Large-Scale Production of Algal Biomass: Raceway Ponds

Yusuf Chisti

Abstract Raceway ponds are widely used in commercial production of algal biomass. They are effective and inexpensive, but suffer from a relatively low productivity and vagaries of weather. This chapter discusses design and operation of raceways for large-scale production of algal biomass.

Keywords Microalgae · Raceway ponds · High-rate algal ponds · Biomass production

Nomenclature

A	Surface area of raceway (m^2)
C_x	Biomass concentration (kg m^{-3})
D	Dilution rate (h^{-1})
d_h	Hydraulic diameter of flow channel (m)
e	Efficiency of the motor, drive, and the paddlewheel
f_M	Manning channel roughness factor (s $m^{-1/3}$)
g	Gravitational acceleration (9.81 m s^{-2})
h	Culture depth in pond (m)
I_L	Local irradiance at depth L (μE m^{-2} s^{-1})
I_o	Incident irradiance on the surface of the pond (μE m^{-2} s^{-1})
K_a	Light absorption coefficient of the biomass (μE m^{-2} s^{-1})
K_i	Photoinhibition constant (μE m^{-2} s^{-1})
K_L	Light saturation constant (μE m^{-2} s^{-1})
L	Depth (m)
L_r	Total length of the flow loop (m)

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l_c Depth at which the local irradiance level is at the light compensation point (m)
P Power requirement for paddlewheel (W)
PAR Photosynthetically active radiation
P_a Areal productivity of biomass (kg m^{-2} d^{-1})
PVC Polyvinyl chloride
P_v Volumetric biomass productivity (kg m^{-3} d^{-1})
p Length as shown in Fig. 1 (length of pond) (m)
Q_f Feed flow rate (m^3 h^{-1})
q Length as shown in Fig. 1 (width of pond) (m)
Re Reynolds number defined by Eq. (3)
Δt Time interval (d)
u Flow velocity in channel (m s^{-1})
V_L Working volume of the raceway (m^3)
w Channel width (m)
X_f Peak concentration of biomass (kg m^{-3})
X_i Initial concentration of the biomass (kg m^{-3})
x_b Pseudo steady state biomass concentration in the pond (kg m^{-3})

Greek symbols

μ Viscosity of the algal broth (Pa s)
μ_{av} Depth-averaged specific growth rate in the illuminated volume (d^{-1})
μ_L Local specific growth rate at depth L (d^{-1})
$\mu_{\max}$ Maximum specific growth rate (d^{-1})
ρ Density of algal broth (kg m^{-3})

1 Introduction

Raceway ponds, raceways, or “high-rate algal ponds”, were first developed in the 1950s for treating wastewater. Since the 1960s, outdoor open raceways have been used in commercial production of microalgae and cyanobacteria (Terry and Raymond 1985; Oswald 1988; Borowitzka and Borowitzka 1989; Becker 1994; Lee 1997; Pulz 2001; Grima 1999; Borowitzka 2005; Spolaore et al. 2006; Chisti 2012). Such production does not use wastewater. This chapter discusses the biomass production in raceways as typically used in commercial processes and not in treating wastewater. The design and performance of raceways are discussed. The factors influencing the biomass productivity in raceways are analyzed. A raceway is an oblong and shallow recirculating pond with semicircular ends as shown in Fig. 1 (Chisti 2012). The flow and mixing are typically generated by a single slowly rotating paddlewheel (Chisti 2012).

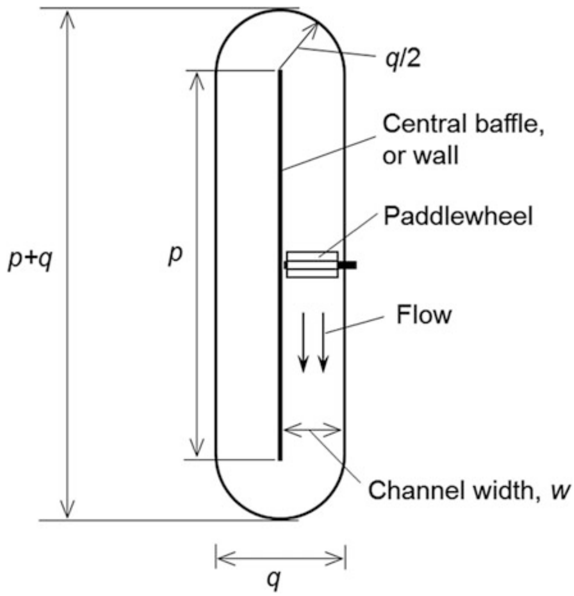

Fig. 1 A top view of a raceway pond as typically used for algal biomass production

2 Raceways

2.1 Typical Configuration

A raceway pond is a closed-loop flow channel with a typical culture depth of about 0.25–0.30 m (Fig. 1) (Becker 1994; Chisti 2007). A paddlewheel continuously mixes and circulates the algal broth in the channel (Fig. 1). An algal biomass production facility will typically have many ponds. The surface area of a single pond does not usually exceed 0.5 ha, but can be larger.

