# Comprehensive Evaluation of High-Rate Algal Ponds: Wastewater Treatment and Biomass Production

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**3 authors:**


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National Institute of Hydrology
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# Comprehensive Evaluation of High-Rate Algal Ponds: Wastewater Treatment and Biomass Production

**Shashi Ranjan, Pankaj Kumar Gupta, and Sanjay Kumar Gupta**

## 1 Introduction

HRAPs are shallow and open raceway ponds that have been used for wastewater treatment using algal species. High-rate algal ponds (HRAPs) offer self-sustainable prospects for high-efficiency wastewater treatment and value-added material and energy recovery, as well as biomass production (Park et al. 2011). As of now, thousands of communities, industries, and farms globally use HRAPs systems for wastewater treatment along with algal biomass production (Pittman et al. 2011). HRAP is gaining more attention of the scientific community and industrial practitioners to implement it for concurrent treatment of wastewater and biomass productions. Further, some key merits of this system established more space among other techniques: (1) high pollutant removal efficiency, (2) high rate of nutrient uptake/sink, (3) low cost of implementation and little maintenance, and (4) high biomass production for biofuels, i.e., produce >20 times more oil per hectare than terrestrial oilseed crops. Initially, Oswald and Golueke (1960) proposed simultaneous production of algal biofuels and wastewater treatment using HRAPs. With time the efficiency of HRAPs has been improved by incorporating the advanced facultative ponds, HRAPs, algal settling ponds, and maturation ponds (Craggs, 2005). Generally, the design of the HRAPs depends on the pollutant loads and biological oxygen demand (BOD) removal. Furthermore, the algal growth and photosynthetic activity under different environmental conditions are important to meet the maximum pollutant removal efficiency and high biomass productions. The crucial environmental (light,

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S. Ranjan · P. K. Gupta
Department of Hydrology, Indian Institute of Technology Roorkee,
Roorkee, Uttarakhand, India

S. K. Gupta (✉)
Environmental Engineering, Department of Civil Engineering,
Indian Institute of Technology – Delhi, New Delhi, Delhi, India

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temperature, etc.), operational (pH, $CO_2$ concentration, and nutrient level), and biological (species diversity of zooplankton, phytoplankton, pathogens) parameters significantly affect the removal efficiency and biomass productions (Torzillo et al. 2003). To accelerate the removal efficiency, generally the controlled conditions are maintained in and around HRAPs by providing appropriate temperature, light, pH, nutrient, additional $CO_2$, and so on. The optimal temperature conditions help to accelerate microbial growth inside the HRAPs along the algal growth. The optimal temperature measured under conditions of maximum algal growth rate varies between algal species but is often between 28 °C and 35 °C for many algae. Increased carbon availability is ensured by the addition of $CO_2$ in the HRAPs to maintain the optimal pH (7.5–8.5) for algal and bacterial growth. Likewise, the light conditions affect photosynthetic activities of algal species (Park and Craggs, 2010). To compensate for the limitation of the nutrient availability, generally fertilizer is added in commercial HRAPs systems. Hence, the optimum and sustainable production of microalgae subsequently with wastewater treatment in HRAPs can be attained by overcoming the limiting conditions and through the control of algal grazers and pathogens.

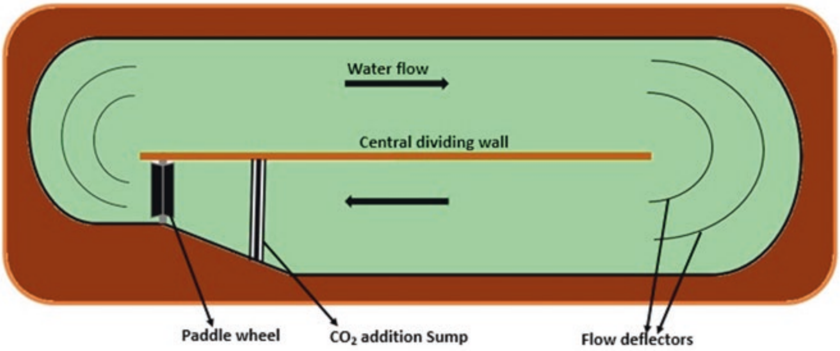
A better understanding of the governing mechanisms involved in HRAPs system is required to treat diverse wastewater and biomass production. Both fundamental and field-scale research is needed to optimize algal production and harvest from wastewater treatment HRAPs while maintaining high effluent water quality. In this chapter, a state-of-the-art review of literature is presented to understand the design, governing process of HRAPs system, and role of different environmental/operational parameters on its performance. Effective implementation of HRAPs system will lead to the production of value-added products like potash in the near future. This chapter may help to frame research work related to improvement/implementation of HRAPs system for effective wastewater treatment and biomass production for fertilizers, feeds, and biofuels.

