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INVESTIGATION OF STRUCTURED LIGHT DISTRIBUTIONS FOR ALGAE PHOTOBIOREACTORS

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Abstract

Fossil fuel dependance is one of the foremost issues of the modern age. Solar energy can meet demand but is hampered by storage and cost concerns. Biofuels are an attractive option for harvesting solar energy because they offer a storage medium that would not require significant changes in infrastructure. One issue plaguing biofuels is that an unsustainably large area of land would be required to produce enough fuel to meet demand. Algae are therefore considered one of the most promising candidates for biofuel research due to very high oil yields for a fixed production area. If algae are going to be used on a large scale, the amount of oil produced in a given area must increase.

Artificial photobioreactors (PBRs), such as thin glass plates or tubes with algae suspended inside, are a topic of great research interest for increasing the density grown in a given volume. These have offered significant gains over ponds, most simple but inefficient method of growing algae, by eliminating shading losses from cells on the surface of the pond. Another increase in culture density is obtainable by flashing light at the cells. This lowers their susceptibility to damage from very intense light and can save power by energy only when the cells can optimally make use of it for photosynthesis. In order to more effectively make use of this flashing light effect in a passive system, novel PBRs will have to be constructed. It would be useful to be able to compare possible designs prior to physical construction by using a mathematical model for algae growth given the geometry of the reactor and illumination pattern.

The contribution of this work is a three dimensional model for predicting algae growth, written in MATLAB. Two dimensional models have previously been developed and were extended into the third dimension. Additionally, arbitrary illumination patterns are easily added to model the effects of concentrating optics, gratings, etc. Square waves were implemented to test for a passive way to achieve the flashing light effect. Although an increase in production efficiency was found when cell motion was constant, brownian motion eliminated all benefits except that of concentrating the light. In the future, this model may be used with optical modeling programs to compare possible PBR designs.

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Acknowledgments

I would like to thank Dr. Giebink for his constant guidance throughout this project.

Chapter 1

Introduction

Concerns about fossil fuel dependence and global warming have led to increased interest in alternative energy sources. It is apparent that the sun provides enough energy to meet yearly demand, the problems of intermittent illumination, energy storage, and energy transfer continue to present major obstacles. Biofuels are an area of major research interest because of their potential to address these concerns while replacing fossil fuels without a significant change in infrastructure [1]. Among these, algae are considered some of the most promising sources of oil for producing biofuels and biodiesel specifically [2].

Traditional biofuels can be produced by feedstocks such as corn, but there are numerous problems hindering large scale implementation. One of the major issues is that the current methods of production would require all of the cropping area in the US to meet less than half of national demand. Some species of algae, under suitable conditions, have demonstrated the ability to produce 50–70% of their dry weight in oil and over 58,700 L of oil per hectare, about one or two orders of magnitude higher than other biofuel sources [2]. Algae bioefuels have 10–30 times the oil yield of oil palm, the next highest oil-yielding crop, and much faster growth rates than plants. Without accounting for other resource constraints, biofuels from an algae feedstock could meet the same demand with only 1–3% of the land required [3]. In spite of this, many challenges remain before large scale production of algae biofuels can take place.

A major factor inhibiting algae growth is the massive self-shading loss present in simple PBRs such as ponds. The typical shallow open flow pond used for microalgae production demonstrates bioproductivity of ~ 1 g/(m$^2 \cdot$ h), which is well below the fundamental limit [4]. The cells at the surface of such systems act as a shield, preventing algae below from receiving light. The surface cells are overexposed, which generates reactive oxygen species that may damage equipment, while the underlying cells are underexposed and do not have the energy required to grow [3]. In order to mitigate this effect a variety of systems have been designed to scatter or otherwise guide light into different distributions.

One particularly promising design is the thin flat-plate reactor. Here, algae is grown between glass plates in a cavity that is only centimeters thick, reducing shading loss. This design has been shown to increase the bioproductivity of *Spirulina plentesis* from 2.5 to 4 g/(m$^2 \cdot$ h) [4]. However, thin PBRs still suffer from a dark area in the center of the reactor at high culture densities.

The effects of many intermittent light patterns have been studied, and it has been shown that the growth rates of many strains of algae can be higher during intermittent light than the growth rate under continuous light with equivalent irradiance [5]. Flashing the light source rather than maintaining constant illumination offers benefits to growth rate by better matching illumination to the photosynthetic timescales while also providing energy savings [6]. Experiments as early as 1996 have demonstrated that flashing light decreased the photoinhibition of both *Chlorella vulgaris* and *Scenedesmus quadricauda*, increasing growth rate [5].

There exist many models of algae growth in various PBR conditions. Greenwald et al. [4] reported that many models, despite using kinetic equations between fluid layers to model turbulent flow, use constant illumination of low irradiance and do not predict the increase in optimal culture density (OCD) that occurs as reactor width is narrowed. Models are now attempting to use computational fluid dynamics to model cell motion, but previous work that assumes that cells move according to white noise around the starting position do not predict the flashing light effect seen at high density in thin reactors [7].

This work presents a model of an algae cell in a thin PBR under structured illumination to recreate the flashing light effect. In the perfect case with a known cell velocity and tailored columns of light, it was shown that the growth rate increases from the flashing light effect are observed as the cell across lit and dark zones. Diffusion was added to the cell's movement to study the decrease in growth rate. Finally, model was expanded in to three dimensions to enable the study of arbitrary light distributions from other modeling programs such as ZEMAX.

Chapter 2

A Brief Review of Algal Photobioreactors

2.1 Photobioreactor Configurations

Open ponds are the oldest photobioreactor configuration, and are still widely used in algal cultivation for their ease of use and low operating costs. These systems may vary in complexity, but usually fall into one of two categories: circular ponds with a mixing arm, or longer raceways in loops stirred with paddle wheels. Open configurations suffer from inherent limitations that make them unsuitable to modern algae production, notably their low light efficiency, susceptibility to intruding organisms, high volume, and lack of operational control for optimization. Closed systems have long since replaced open systems as the photobioreactors of choice in both industry and as the subject of almost all ongoing research [8].

The main factor influencing the design of photobioreactors is maximizing light distribution and thus both photosynthetic efficiency and biomass productivity. The requirements of ensuring maximal surface area to volume ratio while maintaining enough room for mixing, nutrient bubbling, and harvesting have made flat plate and tubular bioreactors the two most common PBRs [8]. More specifically, designs such as vertical columns, flat plates in various orientations, tubular reactors with or without curves, internally illuminated designs, spectral shifters, and reactors incorporating membranes for continuous cultivation of large volumes are all major areas of research [9].