Raceways generally have a flat bottom and vertical walls. If the thickness of the central dividing wall (Fig. 1) is neglected, the surface area A of a raceway such as shown in Fig. 1, can be estimated using the following equation:

$$A = \frac{\pi q^2}{4} + pq \tag{1}$$

The p/q ratio can be 10 or larger (Chisti 2012). If this ratio is too small, the flow in the straight parts of the raceway channel begins to be affected by the disturbances caused by the bends at the ends of the channel. The working volume V_L is related to the surface area and the depth h of the culture broth, as follows:

$$V_L = Ah \tag{2}$$

The surface-to-volume ratio is always $1/h$. A lower depth increases the surface-to-volume ratio and this improves light penetration, but in a large pond the depth cannot be much less than 0.25 m for reasons discussed later in this chapter.

A compacted earth construction lined with a 1–2 mm thick plastic membrane may be used for the pond, but this relatively cheap setup is uncommon for biomass production. Ponds used to produce high-value biomass are often made of concrete block walls and dividers lined with a plastic membrane to prevent seepage. Membranes made of ultraviolet resistant polyvinyl chloride (PVC), polyethylene, and polypropylene are generally used and can last for up to 20 years (Chisti 2012). Depending on the end use of the biomass, special care may be required to use liners that do not leach contaminating and inhibitory chemicals into the algal broth (Borowitzka 2005). The pond design must consider the mixing needs; the feeding and harvesting of the algal culture; the carbon dioxide input; the drainage and overflow; and the cleaning aspects. The key aspects of design and operation are discussed here.

2.2 Culture Flow in the Raceway Conduit

The flow in a raceway conduit needs to be turbulent to keep the cells in suspension, enhance vertical mixing, prevent thermal stratification, and facilitate removal of the oxygen generated by photosynthesis. Whether the flow is turbulent depends on its Reynolds number, Re, defined as follows:

$$Re = \frac{\rho u d_{\mathrm{h}}}{\mu} \tag{3}$$

In Eq. (3), ρ is the density of the culture broth, u is its average flow velocity, d_h is the hydraulic diameter of the flow conduit, and μ is the viscosity of the algal broth. Typically, the density and viscosity of water at the operating temperature are taken to closely resemble the properties of a dilute algal broth (Chisti 2012). The hydraulic diameter d_h for use in Eq. (3) is defined as follows:

$$d_{\mathrm{h}} = \frac{4wh}{w + 2h} \tag{4}$$

In Eq. (4), w is the width of the channel (Fig. 1) and h is the average depth of the broth in it.

The flow in the channel is generally taken to be turbulent if the Re value exceeds 4000; however, the threshold of turbulence in channels is poorly defined and, therefore, a higher Reynolds number of about 8000 is used as safer criterion of turbulence (Chisti 2012). The flow in a rough channel becomes turbulent at a lower

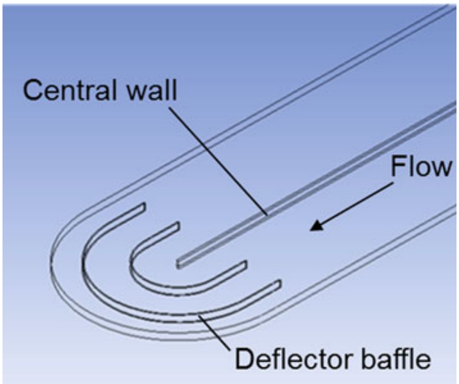

Fig. 2 A raceway pond with deflector baffles

value of Reynolds number compared to the case of a smooth channel. In practice, the average flow velocity in the channel is kept much higher than the minimum required to attain a Reynolds number value of 8000.

In ponds with semicircular ends (Fig. 1), curved baffles or flow deflectors are commonly installed at both ends (Fig. 2). The baffles ensure a uniformity of flow throughout the curved bend and minimizes the formation of dead zones (Chisti 2012). Dead zones adversely affect mixing, allow solids to settle, and cause unwanted energy losses (Chisti 2012). Other methods of preventing the development of the dead zones have been discussed in the literature (Chisti 2012; Sompech et al. 2012).

2.3 Power Consumption for Flow and Mixing

The power requirement P (W) for a paddlewheel to generate a flow of velocity u in the straight channel of a typical raceway is estimated using the following equation (Chisti 2012):

$$P = \frac{1.59 A \rho g u^3 f_{\mathrm{M}}^2}{e d_{\mathrm{h}}^{0.33}} \tag{5}$$

where A (m^2) is the surface area of the pond, ρ (kg m^{-3}) is the density of the culture broth, g (9.81 m s^{-2}) is the gravitational acceleration, d_h is the hydraulic diameter of the flow channel, f_M is the Manning channel roughness factor, and e is the efficiency of the motor, drive and the paddlewheel. Typical values of f_M are 0.012 s m$^{-1/3}$ for compacted gravel lined with a polymer membrane and 0.015 s m$^{-1/3}$ for an unfinished concrete surface (Chisti 2012). The e value is about 0.17 (Borowitzka 2005) for a paddlewheel (Fig. 3) located in a channel with a flat bottom. The hydraulic diameter d_h is calculated using Eq. (4). Equation (5) does not account for

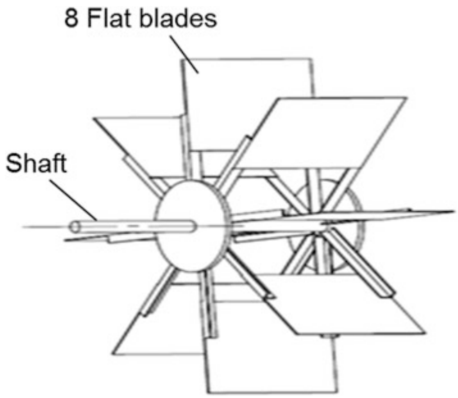

Fig. 3 A typical paddlewheel for mixing and recirculation of the broth in a raceway pond

head losses around bends, but can be used for estimating an approximate head loss in a raceway of the total channel loop length L_r (Chisti 2012).