## 2 Design of HRAPs

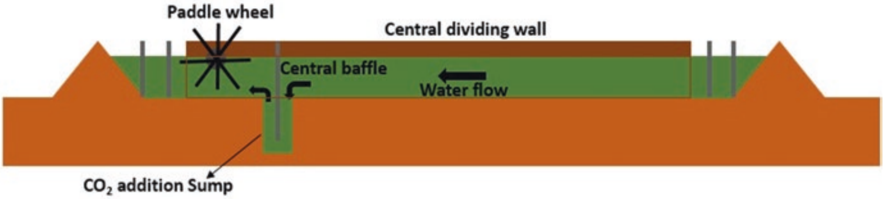
HRAP is an open pond system generally installed in the outdoor area to maintain natural sunlight, referred to as raceway ponds. Some advantages of this pond are (1) low investment and operational costs, (2) easy to maintain, (3) utilizing nonagricultural land, (4) low-energy inputs, and (5) low hydrodynamic stress on algae. HRAPs have shallow configurations to prevent light limitations to algal culture. First, the concern in the design of HRAPs system is to select an area having the low impact of rainfall or flood to prevent dilution of culture. Solar power radiation an important factor for the photosynthetic activity of algal cells which is a minimum of 4.65 kW h $m^{-2}$ $d^{-1}$ is found necessary for algal cultivation in open raceway ponds. Further, the slopy lands having slope more than 5% are usually not suitable for pond construction as they will alleviate the construction cost (Bennett et al. 2014). The depth of HRAPs is crucial for energy efficiency of ponds, and it has been reported that the shallow ponds are highly efficient with higher biomass production. Several factors including the depth of HRAPs, presence of baffles, and paddle wheel speeds affect the power consumption, which generally ranges 1.5–8.4 W $m^{-3}$ (Mendoza et al. 2013). Cell mixing in HRAPs is a crucial factor for the optimal growth of microalgae; it provides periodic light exposure to the cells and helps in homogeneous dispersion of nutrient and cells and the removal of oxygen generated. Usually the C/N ratio of algal cells is much higher than the incoming wastewater; thus the addition of $CO_2$ is recommended for higher production (Brennan and Owende 2010). The increasing pH promotes the higher $CO_2$ absorption rate in HRAPs; generally the pH in open ponds ranges from 7 to 8 (González et al. 2012). The design of HRAPs depends on the scale, pollutant loads, BOD removal, climatic conditions, etc. Generally, the HRAPs are of two types, i.e., raceway ponds and circular ponds. In recent years, with the advancement of instrumentation and research capabilities, several enhancements have been demonstrated and proposed for higher algal production. The focus of such modification was on enhancing the mixing efficiency and residential times of $CO_2$/gas bubbles, etc. (Brennan and Owende 2010). The basic design of HRAPs is highlighted in Table 1 and shown in Fig. 1.

**Table 1** Summary of the design of HRAPs used in wastewater treatment

| HRAPs types | Advantage | Mixing processes | Remarks |
|---|---|---|---|
| HRAPs with manual mixing | Manual mixing raceway ponds is effective if the algal species are well grown in pH >10 conditions | Nonmechanical | Limited nutrient and pathogen removal |
| Paddle wheel-driven HRAPs | Paddle wheel creates eddies which help to mix algae from the bottom to top circulation | Mechanically by paddle wheels | Boxlike shape was found to be the optimum in terms of energy utilization and losses and enhances the mixing (Liffman et al. 2013) |
| Sump-/baffle-/airlift-assisted HRAPs | Countercurrent injection of $CO_2$ to increase the liquid/gas contact time | Sump-assisted HRAPs do not require external energy to maintain the flow | These systems increase the gas/liquid contact time and the dissolution and utilization of $CO_2$ |
| Hybrid raceway ponds | Dual system of photobioreactor and open pond system for enhanced growth | Mechanically | By utilizing the dual system, both the systems complement each other by harnessing the benefits and eliminating the demerits |



(a) Paddle wheel HRAP



(b) Side elevation view

**Fig. 1** Schematic diagram of HRAPs generally used in wastewater treatments. (**a**) Paddle wheel HRAP. (**b**) Side elevation view