The modeling and modification of algae cell movement is the subject of much research interest because of the potential increases in biomass yield that may be derived from a comprehensive understanding of cell motion throughout light gradients inherent in any reactor [6]. Mixing through passive means such as edges or fins in a PBR design would be a way to induce a flashing light effect and to ensure even illumination throughout the culture without requiring active energy input. In 2007, Perner-Nochta and Posten [10] combined computational fluid dynamics with particle tracking in a single phase tubular reactor to illustrate the presence of, and movement of algae between, light and dark zones; this model also defined light-dark cycles of 3-25 Hz when applied to a specific tubular reactor. More recently, computational modeling has been applied to two-phase flow for other PBR configurations. **?**] demonstrated one such fluid flow model using COMSOL multiphysics alongside the first application of optical-ray tracing to algae PBRs in 2015. This work experimentally demonstrated an optimum flashing light frequency of 1.5 Hz alongside active mixing to maximize hydrogen output while computationally describing the flow of the algae cells in and out of the illuminated zones. It did not, however, use a model of photosynthesis to predict algae growth based on the predicted illumination and movement patterns.

2.2 Photosynthesis and the Flashing Light Effect

Photosynthesis is composed of a light reaction period followed by a dark reaction. During the former, energy is collected and stored in ATP and NADPH that are used to produce carbohydrates and oxygen in the latter [11]. The light reaction happens on a sub-nanosecond scale while the dark reaction time is on a sub-millisecond order. The dark reaction is therefore the rate-limiting step, and tailored flashes of light are therefore thought to more optimally distribute energy to the cells [6].

The first experiments with flashing light were performed in 1932 by Emerson and Arnold, who reported that the rates of O_2 and CO_2 uptake were the same under continuous light and very short flashes with the same total intensity. This led them to conclude that photosynthesis does not require continuous illumination [12]. In 1954, Phillips and Myers studied the growth rate of *Chlorella pyrenoidosa* and reported increased photosynthetic rates with short flashes and longer dark periods. This work led Weller and Franck to the theory that photosynthetic mechanisms considered the integration of light intensity, rather than instantaneous light intensity. It was known that, if all other factors such as nutrient availability and flow rate are sufficiently designed, gross photosynthetic rate P_G is some function of light intensity I:

$$P_G = f(I) \tag{2.1}$$

During a flashing cycle, the illuminated time t_f and the dark time t_d can be used to express the fraction of illumination compared to the constantly lit case: $\phi = \frac{t_f}{t_f + t_d}$. Then the photosynthetic rate during flashing should just be reduced by the factor ϕ if no other effects are considered:

$$P_G = \phi f(I) \tag{2.2}$$

Instead it was observed that flashes of light do not simply proportionally decrease the photosynthetic rate. This is the integration effect:

$$P_G = f(\phi I) \tag{2.3}$$

Since photosynthetic rate saturates at high light intensity, $f(\phi I) > \phi f(I)$. The flashing intensity is $I_f = \phi I$, but the rate is not reduced by the same factor ϕ. This is shown in Figure 2.1 [13].

Nowadays, flashing not only is an on-off pattern imposed on the light source at regular intervals, but also implies condensing the energy into shorter pulses. Usually, flashes are compared to continuous light of the same mean irradiance, or the same flux of radiant energy per unit area. The duration and intensity of the ”on” portion of the pulses is then the parameter that has been

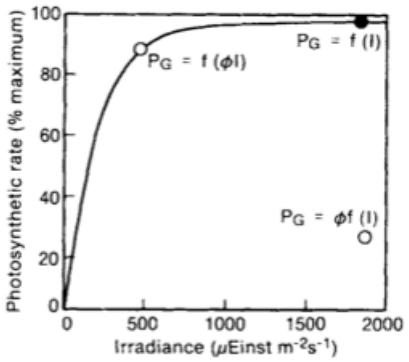

Figure 2.1: Flashing light can reduce intensity by a factor of ϕ while maintaining a similar P_G for intensities close to saturation [13].

the subject of many experiments [6]. This new definition of flashing irradiance is used in efforts to increase the efficiency at intensities that are not close to the saturation point. In light of this, the fact that the optimal production rate of algae has been shown to grow steadily with incoming photon flux in thin flat-plate bioreactors up to a very high saturation intensity [4] makes thin PBRs an optimal candidate for flashes of light at any intensity.

Flashing light has been shown to increase biomass yield over continuous light.Vejrazka et al. [14] demonstrated 35% higher yield using a square wave with a 0.5 duty cycle output from a LED on *Chlamydomonas reinhardtii*, while also recording an average of 10% lower yield at frequencies of 1-10 Hz. In another recent study, optical fibers were used to create vertical columns of light perpendicular to the flow direction. The flashing light effect seen by *Spirulina platensis* on the order of 10 Hz increased growth rate by 43% over the control [9]. Active mixers, baffles for spiral flow, and other flow-altering structures are all being studied as options for increasing growth rate by introducing flashes of light [15]. Gordon and Polle [6] proposed that pulsed LEDs could theoretically be used to produce biomass yield as high as 100 $^{\mathrm{g}}/_{\mathrm{m}^2 \cdot \mathrm{hr}}$, as opposed to the rates of 2-3 $^{\mathrm{g}}/_{\mathrm{m}^2 \cdot \mathrm{hr}}$ recorded for actual closed PBRs. The key factor in this prediction was combining decreased photoinhibition under flashing light with the concentrating power of optics typically used in solar cells.

2.3 Models of Photobioreactors

A typical thin flat-plate PBR has height and width set by the needs of the production plant, but is still just a few centimeters thick [16]. Light may hit one or both sides, and the distribution may be tailored by a variety of methods such as introducing localized roughed sites to scatter internally reflected light from the plate [1]. Nutrients and air bubble up through the algae, creating turbulent flow. Efforts have been made to modulate this flow, including the construction of wing-shaped

foils to induce mixing vortices [13]. Finally, it is worth noting that light intensity attenuates as a function of cell density. This attenuation can be enough to create a dark zone in the center of the plate, even in reactors as thin as a few centimeters [6].

