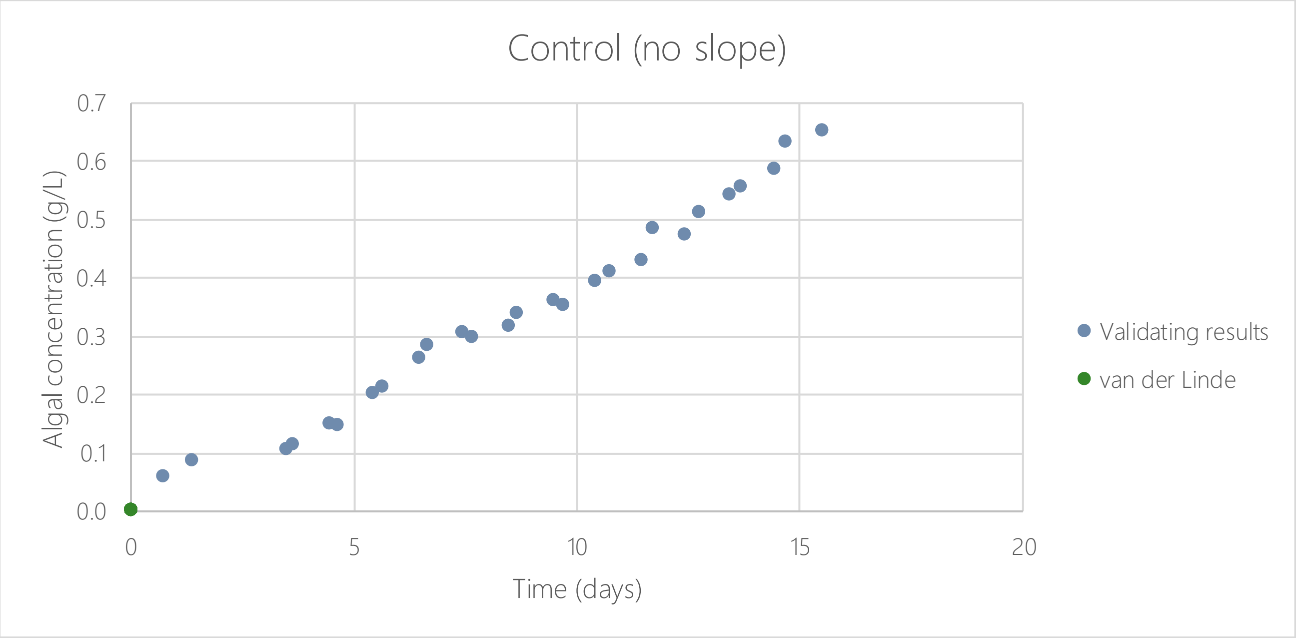


Figure 28 Comparison of the results obtained, for the control with no slope operated at 19.8 rpm, in van der Linde (2022) and the results that were obtained prior to this study.

Table 6 showing the average productivities calculated using dry cell weights.

	Productivity found in this study (g/L/d)	Productivity calculated by van der Linde (2022) (g/L/d)
HHL slope at 19.8 RPM	0.0411	0.0399
Control (no slope) at 19.8 RPM	0.042	0.0449

The absence of an increase in productivity was concluded to be due to increased settling as discussed above. This increase in settling was not able to be quantified and is based on observations made during the experiments. Further work would need to be conducted to quantify the differences perhaps using algal traps in key areas around the raceways. Alternatively, CFD simulations could be conducted to determine whether the slopes create excessive areas of low recirculation which would promote the settling of algae.

The use of the slopes constructed for these experiments may be the cause of the increased settling. The slopes for this study needed to be removable to test multiple slopes and allow the raceways to be used for other research projects. The slopes were placed in the raceway and sealed to the bottom using marine silicon, however it was not possible to achieve a perfect seal and as such there was always significant algae present under the slope when the experiment was concluded. This algal biomass was unable to be quantified, nor the effects on growth that the noncirculating algae had on the system as a whole. It would be advantageous for any commercial system using slopes to have the slope built into the raceway to not allow any settling of algae along the sides or underneath the slopes.

5.4.2 Large Scale (1000 L)

In order to validate the changes seen in the mass transfer rates for the 1000 L system, two growth experiments were conducted in line with the 62 L growth experiments shown above. The growth curves for both experiments are shown below in Figure 29.

