CLEEN
Cluster for Energy and Environment

Research Report nr D602
Helsinki 2014

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WASTEWATER TREATMENT BY ALGAE IN DEVELOPING ASIAN COUNTRIES: AN INTEGRATED APPROACH TO CARBON CAPTURE

ccsp
Carbon Capture and Storage Program

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ISBN XXX-XX-XXXX-X
ISSN XXXX-XXXX

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Report Title: Wastewater treatment by algal in developing Asian countries: an integrated approach to carbon capture

Key words: microalgae, high rate algal ponds, algal turf scrubber, advanced integrated wastewater treatment systems

Abstract

Microalgae cultivation can be used for carbon capture and the biomass produced could be used for bioenergy. During the process of photosynthesis CO_2 is taken up and converted to biomass, but in addition to CO_2, inorganic nutrients, most notably nitrogen (N) and phosphorus (P), are needed. In this report we evaluate the potential of obtaining these nutrients from wastewater, with the focus on developing Asian countries. Algal based systems have a potential for integrating CO_2 capture with wastewater treatment, but the areal footprint will be large. Careful planning is needed to accommodate cultivation to local conditions, key parameters for calculating the CO_2 uptake potential are: the availability of light and land, the source and amount of wastewater and the chemical composition of the wastewater (e.g. nutrient concentration, Biological Oxygen Demand (BOD) and presence of toxic compounds). For the purpose of CO_2 uptake, algal cultivation should be integrated with wastewater treatment in open ponds. Wastewater with high BOD should be treated in a facultative pond prior to the algal cultivation, and in the case of municipal wastewater, a succeeding maturation pond is generally required to reduce the number of pathogens. High BOD would provide CO_2 during oxidation, and would reduce the algal CO_2 uptake from external sources in the facultative pond, but in the algal cultivation pond the algae are commonly carbon limited and the production is enhanced by the addition of external CO_2. Depending on the availability of in-flowing wastewater sources and loss processes (mainly evaporation), recycling of process water is needed to some extent.

Helsinki, November 2014

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1 Introduction

1.1 Background

This study has been carried out in the Work Package (WP) 6 (funding period 4, 2014) of the Carbon Capture and Storage Programme (CCSP), which is the research program of CLEEN Ltd (Cluster for Energy and Environment), funded by the Finnish Technology Agency (TEKES) and the participating partners. The aim of the WP 6: ‘Utilisation of microalgae for CO_2 capture and biogas/-fuel production’, is to identify conditions for feasible and sustainable algae solutions. Mass cultivation of microalgae, e.g. for biofuel purposes, requires a supply of additional CO_2, to prevent carbon limitation of cell growth. Taking the advantage of high photosynthetic potential of microalgae, algal mass cultures may be used to trap CO_2 emissions from power plants and industry. The algae biomass can then be processed and utilized in energy production in power and heat plants or as biofuel.

Microalgae can be characterized as simple plants that live suspended in water or form biofilms on wet surfaces. During photosynthesis inorganic carbon, in the form of CO_2, is taken up and fixed into organic bound carbon. In addition, this process requires other inorganic nutrients, most notably a source of nitrogen (N) and phosphorus (P). A range of other micronutrients are also needed (e.g. iron and manganese), but these are normally not limiting algal growth. In agriculture, different fertilizers are normally used for providing N and P, and this would in principle also work for algal cultivation, but in practice some considerations must be made. Firstly, economic considerations; fertilizers are relatively expensive and large amounts would be needed for a full scale algal cultivation plant. Secondly, environmental considerations; artificial fertilizers are energy intensive to produce, and will not be a viable option for algal cultivation when one of the aims is to reduce greenhouse gas emissions (e.g. Manninen 2013). An interesting option for algal cultivation is to take the nutrients from wastewater, as this would provide nutrients at low cost and also provide an ecosystem service in the form of cleaning the wastewater before it is discarded into local waterways or coastal areas.

The uptake of CO_2 as a way to capture carbon from industrial flue gases have been treated extensively elsewhere (Sonck 2012, Manninen 2013, Teir 2014), and in this report we concentrate on the potential of integrating CO_2 capture with wastewater treatment. The focus is on developing countries, primarily in Asia, as the potential for this technology to be developed into commercial scale is most interesting in areas where there are untreated wastewater sources, available land areas and favorable light conditions (low latitudes) for the algal to run photosynthesis.

1.2 Wastewater sources in developing countries

In developed countries most of the municipal and industrial wastewater is treated by law to some set standard level of quality prior to the release in the waterways. In the developing countries, this is not often the case in practice, despite the possible guidelines or even legislation. For example in India, the percentage of treated domestic wastewater is 30% (CPCB 2013) whereas in Nepal only few treatment plants are working (Shukla et al. 2012) and in Pakistan the common practice is not to treat wastewater prior to disposal (Murtaza & Zia 2012). The reasons for the generally low percentage of treated wastewater are non-existing or malfunctioning of treatment facilities due to e.g. too high operational and maintenance costs, lack of skilled staff, interrupted energy supply and irregular maintenance. It has been recognized that the primary importance should be the treatment of industrial effluents as they contain more hazardous compounds than domestic wastewaters. In India this has been implemented, and 60% of industrial wastewater is treated with various mechanisms whereas in Pakistan the lack of national economic incentives has not encouraged the industry sector to treat their wastewaters and only few out of some hundreds of industries treat their wastewater in any way (Murtaza & Zia 2012). In Bangladesh, many industries have not had treatment facilities to treat their wastewaters until recently when the government required installation of effluent treatment plants to mitigate the water and soil pollution and the public health hazards originating from industry (Sultana et al. 2013). One of the success stories following this is the central bio-electric wastewater treatment plant opened in Dhaka serving Dhaka’s Economic Processing Zone industries.

The untreated wastewaters in these developing countries are either released to waterways and/ or used for irrigation. The receiving water bodies become contaminated with toxins and pathogens while the high nutrient concentrations enhance algal production leading to problems with eutrophication e.g. toxic algal blooms. This forms a health hazard for people living downstream of the release point, as stream waters are frequently used as sources of drinking water. For example, the release of untreated wastewater in Delhi into the Yamuna River contaminates the drinking water of cities downstream (e.g. Misra 2010), and for similar reasons, the Bagmati river water in Kathmandu Valley has been reported to be unsuitable for drinking, recreation and irrigation (Sharma et al. 2005). The rivers often have religious importance, the most famous being bathing in Ganges; one of the most polluted rivers of the world.

Shortage of water is a common problem in developing countries due to droughts, depletion and pollution of ground and surface waters. Water is needed mostly for irrigation, drinking, industry and energy use. Irrigation forms the greatest demand in Asia (85% India, 97% Pakistan, 96% Nepal) and taking into account the high nutrient concentrations in the wastewater providing free or low-cost fertilization for farming, the use of wastewater for irrigation in agriculture has become a common practice in the developing countries (e.g. Minhas & Samra 2004). The irrigation water is taken directly from sewage, wastewater loaded rivers or storage ponds and pools. The high nutrient concentrations as well as harmful constituents in the wastewater might have adverse effects on crop productivity, for example excess nitrogen is known to harm crops of tomatoes, potatoes, citrus and grapes (Bouwer & Idelovitch 1987), and in Nepal the continuous application of wastewater have reduced the crops (Sada 2011). In addition to introducing pathogens to the soil and crop, the industrial component of wastewater exposes soils to a risk of being contaminated with heavy metals and other hazardous substances. The related health risks are experienced both by the farmers and the consumers of the farm products. Therefore, farmers may experience difficulties in selling their products, which have been irrigated with wastewater, and this was experienced by 67% of the interviewed farmers around Hanumate River in Nepal (Sada 2011). In Bangladesh the medical wastewaters have been experienced as nuisance by farmers as they include needles, blades and other disposables (Ullah & Kabir 2012).