This thesis is heavily based off of the work of Greenwald et al. [4] and Gebremariam and Zarmi [16], who present models for algal growth in thin flat plate PBRs. These works both rely on a number of common assumptions that will be adopted and explained here. The first is that incident light intensity I_0 decreases exponentially into the reactor as a some function of culture density ρ:

$$I = I_0 e^{-\mu(\rho)x} \tag{2.4}$$

$$\mu(\rho) = \alpha\rho \tag{2.5}$$

The function $\mu(\rho)$ can be approximated as linear, cornet, or hyperbolic. There is a lack of data on the width of the lit region in very high culture densities, but it is known that this region is typically on the order of $1/\mu(\rho)$, which is less than 1 mm at high density. Thus the linear approximation is adopted with a scaling factor α that has been found to vary from 0.9–1.5 l g^{-1}cm^{-1}, where l is the length of the reactor. The relation $\alpha = .92l$ g^{-1}cm^{-1} has been employed as in [16].

Qualitatively, each individual algae cell diffuses randomly with a diffusion constant D. Estimation of this constant is based on two areas of turbulence-induced diffusion in fluid dynamics. The first is eddy-induced diffusion due to an eddy of size l and velocity μ_0:

$$D \cong l\mu_0/2 \tag{2.6}$$

The second is the case of bubbly two-phase flow, where diffusion constant is approximated based on bubble size l, void fraction β, bubble velocity μ_0, and an empirical constant $k = 0.6$:

$$D \cong k\beta l\mu_0 \tag{2.7}$$

If typical values of $l = 0.2$ cm and $\mu_0 \approx$ 30–50 cm/s are used, $D =$ 3–5 cm^2/s. At $l = 0.5$ cm, $D =$ 7.5–12.5 cm^2/s. In the majority of cases tested in this reactor, the average value of $D = 10\text{cm}^2/s$ was used and weighted to study the perturbation caused by more gradual changes to movement.

The cell's total reaction time, t_r, was described as the summation of the light collection time t_c and dark reaction period t_d. The collection time varied from cycle to cycle but could never exceed a maximum value of $t_w = 80$ ms. The dark reaction period only occurs after a successful collection, and was set at 5 ms [4].

Chapter 3

The Model

3.1 Overview

The model used in this work tracks a single algae cell in a two or three dimensional PBR. Light illuminates a single face and attenuates according to a Beer-Lambert law depending on a variable culture density d and attenuation coefficient α. A cartesian coordinate system is defined with the origin on the bottom left corner of the reactor, with positive x and y extending right and to the left, respectively. In the three dimensional case, positive z extends upwards from the xy plane. Time is split into increments dt of 10 μs, which was chosen to maintain resolution that could capture flashing effects. At each time step, the algae cell moves slightly and collects photons according to the illumination pattern and attenuation.

The cell needs to collect exactly $n_s = 8$ photons in the allotted maximum collection time t_w in order to have a successful photosynthesis cycle. The time that the cell spends collecting photons is t_c, and so a cycle is successful if $t_c < t_w$. If the photon target is achieved in the allotted time, the cell enters a dark reaction period of length t_d during which it cannot use any photons that fall on it. If it does not hit the photon target in the time limit so $t_c \geq t_w$, it loses all of the photons that it has "collected" and starts collection anew. These lost photons are referred to as "dumped" in the model.

The model tracks both the photosynthetic cycles of the cell and how it used the photons that fell on it. Photons that hit the cell can either be used for a cycle, dumped due to not having hit the cycle, or be unused due to the cell being in dark reaction. All of these are tracked. Number of successful cycles N and failed cycles p are also tracked. All of these variables are summarized in Table 3.1.

Parameter	**Function**	Default Value
t_c	Recorded collection time	-
t_w	Maximum alloted collection time	80 ms
t_d	Set dark reaction time	5 ms
t_r	Total reaction time $t_w + t_d$	85 ms
n_s	Target number of photons	8
n	Recorded collected number of photons	-
I_0	Incident light intensity per unit area per reaction center	varied
α	Attenuation coefficient for culture density	0.92 [16]
f	Frequency of the square waves of light across the reactor	-
N	Number of successful photosynthesis cycles	-
p	Number of failed photosynthesis cycles	-

Table 3.1: MATLAB variables

3.1.1 Movement

Two-dimensional movement was modeled as some combination of a velocity in the x direction and diffusion in both x and y. Velocity v was only used to test the "perfect" case. Here it was first based on the frequency of the incident perfect square wave of illumination: $v = \frac{\lambda}{t_r}$. This was to ensure that the highest possible efficiency, 100%, was obtained for the verification of the "perfect case". Once this velocity $v = 1.175^{\text{cm}}/_{\text{s}}$ was found, it was used as a basis for comparison in testing the effects of introducing random diffusion into the cell. In all other cases, cell movement was completely based off of random diffusion in all directions. Random brownian motion was modeled using a Gaussian distribution of mean 0 and standard deviation σ, where:

$$\sigma = \sqrt{2D\triangle t}$$

Different boundary conditions were put in place for different directions and dimensions. In the two dimensional case, the x dimension of the reactor was assumed to extend infinitely. This created an infinite sheet by using a boundary condition that placed the cell at the other end of the reactor upon contact with a wall. The physical boundaries of this reactor, the glass plates, were in the y direction. In this case, the boundary condition was an inelastic collision until the cell randomly diffused away from the wall. In the three dimensional case, these inelastic collisions occurred only in the z direction and the cell was made infinite in both the x and y directions using the same technique as in the two dimensional case.

Unless otherwise noted, the two dimensional L_y was 1 cm. In three dimensions $L_x = L_y = 1$ cm and $L_z = 0.5$ cm.

3.1.2 Creating a Structured Illumination Pattern

The illumination pattern was created using MATLAB's built-in square or sine wave functions. Unless otherwise specified, the square wave was used in order to get a more accurate comparison from the "perfect" case. The square waves were kept to the standard duty cycle of 50%. The frequency of the square waves varied from test to test. Amplitude was scaled for each simulation such that the average intensity is always kept to I_0. This is accomplished by integrating the intensity profile with $A = 1$ over the area of the reactor and defining a new A such that: $A = {I_0}/{\text{integral of waveform}}$. For example, if only one wave is in the reactor, half of the reactor is illuminated and $A = 2I_0$. This is illustrated in Figure 3.1.