As seen in Table 6 above, in the 62 L system the algal productivities seen with a slope and without were similar, and the productivity calculated in the systems with a slope were actually slightly lower. It was hypothesized that this would not be the case in the 1000 L systems. This is owing to two reasons, the average fluid velocity was not as reduced in the 1000 L systems when a slope was used when compared to the 62 L systems, as seen in Figure 14. This would theoretically mean that the system with and without a slope would have similar settling rates. Additionally, the 1000 L systems have a larger straight section opposite the paddlewheel. This typically represents the area with the highest stratification and as such is a crucial area for the improvement of mass transfer. Therefore, the large, stratified area would benefit more from additional mixing at 1000 L, when compared to the 62 L system.

The temperature and humidity of the greenhouse were recorded prior to the experiment being conducted as can be seen below in Figure 29. From these averages, it was determined that the best months to grow algae for productivity would be between November and March. During these months there were similar extreme heat events, but the average and minimum temperatures were higher, providing better growth conditions. However, due to equipment constraints the productivity measurements were conducted later in the year. The first run took place from the 20th of June until the 9th of July 2023, and the second run took place on the 2nd of August until the 27th of August 2023. As can be seen in Figure 29, these were months with low minimum and average temperatures. The average incoming solar irradiance for Cape Town, South Africa is 220 W/m^2, however the average solar irradiance during the dates mentioned above were much lower, as seen in Table 7. In particular the average solar irradiance during the first run was only 94 W/m^2.

The conditions used for the productivity experiments were informed by the mass transfer experiments. The largest difference in mass transfer was seen at the higher paddlewheel speed of 7.5 RPM. As such this was used for both the productivity experiments seen below.