The increasing population in the Asian developing countries (e.g. in India the population is expected to exceed 1.5 billion by 2050) calls for efficient management of water resources as the annual availability of freshwater per capita will continue to be reduced while at the same time the production of wastewater is expected to increase. Part of the solution to this problem could be to include implementing low-cost and efficient wastewater treatment systems to prevent or to reduce the present pollution of natural waters.

2 Current status of wastewater treatment

2.1 Wastewater properties

Untreated wastewater is a health hazard for humans and pollutes the environment and only in the case of significant dilution (>500), it is justified to discharge untreated wastewater. This, however, is rarely the case in developing countries. Many countries have formulated laws and regulations about wastewater treatment, but the lack of resources and skilled manpower prevent these from being effectively applied. Thus, the monitoring on the wastewater properties and treatment efficiency is often non-existent. The wastewater properties vary according to their sources and thus, are different from one geographical location to another. Wastewater strength, derived from the (5 days) Biological Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) values, varies between countries. The quality and quantity are more dependent on sullage than body excretes. Due to the shortage of water, the wastewater strength is higher in the developing than in the developed countries.

The domestic wastewaters are generally rich in organic matter as well as in pathogens such as fecal bacteria, protozoa and helminthic worms, and the applied treatment systems in developing countries are generally aimed to reduce these. Therefore, the variables of interest in the wastewater treatment process are mostly the organic load (measured as COD and BOD) and the fecal coliform bacteria densities, whereas nutrients seem to be of little concern due to possible subsequent use of wastewater in irrigation.

The origin and composition of industrial wastewaters vary according to country. Industries such as iron and steel, cement, petrochemical, paper and pulp, food, textile and sugar production as well as tanneries and refineries discharge wastewaters rich in heavy metals, synthetic organic compounds and other toxic substances. The toxins in industrial wastewaters harm severely the aquatic ecology if released untreated into surface waters as well as the biological treatment systems if released untreated into sewers. Therefore, industrial wastewaters should be pretreated prior to discharge into the sewer.

2.2 Wastewater treatment plants

For a treatment plant to be applicable in a developing country, it should be simple in construction, operation and maintenance, and have low costs, low energy consumption, low use of chemicals, low sludge production and high performance. In developing countries natural options such as waste stabilization ponds and constructed wetlands are preferred as the cost of land is minor compared to the costs of electromechanical equipment and electricity of the advanced technology treatment plants such as activated sludge systems.

Decentralized treatment plants serving smaller areas and lower volumes of wastewater, are a better option for developing countries as the costs of building sewerages and operational costs are less than for larger scale centralized plants (Mara 2004). For example, the centralized plants in Nepal (e.g. oxidation ditches combined to settling ponds, series of anaerobic and aerobic ponds) have problems functioning properly due to lack of expertise and management and shortage of electricity (Regmi 2013), whereas all the decentralized sub-surface flow reed beds are working (Shukla et al. 2012), although sludge accumulation might occasionally cause problems (Green et al. 2003).

2.2.1 Types and efficiency

Generally, wastewaters go through primary treatment, where coarse material and grit are removed by screening, and settleable solids by sedimentation but the succeeding steps vary between and within countries. For example in Pakistan, the secondary unit is missing i.e. only preliminary filters and primary ponds are applied whereas in India the wastewater is treated to the secondary level. Common to all countries covered in this report, is that no tertiary unit aiming for nutrient removal is employed.

In India the sewage water treatment plants have the capacity to treat only 32% of the sewage generated in major cities and towns, which produce 93% of the sewage (CPCB 2013). The treatment plants are primarily oxidation ponds and activated sludge systems, but also waste stabilization ponds and up-flow anaerobic sludge blanket (UASB) technology have been used. However, 40% of the sewage treatment plants have problems functioning properly due to improper design, poor maintenance, frequent electricity break downs and lack of skilled man power (CPCB 2013). Also the utilization of the produced biogas from UASB reactors or sludge digesters is often defective. In Nepal, high operational and maintenance costs have hampered the use of activated sludge systems and pond-based treatment plants, and the only treatment plants in operation are reed bed wetlands. In Pakistan, only a fraction of the cities have any form of wastewater treatment, and most of them are out of use or not functioning properly (Murtaza & Zia 2012). In Yangon City, Myanmar, the wastewaters are treated in activated sludge treatment plant, which is capable of treating 7% of produced wastewater in the area (Zaw 2011).

2.2.2 Quality criteria for treated wastewater

The set quality criteria should take into account the costs as well as the use of treated wastewater (agriculture, aquaculture, and discharge to natural waters), and it is important that the criteria are not too tight as this might hamper the treatment altogether due to financial reasons. The national guidelines for treating wastewater and for the properties of treated wastewater vary depending on the country and on the disposal (e.g. inland surface waters, costal site, irrigation) and in some countries there are no quality criteria for effluents discharged into natural water bodies. India has national standards for many variables such as BOD, suspended solids, ammonia, and heavy metals (Table 1; CPCB 1996) but in Pakistan there are no such standards. In Nepal water quality standards have been suggested/ set for drinking, aquatic life, bathing and agriculture (see Sharma et al. 2005) with demands for efficient wastewater treatment with nutrient and organic load reductions, but in practice the guidelines are not followed.

In many cases the treated wastewater is directed to waterways and if the nutrients are not removed in the treatment process, they cause a variety of severe problems in the receiving water bodies such as eutrophication and related changes in aquatic food webs including diminishing of fish stocks and shifts in the fish community composition. High nutrient concentrations can also pose health hazards; for example excess nitrate (>10 mg L^{-1} NO_3-N) in vegetables and drinking water, often taken from the effluent-receiving water bodies, has been shown to cause blue baby syndrome (Majumdar 2003). High concentrations of free NH_3 are toxic for aquatic life and if the wastewater is used for irrigation, high concentrations of nitrogen can reduce crops by damaging the plants or enhancing the growth of the non-useful parts of the plants. In aquaculture, the high nitrogen concentrations can act through increased algal production exposing the fish to drastic daily variation in O_2 concentrations, and to increasing NH_3 toxicity resulting from elevated pH.

Table 1. Examples of the Indian standards (mg L^{-1}) for environmental pollutants in the treated wastewater (CPCB 1996). The requirement of pH is 5.5-9.0 for all discharges.

	inland surface waters	public sewers	irrigation	marine costal areas
BOD (non-filtered)	30	350	100	100
Tot-N	100	-	-	-
Tot ammonical-N	50	50	-	50
Free ammonical-N	5	-	-	5
NO_3-N	10	-	-	20
Sulphide-S	2	-	-	5
Dissolved phosphate-P	2	-	-	-

The removal of pathogens is the main concern when treated wastewater is used for irrigation. The renewed guidelines of WHO (2006) for the quality of use of wastewater in irrigation, is based on the tolerable additional disease burden from working in wastewater irrigated fields or consuming the wastewater irrigated products. The health protection level of $<10^{-6}$ DALY (disability adjusted life years) per person per year has been set for wastewater used in agriculture. Similarly to earlier guidelines of WHO (1989), greater reductions in pathogens are required if the treated wastewater is used for unrestricted irrigation (vegetables eaten uncooked) than for restricted irrigation (all crops except salad crops and vegetables). The values set by WHO act as guidelines for setting the national standards, which vary according to social, cultural, economic and environmental conditions in each country.