## 3 Wastewater Treatment in HRAPs

The activated sludge treatment is one of the most extensively used traditional approaches for secondary wastewater treatment so far. In conjugation with anaerobic treatment, activated sludge treatment can be applied effectively to various types of wastewater, albeit there are environmental as well as economical concerns with it like external supply for $O_2$ for aeration as well as it lacks in the recycling of nutrient. With the increasing concerns over water scarcity and energy security, the HRAPs are the promising technology as they offer a sustainable and energy-efficient system for wastewater treatment (Kim et al. 2014). The HRAPs are basically a well-mixed shallow pond system which is designed to enhance and optimize the algal growth for a high-rate wastewater treatment. Constant mixing through paddle wheel is essential for algal culture circulation and to prevent the sedimentation of biomass. The HRAP is based on the symbiotic relationship between microalgae and bacteria, in which the oxygen required for organic matter decomposition by bacteria is provided by photosynthesis of algae and the nutrient for algal growth provided by bacterial decomposition of organic matter (Garcia et al. 2000). The algal biomass generated during the wastewater treatment can be harvested for the biofuel production, and it increases the commercial viability of HRAPs (Table 2).

**Table 2** Comparisons of general wastewater treatment system and HRAPs wastewater system

| Factors | General WWT system | HRAPs WWT | References |
|---|---|---|---|
| *Economical aspects* | | | |
| Capital cost | High (to develop multistage reactors) | Low (minimal infrastructures) | Park et al. (2011); Mehrabadi et al. (2015) |
| Operational/ maintenance cost | High (mainly due to aeration) | Low (maintained by algal by-product) | |
| Commercial applicability | Low | High (production of algal biomass for bioenergy) | |
| *Environmental aspects* | | | |
| Water footprint | Significant | None | Mehrabadi et al. (2015) |
| Risk of contamination | High (if advance processes are not working properly) | Less (generally pathogens are not removable) | Cuellar-Bermudez et al. (2017) |
| Nutrient management | Low (no uptake) | High (due to algal uptake) | Bashar et al. (2018) |
| *Social aspects* | | | |
| Acceptance | Rare in rural and remote areas | Easy and has potential for rural and remote area | Efroymson et al. (2017) |

## 3.1 *Mechanism of Nutrient Removal in HRAPs*

The aerobic bacterial degradation of organic compound and nutrient removal by microalgae is a complex and mutualistic process between algae and bacteria. Microalgae can grow photosynthetically even in harsh conditions while assimilating nutrients (nitrogen and phosphorus) to produce huge amount of algal biomass. The photosynthetic aeration of wastewater in HRAPs by algae is beneficial in terms that it provides oxygen to the heterotrophic bacteria and prevent the eutrophication of aquatic environment (Delgadillo-Mirquez et al. 2016). The bacterial population takes up oxygen and facilitates the aerobic degradation of the organic matter while releasing $CO_2$ which is utilized in the photosynthesis of microalgae. Microalgae play a central role in nutrient removal either by direct assimilation of nitrogen or by indirect volatilization of ammonia and precipitation of phosphorus with increased pH due to photosynthetic growth of algae (Delgadillo-Mirquez et al. 2016). The nutrient uptake by microalgae depends on the biomass concentration of elements in the algae; for example, nitrogen uptake by microalgae is higher than phosphorus due to the fact that the nitrogen content for algal biomass is higher than phosphorus (Malik 2002; Whitton et al. 2015). The effectiveness of HRAPs over convention methods has been extensively reported. The nutrient removal process will be elaborated in the upcoming subheadings.

## Nitrogen Removal

Nitrogen is one the constituents of wastewater that is largely responsible for eutrophication of aquatic environment, mainly because the convention treatment systems are unable to remove it below the permissible limit before discharging. Algal ponds have received so much attention due to their nutrient removal capacity. In HRAPs the nitrogen can be removed directly (nitrification/denitrification) as well as indirectly (volatilization/sedimentation) by the growing biomass of microalgae. Wastewater receives influent having high nitrogen content mainly in the form of ammonium nitrogen. High availability of $(NH_4^+ - N)$ leads to the nitrification by the autotrophic bacteria, in a two-step oxidation of ammonium: first it oxidizes to nitrite, and later nitrite oxidizes to nitrate. The most common genera of bacteria involved in the oxidation process are *Nitrosomonas* and *Nitrobacter*. The nitrate will further be used by microalgae present in the suspension. Nitrogen is one of the major constituents in the living matter, present in the form of organic nitrogen (peptide, proteins, DNA, etc.) derived from the inorganic form (nitrite, nitrate, ammonium). The process of conversion from inorganic nitrogen to organic nitrogen is termed as assimilation. During the process, the inorganic nitrogen (nitrate and nitrite) is translocated through the plasma membrane of microalgae and reduced to ammonium to finally get incorporated into amino acid (Cai et al. 2013). The overall nitrogen assimilation is a two-step process: initially the nitrate is transported into the cell where the nitrate reductase enzyme reduces nitrate to nitrite, and further nitrite is transported into the chloroplast and subsequently reduced to ammonium by nitrite reductase enzyme (Fig. 2). The resulted ammonium then is incorporated into amino acid by glutamate synthase (Sanz-Luque et al. 2015). Wastewater contains a