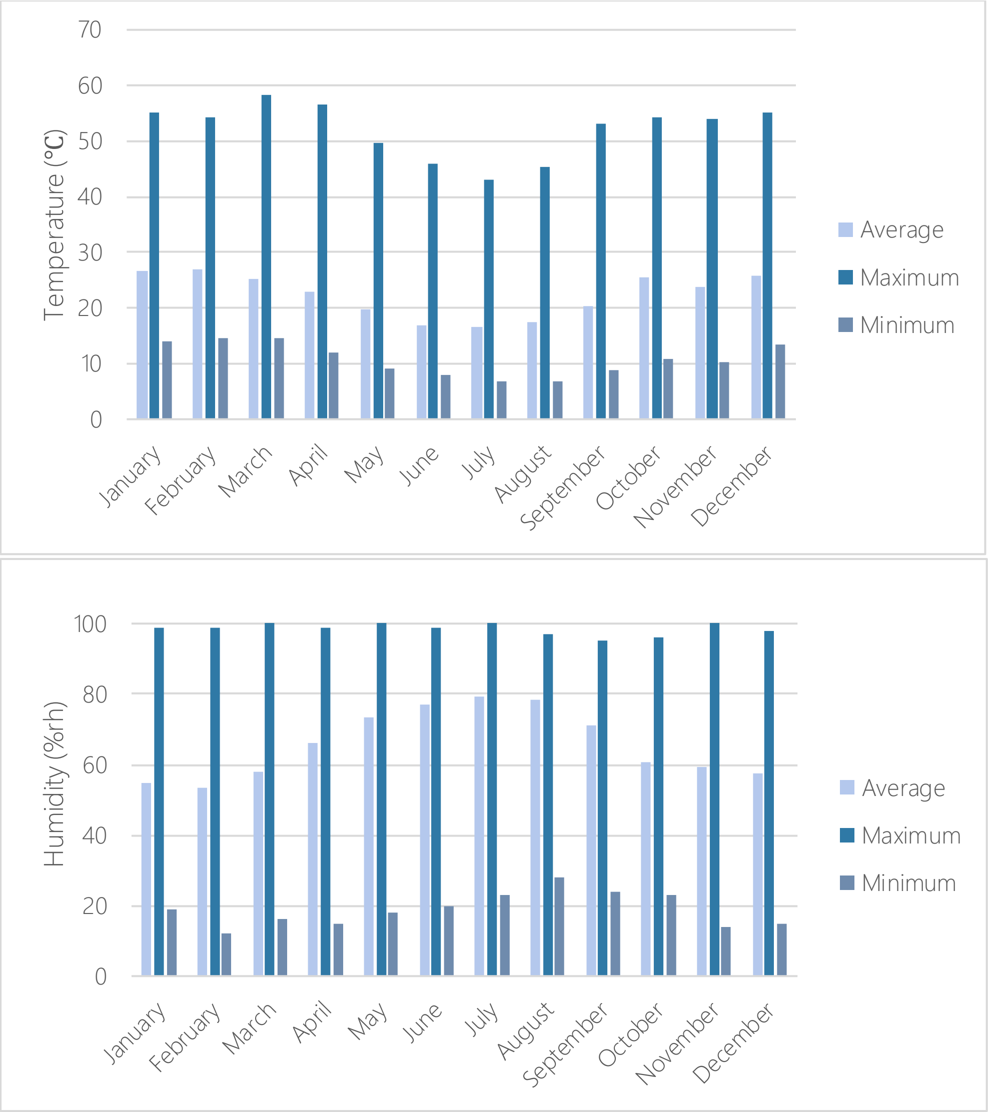


Figure 29 Detailing the conditions experienced inside the UCT greenhouse in each month. The average temperature was an average taken of all values for that month, the maximum and minimum indicate the highest and lowest single values experienced during the respective month.

As can be seen in Figure 30 the growth rate of the algae during Run 1 was substantially lower than Run 2. This is owing to the adverse weather conditions that were experienced during the time of the first run. As can be seen in the solar radiation measured during the experiments, shown below in Table 7. During the time period of Run 1, not only was there a lower amount of light but there were many storms that came through with large fluctuations in conditions. Additionally, Run 1 had to be stopped before 26 days as there was an unknown malfunction that resulted in the paddlewheel in the UL slope raceway to break. The growth conditions experienced in Run 1 were not representative of normal conditions and as such the results from this experiment were disregarded. Only Run 2 was used to assess the growth performance of the slopes. Therefore, this data can only be used to indicate potential differences in the growth performance that can be expected. Further work would need to be done to assess the accuracy of these results.