3 Use of microalgae in wastewater treatment

In many developing countries, the interest of local authorities in wastewater treatment is low due to the lack of economic return. Wastewater treatment with algae has raised interest as the harvested algal biomass can used for downstream applications such as production of biodiesel, bioethanol, biogas and biofertilizer for agricultural use. In addition to being economically compelling, these systems are also environmentally beneficial. Compared to the conventional systems (e.g. activated sludge systems), they are cost-effective, produce less sludge and have lower energy requirement (use of solar energy, no mechanical aeration). In addition, for each produced kg of algal biomass, 1.2-2.0 kg of CO_2 is fixed (Herzog & Golomb 2004). Although this carbon is not permanently bound, it can be used for energy production, which reduces the need for fossil fuels and therefore, abates greenhouse gas emissions. This is contrary to the conventional systems, such as anaerobic ponds and UASB reactors, where the organic carbon of the wastewater is broken down in bacterial processes to CO_2 or CH_4. This gas is released to the atmosphere unless captured technology is implemented in the system. For example, the CH_4 emissions from anaerobic ponds in Mediterranean and equatorial climates varied between 1 428 and 587 331 mg CH_4 m^{-2} d^{-1} (Hernandez-Paniagua et al. 2014), whereas the emissions from facultative pond in tropical climate were less (median 72 mg CH_4 m^{-2} d^{-1}) and varied depending on the photoperiod, being negative during daytime and positive during the night (Silva et al. 2012). For other algal based treatment systems covered in this report, which have lower bacterial contribution than in the facultative ponds, the carbon emissions can be assumed to be negative despite the darkness during night as not all carbon fixed during the day is respired during the night.

Most of the algal systems are tertiary treatments aiming specifically at nutrient removal, but facultative ponds generally operate as secondary treatment in which the bacterial degradation of organic matter (i.e. BOD removal) is supported by the oxygen from algal photosynthesis. In the process, some pathogens such as helminthic eggs are also removed efficiently from the wastewater. The nutrient removal by algae is superior to common tertiary treatment using chemicals (expensive, produces sludge) and microbial processes (time-consuming) providing that sufficient amount of light is available for photosynthesis.

The best efficiency is obtained when algal systems are used jointly like in Advanced Integrated Wastewater Pond Systems (AIWPS; see section 3.3.1) and preferably in parallel series. The algal growth and efficiency is highly dependent on light and temperature. The application with most potential of these systems is thus as decentralized systems in tropical and subtropical climates, and in areas where the cost of land is not prohibitive, making them economically feasible treatment systems for the developing countries.

The challenges for their use include required expertise in algal cultivation, including the influencing factors such as temperature and light, and knowledge on the proper construction of these systems. Once installed and operative, these systems are robust and easy to maintain. As their productivity is dependent on the surface area (photosynthesis), they require considerable land area and depending on the place, the cost of land might be an issue. In addition to land area requirement, the soil should be composed of clay or clay-mixes with low permeability ($<10^{-7}$ m s^{-1}) unless lining is used. In warm climates, high evaporation losses should also be taken into consideration. If there is a rainy season, special considerations need to be taken, as it affects the solar insolation and increases the wastewater flows at times with higher precipitation. This in turn, might reduce the efficiency of the wastewater systems.

3.1 Key variables

3.1.1 Light and temperature

Light is the main controller of algal photosynthesis and therefore, of the efficiency of wastewater treatment in algal-based systems. Thus, the systems should be constructed according to winter values i.e. the annual irradiance minima. Temperature affects photosynthesis to some extent, but will mainly affect all other metabolic processes in the cultivation system such as respiration and bacterial production. In northern industrial countries, the uneven distribution of temperature and solar irradiance between seasons poses a significant problem, but this is generally not the case in developing countries where the irradiance and temperature are more stable throughout the year. For example, excluding the mountain areas, the average annual temperature in India is above 20 °C and most of the country receives annually >4 kWh m^{-2} d^{-1} of solar radiation (global horizontal).

The diurnal variations in temperatures and light introduce also diurnal variation on the performance capacity and therefore it is recommended that for the dark hours, the flow rate is reduced. While the up-take of nutrients is not efficient during the dark hours of the day, the respiration can be used as CO_2 input to the system.

3.1.2 CO_2

The algal based systems commonly receive their influent from the BOD removal step (anaerobic/facultative pond), in which the already low C : N ratio of raw sewage (3-7) is further reduced (e.g. Benemann et al. 2003). Input of additional CO_2 is commonly required for obtaining high algal growth and efficient nutrient removal and for preventing the rise of pH to harmful levels (e.g. NH_3 becoming toxic). In facultative ponds, the CO_2 is derived from bacterial degradation processes but in the other ponds the bacterial production of CO_2 is generally insufficient, and CO_2 has to be provided from other sources. A number of cost-efficient sources have been suggested/ tested and they include CO_2 from the digestion of algal residues and settled raw sewage, and use of flue gas from power plants, assuming that the wastewater treatment plant is in the vicinity. CO_2 can be introduced directly to open wastewater treatment ponds but is the rapidly lost from the system to the atmosphere. Better incorporation of CO_2 can be obtained by additional technology such as absorbers (Teir 2014).

3.1.3 pH

The carbon chemistry in water is tightly coupled with the pH. Dissolved CO_2 is a weak acid and the uptake of CO_2 by algae increases the pH of the system. This can be used actively to reduce the amount of pathogens. For example, a pH of 9.4 has been shown to efficiently kill most of the fecal bacteria as it is ca 2 units higher than the optimal intracellular pH of these bacteria (Pearson et al. 1987). High pH also acts in the adsorption of heavy metals, therefore reducing their toxicity. High pH favors also ammonia volatilization and phosphate precipitation. By elevating pH, algae also create conditions where carbon dioxide is in the form of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) and hence, control the release of gaseous CO_2.

3.1.4 Species composition

For optimizing the performance of algal based systems, attention has to be paid to the species composition and to the cell concentrations, and a basic knowledge on algal-bacteria interactions is a prerequisite. Maintaining of monocultures is generally impossible when algae are used for wastewater treatment and therefore, the algal communities in these systems are naturally occurring mixed cultures. The dominating species must have high tolerance to toxic substances (incl. ammonia) and wide temperature and light ranges. Ideally, these species should also have high nutrient removal efficiency, high growth rates, have the capacity to form aggregates to ease the harvesting and should accumulate lipids or other valuable products for downstream applications. Besides nutrient removal, the species may possess specific properties such as removal of lead (II) ions (*Chlorella* sp.), cadmium and copper (*Scenedesmus abundans*, *Dunaliella salina*) and other metals (*Ankistrodesmus* sp.) (Oilgae 2013).

3.2 Harvesting and use of the algal biomass

The appeal for using microalgae based wastewater treatment systems instead of conventional systems is the economic return from the algal biomass production (e.g. biodiesel, biogas). However, harvesting of the algal biomass is one of the major bottlenecks, limiting larger scale application of these systems (Uduman et al. 2010, Christenson & Sims 2011). With the suspension based systems (see section 3.3.1), the major challenge of harvesting originates from the low solid concentrations (0.01-0.04%), cell densities similar to water (1.08-1.13 kg L^{-1}), small cell size (5-25 µm) and strong negative surface charge (Craggs et al. 2013). The most common method is chemical flocculation with lime or ferric chloride, but as this is expensive in larger scale and affects the application of algal biomass, use of species capable of self-flocculation (>90% solid removal by settling) is a better option. Immobilized systems (see section 3.3.2) might offer a partial solution to this as harvesting of attached algae done by scraping, is easier and cheaper compared with suspended algae. The need for water removal will also be dependent on the use of the algal biomass. Using the algal biomass as feedstock for biogas production will not require as much water to be removed as many other uses such as bio-fertilizer.