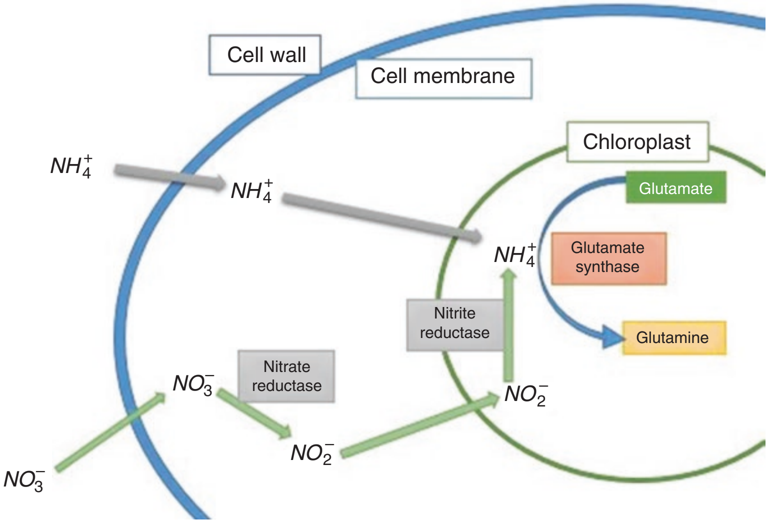


**Fig. 2** Nitrogen assimilation by algal cell

high amount of ammonium available for microalgae, and most of the algal species prefers ammonium over nitrate because it requires less energy for ammonium assimilation. Ammonium is directly translocated into the algal cell and incorporated into amino acid by glutamate synthase for protein formation.

A large part of nitrogen removal from wastewater occurs through indirect means by ammonia striping mainly because of change in pH and temperature.

$$NH_4^+ + OH^- \rightleftharpoons NH_3 + H_2O \tag{1}$$

In the daytime, due to microalgae photosynthesis, the $CO_2$ and carbonate ion concentrations decreases, results in higher pH (>9) of wastewater, and the raised temperature due to diurnal change, which leads to ammonium ($NH_3 - N$) striping. With increasing pH (>7), the equilibrium shifts to the right in Eq. 1, with production of $NH_3$ gas (Martínez 2000). Garcia et al. (2000) have reported ammonium ($NH_3 - N$) striping as high as 60% due to the combination of raised pH and temperature and based on that suggested it as the main mechanism of nitrogen removal in HRAPs. They have also reported the total nitrogen removal of 73% in which 47% by ($NH_3 - N$) striping and 26% by algal assimilation and further separation.

## Phosphorus Removal

Wastewater contains phosphorus in three forms: orthophosphate (Ortho-P), polyphosphates, and organic phosphorus compounds. The latter two forms of phosphorus are hydrolyzed and decomposed, respectively, to Ortho-P, which constitutes 80% of the total phosphorus in wastewater. At normal pH, $HPO_4^{-2}$ is the principal form of Ortho-P. In the presence of carbonate salt of calcium, magnesium, and other metal salts at higher pH (>8), the Ortho-P precipitates as the insoluble complexes (Nurdogan and Oswald 1995). The induced precipitation of Ortho-P by the addition of metal salts is termed as auto-flocculation. Phosphorus assimilation by microalgae is essential in terms that it is needed for phospholipids and nucleic acid synthesis and for the energy transfer in the cell. Phosphorus, preferably in the form of $H_2PO_4^-$ and $HPO_4^{-2}$, gets across the plasma membrane through active transport (Whitton et al. 2015). The Ortho-P is incorporated into the nucleotides by going through a three-step process: (a) phosphorylation, (b) oxidative phosphorylation, and (c) photophosphorylation. At the end of these processes, ATP (adenosine triphosphate) is formed from ADP (adenosine diphosphate). As compared to nitrogen, the phosphorus assimilation is quite low due to the reason that phosphorus content in algal biomass is less than nitrogen. The nutrient removal from animal waste through HRAPs shows nitrogen removal of 78% over the phosphorus removal of 54% (Fallowfield et al. 1999).