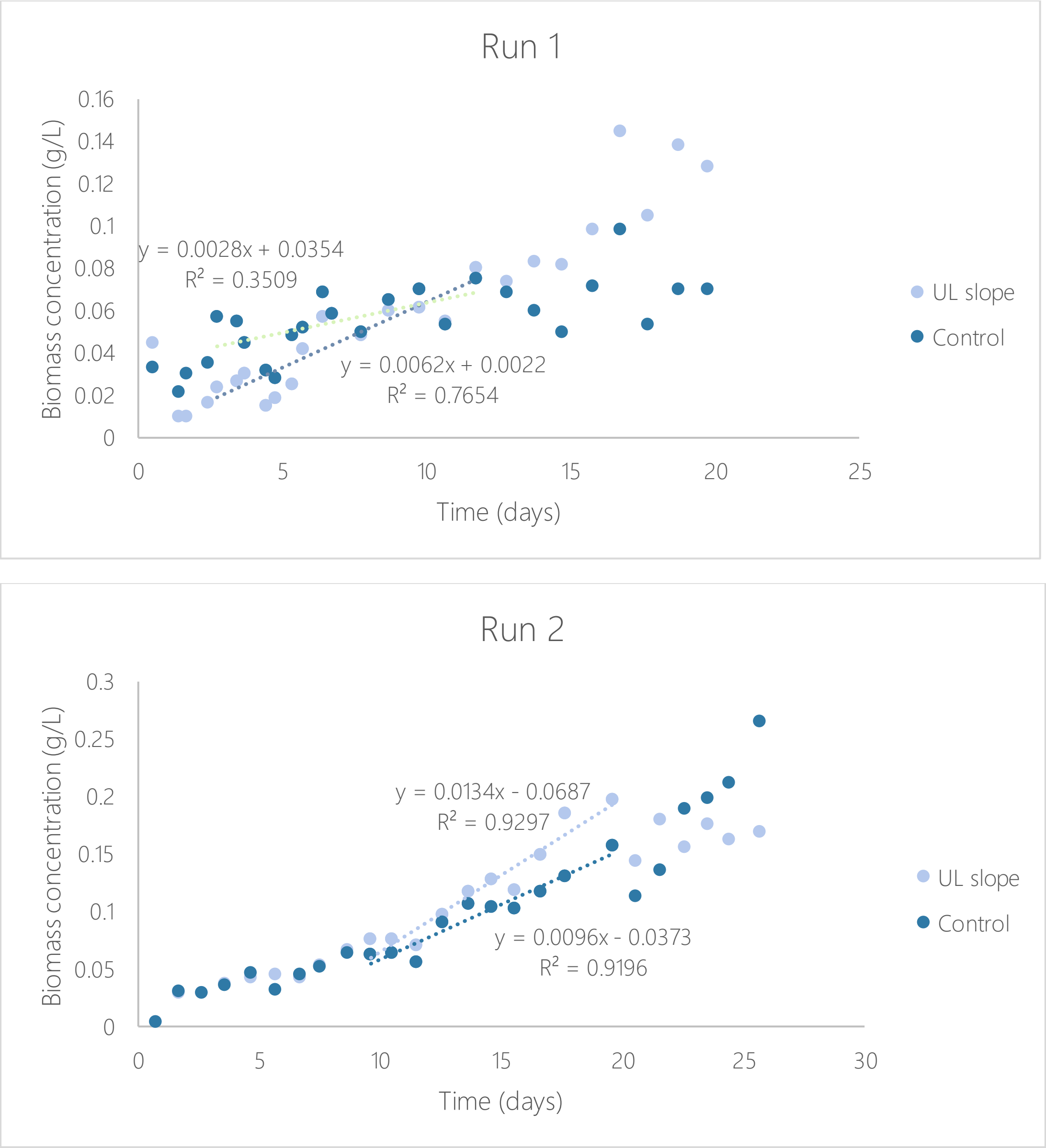
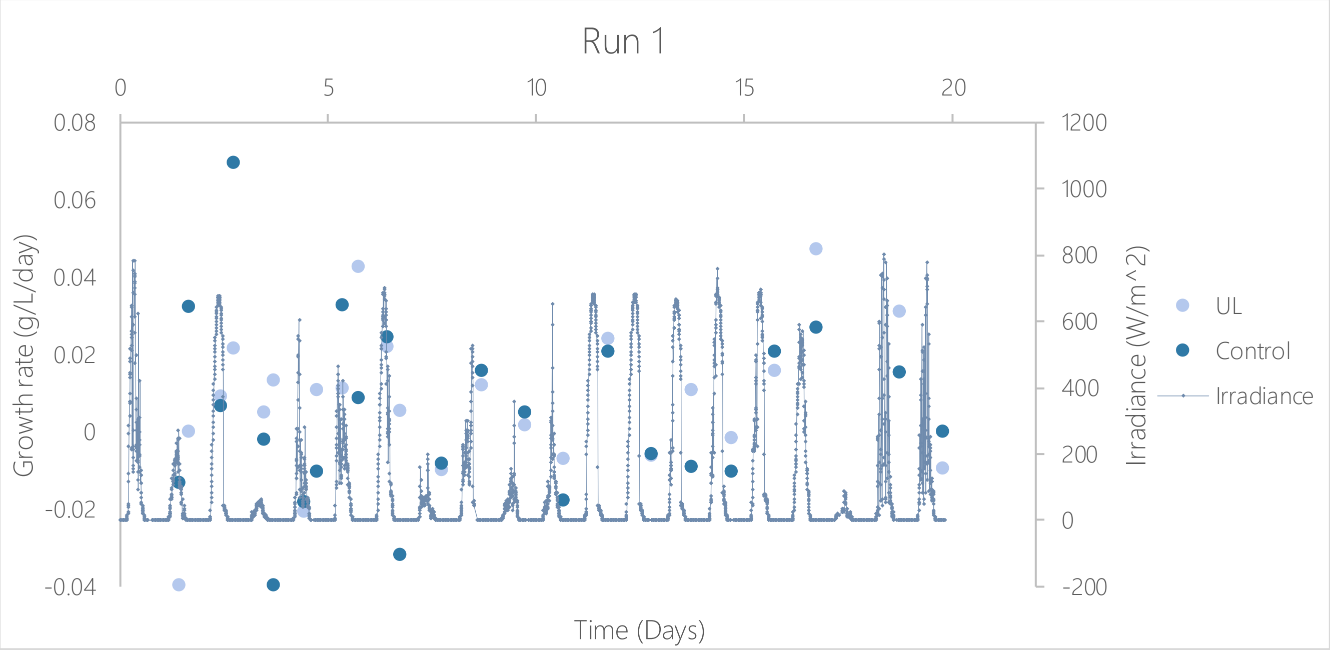


Figure 30 The biomass concentrations over time for the 1000 L raceway. Linear trend lines are shown during the maximum growth period to indicate the maximum productivity of each pond during the growth period.