Light intensity is attenuated exponentially by a factor $\mu(\rho) = \alpha\rho$ and $\alpha \sim 0.92L_{z,y}\frac{1}{\text{g}\times\text{cm}}$ via experimental results [16]. In the 3D case and 2D cases α scales with L_z and L_y, respectively. The effect of this attenuation is pictured in the two-dimensional case PBR Figure 3.2, and in the 3D

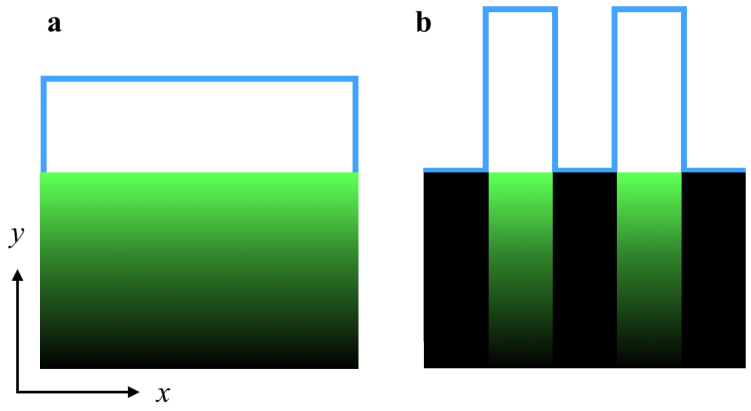

Figure 3.1: The 2D PBR under two illumination patterns. **a** shows the constant illumination case. **b** shows a square wave with adjusted amplitude. Since $^2/_3$ of the reactor is illuminated, the amplitude of this wave would be $^3/_2$ the intensity of **a**.

case in Figure 3.3.

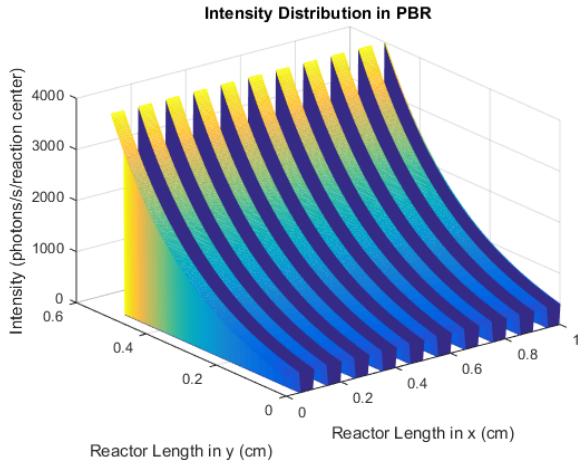

Figure 3.2: The intensity distribution in the two-dimensional PBR with culture density $d = 10\frac{\text{g}}{\text{cm}^3}$, duty cycle scaled to $^{t_w}/_{t_r}$, and average incident intensity $I_0 = 12000\frac{\text{photons}}{\text{s}\times\text{reaction center}}$.

3.1.3 Photon Collection

Photon collection over t_w is sum of the fractions of I_0 available at each point along the cell's path. In the 3D case, the photons collected can be expressed as an integral over the simulation time:

$$n = \int_{t_1}^{t_2} I_0 f(x,y) e^{-\mu(\rho)z} dt \tag{3.1}$$

Where $f(x,y)$ is the square wave or other modulation function. The 2D case would simply replace the modulation function with $f(x)$ and attenuation based on distance in the y. The timestep

dt is kept sufficiently small so that the model can add up the photons available to the cell during each dt. The photon fraction collected at each time step is zero on the unlit regions. In lit regions, the fraction is the incident radiation attenuated in the z direction by culture density. The modulation into square waves and the attenuation in the z direction are both illustrated in Figure 3.3.

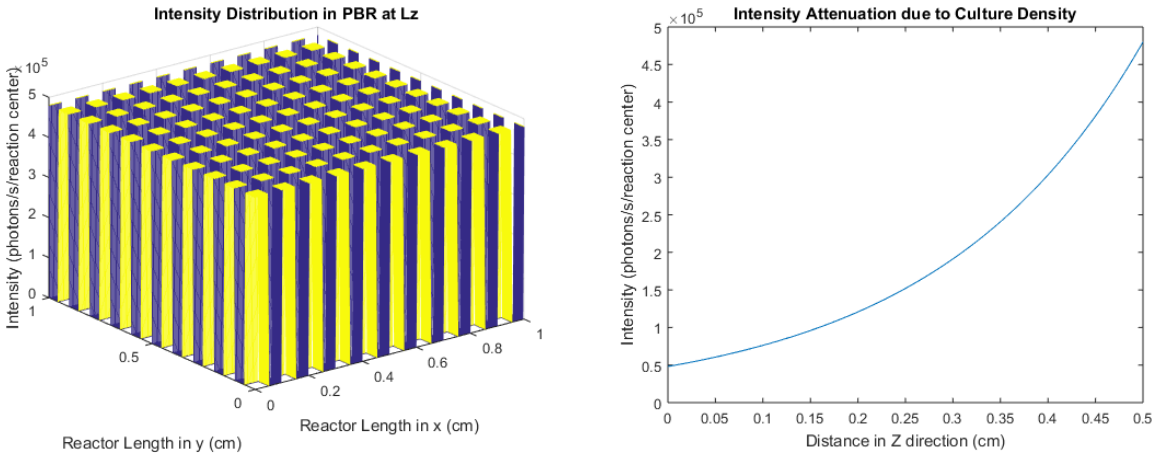

Figure 3.3: The intensity distribution in the three-dimensional PBR with average incident intensity $I_0 = 12000 \frac{\text{photons}}{\text{s} \times \text{reaction center}}$ and 10 square waves along the x and y dimensions. Also pictured is the attenuation in the depth direction z due to culture density $d = 10 \frac{\text{g}}{\text{cm}^3}$.

Separate counters are used to keep track of photons used for a photosynthesis cycle, photons that are unused due to the cell being in dark reaction, and photons unused due to not hitting $n = 8$ in the collection time limit. Additionally, the number of successful and failed photosynthesis cycles is tracked for the determination of photosynthetic rate P_v, which is:

$$P_v = d\frac{N}{T}$$

Where N is the number of completed cycles, d is culture density, and T is the total simulation time, usually 100 seconds. Having d as a part of P_v allows for direct comparison with Gebremariam and Zarmi [16], who use this definition to plot P_v versus d to determine optimum culture density.

Chapter 4

Results

4.1 Model Validation by Testing Extreme Cases

Validation of the model was first carried out by testing extreme cases. Each case and its observed result are listed in Table 4.1. Note that I_0 could not be set to ∞ for testing due to the way that the amplitude of the square waves is calculated. The integral cannot be computed in MATLAB. This also applied to n_s and α.