### BOD Removal

A major part of wastewater consists of organic material (proteins, carbohydrates, oil, and fats) which requires oxygen to get degraded by bacteria aerobically. Oxygen provided by microalgae photosynthesis is used by bacterial consortia to oxidize the organic content to generate energy for cell synthesis and maintenance (Batten et al. 2013). BOD removal of 50–80% was reported by Craggs et al. (2012) without $CO_2$ addition in a pilot-scale HRAPs having influent BOD of 63 gm/m$^3$ of wastewater. In a mixed algal pond system, heterotrophic microalgae use organic carbon as a carbon source for their cellular growth, enhancing the BOD removal (Gonçalves et al. 2017). Apart from the nitrogen and phosphorus, microalgae can also take up the dissolved metals in aqueous phase, which was demonstrated by Oswald (1988). Majority of heavy metals like iron, zinc, cobalt, chromium, nickel, etc. can get accumulated in algal biomass. Uptake of some toxic metal limits the use of algal biomass as food supplements.

## 4 Production of Algal Biomass in HRAPs

The effectiveness of HRAPs as a wastewater treatment system at different scales has been reported and demonstrated in literature extensively (Craggs et al. 2012; Garcia et al. 2000). Algal farming is considered to be beneficial over the traditional agricultural crops due to high growth rates, less requirement of land and water, and ability to grow over the year. Algal biomass production in HRAPs for fertilizers, feed, and feedstocks for biofuel production is an additional advantage, and this makes it an economical and sustainable option for wastewater treatment. Most of the algal biomass for biofuel production is produced from the open raceway algal ponds, but commercial algal biomass production requires a large amount of nutrient and freshwater, which increases the cost of production. Alternately HRAPs are economically very cheap, as they take wastewater as the input and perform the dual function of wastewater treatment and biomass production. As the wastewater provides abundant nutrients (nitrogen, phosphorus, and carbon), it provides a perfect medium for the biomass production with the additional benefit of phycoremediation. The productivity in the HRAPs is reported to be almost the same as photobioreactors (20 gm m$^{-2}$d$^{-1}$ of maximum biomass concentration), but due to the zooplankton grazers and pathogens, often biomass productivity is less than expected (Gera et al. 2015). Typically in raceway ponds with wastewater, the algal productivity ranges from 5 to 15 gm m$^{-2}$d$^{-1}$ without the addition of $CO_2$. The biomass productivity increases up to 30 gm m$^{-2}$d$^{-1}$ with addition of optimum $CO_2$ (Sturm and Lamer 2011) (Table 3).

Biomass production in HRAPs with wastewater comes with a potential drawback; the lipid content of algal biomass grown in HRAPs is generally lower than the freshwater grown. Lower lipid content is the limitation to use the HRAPs-grown algal biomass as biofuel. The production of the algal biomass for commercially viable products is subjected to different factors which include physical, operational, and biotic factors. Biomass harvesting from open pond is the limiting step in bio-

**Table 3** Biomass productivity by different microalgae species under different growth medium

| Microalgae species | Growth medium | Biomass productivity (gm $m^{-2}d^{-1}$) | Lipid productivity /nutrient removal | References |
|---|---|---|---|---|
| *Chlorella vulgaris* | Open pond freshwater | 0.339 | 0.825 gm $L^{-1}$ $d^{-1}$ | Bhola et al. (2011) |
| *Neochloris oleoabundans* | Artificial wastewater | 0.350 | 99% N and 100% P removal | Wang and Lan (2011) |
| *Neochloris oleoabundans* | Secondary municipal wastewater | 0.233 | | Wang and Lan (2011) |
| *Chlamydomonas reinhardtii* | Municipal wastewater | 2.0 | 25.5% oil content<br>83% N and 14.25% P removal | Kong et al. (2010) |
| *Chlorella* sp. | Secondary municipal wastewater | 0.74 | 0.029 gm $L^{-1}$ $d^{-1}$<br>92% N and 86% P removal | Cho et al. (2011) |
| *Scenedesmus obtusus* | Freshwater bioreactor | 0.212 | 0.0607 gm $L^{-1}$ $d^{-1}$ | Xia et al. (2013) |
| *Chlorella* sp. | Secondary municipal wastewater | 0.92 | 0.12 gm $L^{-1}$ $d^{-1}$<br>89.1% N and 80.9% P removal | Li et al. (2011) |
| *Chlorella pyrenoidosa* | Soya bean processing wastewater | 0.64 | 0.40 gm $L^{-1}$ $d^{-1}$<br>88.8% N and 70.3% P removal | Hongyang et al. (2011) |
| *Chlorella pyrenoidosa* | Municipal wastewater | 0.16 | 95% N and 81% P removal | Dahmani et al. (2016) |
| *Chlorella vulgaris* | Brewery wastewater | 0.227 | 0.108 gm $L^{-1}$ $d^{-1}$ | Farooq et al. (2013) |
| *Chlorella vulgaris* | Municipal wastewater | 0.195 | 9.8 mg $L^{-1}$ $d^{-1}$ N and 3.0 mg $L^{-1}$ $d^{-1}$ P removal | Cabanelas et al. (2013) |

