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## **Photobioreactor Design**

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Summary: Photobioreactor (PBR) design encompasses many subsystems of the PBR. The PBR volume can be based on removing contaminants (nutrients) from livestock facilities. Ammonia and carbon dioxide are used to determine PBR volume. Light penetration is hindered by high algal concentration. Methods to estimate light penetration are presented as well as the use of light guides. Light sources do not provide all of the light energy in the photosynthetic range and the use of the light supply coefficient is discussed. Mixing is enhanced by small bubbles with high velocity. This also enhances gas transfer.

**Keywords:** photobioreactor, light penetration, algal concentration, light supply coefficient

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## INTRODUCTION

It has been known for several decades that different algal species can produce many different useful products. Pharmaceuticals, chemicals, health foods, animal feed, and human food are examples of products that can be made algae biomass. Table 1 from Benemann, et.al. (1987) is a comprehensive list of possible products from algae biomass. Algae may also be used to treat waste through two different mechanisms. The first mechanism is by producing oxygen that is dissolved in the waste thereby being available for use by bacteria to oxidize wastes; i.e. supplying the oxygen demand of the waste as indicated by its biochemical oxygen demand. Secondly, algae may also use nutrients in waste such as ammonia in its own biomass production. Javanmardian and Palsson (1991) show that for every gram of ash free biomass produced by algae (gram molecular weight of 22.7) 0.11 grams of ammonia will be used along with 1.93 grams of carbon dioxide. The ash free biomass is approximately 50% carbon ( $12\text{g}/22.7\text{g} \times 100\%$ ). Oxygen is estimated to be produced at the rate of 0.0495 moles per gram of algal biomass ( $\sim 1.11$  oxygen per gram of algal biomass =  $0.0495$  moles  $\times 22.41$  per mole). Markov (2000) reported that 50% of the phosphorous had been taken up from solution in 5 days by cyanobacteria in a hollow fiber PhotoBioReactor (PBR) showing that a PBR may be used to remove phosphorous from live stock waste streams.

Algae is well suited for producing useful products and reducing nutrients in livestock waste streams because it is a very fast growing, which results in high production of product and high consumption of nutrients from the agricultural wastes. Hu, et. al. (1998) reported producing 84g/l algae in a flat plate PBR with a light intensity of 2000 micromoles per second per meter squared (3-15g/l are more common though). The light path was 10mm. Lee and Palsson (1994) found that both light path and light intensity increased algal biomass production with light path possibly having a greater impact. Algae biomass production requires few relatively simple inputs like carbon dioxide, water, light, and mineral salts or other nutrient sources, Olaizola (2001). Algal biomass production has the potential of reducing odors from agricultural waste. The algae will use odorous compounds like ammonia for biomass production while the principally water growth medium the algae are produced in will dissolve and/or ionize odorous compounds like

hydrogen sulfide. Dust will also tend to be reduced if air from livestock facilities is brought into contact with the alga biomass growth medium. Systems that control dust remove particulates and odors from livestock facility exhausted air.

An efficient large scale PBR has yet to be developed, Ogbonna and Tanaka (1997). This has left commercial production of algae to open ponds. Open ponds do not provide conditions necessary for high density algal biomass production because of diurnal and annual variation in light intensity and temperature. Chen (1996) states that enclosed PBRs have the following advantages over open pond production.

1. Better control of algal culture
2. Large surface-to-volume ratio
3. Better control of gas transfer
4. Reduction in evaporation of growth medium
5. More uniform temperature
6. Better protection from outside contamination
7. Higher algal cell densities are possible.

Covering ponds does alleviate some of the disadvantages, but enclosed systems will still provide better control of temperature, light intensity, better control of gas transfer, and larger surface area-to-volume ratio. An enclosed PBR design will enhance commercial algal biomass production by keeping algae genetics pure and reducing the possibility of parasite infestation.