Limiting Case	Result
$I_0 = 0$	No photons fell on the reactor.
$I_0 = 999999$	Every cycle was successful, and the collection time $t_c = dt$. Additionally, the number of photons that fell during dark reaction was 99% of all photons that fell.
$t_w = 0$	No cycles were completed.
$t_w =$ total simulation time	Every cycle is completed. No photons are dumped due to hitting the time limit.
$t_d = 0$	No photons fell during dark reaction period.
$t_d =$ total simulation time	One cycle is completed. No cycles are marked as failed, because no other cycles are attempted. Only n_s photons are used and the rest fell during dark reaction time.
$n_s = 0.000001$	$t_c = dt$ at higher I_0 values. No cycles are failed.
$n_s = 999999$	No cycles are completed. Every photon that fell on the cell is dumped whenever t_w elapses.
$\alpha = 99999$	Intensity attenuates almost immediately. Number of cycles approaches 0 as α increases.
$\alpha = 0$	Intensity does not attenuate with culture density.

Table 4.1: Limiting cases and results

4.1.1 Flashing Light Effect in the Perfect Case

The model was also tested to ensure that 100% photon utilization could be achieved. The reactor area was illuminated with a square wave with $\lambda = 0.5$ cm. In this "perfect" case, t_c and t_d were set such that the cell spent all of the collection time in the lit region and all of the dark reaction time in the unlit region, eliminating any loss due to the dark reaction period. Diffusion was set to 0, and velocity was introduced to ensure that the cell spent exactly the amount of time in the lit regions to collect n_s photons. Incident intensity and the duty cycle of the square waves were similarly optimized. In this case, the cell completed all cycles and every photon that fell on it

was used. No photons fell during the dark reaction periods because the cell spent that time in the dark zones.

Figure 4.1 shows the effects of altering the frequency of waves in the reactor. Efficiency, here the percent of photons successfully used for photosynthesis, peaks when there is an integer number of waves in the reactor. These are cases when the cell gets the perfect amount of illumination while it is collecting and immediately leaves the lit zone when $n_s = 8$ is reached. A low I_0 is used because there is no shading loss. Solar power consumption is lowered because light is not wasted on the cell whenever it is in dark reaction.

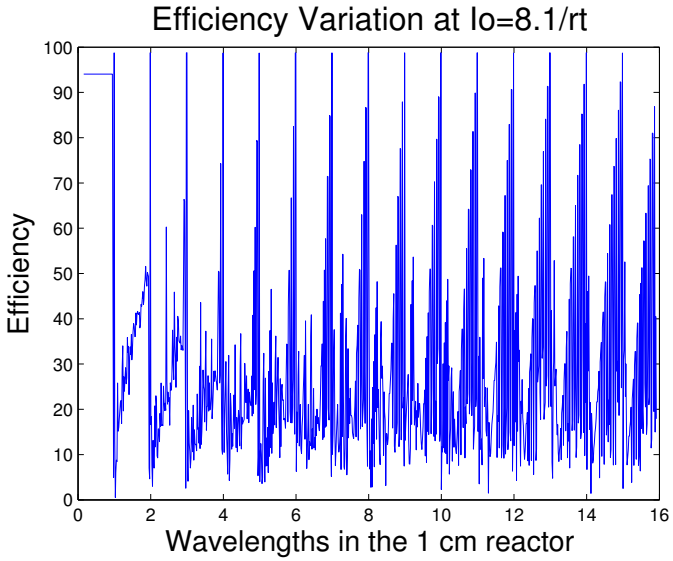

Figure 4.1: When I_0 is 8.1 photons in the reaction time (rt), which is just over the target $n_s = 8$, the model returns near 100% photon utilization efficiency when the number of square waves over the reactor reach any positive integer.

4.2 Comparison to Literature

A second way to validate the model is by comparing it to the literature. Greenwald et al. [4] define the optimum culture density of a theoretical PBR as the culture density at which photosynthetic rate $P_v = d\frac{N}{T}$ is maximized. Their results are shown in Figure 4.2. Plotting P_v versus $\mu = \alpha d$ in the 2D case for our model yielded curves of a similar shape as shown in Figure 4.3. Similarly, our model shows the expected dependance on collection time in Figure 4.3. Some of the quantitative differences in our results are due to the fact that their model was illuminated from both sides and of an unknown width in the y direction.

One important note on Figure 4.3 is that the cell had to start on the surface of the photobioreactor in order to see the straight line for the $D = 0$ case. If there is no diffusion, photosynthetic rate

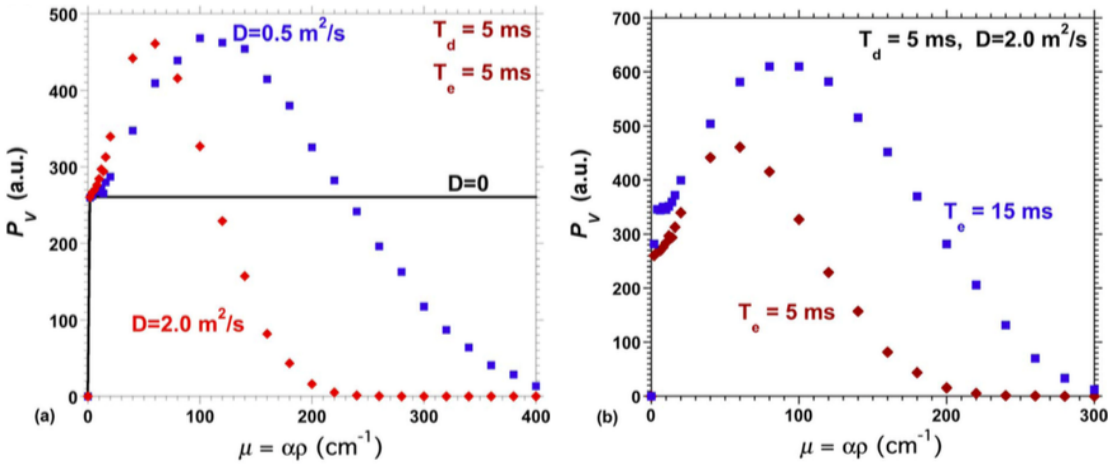

Figure 4.2: Model results from the literature. **Left:** Greenwald et al. [4]'s predictions of diffusion's effect on optimum culture density. **Right:** They also predict that a longer collection time limit will raise optimum culture density. Here, $T_e = T_c$ is the photon collection time limit.