mass production. The life cycle of algal species varies; hence it possesses difficulties during the harvesting phase (Renuka et al. 2015). Most of the facility uses flocculation followed by gravity settling for harvesting the biomass. Chemical flocculants are used (multivalent cations and cationic polymers) to agglomerate the microalgae cells in the mixed suspension by neutralizing the negatively charged surface (Gera et al. 2015).

## 5 Factors Affecting Biomass Production and Nutrient Removal in HRAPs

Various factors affect the algal growth and nutrient removal in HRAPs including physical (light and temperature), operational (pH, $CO_2$, nutrient, dissolved oxygen, mixing, hydraulic retention time), and biotic factors (zooplankton grazers and pathogens).

## *5.1 Physical Factors*

### Light

Autotrophic microalgae obtain energy from sunlight (photosynthetically active radiance 400–700 nm) to convert inorganic carbon to organic carbon to accumulate biomass, and the process is called photosynthesis. A very small part of sunlight (12–14%) is converted into biomass, and majority is lost as heat (Larsdotter 2006). In a nutrient-sufficient condition, the increasing light intensity supports a maximum growth for microalgae till the saturation point; beyond this point, the increasing light intensity can damage the photosynthetic microalgae, termed as photooxidation. As the biomass and concentration of microalgae increase in the pond, the shading effect decreases the sunlight penetration below 15 cm of pond depth, so optimized HRT (hydraulic retention time) and vertical mixing are required to ensure proper sunlight exposure (Lee and Lee 2001; Park et al. 2011). Light and dark cycles during waste treatment with algae affect the nutrient uptake and biomass production. Nitrate uptake and cell growth by *Chlorella kessleri* are reported to be higher under continuous light illumination, but carbon removal efficiency was better under alternate light and dark conditions (Lee and Lee 2001).

### Temperature

The temperature of the mixed system and the surrounding environment influences the metabolic rate, biomass composition, and nutrient requirement. Seasonal temperature variation as well as the daily fluctuation in temperature can affect the growth of microalgae. Majority of microalgae can grow over a wide range of temperature (10–40 °C), but the optimal temperature range is 20–35 °C (Mehrabadi et al. 2015; Ras et al. 2013). The maximum growth rate for *Chlorella vulgaris* in a heterotrophic bacterial mixed system is obtained at an optimum temperature of 32.4 °C (Mayo 1997). Further, temperature is a crucial factor for the biochemical composition of the algal biomass, and a general trend of increased saturation of fatty acids has been shown with increasing temperature. Temperature also affects the total lipid content of algal biomass (Hu et al. 2008). Hence, temperature is found to be an important factor for algal growth and the biochemical nature biomass.

## *5.2 Operational Factor*

### pH

The pH of the mixed system influences the algal photosynthesis, the biomass regulation, the nutrient availability, and even the species composition of algae. The alkalinity and ionic composition of nutrient and different elements in the aqueous medium are defined by the pH. In the daytime when due to photosynthetic uptake of $CO_2$ and $HCO_3^-$ by microalgae raises the pH, which in turn increases the ammonia striping and phosphorus precipitation, which was described earlier. Majority of freshwater algae grow optimally in a pH range of 7–9. Some of the species can live in higher pH; for example, *Chlorella vulgaris* grow optimally at pH 6.5, whereas the optimum pH for *Spirulina maxima* is about 9.5 (Mayo 1997). Large variations in the optimal pH can cause physiological and productivity issues in microalgae (Pulz 2001).