PBRs are complex systems composed of several subsystems. Javanmardian and Palsson (1991) list six subsystems as:

1. Light source
2. Optical transmission system
3. Reaction area
4. Gas exchange system
5. Filtration system (remove algal biomass)
6. Sensing system

Several of the subsystems of a PBR interact. The optical transmission system and gas exchange system interact via the mixing that takes place in the reaction area. Algae are moved into and out of lit areas by mixing. Assuming that the algae require time to

complete the photosynthetic process once sufficient energy is absorbed to initiate photosynthesis, energy efficiency may be increased by moving algae into a dark area after it has absorbed sufficient energy. Hu et. al. (1998) state that 1ms is the time required to complete a single cycle of the light reaction in photosynthesis. Moving algal cells into a dark region of the reactor for a millisecond would likely not affect photosynthesis. Energy absorbed by the algal cell once it has initiated photosynthesis most like is converted to thermal energy. The thermal energy is then lost as heat or raises the temperature of the algae cell.

The development of a large scale enclosed PBR coupled with future scale up requires new and innovative designs for the PBR in general and the subsystems that compose the PBR. Given that the PBR will be used to control air borne contaminants from livestock facilities, the PBR must be designed so that it can interface with conventional air handling systems. Treatment of the liquid portion of livestock waste will add a second interface issue as well as algal biomass harvesting. However, this paper will be limited to the use of the PBR to algal production and air contaminant control.

## **OBJECTIVES**

A general design for a 500gal (1900 l) PBR will be presented. The design of the below listed subsystems and the interaction of the subsystems will be discussed.

1. Light source
2. Reactor volume
3. Optical transmission system
4. Gas transfer/mixing system

## **GENERAL PBR DESIGN**

Removal of contaminants from air streams requires that the air be brought into contact with the growth medium (principally water) in the reactor area of the PBR. Air with contaminants may be moved over the surface of the growth medium, but this will likely yield low gas transfer rates and will not enhance mixing of the algae-growth medium

solution. Without mixing, the algae will tend to settle towards the lower portion of the PBR, Lee and Palsson (1994). Mixing also reduces temperature gradients and enhances nutrient distribution in the solution. Mechanical mixing requires the addition of another system. Mixing the reactor solution with air containing contaminants (nutrients) can be done with perforated tubing or diffusers at the bottom of the reactor. These systems do not readily lend themselves to air handling equipment, but rather compressed air systems. A large chamber (plenum) under the reactor volume would readily connect to conventional air handling equipment such as duct work. The concept does require a porous membrane to be placed between the plenum and the reactor area. The plenum concept was selected even though it has the disadvantage of requiring higher air pressure than the air over the surface system and has a greater risk of fouling with particulates in the air stream. It also requires the plenum walls to carry most of the weight of the PBR.

The optical system chosen is generally described as a flat plate system. It is desirable to provide a large lit surface area-to-volume ratio for the reactor. High density algae cultures are relatively impervious to light transmission. Ogbonna and Tanaka (1997) give the light extinction coefficient as 200 meters squared per kilogram. A 10g/l algae concentration would yield an 86% loss of light energy at 1mm depth, see equation 1.

$$\ln(I/I_0)=200 \times C \times d \quad 1$$

where,

I-light intensity at depth of penetration d

I<sub>0</sub>-initial light intensity

C-algae concentration, kg/cubic meter or g/l

Javanmardian and Palsson (1991) give the depth of light penetration (d in millimeters) as:

$$d=60/C \quad 2$$

A 10g/l algae concentration would yield a penetration depth of 6mm from equation 2. Both light penetration equation show how light penetration limits algal biomass production by limiting light penetration. Data from Ogbanna and Tanaka (1997) show that photosynthesis can be maintained with a light intensity of 7.3 μmol/m<sup>2</sup>/s. They also state that a better measure of light supply is the product of the light distribution coefficient defined as the algal concentration at which 50% of the reactor volume receives sufficient light to

maintain photosynthesis and the energy per unit volume. Given a target algal production of 10g/l algal biomass production and a 6” (152mm) reactor depth lit on both sides yields a desired light input of  $7.4 \times 10^{33} \mu\text{mol}/\text{m}^2/\text{s}$ . This light intensity is impractical. PBR design must include mixing effects to move algae into and out of the light area of the reactor. Also other techniques need to be explored for increasing lit volume of the reactor volume. Light guides were developed for this purpose and will be discussed latter.