The growth per day was looked at against the incoming solar irradiance for each day, as shown below in Figure 31. This showed good correlation, where the incoming solar irradiance affected the growth for that day. The growth rate was taken as the dry mass of the previous day subtracted from the dry mass of the day observed. This was converted to a concentration change per day. This showed that it is very likely that during the periods investigated the limiting factor was the incoming light rather than the mass transfer of CO_2. Particularly for the first run as it is noteworthy that the incoming light was significantly lower for the period observed compared to the conditions that occurred during the second run. As seen in Table 7, where the average incoming solar irradiance during the period investigated for the second run was almost double that of the first. The local weather in Cape Town, South Africa during the first run had a great deal of cloud cover and precipitation which led to lower solar irradiance.

A)



B)

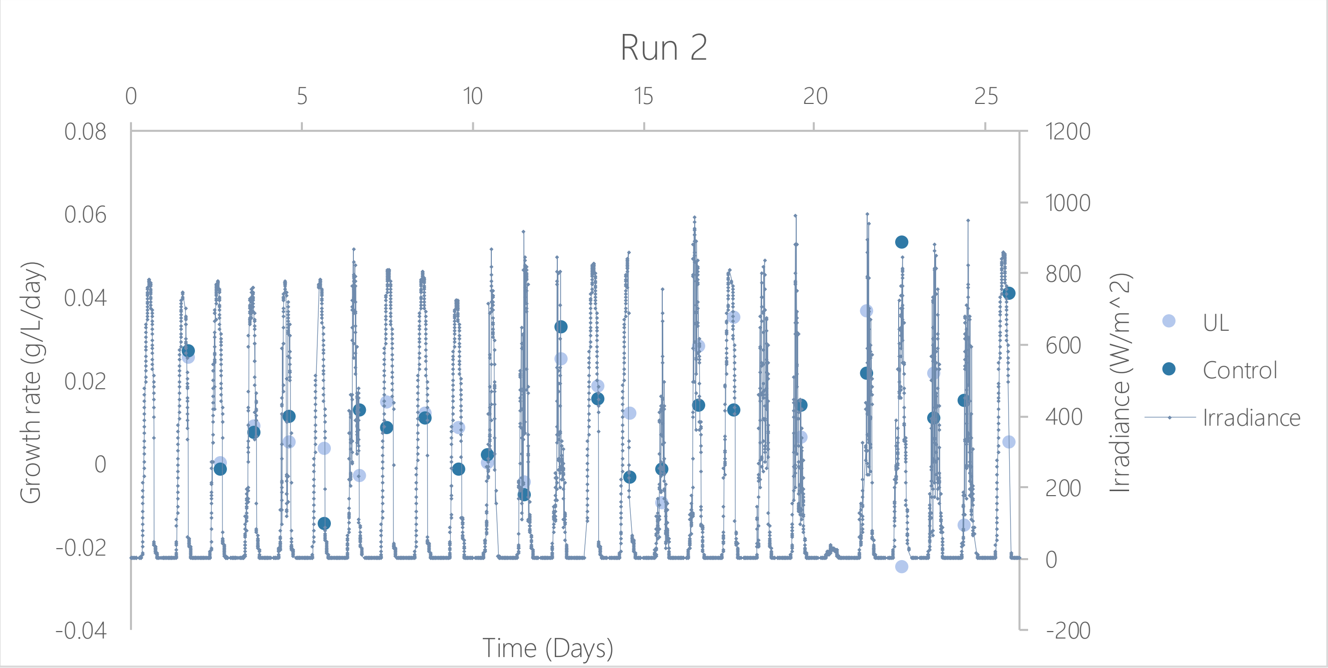


Figure 31 Showing the growth rates for the 1000 L raceway grown with Scenedesmus spp. for the UL slope (blue) and control (orange) for both growth experiments conducted. This is to highlight the relationship between the incoming solar radiation experienced during the time of the experiment (grey) and the growth rates seen for Run 1 (A) and Run 2 (B).

Table 7 showing the average incoming solar irradiation during the time of the growth experiments.

	Average irradiance (W.m^{-2})
Run 1	94.10867
Run 2	162.1311

The productivity measured with the use of a slope was higher than the control as seen in Table 8. These values suggest that the use of a slope increases the growth rate of algae in the system. While the R^2 values are not above the traditional 0.95 cut off point, they do show that a significant amount of the variation is explained by the linear regressions. Given that the ponds are outside and subject to environmental conditions, a better agreement cannot be expected. The use of the outside, open systems was deemed crucial for this project as in all ways it was important to mimic 1000 L cultivation, which takes place in highly variable conditions.