As reflected in Eq. (5), the power required depends strongly on the flow velocity and, therefore, the flow velocity must remain at a low value that is consistent with a satisfactory operation (Chisti 2012). Although a flow velocity of 0.05 m s^{-1} is sufficient to prevent thermal stratification, a higher velocity of around 0.1 m s^{-1} is needed to prevent sedimentation of algal biomass (Becker 1994). In practice, a straight channel velocity of at least 0.2 m s^{-1} is required to ensure that the velocity everywhere in a raceway is above the necessary minimum value of 0.1 m s^{-1} (Becker 1994). Raceways for biomass production are frequently operated at a flow velocity of 0.3 m s^{-1} (Becker 1994). At this velocity, the Reynolds number in a 1.5 m wide channel with a broth depth of 0.3 m would be around 257,000.

The turnaround of the flow at the ends of the raceway contributes substantially to the total power consumption. Installation of suitably designed semicircular flow deflector baffles (Fig. 2) at the ends of the raceway is known to reduce the specific power consumption (Sompech et al. 2012; Liffman et al. 2013) relative to baffle-free operation, but contrary data have also been reported (Mendoza et al. 2013a). Design of raceway ends to minimize the power required for a given flow velocity is further discussed in the literature (Sompech et al. 2012; Liffman et al. 2013).

Under typically used conditions, the mixing of fluid between the surface and the deeper layers is poor (Chisti 2012; Mendoza et al. 2013b; Sutherland et al. 2014b; Prussi et al. 2014). This adversely affects productivity. In particular, poor mixing results in inadequate oxygen removal during period of rapid photosynthesis and an accumulation of dissolved oxygen to far above the air saturation concentration. Improving mixing substantially would require prohibitively high input of energy. Mixing requires energy and installation of devices to reduce the energy dissipation associated with the turnaround of flow at the ends of a raceway actually reduces mixing (Mendoza et al. 2013a; Prussi et al. 2014). Other measures have been suggested for improving the energy efficiency of raceway ponds (Chiaramonti et al. 2013).

Typically, the flow in raceways is characterized as being plug flow with little mixing occurring in the direction of flow. Most of the mixing occurs in the region of the paddlewheel and at the semicircular ends where the flow turns around. In a 20 m^3 raceway with a loop length of 100 m and total width of 2 m, operated at a water depth of 0.2 m, the power consumption of the paddlewheel ranged from 1.5 to 8.4 W m^{-3}, depending on the velocity of flow (Mendoza et al. 2013a). This was much greater than the range of 0.5–1.5 W m^{-3}, typical of larger commercial raceways. The 100 m raceway required between 15 and 20 flow circuits for 5 % deviation from the state of complete mixing in the configuration without the semicircular deflector baffles installed at the ends (Mendoza et al. 2013a). The mixing time ranged from 1.4 to 6 h (Mendoza et al. 2013a). With the deflector baffle installed, the mixing time was longer, with 30–40 flow circuits being required for 5 % deviation from complete mixing (Mendoza et al. 2013a). This was likely because the deflector baffles reduced the mixing potential of the semicircular ends. The specific power consumption increased if the depth of the fluid increased or decreased from 0.2 m (Mendoza et al. 2013a).

Computer simulations of pond fluid dynamics have resulted in design recommendations for minimizing energy consumption while achieving sufficient mixing to prevent sedimentation and dead zones (Sompech et al. 2012; Hadiyanto et al. 2013; Liffman et al. 2013; Prussi et al. 2014; Huang et al. 2015). The power consumption can be greatly reduced by lowering the channel flow velocity at night (Chisti 2012). The paddlewheel motor should always be sized for a flow velocity of at least 0.3 m s^{-1} and a further safety factor on power demand should be added (Chisti 2012). The motor and drive should allow a variable speed operation, unless the operational performance of a comparable raceway has been previously confirmed over an extended period (Chisti 2012). The drive mechanism should have a turndown ratio of at least 3:1 (Dodd 1986).

2.4 *The Paddle Wheel*

Paddlewheels (Dodd 1986) are generally believed to be the most effective and inexpensive means of producing flow in raceways. A raceway is typically mixed by a single paddlewheel to avoid interference between multiple paddlewheels (Dodd 1986). An eight-bladed paddlewheel (Fig. 3) with flat blades is generally used (Dodd 1986), but paddlewheels with curved blades are also in use. Other newer configurations of paddlewheels (Li et al. 2014) are being developed and may well be more efficient than the traditional paddlewheel of Fig. 3.