A lab scale PBR was built and tested at SDSU, Kleinjan (1999). The PBR was 10.67”x10.67” (271mmx271mm) with a depth of 2” (50mm). The volume of the reactor area was 3.7l and an algal biomass of 7.1g/l was produced in 14d. Light was provided by 650nm LED on circuit boards provided by DAKTROICS, Inc on each side of the PBR.. The boards provided 14.1W per board yielding a light intensity of  $6.04 \times 10^{14} \mu\text{mol}/\text{m}^2/\text{s}$  ( $0.073\text{m}^2$  surface area). Equation 1 would estimate a potential algal biomass of 8.4g/l (light distribution factor) indicating that the full potential of the PBR was not met. The light supply for the PBR was  $7.7\text{kJ}/\text{s}/\text{m}^3$ . Combining the light distribution factor and the light supply results in a light supply coefficient of  $64.7\text{kJ} \cdot \text{kg}/\text{m}^6/\text{s}$ . The PBR had staggered acrylic light guides 3/8” (9.5mm) in diameter that may have enhanced light distribution.

The 500gal PBR will be composed of 21- 48”x 19” (1220mmx483mm) compartments with a depth of 6” (152mm) lit on both sides. Light will be provided by fluorescent lights (1, 2, 5, or 8-40W bulbs on each side), 625nm LED (1536, 3072, and 6144 LEDs per side), grow lights, and metal halide lights. Light supply coefficients will be determined for all lighting systems used. The light supply coefficients will be based on the usable wavelengths of light in a spectrum. Usable wavelengths for algae are generally assumed to be the red and blue visible regions around 436nm, 460nm, and 680nm, Matthijis et. al. (1995).

**Power Based on Algae Growth:** The power required changes as the algal biomass changes; grows. Kleinjan (1999) provides the following equation for energy demand of algae.

$$E=2500 \times C_x \times V_x e^{0.03t} \quad 3$$

where,

E-energy required, J

2500-J/g of algae mass

V-reactor volume, l

$0.03 = \ln 2 / 24\text{h}$ -doubling time for algae culture

t-time, h

The integral of equation 3 yields the power (P, W) required by algae at any given time.

Equation 4 is the integral of equation 3.

$$P = 750 \times C_x \times V e^{0.03t} \quad 4$$

Assuming that the desired doubling time is 24h, equation 4 reduces to:

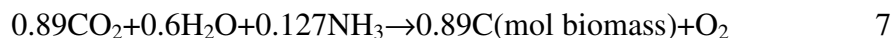
$$P = 1541 \times C_x \times V \quad 5$$

Kleinjan (1999) reported an energy efficiency of the algae of 22% which compares well with the 23% obtained by Javanmardian and Palsson (1991). Adjusting for algae efficiency gives:

$$P = 7000 \times C_x \times V \quad 6$$

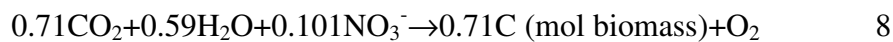
A PBR design must satisfy the energy/power needed for algal production as derived by equations 3-6.

**Required Algal Biomass Production:** Assuming the PBR is being designed to remove air contaminants from livestock units, the algal biomass production must be sufficient to remove the contaminants. Javanmardian and Palsson (1991) give equation 7 as the photosynthesis equation for ammonia as the nitrogen source.



The mole biomass is assumed to have the formula of  $\text{C}_{1.0}\text{H}_{1.8}\text{O}_{0.432}\text{N}_{0.143}$  with a formula weight of 22.7. Equation 7 shows that 0.11g of ammonia will be required to produce a gram of algae biomass  $((0.127\text{mol} \times 17\text{g/mol}) / (0.89\text{mol biomass} \times 22.7\text{g/mol}))$ . Similarly, the oxygen produced per gram of algae biomass is 1.58g and the carbon dioxide used is 1.93g. ASAE D384.1 shows the ammonia in swine waste to be 290g +/-16g per 1000kg of pig per day. Data from Table 1 of Gallmann et. al. (2002) can be used to derive an ammonia emission rate of 307g per 1000kg of pig per day for an 42kg pig  $((6.0 \pm 0.37\text{g NH}_3/\text{h-LU}) \times (2\text{LU}/1000\text{kg pig}) \times (24\text{h}/\text{d}))$ . The algae required to remove the ammonia from air is then 27911g/d per 1000kg pig  $((307\text{g}/1000\text{kg pig}/\text{d}) / (0.11\text{g ammonia}/\text{g biomass}))$ . If the ammonia in the waste is to be used too, the algae production would need to be 5709g/d per 1000kg pig  $((307+306)/0.11)$ . Assuming the algae production is 7g/l with a 24h doubling time yields a PBR volume of 816l/1000kg of pig.