Table 8 The productivity and μ_{max} values for Run 2 are given with their respective coefficients of determination.

	Productivity (g/L/day)	Coefficient of determination (R^2)	μ_{max}	Coefficient of determination (R^2)
UL slope	0.0134	0.930	0.111	0.926
Control	0.0096	0.920	0.099	0.881

As can be seen from the growth experiments conducted in the 1000 L raceways, there is still a significant amount of work required to understand the effect of slopes on growth at this scale. Further work would be needed that prioritizes assessing the changes in algal productivity in different seasons to determine the commercial applicability of slopes in algal raceway ponds. It would be beneficial to conduct the growth experiments in summer months where there is potentially a surplus of light during the exponential growth phase. During this phase the mass transfer of carbon dioxide would be the limiting factor and as such it would provide a much better indication of the potential use of slopes on larger scales.

The improvement in productivity was not as great as the improvement in mass transfer at the same paddlewheel velocity. This suggests that the system remains at least partly light-limited during the linear growth phase. However, the increase in productivity due to the slopes suggests that the slopes decrease the carbon limitation, but also may aid in reducing the light limitation. Additional work decoupling the carbon and light limitations would be valuable to understand the limitations during different periods of growth. Further experimentation with surplus of available carbon to assess improvements in light availability, as well as experiments with surplus of light to assess carbon limitation improvements would be beneficial to understand the potential improvements caused by the addition of slopes. The results above suggest that there is some improvement in both carbon and light availability. The reason for this is that if carbon was the sole limiting factor, then there would be proportional improvements in the mass transfer of CO_2 and productivity, and if light was the sole limiting factor there would be no improvement in productivity assuming that the addition of slopes do not improve light availability. The growth studies conducted using the 1000 L raceways give no indication of decreased productivity, as seen in the 62 L raceways. This is a positive finding but requires further experimentation to confirm.

6 Conclusions and recommendations

High-rate algal raceway ponds continue to be the most common form of commercial algal cultivation; however these systems have significant drawbacks when compared to closed photobioreactor systems. The primary drawback is that raceway systems have lower areal productivity than photobioreactors. This is largely due to light and mass transfer limitations. Both issues are related to the low surface area to volume ratios and poor mixing capabilities. The low surface area to volume ratio can be mitigated by increased mixing as it decreases the concentration gradients of dissolved gases, as well as increasing the frequency with which algae enter the photic region of the culture. As such the addition of slopes into the system as a mechanism for increasing turbulence was investigated as it represents a possible low impact, low-cost solution to the issues faced in commercial applications of algal cultivation.

This project aimed to investigate the addition of slopes into raceway systems to improve the mass transfer of CO_2 specifically. This was done by further investigating the effects in 62 L raceways to build on the work conducted by Burke (2016) and van der Line (2022). Then to design, construct and test 1000 L raceways. The introduction of slopes into these systems would theoretically improve the algal productivity by increasing the mass transfer of CO_2 via increased turbulence and air entrainment. The increased turbulence stems for the slope creating an obstacle to flow in the straight channel of the raceway (an area typically associated with laminar flow with low mixing), which would decrease the concentration gradient of CO_2 in the fluid by mixing the stratified fluid. Air entrainment theoretically could be caused as a result of breaking waves introducing air bubbles into the fluid. The air bubbles would have a higher surface area to volume ratio than the air/liquid interface and therefore would increase mass transfer. This air entrainment caused by breaking waves was hypothesized, however the entrainment of air bubbles was not seen during experimentation. The signal created by the paddlewheel was not large enough to overcome the force of the surface tension and as a result no breaking waves were observed. It appeared from observation that the bend in the raceway system caused the signal to deteriorate so when it reached the slope it was not sufficient to form breaking waves. In future work, if slopes are to be used there must be careful consideration paid to the bend in the system to allow for better signal propagation. This would likely require modeling of the propagating wave around a number of different bend angles to ensure that the theoretical signal would propagate around the bend. Alternatively, the placement of the slope relative to the paddlewheel could be investigated so that they are in the same channel, could allow for better signal propagation. This negates the need for the signal to travel around a bend, but it does not address the issue of the low mixing in the straight channel opposite the paddlewheel. This would need to be investigated in detail to determine the relationships between the many factors that determine the productivity of the system.