The collected algal biomass from the wastewater treatment systems can be used for several purposes such as production of methane (anaerobic digestion), bioethanol (fermentation of algal carbohydrates) and hydrogen (gasification). The biogas production yield ca. 1 kWh_e per kg algal biomass (Oswald 1988a, b) and the energy value of 1 m^3 of biogas corresponds to ca. 1 L of petrol (34 MJ) (Craggs et al. 2011). The energy produced during anaerobic digestion is more than the consumption in algal based systems, whereas conventional systems (e.g. activated sludge) consume more energy than they produce (Woertz et al. 2009). The biodiesel production from algal lipids is generally limited as efficient nutrient removal contradicts with lipid production in algae (maximization of lipid contents requires nutrient limitative conditions), and a lower biodiesel production (0.12 L per kg algal biomass) is achieved when wastewater treatment is the primary function (Craggs et al. 2011). The same holds true also for bioethanol production with an average yield of 0.13 L per kg algal biomass. However, the conversion to crude bio-oil can be done from wet algal biomass (i.e. drying not required and the whole algal biomass can be utilized), and is a potential application with estimated yield of 0.4-0.5 L per kg algal biomass (Craggs et al. 2011). For increasing the value of wastewater grown algae, pigments such as chlorophylls and carotenoids, could be extracted. The collected and dried algal matter contains high portion of nitrogen (10%), phosphorus (1%) and micronutrients, and therefore has value as fertilizer in agriculture and hence, reducing the CO_2 emissions from inorganic fertilizer manufacture (e.g. 0.23 kg CO_{2EQV} per kg algal biomass) (Craggs et al. 2011). Algae are generally rich in protein (0.5 kg per kg algal biomass), but the possible toxins in the wastewater may limit the use of the algal biomass as food or feed for livestock.

3.3 Treatment systems

Wastewater can be treated by microalgae either in suspension (section 3.3.1) or immobilized on a surface (section 3.3.2). The suspension systems are well established (e.g. Cai et al. 2013) while the immobilized systems are mainly at developmental stage (Kesaano & Sims 2014). Algal based systems are generally fed with secondary effluent and the raw wastewater should be screened from larger items and de-gritted (i.e. heavy inorganic and organic solids removal) prior to entering the wastewater treatment system. High organic load reduce light penetration and induce clogging, especially in the immobilized systems, and the BOD should be reduced in a preceding facultative pond to get around this problem.

The level of wastewater treatment depends on the end-use of the effluent. If it’s directed to natural water bodies or used for unrestricted irrigation, treatment up to tertiary level (i.e. passage through several ponds) is generally required. For fish ponds (carps, tilapia) or restricted irrigation, the effluent can be drawn from the secondary level facultative pond. For example in India, the regulations depend on the disposal and highest restrictions are set for discharge to inland surface waters whereas some variables such as phosphate have no limitation when disposed to public sewers, used for irrigation or disposed in marine coastal waters (Table 1; CPCB 1996).

3.3.1 Suspended systems

In these systems algae are suspended within the wastewater. These systems require some level of mixing generated either by wind or electrically operated device such as paddlewheel, for maintaining the algal cells suspended. Preventing settling of the algae is critical for efficient growth and sequestering of nutrients. The two most common suspended systems are facultative and high-rate algal ponds, which can also be integrated into a set of ponds such as in the Advanced Integrated Wastewater Pond Systems (AIWPS).

Facultative ponds

Based on the reviews by Pearson (2003), Mara (2004)

1. Principle and efficiency

   Facultative ponds (Fig. 1) are one of the most common examples of the suspension based systems and in this treatment system bacteria and algae operate together (Fig. 2): algae remove the CO_2 produced by bacteria and produce O_2 for bacterial degradation of organic matter. The effectiveness of this process is directly proportional to the temperature but other factors affect as well. For maximal performance, the suspension needs to be mixed to minimize the short-circuiting (i.e. reduced retention time) and to keep algae close to light. Normally, the mixing is induced by wind and temperature difference, but as these are never constant in nature, an aerobic photosynthetic upper layer and an anaerobic lower layer are frequently observed in a facultative pond. The proportions of these layers exhibit diurnal variation along with photosynthesis and a deeper aerobic layer is observed during daytime. During night the pond can become nearly anaerobic. In the bottommost part of the anaerobic layer are the sulphate-reducing bacteria (SRB), which are covered by a layer of purple and green sulphur bacteria oxidizing the H_2S produced by the SBR and acting as an odor guard. However, some level of sulphides is beneficial as they react with heavy metals forming insoluble precipitates and in small concentrations (≥ 3 mg L^{-1}) and are rapidly lethal to the pathogen *Vibrio cholera*.

   Facultative ponds can operate as primary ponds, which receive screened and de-gritted, raw wastewater, or as secondary ponds, which receive settled wastewater, usually from anaerobic ponds. The main function is removal of organic material measured as the removal of BOD (>90% filtered BOD in primary pond) and total suspended solids (TSS). At the same time nutrient concentrations are reduced, almost all helminthic eggs are removed by sedimentation and fecal bacteria and viruses are killed efficiently by the high pH (>9.4) and oxygen concentration (up to 20 mg L^{-1}) resulting from photosynthetic activity. However, depending on the downstream application of the treated wastewater, the pond effluent might have to be further treated in maturation ponds in order to remove more pathogens, or polished by filtration through e.g. rock/ sand filters or wetlands to remove the bacteria and algae from the effluent.

The performance of the pond is related to the surface area, due to the algal requirement for light, and the optimal surface loading of BOD is 100-400 kg ha^{-1} d^{-1} depending on the temperature. The bacterial production of CO_2 may increase algal photosynthesis; for example a BOD load of 250 kg ha^{-1} d^{-1} generated >400 kg O_2 ha^{-1} d^{-1} at 25°C in Brazil. In the effluent, two thirds of phosphorus is inorganic and one-third organic phosphorus summing up to ca. 45% phosphorus removal (Huang & Gloyna 1984). The removal of total nitrogen is dependent on the retention time and temperature (Reed 1985). For example, for 45% nitrogen removal at pH 8, a 5 d retention time at 21 °C is required, whereas at 18 °C the same removal percentage would need 16 d retention time (Reed 1985).

The algal species composition varies from pond to pond but flagellated species of Chlorophyta and Euglenophyta such as *Chlamydomonas* and *Euglena* are common in facultative ponds. The algal biomass productivity is generally low (3-4 g m^{-2} d^{-1} DW) (Craggs et al. 2003) and therefore, the harvesting is not economically feasible but in order to increase the economical return of the wastewater treatment, food trees can be grown on the embankments.


http://usf-reclaim.org/2013/12/stabilizationponds/

Fig 1. Facultative pond in Bolivia

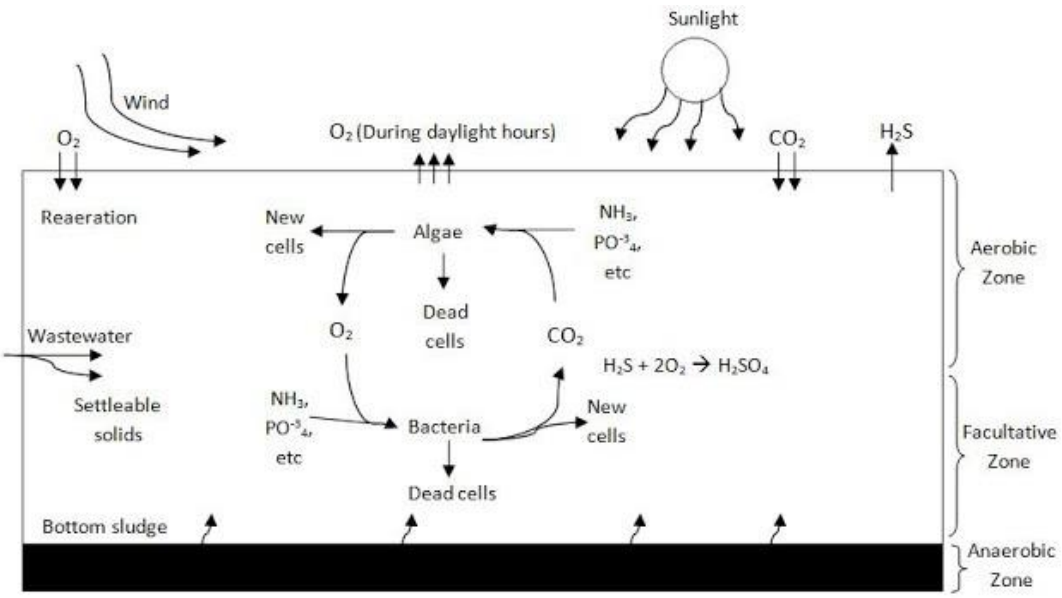

Fig 2. Process chart of facultative pond (after Tchobanoglous & Schroeder 1985).