The carbon dioxide production of the animals can be found from data provided by Gallmann et.al. (2002) as 62352g per 1000kg pig ((1131+/-168g CO<sub>2</sub>/h-LU)x(2LU/1000kg pig) x 24h/d). The algae production to use the carbon dioxide is 32307g/d yielding a PBR size of 4615 l (1200gal). Note that for a 40kg pig, data from Albright (1991) would yield a carbon dioxide generation rate of 21387g/d which is only about half that given by Gallmann et. al. (2002). Gallmann et. al. carbon dioxide generation rate considers all sources of carbon dioxide to include the pit. Albright (1991) is based on the animal total heat production; i.e. animal source only. There does not appear to be data available for the carbon dioxide that may be in the animal waste. If additional nitrogen source is not made available, it is apparent that only 18% of the carbon dioxide will be used by the algae biomass. If nitrate is used to supplement the ammonia, equation 8 from Javanardian and Palsson (1991) can be used to estimate the nitrate required.



The biomass molecular makeup is C<sub>1.0</sub>H<sub>1.68</sub>O<sub>0.365</sub>N<sub>0.163</sub> with a molecular weight of 21.8. Equation 8 shows that 2.02g of carbon dioxide will be reduced for each gram of algal biomass produced. The carbon dioxide to be reduced under nitrate as the nitrogen source is 51334g/d-1000kg pig (62352-1.93x5709). The biomass produced is 25413g/d-1000kg pig. Equation 8 requires 0.4g of nitrate for each gram of algae biomass which means that 10165g/d of nitrate would be required for each 1000kg of pig. The PBR size would be 4447 l (1175gal)/1000kg pig (25413/7+817). Algae tend to utilize urea first, ammonia second and nitrate last, Metz (2000).

The oxygen production is 1.58g/gram biomass-d for ammonia and 2.07g/gram biomass-d for nitrate from equations 7 and 8. The oxygen production from ammonia reduction is 9020g/d-1000kg pig (1.58g O<sub>2</sub>/g biomass) and it is 12268g/d-1000kg pig (2.07g O<sub>2</sub>/g biomass) for nitrate reduction. ASAE D384.1 gives a BOD (5d) demand of 3100+/-720g O<sub>2</sub>-1000kg pig. The waste BOD would be satisfied with an excess oxygen production of 17468g/d-1000kg pig. The excess oxygen must be removed from the PBR. Rubio et. al. (1999) found that photosynthesis increased 14% in the absence of dissolved oxygen and decreased by 35% when the dissolved oxygen content of the growth medium was 1.38mol/m<sup>3</sup> at 20C (0.0442g O<sub>2</sub>/l). High irradiance levels with high dissolved oxygen content can cause severe photo-oxidation.

## OTHER DESIGN CONSIDERATIONS

**Airflow:** The rate of airflow through the PBR will be dictated by the contaminate concentration in the ventilation air, ventilation required for the animals, and the air velocity through the reaction chamber. Algae can be damaged by shear stress caused by aggressive mixing (high velocities). Gallmann et. al. (2002) found the ammonia concentration and carbon dioxide concentration to be 23.2+/-1.7ppm and 1941+/-240ppm respectively. These concentrations correspond to 0.019g NH<sub>3</sub>/m<sup>3</sup> and 4.28g CO<sub>2</sub>/m<sup>3</sup>. A total of 62352g CO<sub>2</sub>/d-1000kg pig is produced. The airflow rate to remove the carbon dioxide is 0.17m<sup>3</sup>/s-1000kg pig compared to the mean ventilation rate of 0.22m<sup>3</sup>/s-1000kg pig reported. An airflow rate of 0.19m<sup>3</sup>/s-1000kg pig is needed to remove the air borne ammonia. Given the initial reactor dimensions of the PBR that provide 0.1858m<sup>2</sup> per 90l, the air velocity would be 0.23m/s ((0.19m<sup>3</sup>/s-1000kg pig)/(398l/1000kg pig/90l per 0.1858m<sup>2</sup>x0.19m<sup>3</sup>/s-1000kg pig)). The actual ventilation rate would yield an air velocity of 0.27m/s. If the reactor is sized for all ammonia, the air velocity would be 0.11m/s. Sizing for carbon dioxide removal yields an air velocity of 0.024m/s with the actual ventilation rate.