## $CO_2$

During photosynthesis microalgae take up the carbon and convert it in the biomass. Carbon is assimilated by microalgae in one of either inorganic ($CO_2$ or $HCO_3$) or organic (sugar, organic acids, glycerol, etc.). Generally, most of the microalgae uses the organic as well as organic carbon, but some heterotrophic algae strictly can assimilate only the organic carbon (Gera et al. 2015). Carbon-to-nitrogen ratio of the wastewater is important for the growth of microalgae; generally it is well below (C/N 2.5–3.5:1) than what is required for the rapid growth of algae. Hence, most of the HRAPs employ additional $CO_2$ for the steady growth of microalgae; besides growth they also affect the fatty acid content of algal biomass. The $CO_2$ concentration of wastewater further alters the saturation of fatty acids. *Chlamydomonas* species was grown under different $CO_2$ concentrations, and the composition of the total saturated lipids was found to be 65.3% under 4% $CO_2$ and 58.1% under 2% $CO_2$ condition (Nakanishi et al. 2014).

## Nutrient

Often nutrient becomes a limiting factor for the growth of microalgae; among all nitrogen is the most critical one. Algal biomass has a general composition of $C_{106}H_{181}O_{45}N_{16}P$, so nutrient in the proportion of 16:1 would be required with respect to nitrogen and phosphorus (Lannan 2011). Although N/P ratio can vary from 4:1 to 40:1 in different algal species (Craggs et al. 2014). The nutrient concentration in the mixed system defines the microalgae species dominance in the algal ponds. In general the wastewater contains excess of phosphorus for the nitrogen available in the wastewater (Mehrabadi et al. 2015). Beuckels et al. (2015) studied the effect of nitrogen supply on nutrient uptake in two species of microalgae. They found that the removal of phosphorus from wastewater is directly related to the concentration of nitrogen in wastewater. The nitrogen concentration in wastewater also affects the biochemical composition of algal biomass; at high concentration of nitrogen, the carbohydrate and lipid concentration in the algal cell decreased by around 20%. Even phosphorus limitation can lead to increased lipid content especially triacylglycerol (TAG) in several microalgae species (Hu et al. 2008).

### Dissolved Oxygen

Due to photosynthesis in the daytime, the dissolved oxygen concentration in the mixed system can shoot up to 200% of saturation level albeit the increased oxygen concentration can impact the algal growth (Garcia et al. 2000). At the optimum dissolved oxygen, the photosynthetic activity and the biomass generation stay steady. At a high dissolved oxygen concentration, more than 470% of air saturation inhibits the photosynthesis, but they do not cause cell destruction (Molina et al. 2001).

### Mixing

Mixing in the algal ponds promotes the balanced distribution of sunlight and homogenization of carbon and other nutrients. Stagnation in algal ponds can induce the thermal stratification and formation of a boundary layer around the microalgae cells; these can reduce the nutrient assimilation, gas exchange, and photosynthetic activity of microalgae (Mehrabadi et al. 2015). Mechanical mixing mainly achieved through paddle wheels nowadays increases the sunlight exposure of the algae in shallow algal ponds, which promotes steady photosynthetic activity throughout the algal consortia. Ogbonna et al. (1995) have studied the effect of mixing on the productivity of the algal species (*Chlorella pyrenoidosa*) and found that the productivity of algal cells can be increased with the mixing as well the cell density in the mixed system increases, although there were no effects found when the cell density was low.

### Hydraulic Retention Time (HRT)

For algal ponds, HRT is an important factor, influencing the cell density, algal species, algal/bacteria ratio, and nutrient removal efficiency. HRT also determines the algal population dynamics as the growth rate of species is different, and in turn it affects the biochemical nature of the total algal biomass (Mehrabadi et al. 2015). HRT should be optimized; it should not be too long or too short. The long HRT slows the algal growth due to shading and nutrient deficiency; with shorter HRT, the algal pond will be unable to remove the nutrient from the wastewater. HRT shorter than the minimum generation time of algal cell will lead to washout of algal cells (Larsdotter 2006). For wastewater-treating algal ponds, the HRT is commonly 2–7 days.

### 5.3 *Biotic Factors (Zooplankton Grazers and Pathogens)*

In a completely mixed system, apart from the environmental and operational factors, some biotic factors like internal species competition and zooplankton grazers and pathogens also affect the algal growth and productivity. In the mixed system, the competition between the species for space and nutrient is evident. In case of monoculture system, the zooplanktons, which enter the HRAPs as pollutant, can have detrimental effect on the wastewater treatment, as the zooplankton consumes microalgae. Ciliates, rotifers, cladocerans, copepods, and ostracods are the major herbivorous zooplankton grazers in HRAPs. These zooplanktons can consume the algal biomass within a short duration, affecting the efficiency of HRAPs; thus grazer management is an essential step for effective wastewater treatment through algal ponds (Montemezzani et al. 2015).