2. Technical considerations

The depth of facultative pond is generally between 1 and 2 meters (1.5 m most common). With shallower depths, the risk of mosquito breeding increases due to the emergence of aquatic vegetation while in deeper ponds, the anaerobic zone increases. The length of the pond should be around 100 m in order to maximize wind-driven mixing. The primary facultative ponds are recommended to have length to breadth ratio from 1 to 3 for minimizing the sludge accumulation close to the inlet, but at secondary level it can be up to 10. The single inlet and outlet should be diagonally in the opposite corners of the generally rectangular pond for reducing the risk of hydraulic short-circuiting, and the inlet should always be below the water surface. The introduction of wastewater to the lower part of pond (0.8 m) also reduces the toxic effect of H_2S on algae as it is oxidized by anaerobic bacteria. Optimally, the pond should have a scum guard reaching down to 60 cm below the surface at the outlet of the pond to prevent scum and algae discharge from the pond.

Geotechnical considerations are also important when designing a facultative pond. The soil characteristics determine if the soil is impermeable enough as it is or if the pond should be lined with plastic or clay. The construction of the embankments (e.g. slopes, material) also needs careful consideration.

For operational flexibility, the recommended design is to have the two or more ponds in parallel. The retention time is dependent on the local conditions, bacterial BOD removal and hydraulic regime of the pond. Generally, the minimum retention time is 5 days at temperatures below 20 °C and 4 days above 20 °C. Increasing the BOD loading has negative effective on algal biomass through increased turbidity, and also through sulphide toxicity originating from the increased growth and activity of sulphate-reducing bacteria.

The induced production of H_2S leads to proliferation of purple photosynthetic bacteria turning the pond purple in color and devoid of oxygen. In case of overloading, use of electricity consuming mixers is one option but a cheaper alternative is to have a preceding anaerobic pond.

3. Operation and maintenance
   At the initial steps, the pond is filled with river or lake water or raw wastewater, which is allowed to develop its algal and bacterial populations. In a healthy pond, the Chlorophyll *a* (Chl-*a*) concentration is 500-2000 µg L^{-1} and the color of the water is dark green. The maintenance is simple but must be regular. In order to maintain maximal photosynthesis and prevent fly and mosquito breeding, the operations on the surface of the pond are vital and include removing the scum and floating macrophytes (e.g. duckweed). The other maintenance operations include the removal of screenings from the preliminary step, removing the grown vegetation from the embankments (grass) as well as removal of accumulated solids from the inlets and outlets. Sludge removal may take place once per decade if the facultative pond is primary, but in the secondary ponds the sludge is anaerobically digested within the pond.

4. Applications and feasibility in developing countries
   Facultative ponds are reliable, easy to operate and the cost of construction, operation and maintenance is low as no electricity is needed. Therefore, they have long been used for the wastewater treatment in warm, developing countries, where the areal requirement of facultative ponds has not posed a problem. In Asian countries, they have typically been used in a series of different ponds, but due to overloading, neglected maintenance or even abandoning, many of these systems are only partially working or not working at all (Mara 1997, Shukla et al. 2012, Regmi 2013). These ponds provide the necessary BOD removal but for efficient nutrient and pathogen removal, they should be succeeded by other ponds such as the high-rate algal pond presented below. By educating the operators on the functioning and maintenance of facultative ponds, the problems could be avoided.

High rate algal ponds

Based on the reviews by Hoffmann (1998), Christenson & Sims (2011), Craggs et al. (2011, 2012a, b, 2013)

1. Principle and efficiency
   High rate algal ponds (HRPs) are the most commonly used system for both cultivation of microalgae and for wastewater treatment due to their relatively inexpensive construction and operation (Fig. 3). HRP is an open raceway type pond, where the mixing of water is achieved by a large paddlewheel, creating continuous circulation needed for preventing the sedimentation of algae.

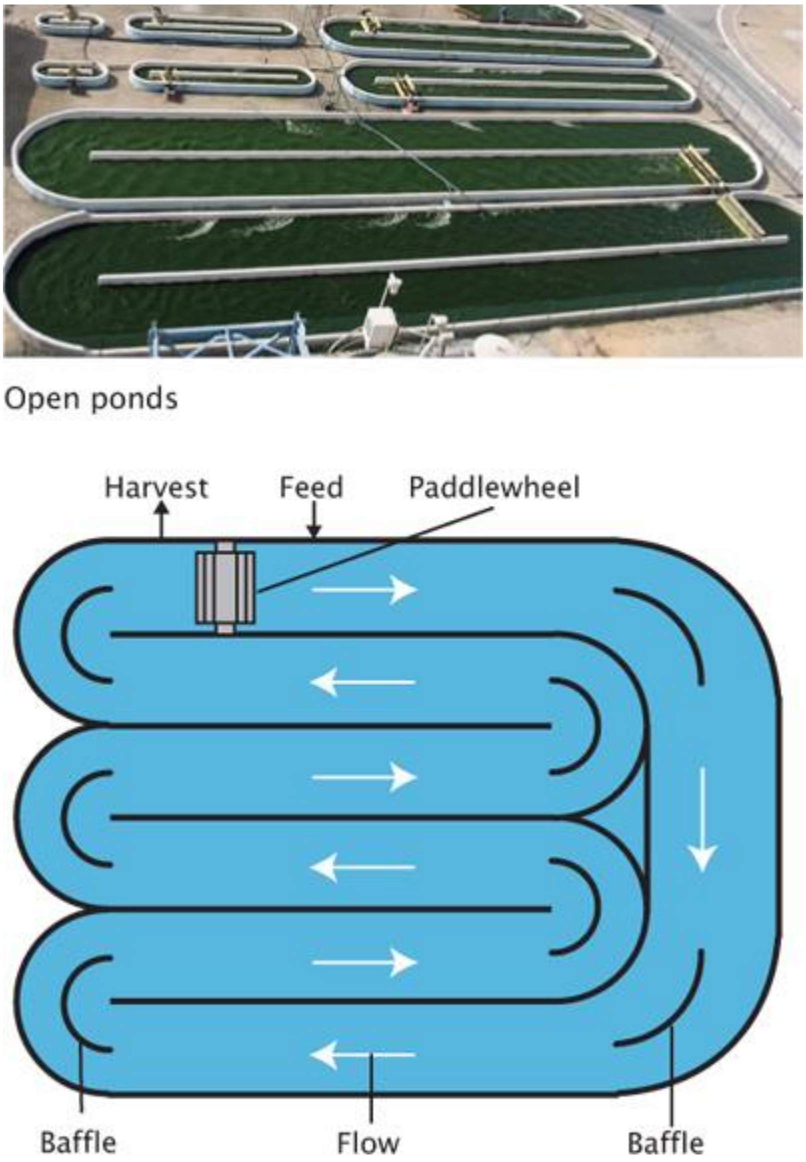

Fig 3. High rate algal pond design (Wen & Johnson 2009).