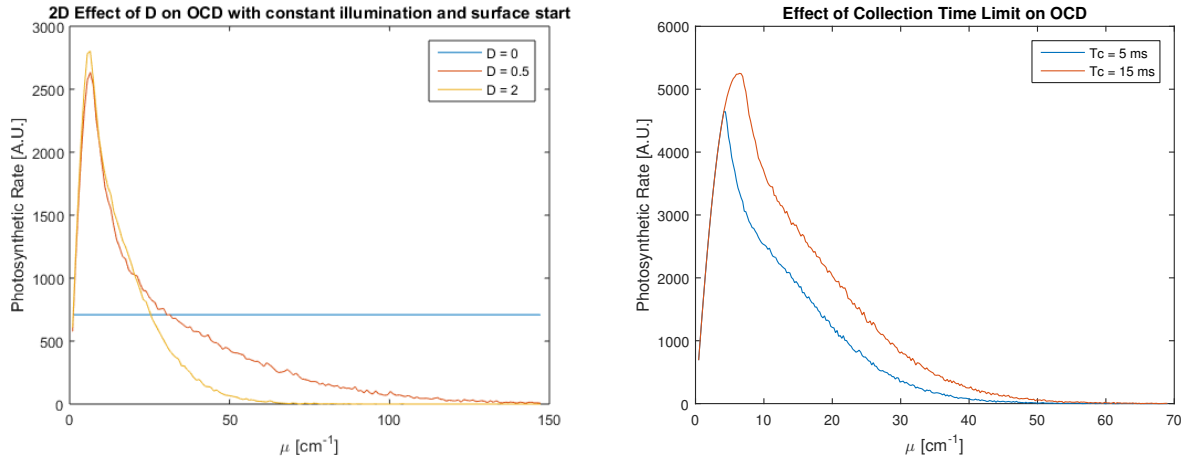

Figure 4.3: The model's results with parameters as in Figure 4.2.

is constant only in this case. If the cell starts at a y value that is not the surface of the 2D reactor, the photosynthetic rate will crash once culture density becomes high enough to completely block illumination to its y position. This is shown in Figure 4.4.

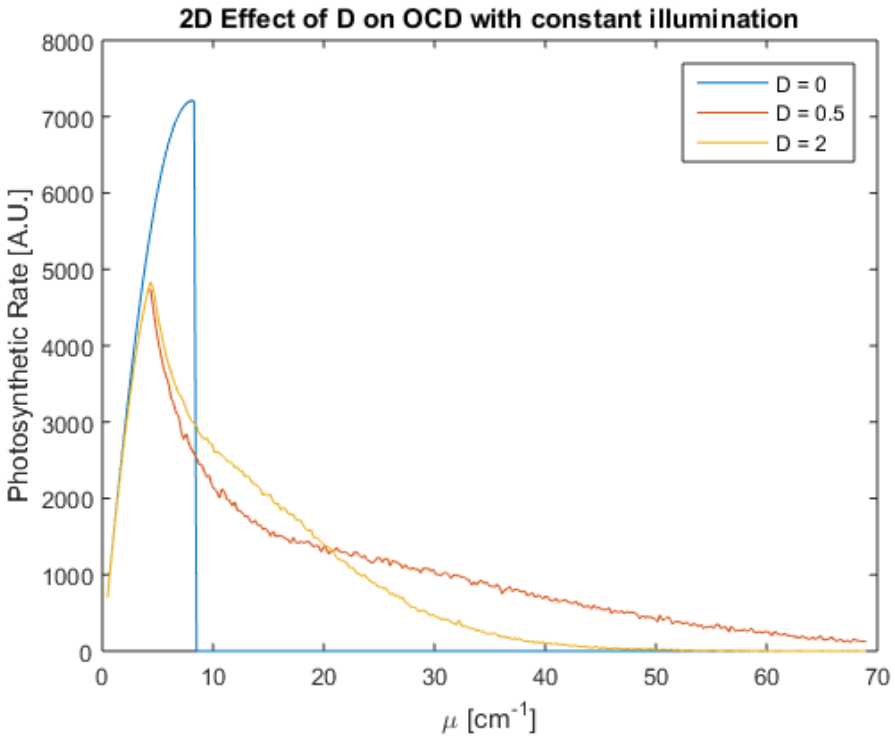

Figure 4.4: Photosynthetic rate $\times$ culture density climbs until the cell is no longer in the lit region. If the cell stays on the surface, it is always lit.

4.3 Adding Third Dimension and Structured Illumination

Moving the model from 2D, which is explored in the constant illumination case in the literature, to 3D can yield more interesting results. Figure 4.5 shows that varying the collection time limit has less effect on the same cell in three dimensions. Two differences between this and Figure 4.3 are significant: first, a smaller time limit actually slightly increased the photosynthetic rate. This may be due to the cell dumping photons in less well-lit regions more quickly. Second, the photosynthetic rate does not go to 0 as quickly as in the 2D case, showing that culture density has less effect on photosynthetic rate.

Varying square wave frequency and forming columns of light is another possibility for the model. Figure 4.6 was obtained by keeping D at 2 $\mathrm{m^3/s}$, culture density at 10 $\mathrm{g/cm^3}$ and without any velocity. It shows how photosynthetic rate increases versus the constant illumination case, which is shown as the horizontal line for each culture density. Note that the light beams get more

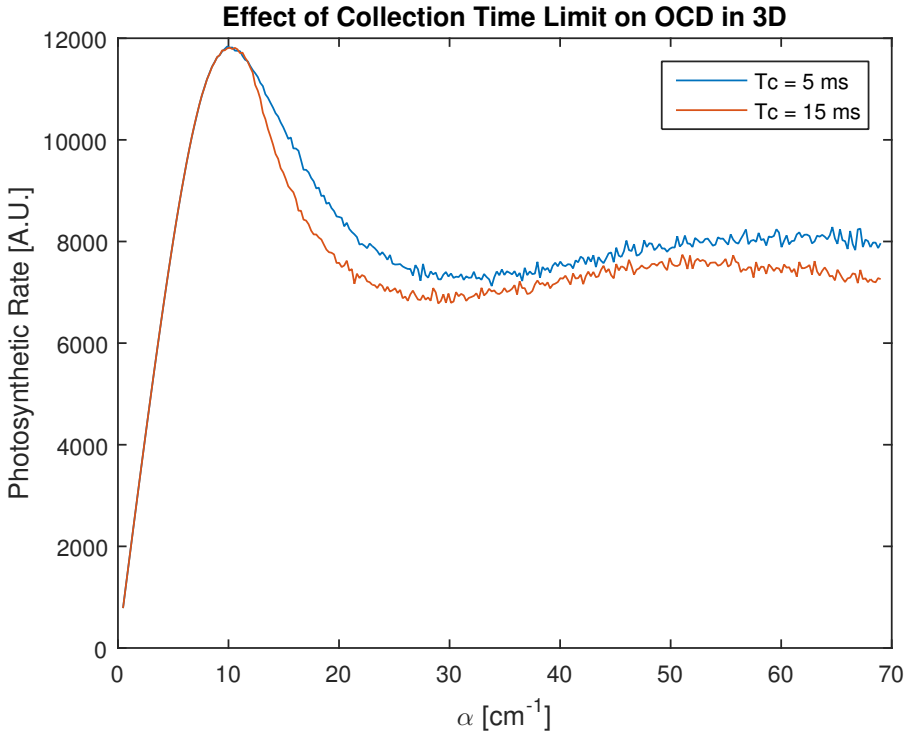

Figure 4.5: The model returns markedly different results for the effect of collection time on OCD in 3 dimensions.