The raceway channel directly below the paddlewheel is generally flat, but a more efficient configuration with a curved pond bottom has been described (Dodd 1986; Borowitzka 2005; Chisti 2012). The load on the drive mechanism oscillates as the paddles of a conventional paddlewheel (Fig. 3) move in and out of the algal broth. The power demand and load oscillations may be reduced by displacing the paddles at mid channel by 22.5° (Dodd 1986). This also lowers the maintenance demands

(Dodd 1986). Paddlewheels are generally considered superior to pumps and propellers for driving the flow in a raceway pond.

2.5 Climatic and Topological Considerations

The geographic location (Dodd 1986; Oswald 1988) of a raceway-based production facility has the greatest impact on biomass productivity. The climatic conditions of the chosen location should be such that a consistently high biomass productivity is achieved throughout the year. The main factors influencing productivity are the average annual irradiance level and the prevailing temperature. Ideally, the temperature should be around 25 °C with a minimum of diurnal and seasonal variations (Chisti 2012). Other considerations are: the humidity and rainfall; the wind velocity; the possibility of storms and flood events; and the presence of dust and other pollutants in the atmosphere (Chisti 2012). Access to carbon dioxide and water of a suitable quality are important.

Freshwater is always needed to make up for evaporative loss and prevent an excessive rise in salinity (Chisti 2012). Evaporation rate depends on the local environment, especially on the level of irradiance, the wind velocity, the air temperature and the absolute humidity. An average freshwater evaporation rate of 10 L m^{-2} d^{-1} has been noted for some tropical regions (Becker 1994). This amounts to 0.01 m^3 m^{-2} d^{-1}, or 10 mm per day (Chisti 2012). The evaporation rate of seawater from a pond is generally a little less than the evaporation rate of freshwater under the same environmental conditions (Chisti 2012).

The price of land is a further factor to consider. Local topography and geology must be suitable for construction of raceway ponds (Dodd 1986).

2.6 Temperature and Productivity

The culture temperature strongly affects the algal biomass productivity and in some cases the biochemical composition of the biomass (Goldman and Carpenter 1974; Geider 1987; Raven and Geider 1988; James et al. 1989; Davison 1991). Furthermore, the daytime temperature history may affect the biomass loss by respiration during the subsequent night (Grobbelaar and Soeder 1985; Richmond 1990). Most algae grown in warm climates in raceways generally have an optimal growth temperature in the range of 24–40 °C (Chisti 2012). Optimal growth temperature typically spans several degrees, rather than being a sharply defined value.

The temperature in a raceway is governed by the sunlight regimen, evaporation, and the local air temperature. Temperature is typically not controlled, as doing so is impractical (Chisti 2012). Therefore, the temperature varies cyclically (Moheimani and Borowitzka 2007; Tran et al. 2014) with the day–night cycle and the amplitude of this cycle is affected by the season (Tran et al. 2014). In a tropical location with a uniformly warm temperature during the year and a moderate diurnal variation, a high biomass productivity can be sustained year-round in a raceway without temperature control so long as the alga being grown has been adapted for the local conditions (Chisti 2012).

In temperate regions, the length of the growing season strongly influences the average annual algal productivity (Chisti 2012). In production of high-value products, implementing some level of temperature control may be feasible by recirculating the algal broth from the raceway through external heat exchangers (Chisti 2012), but this is rarely done.

Diurnal and seasonal variations in temperature in a raceway can be modeled reasonably well (James and Boriah 2010). In a tropical climate, because of evaporation and other heat losses, the diurnal variation in temperature is generally less than 10 °C (Chisti 2012). Growth may cease at the diurnal extremes of temperature, but algae generally survive short periods at up to 40 °C (Chisti 2012). Increasing temperature typically reduces the efficiency of photosynthesis as the rate of respiration increases faster with temperature compared to the rate of photosynthesis (Davison 1991; Pulz 2001).

2.7 The pH and Carbon Supply

Algal biomass typically contains 50 % carbon by weight. All carbon in photoautotrophically grown biomass comes from carbon dioxide or dissolved carbonate. Stoichiometrically, therefore, about 1.83 tons of carbon dioxide is needed to produce a ton of algal biomass (Chisti 2007). If carbon dioxide is consumed rapidly and not replenished, the pH becomes alkaline. A pH rise during periods of peak photosynthesis is commonly seen in raceways (Becker 1994; García et al. 2006; Moheimani and Borowitzka 2007; Craggs et al. 2014; Sutherland et al. 2014a) and is an evidence of carbon limitation. Carbon dioxide absorption from the atmosphere through the surface of a raceway is entirely insufficient to support photosynthesis during sunlight. This carbon deficit is accentuated during peak sunlight periods. A supply of carbon dioxide is necessary to avert carbon limitation and attain high biomass productivity. Carbon dioxide can be effectively supplied in response to a pH signal. The pH should be controlled well below eight by injecting carbon dioxide. An alkaline pH is not wanted as it results in generation of toxic ammonia from dissolved ammonium salts and this inhibits algal productivity. The generation of ammonia as a consequence of inadvertent rise in pH is best prevented by using nitrate as the source of nitrogen, although algae use ammonium more readily than nitrate. The carbon dioxide supply system should be designed to effectively control the pH during peak demand periods of high irradiance (Chisti 2012).