HRPs can be used for BOD and nutrient removal from a variety of wastewaters of domestic and industrial origin. The organic loading rate (BOD_5) varies from 100 to 150 kg ha^{-1} d^{-1} and up to 24 kg N ha^{-1} $d^{-1}$and 3 kg P ha^{-1} d^{-1} can be assimilated in the HRPs. Also the fecal bacteria concentration can be reduced by 99% (Wells 2005). HRPs are more efficient than facultative ponds both in the terms of wastewater treatment and algal biomass productivity (ca. 10 g DW m^{-2} d^{-1}), and both of these can be increased by adding CO_2 to the system (Park & Craggs 2010). The CO_2 addition also promotes algal flocculation with bacteria, which enhances the settling of algae and thus, facilitates harvesting (Park & Craggs 2010).

2. Technical considerations

The length to width ratio affects the power consumption, area of dead zones, velocity uniformity and shear stress, and for optimal performance, a ratio of 10 or above should be applied (Hadiyanto et al. 2013). The depth of HRPs varies with climate and turbidity of wastewater being between 0.2 m and 0.8 m. Deeper ponds (40 cm) maintain the pH more stable and achieve greater carbon storage, NH_4-N sequestering and areal productivity than shallower ponds (20 cm) (Sutherland et al. 2014), but also increase energy consumption (Hadiyanto et al. 2013). For keeping the algae in suspension, the paddlewheel, which optimally has 8 blades, needs to have horizontal velocity of 0.15-0.3 m s^{-1}; at rates >0.3 m s^{-1} the electricity consumption becomes too high, scouring of the unlined pond starts and algae becomes potentially damaged. Similarly to facultative ponds, if the soil is too permeable, these ponds need to be lined either with plastic or clay. In raceway ponds, the curves need to be protected from erosion.

The retention time varies depending on the solar radiation and temperature (4-10 d). Shallow HRP allows higher light penetration due to lower biomass, but it may induce the growth of faster growing species over colonial ones, which would hamper harvesting (Shuterland et al. 2014). The maximum optimal algal concentrations are around 400 g TSS m^{-3}. With higher densities, the system becomes light-limited affecting also nutrient removal capacity. Small colonial algae such as species of *Scenedesmus*, *Micractinium*, *Actinastrum* and *Pediastrum*, which settle reasonably well under quiescent conditions (50-90% removal) and are resistant to grazing, are common in wastewater treatment HRPs. The recycling of a portion of the gravity settled biomass back to HRP has been shown to maintain the dominance of the desired species (e.g. *Pediastrum*) and to increase the productivity and settleability resulting enhanced harvest efficiency (Park et al. 2011, 2013).

Algal photosynthesis increases the pH, and at levels above pH 9 this efficiently kills the pathogen *E. coli*, but mixing and constant input of wastewater reduce the rates of disinfection. The release of NH_3 gas increases at pH>9 but the high surface area of the paddlewheel blades can maintain high release rates even when pH<9. If needed, a sand filtration step can be added to the end of the system to remove residual turbidity.

3. Operation and maintenance

The regular maintenance and cleaning of open ponds is relatively easy. However, there are some issues related to operating open pond systems that needs to be considered. Firstly, they are susceptible to seasonal changes in temperature and irradiance similar to all algal-based systems. Secondly, the growth conditions have to be maintained such that the contamination by bacteria, virus or other algae is prevented. Densities of herbivorous zooplankton must also be controlled as they can consume most of the algal biomass within few days if occurring in high densities. Thirdly, the harvesting is laborious and costly as algae are small (5-20 µm), and their proportion in the open ponds is low (ca.1 g L^{-1}). The most cost-effective harvesting method is the use of species that form large colonies (50-200 µm) (see above), which settle under calm conditions.

4. Applications and feasibility in developing countries

The HRPs have relatively high demand for land area, but it is lower than for facultative ponds. The temperature and solar insolation has decisive role in the land demand and it decreases with decreasing latitude. For example, for 1 Million Liters per Day (MLD) flow, the area requirement in Southern California is around 1.7 ha whereas for the same load in New Zealand, an area of 2.7 ha is required (Park and Craggs 2010). Although the land requirement is larger than for activated secondary level sludge systems, the operational costs of HRPs are less than one third.

The dependency on electricity makes HRPs not very suited for developing countries but in case the electricity can be secured by using e.g. the biogas produced in the primary pond, from algal biomass or solar power, the system becomes more feasible.

Advanced integrated wastewater pond systems (AIWPS)

Based on the reviews by Green et al. 1996, Craggs et al. 2003

1. Principle and efficiency

In USA, a system called Advanced integrated pond system (AIWPS) was developed (Oswald 1990) aiming primarily for wastewater treatment and only secondarily for biomass production (Fig. 4). In New Zealand, the same system is called advanced pond system (APS) (Craggs et al. 2003) whereas in Africa it goes by the name integrated algae pond systems (IAPS) (Cowan & Render 2012). AIWPS is not a separate treatment type itself but a combination of different types of ponds consisting at minimum of 4 ponds in series (advanced facultative, HRP, algal settling pond, 1-2 maturation ponds). The advanced facultative pond (AFP) act in the removal of BOD (methane fermentation), TSS (sedimentation), helminth eggs, nutrients (denitrification) and heavy metals (precipitation) while the HRP produces oxygen and remove nutrients (algal assimilation, volatilization, precipitation). The algal biomass is then collected in the algal settling pond (ASP) and the final maturation pond reduces the numbers of pathogenic bacteria and remaining algae. The surface organic loading affects the algal community composition and a less diverse, flagellate-dominated community is characteristic for an AFP whereas the communities in maturation ponds are more diverse and dominated by non-flagellate species (Pearson 2003). The treatment potential is dependent on the temperature and in warmer climates, the removal percentages are high: BOD >96%, tot-N 90%, fecal coliforms 96-100% (Ertas & Ponce 2005).

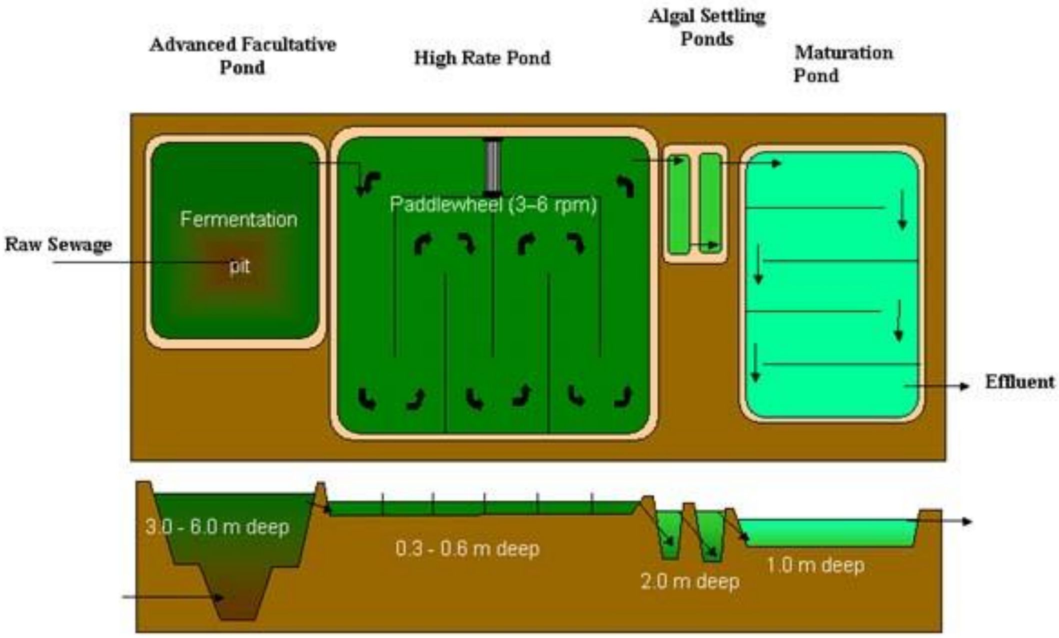

Fig. 4. Advanced integrated wastewater pond system (AIWPS; Ramadan & Ponce).