The air must move through the plenum into the reactor area through a porous membrane. Test conducted on a sinister porous membrane with an effective opening of 40microns yielded equation 9.

$$R=2.65+0.53xV'+1.32xD-0.03xV'xD \quad 9$$

where,

R-resistance to air flow, in water

V'-air velocity, fpm

D-depth of water air moves through, in

The 0.27m/s (53fpm) air velocity moving through 483mm (19") of water yields a static pressure of 650mm of water (25.6"). The air velocity of 0.024m/s (4.72fpm) must overcome a resistance of 699mm of water (27.5"). As the velocity decreases and the depth remains constant, equation 9 shows the resistance to increases. Low air velocities tend to yield larger bubbles that form relatively slowly. The large slow forming bubbles generally bridge the entire opening in the porous membrane requiring the air to lift all the water over the opening and also allows for a larger length that surface tension between the forming

bubble and the porous membrane can act over. The combined effects result in an increase in resistance. Lee and Palsson (1994) give the mass transfer coefficient as 110/h for 20m/h aeration with 3mm diameter bubbles and as 200/h for aeration of 20m/h with 1mm diameter bubbles. Decreasing the bubble diameter by 1/3 increased the mass transfer coefficient by nearly 2 fold. Note that equation 9 indicates that there will be a resistance of 67mm water (2.65") with no water and no air flow. Testing has shown that with no water depth, resistance is negligible for the air velocities tested. The static pressures from equation 9 indicate that a high pressure fan will be required to move air through the PBR. This fan would likely be a boost fan in the duct work outside the animal area in the building.

**Light Guides:** As stated previously, injecting light into a dense algal culture is difficult. Light guides may aid in this effort. The light guides are 9.5mm (3/8") diameter acrylic rods with either a cone shaped end (30 deg cone) or flat end. The rod ends are polished and buffed. Test conducted in air have shown that the flat end guides project light forward at an 18 deg angle. The cone guides generally project light equally forward and to the side of the cone. Fresnel's formulae and Snell's law were used to verify test results and predict behavior of the light guides when the guides are placed in water (index of refraction is 1 for air and 1.49 for water). The analysis suggests that 95% of incident light will enter the guide if the incident angle is less than 45deg. Also, 90% or more of the light incident on the guide at a 45deg angle or less will exit the guide at the far end. The water will reduce the divergence angle to 12deg for the flat end guide while the cone end has about 1/2 of the light leaving the front of the guide at a 4deg convergence angle with the remaining light leaving through the sides of the cone at a 75deg angle from the guide center line. The guides will increase light penetration into the biomass. Light guides of either 25mm (2") or 75mm (3") lengths have been placed on every other LED row so that 1 out of 3 LEDs does not have a light guide over it. The LEDs are nominally 19mm (3/4") on center. This arrangement leaves 67% of the light at the reactor wall and 16% at 25mm and 75mm into the medium. Another pattern used about 1/2 the number of light guides. The 25mm light guides are cone shaped while the 75mm light guides are flat end. Without mixing, the light guides should increase the lit area of the reactor proportional to the light brought into the

guides. Mixing will be enhanced by the guides and increased mixing will increase light penetration.

### **SUMMARY**

1. Design volumes of the PBR reactor were presented based on contaminate (nutrient) supply to the PBR and oxygen removal.
2. The effect that algal biomass concentration has on light transmission in the reactor was quantified and methods of projecting light into the reactor volume via light guides was presented.
3. Mixing velocities were found for a given reactor volume and plenum inlet area. Gas transfer coefficients are a function of bubble diameter and bubble size is a function of air velocity. Higher air velocity yields better mixing and smaller bubbles.
4. Light sources have different percentages of light in the usable range of light for the algae. Only usable light is available for photosynthesis. The light supply coefficient is a method to evaluate which light source/optical transmission system produces the better growing conditions for the algae. Further, the light supplied should be matched to the algal biomass concentration particularly when the biomass is changing; i.e. day to day increases in biomass concentration.

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