Microporous gas diffusers (Fig. 4) are used in raceways to provide carbon dioxide in the form of fine bubbles (Chisti 2012). Carbon dioxide diffusers are placed at intervals along the flow path at the bottom of the raceway channel (Chisti 2012). The diffusers should be easily removable from the gas distribution tubing for

Fig. 4 A microporous gas diffuser for dispersing carbon dioxide in a raceway culture. Courtesy of Mott Corporation, Farmington, CT, USA

cleaning and replacement (Chisti 2012). Between 35 and 70 % of the pure carbon dioxide sparged into a pond is lost to the atmosphere (Weissman et al. 1989). This translates to a significant monetary loss (Chisti 2012). For algae that grow at alkaline pH, inorganic carbon may be supplied as bicarbonate (Chi et al. 2011). Doing so may potentially reduce the cost of providing carbon (Chi et al. 2011). Growth under alkaline pH may not be possible for oceanic algae as marine salts precipitate at pH values of >8 (Chisti 2012). In most cases, the carbon dioxide supplied is actually taken up by the alga as bicarbonate.

Carbon dioxide requirements can be estimated from the expected biomass productivity of the raceway, accounting for the inevitable losses to the atmosphere as previously discussed (Chisti 2012). The demand for carbon dioxide varies with the rate of photosynthesis which is controlled by the irradiance. Therefore, the best strategy to ensure a sufficiency of carbon and minimize loss is to inject carbon dioxide in response to a signal from a pH controller (Chisti 2012). Periodic injection without automatic pH control may be feasible, depending on historical experience with a given alga and location (Becker 1994).

In principle, a suitably pretreated flue gas resulting from burning of fossil fuels can be used to provide relatively cheap carbon dioxide for growing microalgae, but most commercial algae production operations do not use it. Desulfurized flue gas from a coal fueled electric power plant typically contains 12–14 % carbon dioxide by volume, the rest being mostly water vapor and nitrogen (Chisti 2012). The flue gas must be free of heavy metals (Chisti 2012). Cooled desulfurized flue gas is a satisfactory source of inorganic carbon, but the flow rates required are substantially greater than if pure carbon dioxide is used (Chisti 2012). This is because absorption of carbon dioxide from flue gas into water is slower than absorption from pure carbon dioxide. Successful use of flue gas from diesel powered boilers has been reported for growing algae (de Godos et al. 2014; Tran et al. 2014). If carbon dioxide is fed in the form of flue gas, the loss to atmosphere is expected to be well above 80 % (Chisti 2012) although this may be reduced substantially by controlled feeding using a well-designed supply system (de Godos et al. 2014). Carbon dioxide absorption rate is pH dependent and is reduced at pH values less than 8. At

25 °C, the solubility of carbon dioxide in seawater is nearly half of its solubility in freshwater and this need to be considered in photoautotrophic production of marine algae (Chisti 2012).

2.8 Oxygen Inhibition of Production

Photosynthesis generates oxygen and is inhibited by an accumulation of dissolved oxygen in the culture broth (Shelp and Canvin 1980; Suzuki and Ikawa 1984; Molina et al. 2001). Other than agitation by the paddlewheel, no oxygen removal mechanism is used in a typical raceway. In some cases, the culture may be sparged with air to control buildup of oxygen. Despite a high surface area relative to the culture depth, the oxygen removal from raceway ponds is poor (Chisti 2012; Mendoza et al. 2013b) and the dissolved oxygen concentration increases dramatically during periods of peak photosynthesis. The paddlewheel assists with oxygen removal, but is mostly ineffective. As a result, the broth undergoes a diurnal change in concentration of dissolved oxygen (García et al. 2006; Moheimani and Borowitzka 2007). During peak sunlight, the level of dissolved oxygen may exceed 300 % of the level in air saturated water (Richmond 1990; Moheimani and Borowitzka 2007). Such high levels of dissolved oxygen can reduce the rate of photosynthesis (Becker 1994; Molina et al. 2001) and adversely affect the biomass productivity (Mendoza et al. 2013b). The composition of the algal biomass may also be affected by the concentration of dissolved oxygen (Richmond 1990).

Sparging of the pond with air may reduce the oxygen inhibition of photosynthesis, but requires energy. The energy associated with this sparging has been claimed to be compensated by improved biomass productivity made possible by a reduced inhibition by oxygen (Mendoza et al. 2013b). For a given fluid depth, a relatively small pond achieves better oxygen removal than a larger pond. This is because the proportion of the zone of good mixing and mass transfer in the vicinity of the paddlewheel is larger in a small pond compared to a larger one. This explains the sometimes reported better productivity of small ponds relative to the equally deep larger ponds placed under the same climatic conditions.