intense as the number of waves in the reactor increases, but they still attenuate exponentially in the z direction. Increasing the number of waves in the reactor at small numbers, e.g. 1 to 2, also causes much more of the reactor area to be lit. This is why there are spikes in photosynthetic rate at small numbers of waves in the reactor.

The key result illustrated by Figure 4.7 appears to be that increasing the number of square waves in the reactor area increases P_v versus the constant illumination case. However, since power is conserved over the 1 cm^2 reactor area, the amplitude of each square of light increases as area decreases. This causes intense, albeit shallow, light spots where the cells meet the n_s target nearly instantly. This effect is even more important at higher culture densities where the cell cannot meet the photon target in most of the reactor volume. In order to determine whether Figure 4.7 actually illustrates a flashing light effect, it is necessary to decouple the results from this effect of increasing light intensity to keep power constant.

Figure 4.8 shows what happens when the amplitude of the square wave is kept at I_0. This is $I_0 = 12000$ $^{\text{photons}}/_{\text{s} \times \text{reaction area}}$ is the amplitude used in all tests of constant illumination. A wide range of "waves in the reactor" was used. Physically,the area of a "square" of light ranges from 1 cm^2 in the constant case to 4 nm^2 at 200 waves in the reactor. It is clear that at no point does the cell's movement line up with the structure of light and dark to produce a spike in P_v, which would

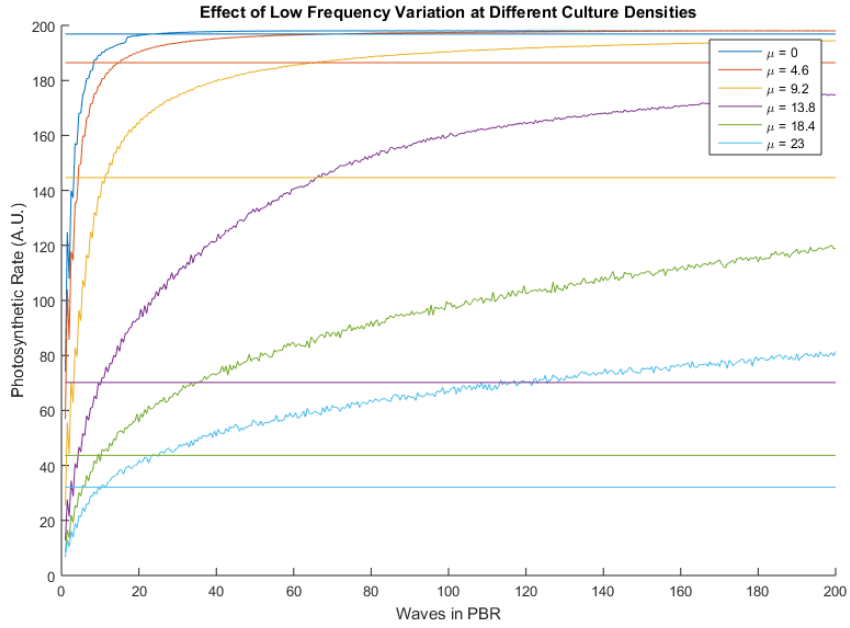

Figure 4.6: Structured square waves in the 3D reactor show an increase in photosynthetic rate when compared to constant illumination, shown with horizontal lines. At low numbers of waves, each new wave causes much more of the reactor surface to be lit, leading to increased P_v

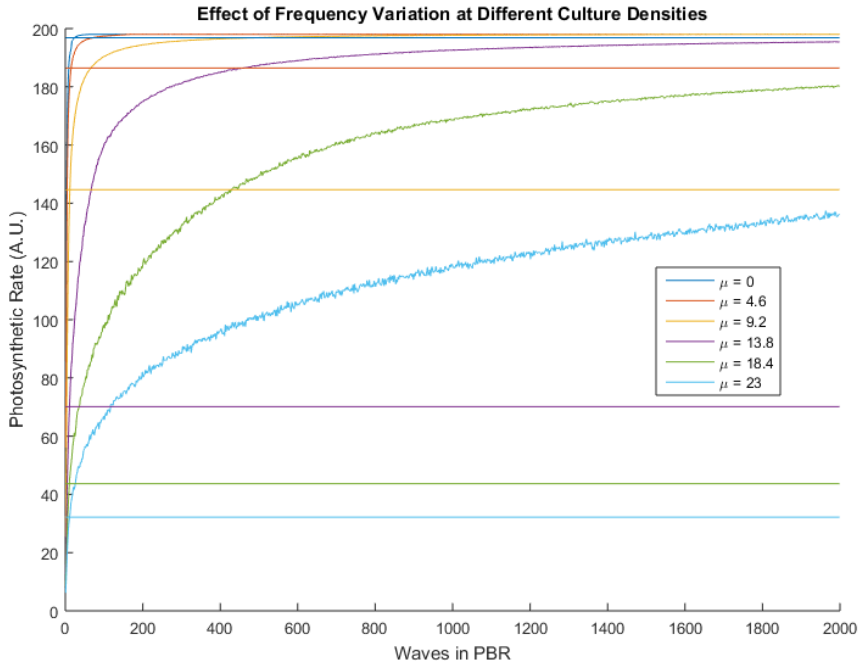

Figure 4.7: Effect of structured illumination over a broad range of square wave frequencies, and thus waves in the reactor. At higher culture densities μ the photosynthetic rate saturates more slowly but also surpasses the constant illumination case by a greater margin.

indicate the presence of the flashing light effect.