2. Technical considerations

The AFPs (preferably 2 in parallel) have been designed to enhance the anaerobic processes and in order to maintain the division into aerobic upper layer (upper 1 m) and anaerobic lower layer, they are deeper (4-6 m) than the normal facultative ponds and they have a special pit for the sedimenting material and anaerobic processes. The sludge fermentation is generally complete and sludge removal is not necessary when temperature is kept above 15 °C. A submerged gas canopy can be used for collecting the produced biogas from the pit. As the water level in AFPs is kept constant, a concrete paved water line is recommended for the prevention of erosion. The outlet should be placed below the surface for preventing the outflow of floatable scum. The typical retention times in AFPs are between 20 and 30 days.

The following step after AFP is a paddle-wheel mixed HRP (see above). The replacement of secondary facultative pond with HRP produces greater treatment due to shorter retention time and oxygen production compared to conventional system. Part of the warm, oxygen-rich HRP effluent is returned to surface of AFP for absorbing any odors coming from the anaerobic layer and assuring the presence of algae in the aerobic layer of AFP. By programming the transfer to occur during daytime, the advantages (e.g. disinfection) of elevated pH can be maximized. The retention time in HRP is typically around 10 days.

From 50% to 80% of the algal biomass is settled in the subsequent ASP. This biomass can be retained in the bottom of the ASP even for years without marked nutrient release but collection is more favorable as the biomass can then be used for downstream applications. The wastewater from HRP can also be directly used for irrigation, in which case the algae need not to be removed. Harvesting is also a key issue in AIWPS and for collecting the settled algal biomass from an ASP, a parallel unit is needed.

Maturation ponds are 1-1.5 m deep ponds with 10-15 d retention time and their main purpose is to remove pathogenic bacteria (by settling, grazing, solar UV) and to reduce the remaining algal biomass (by zooplankton grazing). The fecal viruses are mainly removed by adsorption onto settleable solids. If unrestricted irrigation is the desired use of the effluent, twice as high area is required compared to restricted irrigation.

Oswald (1991) reported a total retention time of 35 days for a system consisting of AFP (20 d), HRP (10 d) and ASP (5 d) for AIWPS in California. If maturation pond is added to the system, the retention time increases to 45-50 d. For APS in New Zealand, the retention time was somewhat shorter (HRP 7.5 d, ASP 2 d, MP 20d) (Craggs et al. 2003).

3. Operation and maintenance
   The same maintenance considerations as mentioned above for facultative and high rate algal ponds, apply for the ponds in AIWPS. For avoidance of BOD and nutrient recycling in ASPs, the algal biomass should be collected frequently.

4. Applications and feasibility in developing countries
   The advantages of AIWPS, in comparison to other mechanical treatment system, is that it has very low energy and land requirements (same as for 2-pond facultative system) and operation and maintenance demands are less (fewer odors, low sludge production). Together with high treatment efficiency and resource recovery in the form of biogas from AFPs and harvested algae from ASPs, AIWPS are feasible systems for developing countries, assuming that the required skills for the construction exist, the issue with harvesting has been resolved and the harvested algal biomass has further use e.g. as biofertilizer. For example, construction of AISWP in Varanasi, India with a capacity of 300 MLD has been initiated as part of the second phase of Ganga action plan. The plan is to have 6 AFPs, 12 HRPs, 24 ASPs and 3 MPs in an area of 330 ha.

3.3.2 Immobilized systems

The use of biofilms is a well-known way to treat wastewater. Trickling filters, where wastewater is allowed to drain through a biofilm of primarily bacteria and fungi on a highly permeable medium such as rock bed, are most commonly used. The main aim is to reduce BOD and the amount of suspended solids including pathogens. Although some algae are included in the biofilms, their role is mainly to produce oxygen for the degradation processes. In algal biofilms, on the contrary, the algae have the main role. These systems have easier harvesting compared to suspended systems, the species control is better, the nutrient removal rates (i.e. higher loading rates) are higher, the washout is avoided and cell-free effluent is produced. The immobilized systems can be divided into two kinds: algal mats, where algae that are immobilized in Extracellular Polymeric Substances (EPS) and algal turf scrubbers, where filamentous algae are attached to a plastic mesh. Algal turf scrubbers (ATS) are a literally an extension from algal mats as the filamentous algae extend above 20 cm from the biofilm base.

Algal mats

Based on the reviews by Hoffmann (1998), Roeselers et al. 2008, Christenson & Sims (2011), Cai et al. (2013), Kesaano & Sims (2014)

1. Principle and efficiency
   Algal mats are based on the natural growth of algae on outdoor submerged surfaces. The attachment of algae to the surface is based on the secreted EPS consisting of polysaccharides, proteins, nucleic acids and phospholipids. EPS provide easy attachment to surfaces and protect the cells from desiccation and toxic substances. Wastewater enhances biofilm formation (Irving & Allen 2011) and the bacteria compose the first layer that the algae are attached to. Immobilization of algae can be achieved also by using e.g. chitosan and alginate, but so far this has been limited to laboratory experiments and the costs prohibits larger scale applications. Biofilms exhibit a layered structure with steep redox, chemical and light gradients, where the green and purple sulphur bacteria form the first layer. Above this is the oxygenic layer consisting of algae. Benthic species of green algae (e.g. *Chlorella*, *Scenedesmus*, *Pediastrum*), diatoms (e.g. *Diatoma*, *Nitzschia*) and cyanobacteria with varying morphology (unicellular, filamentous) have been reported to occur in biofilms. The system functions as facultative systems i.e. the oxygen produced by algal photosynthesis is consumed by bacterial processes. The main purpose of these biofilms is to reduce nutrients by algal uptake and after harvesting, the algal bound nutrients can be used e.g. as biofertilizers in agriculture. In addition, the increased pH results in precipitation of dissolved phosphates and die-off of fecal coliforms. Biofilms are also efficient in heavy metal removal through both passive processes (e.g. ion exchange, adsorption, chelation) and active uptake. The removal rate for nitrogen is 0.1-1.3 g m^{-2} d^{-1} and for phosphorus 0.006-0.19 g m^{-2} d^{-1} (Boelee et al. 2014), and with a retention time ≥4 d, 73-93% of nitrogen and 62-79% of phosphorus is removed. The biomass production rates vary from 2.2 to 5.5 g DW m^{-2} d^{-1} but provided that surface area is large enough, the production can yield up to 31 g DW m^{-2} d^{-1} (Christenson & Sims 2012).

2. Technical considerations
   Flow velocity and water depth are critical parameters for the functioning of biofilm systems. High velocities induce shear stress and reduce colonization whereas as low velocities increase the thickness of the boundary layer, which water-layer next to the biofilm where diffusion is the only mode of transportation for molecules. Water depth influences the light intensities, but too shallow system might result in nutrient limitation. In the studies of Posadas et al. (2013, 2014), the maximum water level was 0.5 cm. Due to the lower water volume, the evaporative losses up to 5 L m^{-2} d^{-1} (Posadas et al. 2013) and

temperature fluctuations in the biofilm system are greater than in suspended systems (Murphy & Berberoglu 2012).