2.9 Culture Contamination

Open ponds are exposed to rain, dust, and other debris. Ponds may be placed within greenhouses, but this is not feasible for facilities occupying large areas. Other contamination issues include infestations of predators feeding on algae (Turner and Tester 1997; Richmond 1990); viral infections (Van Etten et al. 1991; Van Etten and Meints 1999; Wommack and Colwell 2000); and contamination by unwanted microalgae (Richmond 1990), fungi, and bacteria. The low peak alga concentration in a raceway accentuates the effects of predators and other unwanted microorganisms (Chisti 2012). Filtration of water may help reduce the frequency of certain types of infestations, but filtration is expensive. The typically used microfiltration does not prevent contamination with viruses (Chisti 2012). Management practices can be used to reduce the frequency of culture contamination and failure (Chisti 2012). Predator control in raceways is potentially possible (Lass and Spaak 2003; Borowitzka 2005; Van Donk et al. 2011), but has not received much attention (Chisti 2012). Contamination with heterotrophic bacteria is inevitable (Erkelens et al. 2014) and not necessarily harmful, but may necessitate implementation of specific controls depending on the final application of the alga being grown.

2.10 Dependence of Photosynthesis on Culture Depth

Growth is driven by photosynthetically active radiation, or PAR, the component of the sunlight that is within the wavelength range of 400–750 nm. Although the peak sunlight level at solar noon at the surface of a raceway in a tropical location may be as high as 2000 μE m^{-2} s^{-1}, photosynthesis saturates at roughly 10–20 % of the peak PAR value. Therefore, the rate of photosynthesis does not increase beyond a PAR value of about 100–200 μE m^{-2} s^{-1} (Chisti 2012) and all the excess light is wasted. Nevertheless, an increasing incident irradiance level generally increases raceway productivity, as the local irradiance level in the broth declines rapidly with culture depth and a high surface irradiance generally means a larger illuminated culture volume.

Algal cultures become photoinhibited once the PAR value exceeds the saturation threshold. In a photoinhibited culture, the rate of photosynthesis actually decreases with a further increase in irradiance. During peak light, the culture near the surface of a pond is photoinhibited, but deeper layers of a dense culture are light limited. If the pond is sufficiently deep, or the culture sufficiently dense, the light will not penetrate the entire depth. In fact, most of the depth of a dense raceway culture is optically dark and contributes nothing to photosynthesis. Photosynthesis stops once the irradiance level declines to the light compensation point. The biomass at and below the light compensation point, consumes itself by respiration.

For a fixed incident light level I_o on the surface of the raceway, the irradiance declines rapidly with depth as the light is absorbed by the cells. The local irradiance I_L, at any depth L from the surface, is estimated by the following equation (Chisti 2012):

$$I_{\mathrm{L}} = I_{\mathrm{o}} e^{-K_{\mathrm{a}} C_x \mathrm{L}} \tag{6}$$

In the above equation, K_a is the alga-dependent light absorption coefficient of the biomass and C_x is the concentration of the biomass. The strong decline in local irradiance with depth is shown in Fig. 5 for various values of the biomass concentration in the culture.

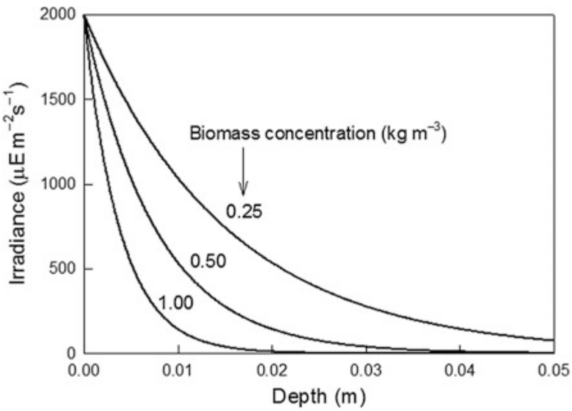

Fig. 5 Irradiance variation with depth in a 0.3 m deep raceway at various concentrations of the algal biomass in the broth. The local irradiance profiles were calculated for an alga with a K_a value of 2.632 μE m^{-2} s^{-1} and an incident irradiance of 2000 μE m^{-2} s^{-1} at the surface of the raceway

In a typical culture at a peak biomass concentration of about 0.5 kg m^{-3}, more than 80 % of the culture volume in a raceway is in the dark at solar noon. That is, the biomass in all this volume is actually consuming itself rather than photosynthesizing. In the same raceway, less than 4 % of the culture volume is photoinhibited; less than 3 % of the volume is light-saturated; and about 9 % of the culture volume is light limited (Chisti 2012).

2.11 Specific Growth Rate

The specific growth rate of a microalga in a pond varies with depth because the light intensity declines with depth (Fig. 5). If light is the only growth limiting factor, the specific growth rate μ_L at any depth L can be estimated from the local value of irradiance I_L (Eq. 6) at that depth (Chisti 2012). For example, the local growth rate may depend on local irradiance in accordance with the Haldane light-inhibited growth model, as follows:

$$\mu_{\mathrm{L}} = \frac{\mu_{\max} I_{\mathrm{L}}}{K_{\mathrm{L}} + I_{\mathrm{L}} + I_{\mathrm{L}}^2/K_{\mathrm{i}}} \tag{7}$$

where $\mu_{\max}$ is the maximum specific growth rate, K_L is the light saturation constant, and K_i is the photoinhibition constant. The values of the constants $\mu_{\max}$, K_L, and K_i depend on the alga and the culture temperature (Richmond 1990).