The 62 L raceways were investigated to inform the best operating conditions for the 1000 L raceway as well as to understand the influence of the slopes on the hydrodynamics and mass transfer characteristics. It was found that the slopes caused significant reductions in the average fluid velocity in the raceways. This decrease depended on the paddlewheel speed as each slope resulted in a different linear equation to show the average fluid velocity as a function of paddlewheel speed, however, typically there was about a 50% decrease in the average fluid velocity when a slope was added to the system. This represents a substantial decrease, that had negative effects on localized areas which experienced significant settling of algae. The mixing times did however decrease with the addition of the slopes, indicating that there was an overall increase in the turbulence of the system as total turbulence and mixing time are inversely proportional to each other. The localized areas of low mixing or specific recirculation zones were not investigated in this study as it was beyond the scope of this work. This could represent an interesting avenue for inquiry to determine the location and effect of the localized zones of low mixing. The mixing time reductions were far more evident in the 62 L raceway systems, however in the 1000 L raceways substantially decreased mixing times were only noted at lower paddlewheel rotational velocities. It appeared that the measurement technique was not suitable at this scale and would need to be addressed in any further investigations. It would likely be more beneficial to measure turbulence in the fluid, as the mixing time was used as a proxy for the turbulence in the system in this investigation. In particular, the movement in the vertical direction is of importance to raceway systems concentration gradients of CO_2, light and nutrients occur in this plane.

The use of slopes did significantly increase the mass transfer of CO_2 in the 62 L raceways representing an increase in mass transfer of between 10 and 100% depending on the conditions used. When operated at the same paddlewheel speeds there were smaller increases in mass transfer. However, at the same paddlewheel speed there were vastly different average fluid velocities in the systems. To account for this difference the systems were operated at identical average fluid velocities, this resulted in the systems with slopes having much higher mass transfers, approximately 70% and 100% increases for the UL and HHL slopes, respectively. Power consumption increased dramatically when the paddlewheel speeds were adjusted to maintain the same fluid velocities, 107% and 114% for the HHL and UL slopes, respectively. The fluid velocity chosen was conservative for a commercial raceway (15 cm/s) so the mass transfer for both conditions would be higher if the experiment was conducted at a more standard fluid velocity of perhaps 25 cm/s. However, it was not possible to replicate this as with the slopes in the system in the 62 L raceway, the fluid velocity was not able to reach that speed without significant water loss from the paddlewheel.

The 1000 L raceways were designed and built to test the efficiency of the slopes on a larger scale. The information collected using the 62 L raceways suggested that the system would function better on a larger scale. It was thought that the slope caused a proportionally larger impediment to the flow which resulted in a larger decrease in average fluid velocity and more settling of algae. This was confirmed to be the case once the hydrodynamic assessment of the 1000 L raceways was completed, as discussed in more detail further below. Additionally, the larger signal created by the larger paddlewheel in the 1000 L raceway would produce a larger standing wave, this would increase the amount of turbulence generated in this area.

It was determined that the use of weir-like slopes was more effective in the 1000 L raceways than in the 62 L raceways, following the investigations into the hydrodynamic, mass transfer and growth performances of both systems. An overview of the findings can be seen below in Figure 32.