Spikes in P_v at low numbers of waves in the reactor occur at the same place regardless of culture density. This indicates that they are due to a sudden increase in the area of the reactor that is lit, and thus an increase in total power being delivered to the reactor volume. At higher numbers of waves and higher culture densities, this increase in power matters less and less because the cell cannot reach n_s photons in the brief time that is resides in a lit square.

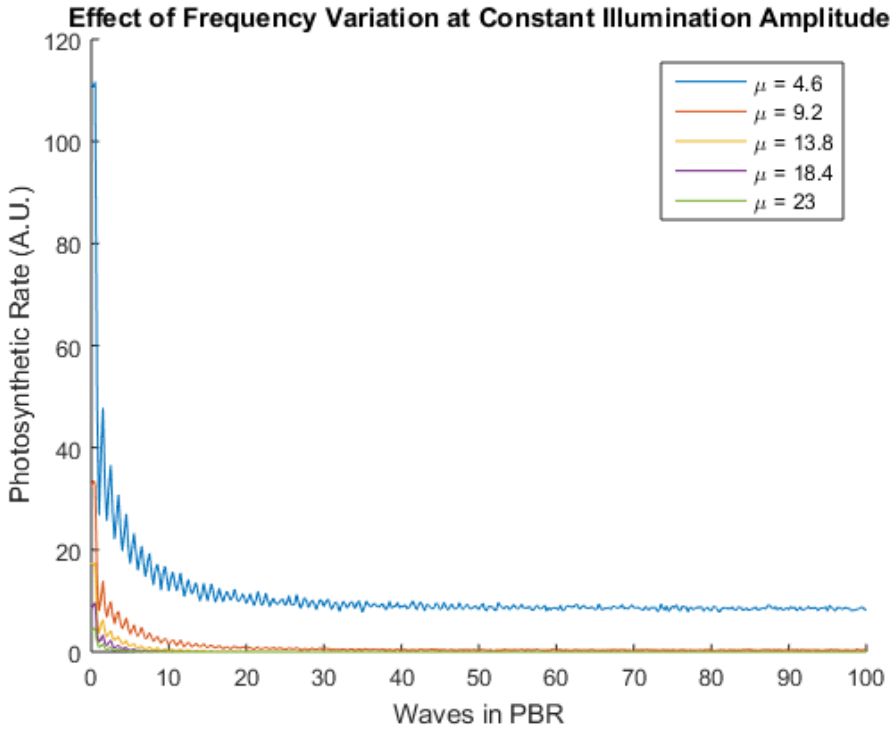

Figure 4.8: Effect of constant I_0 as compared to Figure 4.7, which increased I_0 to keep power constant when less of the reactor was lit.

Chapter 5

Summary and Conclusion

Algae photobioreactors represent a promising opportunity for biofuel production. In this field, increasing the mass of algae grown per unit volume is one of the main concerns. Although much work has been done on ponds, raceways, and even flat plates, no one passive design has emerged as a clear, cost-efficient choice. One way to increase the amount of algae is by structuring light, which can be done passively with novel reactor designs. The two benefits of passively structuring solar radiation are concentration and the potential for the algae cells to experience the flashing light effect. In order for these novel configurations of optics to be found, it is necessary to have an algae growth model that will predict culture density in three dimensions.

This work presents such a model for predicting algae growth in three dimensional photobioreactors. First, a two dimensional model based on random diffusion was constructed and compared to the literature. This model agreed with Gebremariam and Zarmi [16] and gives expected results in limiting cases. The model was then extended to three dimensions, where a simple structured light distribution of square waves was tested. It was found that concentrating light into smaller areas worked better than lower intensity, higher area illumination. If illumination intensity was kept constant, an increase in photosynthetic rate was not found when structuring the light distribution in this way. The flashing light effect was observed in the two dimensional case without diffusion by synchronizing light and dark zones to cell movement and reaction times.

In the future, it would be beneficial to use this model to study an actual photobioreactor with movement parameters based on fluid dynamics. It is was shown that it is possible to increase photosynthetic rate with a structured light distribution, but only by basing illumination off of predictable cell movement. Concentrating light into a smaller area, however, represented an increase in culture density regardless of the amount of randomness in the cell's motion. Potential following studies may use this model to compare possible photobioreactor designs and therefore cut down on research time and cost.

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EDUCATION

The Pennsylvania State University **University Park, PA**
College of Engineering, Schreyer Honors College **Graduation:** December OR August 2016
Major: Electrical Engineering (Master of Science), Engineering Science (Bachelor of Science)
Minor: Engineering Leadership Development

EXPERIENCE

Kimberly Clark Corporation
Electrical Engineering Co-op *May 2015 – December 2015*

- Wrote new software in LabVIEW to control electrical stimulation and manage data for upcoming research study
- Collaborated with vendors to further KC's use of IO-Link by testing new sensors. Developed PLC code in RsLogix 5000 to control sensors via IO-Link and display controls on human-machine interface for operators
- Gained experience in AutoCAD in external training class and applied it by designing new drive panel enclosure

AECOM (formerly URS)
Engineering Intern *May 2014 – August 2014*

- Wrote draft chapter on disaster resilience of transportation systems for the National Institute of Standards and Technology, which was presented at their workshop.
- Worked with the US Coast Guard to collect expert consensus for the National Maritime Strategic Risk Assessment.

Baobab and Moringa Seed Oil Extraction Team
Engineering Leadership Development *August 2011 – May 2012, January 2013 – May 2014*

- Worked alongside two teams of students to build a prototype of a baobab seed oil extractor for a collective in Benin
- Explored issues of ethical leadership, staying within design constraints, working with your customer, and coordinating teams of people
- Was recruited afterwards to be a teaching assistant for a semester, and then a teaching intern for another semester

RESEARCH

Applied Optoelectronics and Photonics Laboratory
Master of Science Paper: Optical Plastics for Lenslet Solar Concentrators

- Analysis of optical plastics, including transmission measurements before and after accelerated aging, to determine best candidate for commercialization of solar concentrator design
- For undergraduate thesis, constructed a model in MATLAB to produce monte carlo simulations of algae cells to show higher productivity under structured illumination in three dimensions

AWARDS AND OTHER ACTIVITIES

Springfield THON *May 2011 – Present*
Society of Engineering Science *August 2012 – Present*
IEEE *January 2015 – Present*
Penn State Science Lions *August 2011 – May 2012*

Air Products Innovation in Engineering Design Award *February 2011*
Eagle Scout *August 2008*

SKILLS

Programs: RsLogix 5000, LaTeX, LabVIEW (CLAD certified), Microsoft Word, Powerpoint, Excel, MATLAB, Solidworks, AutoCAD