The depth-averaged specific growth rate μ_{av} in the illuminated volume of the pond may now be estimated (Chisti 2012), as follows:

$$\mu_{av} = \frac{1}{L}\int_0^L \mu_L \mathrm{d}L \tag{8}$$

or

$$\mu_{av} = \frac{1}{L}\int_0^L \left(\frac{\mu_{\max} I_L}{K_L + I_L + I_L^2/K_{\mathrm{i}}}\right)\mathrm{d}L \tag{9}$$

where L is the distance from the surface. Equation (8) is applicable so long as $L \leq l_c$ where l_c is the depth at which the local irradiance level is at the light compensation point (Chisti 2012). If the pond has a dark zone, the self-consumption of the biomass will occur in this zone and the actual average specific growth rate will be lower than the value calculated using Eq. (9).

So long as all the nutrients are provided in excess and the temperature and pH are satisfactory, the productivity of biomass depends only on the availability of sunlight. Light enters the pond only through its exposed surface. The light available per unit volume of culture declines if the depth of the culture is increased. Therefore, shallower ponds are more productive than deeper ponds so long as the growth is exclusively photoautotrophic.

Unfortunately, in a raceway spanning a large area, achieving a culture depth of less than about 0.25 m is impractical as a small tilt of the bottom relative to the horizontal causes a large difference in depth in different parts of a large pond. A perfectly flat bottom is difficult to construct. In addition, to drive the circulation, the paddlewheel must create a hydraulic pressure gradient, so that the depth of fluid in front of the paddlewheel is higher than the depth behind the paddlewheel (Chisti 2012). If the static depth of the culture is too small, the region behind the paddlewheel could become too shallow for stable recirculation to occur.

2.12 Cost of Construction and Operation

Plastic lined earthen raceways are apparently the least expensive to build. Unlined earthen ponds are used in wastewater treatment operations, but not generally considered satisfactory for producing algal biomass (Chisti 2012). For a 100 ha plastic lined pond of compacted earth, a construction cost of \$69,500 per ha has been estimated (Benemann et al. 1987). This historical cost data corrected for inflation (Chisti 2012) provides a reasonable estimate of the current cost. A cost of \$144,830 per ha was estimated for 2014. This estimate included the earth works, the plastic lining, the carbon dioxide supply tubing, inlets and outlets, the baffles, the paddlewheel and motor (Benemann et al. 1987). The cost would be higher if, for example, the ends of the raceway and the dividing baffle are designed to eliminate dead zones

(Chisti 2012; Sompech et al. 2012). Plastic lined concrete ponds are significantly more expensive than the plastic lined compacted earth ponds (Chisti 2012). For a 5 ha, 0.35 m deep, unlined pond of compacted earth, intended for use in wastewater treatment, an installed cost of NZ$89,600 (June, 2009) per ha has been reported (Craggs et al. 2012). In 2014, such a pond would cost US$74,260 per ha. This includes the earth works, the carbon dioxide distribution piping, the flow deflector end baffles, the pH controller and valves, the paddlewheel, and the motor.

Ponds enclosed in glass houses or plastic-covered greenhouses are relatively protected from contamination compared to open ponds and allow a better control of the growth environment (Chisti 2012). Such ponds may be suitable for high-value low-volume products such as nutraceuticals and have been commercially used (Becker 1994; Lee 1997).

The cost of producing dry *Dunaliella* biomass in outdoor commercial raceway ponds in Israel has been estimated to be about $18/kg (Ben-Amotz 2012). This included the cost of purchasing the carbon dioxide, recovering the algal biomass from the broth by continuous flow centrifugation in disc-stack centrifuges and subsequent drying of the biomass paste. Both drying and biomass recovery by centrifugation tend to be expensive (Chisti 2012). This notwithstanding, when applicable, the raceway-based production of biomass is generally claimed to be the least expensive production option.

3 Biomass Production in Raceways

A raceway may be operated as a batch culture, or a pseudo steady state continuous culture. In a batch process, the nutrient medium is placed in the raceway and inoculated with a culture of the chosen alga. The inoculum generally constitutes about 10 % of the operating volume of the raceway. The inoculum is generally grown (Fig. 6) in the same medium as used in the raceway and is in exponential

Fig. 6 An early monoseptic stage of production of an algal inoculum for a small raceway

phase of growth just prior to inoculation. The biomass concentration in the inoculum is generally at least 0.5 kg m^{-3} if the inoculum has been produced in a raceway. Often, the concentration is much higher if a photobioreactor is used to produce the inoculum. Multiple inoculum generation stages may be necessary for inoculating a large raceway. Other than carbon dioxide, air for possible oxygen removal, and the makeup water, nothing is added to the raceway during a batch operation. The biomass grows to peak concentration of about 0.5, or 1 kg m^{-3} in the best of circumstances (Borowitzka 2005). Productivity is enhanced by periodic dilution of the raceway culture to maintain the biomass concentration at less than the typical maximum value. Dilution improves light availability in the raceway.