## 6 Environmental and Economic Sustainability of HRAPs

Economically the production of algal biofuels and concurrent treatment of wastewater using HRAPs is one of the most possible approaches to achieve environmental sustainability. Algal productivities measured in both commercial production and wastewater treatment HRAPs range widely from 12 to 40 g/m$^2$/d (Park et al. 2011). Furthermore, Mehrabadi et al. (2017) reported up to 47.4% of the biomass energy (19.7 kJ/g) recovery as bio-crudes from algal production. Zhu et al. (2017) highlighted high lipid yields (up to 52%) from algal biomass. Biomass can be used for bioethanol production to enhance the biorefinery economics. Ashokkumar et al. (2015) achieved the maximum biodiesel yield of 0.21 g/g of dry weight and a bioethanol yield of 0.158 g/g of dry weight. Patnaik and Mallick (2015) obtained 38 g of biodiesel, 3 g of glycerol, 2 g of omega-3 fatty acids, 0.06 g of β-carotene, and 17 g of bioethanol from 100 g of *S. obliquus* biomass.

Wastewater treatment is a major concern of twenty-first-century world where urbanization and population significantly degrade the quality of water resources. Low socioeconomic communities, especially remote communities, are still waiting for such treatment facilities. In this situation, HRAPs are low-cost treatment techniques which provide an opportunity to replace high-cost treatment facilities.

The electromechanical secondary-level activated sludge treatment is generally costly, and the capital and operating cost are estimated to be three or four times higher than the HRAPs systems (Downing et al. 2002). On the other hand, HRAPs system is a well-reported system acting as a sink of $CO_2$ or greenhouse gas which may help to reduce atmospheric $CO_2$ concentrations (Clarens et al. 2010). The biomass from HRAPs helps to produce fertilizers having sufficient nitrogenous compounds and biofuels to ensure energy demands. The wastewater contains high amount of nutrient, which is used by the algae in HRAPs system and recycled. Biomass produced from the HRAPs wastewater treatment may further be used as bio-fertilizer and bio-feed which significantly contribute wealth to society. Thus, HRAPs system is one of the sustainable approaches to meet the effective wastewater treatment and biomass production.

## 7 Research Need and Future Prospects

In this chapter, an overview of HRAPs system has been discussed with special emphasis on the role of environmental and operational conditions on wastewater treatment and biomass productions. Although there is a huge potential for algal production for biofuel, the approach still needs a lot of attention and improvement, so as to commercialize the biofuel. The following points are highlighted which can possibly provide a clear idea for near future research and development.

1. *Improvement in HRAPs designs:* More engineering attention should be given on the low-energy or self-sustainable solar-powered designs of HRAPs in the near future. Further, one should have to focus on climatic suitable design of HRAPs to reduce the impact of rainfall, evaporations, floods, etc. Microalgae are photosynthetic species growing in HRAPs, and thus it is particularly important to design and develop the suitable HRAPs for the maximum production of biomass.
2. *Biotechnological/biochemical approaches:* The biological properties such as photosynthetic efficiency, high lipid production, and enhanced tolerance capacity toward the environmental factors of microalgae can be enhanced biotechnologically (Hamilton et al. 2014). Most of the open ponds cultivate the monoculture of algal species. Microalgae are diverse organisms, and it's not possible to grow all the species at commercial scale; thus species should be identified, and their enhancement through biotech will be fruitful for the improved productivity. Genetic and metabolic engineering toward improving algal properties has been widely reported in literature (Zhu et al. 2017). To improve the performance of target algal species and production of biocatalysts. It is important to identify algal strains that thrive in the HRAP environment and also important to improve the lipid extraction methods and glycerol production to accelerate algal biodiesel economics.
3. *Environmental/operational parameter optimization:* Most of the earlier studies investigated the impact of single parameters on HRAPs performance. There are urgent needs to investigate the combined role of different environmental and operational parameters on the wastewater treatment in HRAPs. The various parameters (light and temperature, pH, $CO_2$, nutrient, dissolved oxygen, mixing, hydraulic retention time, zooplankton grazers, and pathogens) affect the algal growth and nutrient removal in HRAPs, and to attain the better yield, a thorough understanding of these factors is required. The role of all these parameters on the algal production and their lipid content need to be investigated in large field-scale HRAPs for proper understanding.

4. *Performance evaluation for all pollutants:* Wastewater contains large numbers of pollutants like hydrocarbons, heavy metals, emerging contaminants, and so on. Low removal of heavy metals and pathogens is a disadvantage of HRAPs; thus it is needed to develop new species capable to remove these pollutants from wastewater (Rajasulochana and Preethy 2016). Thus it is important to evaluate the performance of HRAPs for all pollutants in separate and mixed forms under varying environmental conditions.

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