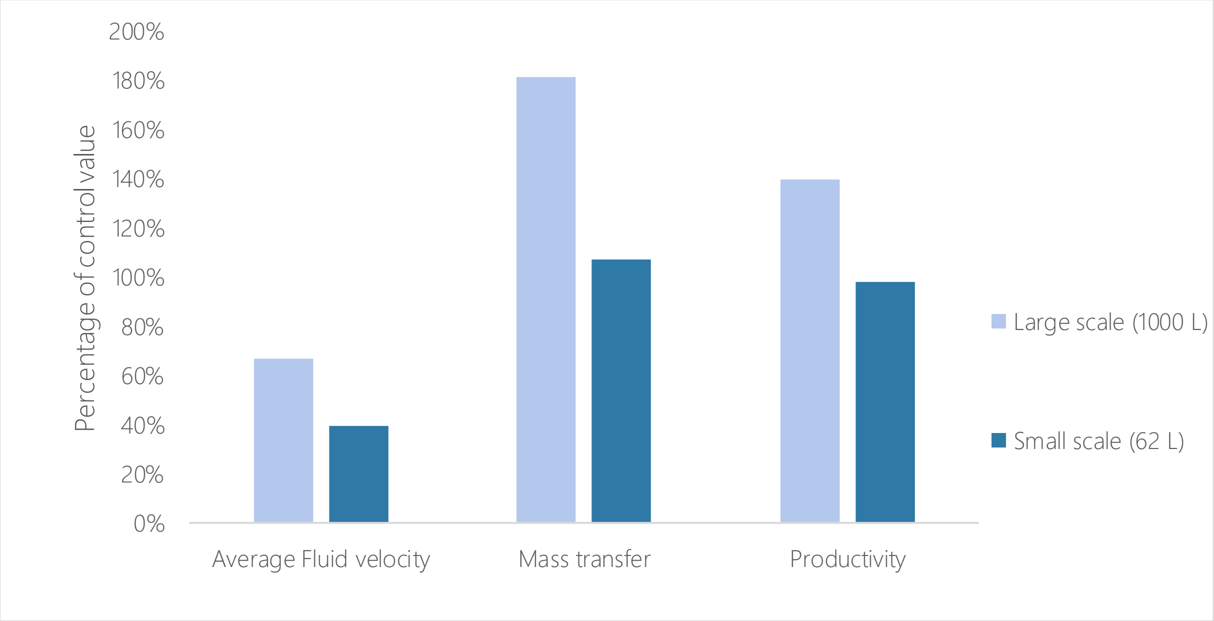


Figure 32 The average fluid velocity, mass transfer coefficient and maximum productivity expressed as a ratio of the value with a slope divided by the value of the control (without a slope) for each respective experiment. The ratio is for the slope that provided the highest mass transfer coefficient, in the 1000 L system this was the UL slope and in the 62 L system it was the HHL slope.

As can be seen above in Figure 32, the addition of slopes had a greater effect at a larger scale as was hypothesized. The use of slopes in the larger system did not decrease the average fluid velocity as much as it did in the 62 L system. The higher average fluid velocity in the 1000 L systems with slopes added contributed to the improved mass transfer and growth productivity, when compared to the 62 L system. The large improvement in mass transfer is particularly noteworthy as a much smaller change was seen in the 62 L system. In the 1000 L raceways, the fluid travels further to circulate around the raceway. Therefore, the fluid spends a longer time in the straight channels of the raceway. These are areas of lower mass transfer and higher degrees of stratification. This likely increased the difference between the control and slope conditions as the slopes introduced turbulence to an area with a higher degree of stratification than the same location in the 62 L raceway. This remains a hypothetical explanation for the larger increase in mass transfer seen in the 1000 L raceways when compared to the 62 L raceways. A computer simulation would need to be done to assess the changes in turbulence and mass transfer. Alternatively, the concentration gradient of CO_2 could be assessed by multiple pH probes placed at various depths in the same location. Further investigation would need to be conducted to conclude the feasibility of these measures.

It may also be that at in the 1000 L system the weir height resulted in more bubble entrainment causing a higher mass transfer. In the 62 L system the turbulence was dominated by surface tension forces which would reduce the possible air entrainment. Further work would need to be done to quantify the amount of air entrainment in each system to corroborate this hypothesis, as quantifying the air entrainment was beyond the scope of this project.

Growth experiments were conducted to corroborate the above-mentioned improvements to CO_2 mass transfer. The same scale of improvement to algal productivity was not seen. In the 62 L raceways, a slight decrease in productivity was seen when using the slopes, however this was not a statistically significant difference. In the 1000 L raceway a slight increase in productivity was noted. Though a single experiment of the algal growth was possible due to time constraints in the project, this is only a suggestion of possible improvements.

In conclusion, the mass transfer coefficient for CO_2 was greatly improved with the addition of slopes into the 1000 L system. This increase was larger than in the 62 L system, which was in line with the hypothesized results. The slopes did not cause as large a reduction in average fluid velocity when compared to the 62 L raceways which likely improved mass transfer. The increase in mass transfer was not able to be fully corroborated by growth experiments due to time and funding constraints. The results obtained in the single successful growth experiment suggest positive results, however too much speculation based on this is unwise. The results for the use of slopes in larger scale raceway ponds appear positive and further work is warranted to quantify any improvements to the algal productivity.

Suggested further work:

- Additional growth experiments with the slopes in the 1000 L raceway ponds.
- Assessing the growth performance of the system in both carbon and light surplus to determine the impact of slope addition on both metrics.
- Quantification of the algal settling caused by the slopes.
- The design and testing of the progressive wave slope in the 1000 L raceway ponds.
- Quantification of the turbulence in different locations around the raceways with and without the slopes, perhaps using ADV or PIV systems.
- The accurate determination of the mixing times with the slopes in the 1000 L raceways.
- A commercial analysis of the improved productivity vs additional power requirement for using the slopes in the system.

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