In a sunny locale with a stable diurnal temperature of ~25 °C, an alga capable of rapid growth can attain an average annual dry biomass productivity of around 0.025 kg m^{-2} d^{-1} in a well-operated raceway (Chisti 2012; Mendoza et al. 2013a), but higher daily productivities have been recorded (Terry and Raymond 1985; Grobbelaar 2000; Moheimani and Borowitzka 2007) during suitable weather conditions. Biomass productivities in excess of 0.05 kg m^{-2} d^{-1} have been documented (Weissman et al. 1989). Of course, not all algae are equally productive (Chisti 2012). In mixotrophic growth as is commonly encountered in high-rate algal ponds treating wastewater (Craggs et al. 2012, 2014), dissolved organic compounds contribute to growth leading to a generally higher productivity than is possible with purely photoautotrophic growth. For example, in a 0.2 m raceway pond operated mixotrophically, Sing et al. (2014) observed a peak dry biomass productivity of 37.5 kg m^{-2} d^{-1} over an extended period.

A photoautotrophic culture requires supplementation with carbon dioxide to attain high biomass productivity. The carbon dioxide in the ambient atmosphere is insufficient to support productivities that are biologically feasible under otherwise nonlimiting conditions. In the ambient atmosphere without supplemental inorganic carbon, the productivity in a raceway may be <13 % of the productivity likely to be possible with an unlimited supply of inorganic carbon (Raes et al. 2014). The peak biomass productivity attainable in a typical non-limiting raceway is far lower than the limit imposed by the algal biology (Chisti 2012).

Although high biomass productivities are biologically attainable, vagaries of weather influence an exposed raceway so much so that the maximum annual average productivity may be reduced to only 0.01 kg m^{-2} d^{-1}, or less (Chisti 2012). As a result, a raceway can take 4–6 weeks from inoculation to attain the peak biomass concentration of around 0.5 kg m^{-3} (Pulz 2001). Once the peak biomass concentration is attained, all or most of the broth may be harvested in a batch process to recover the biomass (Chisti 2012). The residual broth may become the inoculum for the next batch, or an entirely fresh batch may be initiated after the raceway has been cleaned (Chisti 2012).

A continuous culture generally begins as a batch operation. Once the algal biomass has grown to a sufficient concentration, the operation is switched to a continuous flow mode. In continuous culture, the raceway is fed with the fresh medium at some specified flow rate. The feed point is typically located just forward of the paddlewheel. During feeding, the algal broth is withdrawn, or harvested, from the raceway at a rate equal to the feed flow rate. Feeding and harvesting occur only during daylight and must stop at night, or the biomass may washout out of the raceway overnight. Prolonged continuous culture operation under stable weather and day–night cycle allows a pseudo steady state biomass concentration to be maintained in the raceway (Chisti 2012). The daytime feed flow rate Q_f must be such that the dilution rate D remains below the maximum specific growth rate ($\mu_{\max}$) of the alga under the specific conditions of operation of the raceway (Chisti 2012). The culture will washout if the dilution rate exceeds the maximum specific growth rate. The dilution rate D is calculated as follows:

$$D = \frac{Q_{\mathrm{f}}}{V_L} \tag{10}$$

where V_L is the working volume of the raceway.

Irrespective of whether batch or continuous operation is used, up to 25 % of the biomass produced by the end of a daylight period may be consumed during the following night through respiration (Chisti 2012). The magnitude of this respiratory loss depends on the irradiance level during growth, the daytime temperature of growth, and the temperature during the night (Grobbelaar and Soeder 1985; Richmond 1990).

3.1 Biomass Productivity

The biomass productivity of a culture system is a measure of its ability to produce biomass. Productivity may be expressed either in volume terms, or in terms of the surface area of the culture pond. In a batch culture, the volumetric productivity (P_v, kg m^{-3} d^{-1}) of the biomass is determined as follows:

$$P_{\mathrm{v}} = \frac{X_{\mathrm{f}} - X_{\mathrm{i}}}{\Delta t} \tag{11}$$

where X_i (kg m^{-3}) is the initial concentration of the biomass, X_f (kg m^{-3}) is the peak concentration of the biomass, and Δt (d) is the time interval between inoculation and the attainment of the peak biomass concentration (Chisti 2012).

In a continuous flow operation, the volumetric productivity of the biomass is calculated using the following equation (Chisti 2012):

$$P_{\mathrm{v}} = \frac{Q_{\mathrm{f}} x_{\mathrm{b}}}{V_L} \tag{12}$$

where Q_f is the flow rate of the feed to the pond, x_b is the pseudo steady state biomass concentration in the broth leaving the raceway and V_L is the volume of the broth in the raceway.

The areal biomass productivity (P_a, kg m^{-2} d^{-1}) and the volumetric productivity (P_v, kg m^{-3} d^{-1}) of a raceway are related as follows (Chisti 2012):

$$P_{\mathrm{v}} = \frac{P_{\mathrm{a}}}{h} \tag{13}$$

where h is the depth in m. Productivity is high in a dilute culture, but declines rapidly as the biomass concentration increases. The maximum attainable biomass concentration in a raceway is of the order of 0.5–1.0 kg m^{-3}.

4 Concluding Remarks

Large-scale commercial production of algal biomass generally relies on open raceway ponds. This chapter outlined the raceway pond design, operation, and limitations. Raceway ponds require a relatively low investment in capital and, therefore, remain the production system of choice despite their low productivity.

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