The biofilm-based treatment systems have mainly been operated at laboratory scale, both at the continuous and batch modes, with retention times from 2 to 15 days. The thickness of biofilm in active growth phase varies from 0.5 mm to few millimeters depending on the harvesting frequency. The biofilm becomes less dense with age, which could enhance nutrient removal (Boelee et al. 2014) and also help retaining the CO_2 produced by bacteria within the biofilm. It is therefore recommendable to harvest less frequently.

Biofilms require substratum to grow on and the pond need to be lined. The materials show great variability in the biofilm attachment and cellulose-based materials support thicker biofilms than synthetic ones (Christenson & Sims 2012). The substrate material affects the overall algal biofilm productivity (Genin et al. 2014), and materials such as cellulose acetate support higher growth than acrylic material. Currently there is no consensus on the best material, but cost, durability, availability and reliability are important factors to be considered in addition to how well the algae attach and grow.

High BOD loading turns the biofilm more heterotrophic and therefore the BOD in the wastewater is preferably reduced in a preceding facultative pond. CO_2 might become limiting within the biofilm and addition of external CO_2 might be required to maintain the high growth rates.

Recently a Rotating Algal Biofilm Reactor (RABR) used in conjunction with a paddlewheel was developed, mimicking the rotating biological contactors with bacterial biofilms, and tested in scales varying from bench to pilot (Christenson & Sims 2012). In this design, the RABRs rotate in a 0.9 m deep continuous flow channel so that 40% of the reactor is submerged. This increases the biofilm surface area without increasing land requirements and reduces the evaporation loss of water (Fig. 5).

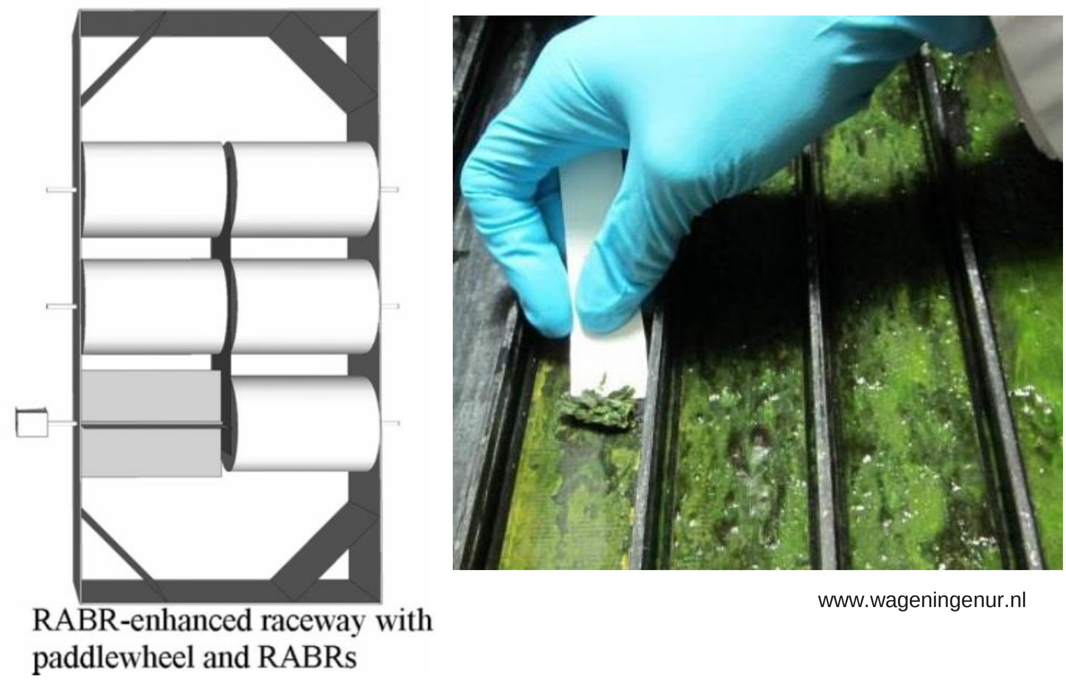

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Fig. 5. A medium-scale Rotating Algal Biofilm Reactor (RABR) of 535 L (on the left, Christenson & Sims 2012) and algal biofilm grown on a lab-scale reactor (on the right, Boelee et al. 2014).

3. <u>Operation and maintenance</u>

The thickening (i.e. aging) of biofilm induces losses due to respiration, parasitism, cell death, disease and grazing as well as increases the risk of sloughing and biofilm washout. All of this reduces the nutrient removal capacity. To maintain the growth in exponential or linear, regular harvesting should be performed e.g. 12-20 d intervals (Christenson & Sims 2012). The biofilm can be harvested actively by e.g. scraping, or passively by letting the biofilm reach a thickness high enough for natural detachment. In the latter option, the biofilm is aged pass the active growth phase (i.e. respiratory losses high) and collecting the material would require an additional settling pond and therefore, active harvesting is preferable.

The initial attachment has a lag phase. Reusing a harvested, seed culture reduces or eliminates this lag time and is therefore recommended. This is achieved by leaving a fraction of biofilm on the substratum, i.e. not completely removal during scraping (Boelee et al. 2014). The algal mats are susceptible to grazing, and if not controlled, the algal biofilms can become completely eaten by e.g. chironomid larvae. If the grazer population has increased to high numbers, drying the algal bed and re-inoculation of the algae is required (Craggs et al. 1996).

4. <u>Applications and feasibility in developing countries</u>

Algal biofilms have rarely been used beyond laboratory scale and the reported cases have included rotating aluminum disks, Styrofoam or drums (RABRs). However, taking into consideration the ease of harvesting and nutrient removal efficiency, the use of algal biofilms in wastewater treatment should be further studied. Compared to HRPs, the algal biomass in biofilms is up to 300 times more concentrated, reducing the energy use for dewatering by 99.7% and producing net energy ratio of 6 (cf. 1.06 for HRPs) (Chisti 2007, Ozkan et al. 2012). Other advantages include less frequent harvesting, which allows more wastewater to be treated per harvesting (2-3 times).

For example in AIWPS, the HRP could be replaced with a biofilm system. In this case, no separate algal settling pond would be required. The high demand for surface area could be reduced by using the RABR system.

Algal Turf Scrubbers

Based on the reviews by Craggs et al. (1996), Christenson & Sims (2011), Adey et al. (2011)

1. Principle and efficiency

   The term Algal Turf Scrubbers (ATS™) refers to a patented system (US patent No.: 4 333 263, 5 851 398). The system mimics the periphytic assemblages of nutrient enriched stream waters consisting of filamentous algae less than 20 cm in height (e.g. green algae). These algae form turfs, and microalgae and bacteria form a mat at the base of these turfs. The microalgae can also growing epiphytically on the filaments. The algae and bacteria are attached to a plastic mesh in an inclined system and retain nutrients, heavy metals and suspended solids from the wastewater. The BOD removal is promoted by the bacteria inhabiting the surface of the filaments and the mat. Nutrient removal is based uptake by algae and physical attachment of nutrients to the mucus produced by the biofilm at the base of the turfs. If the influent is heavy with particulates, a prior settling pond for their removal is recommended. The flow rate through ATS is determined by the size of the flow-way, and can for a single flow-way be up to 95 000 m^3 d^{-1} (HydroMentia 2014). The nutrient removal rate is dependent on the nutrient loading rates. At loading of 1 g N m^{-2} d^{-1}, it can be 80-100%, but when then rate increases to 2.5 g N m^{-2} d^{-1}, the removal decreases to 40-60%. Accordingly, the biomass production can vary from 5 to 35 g DW m^{-2} d^{-1}.

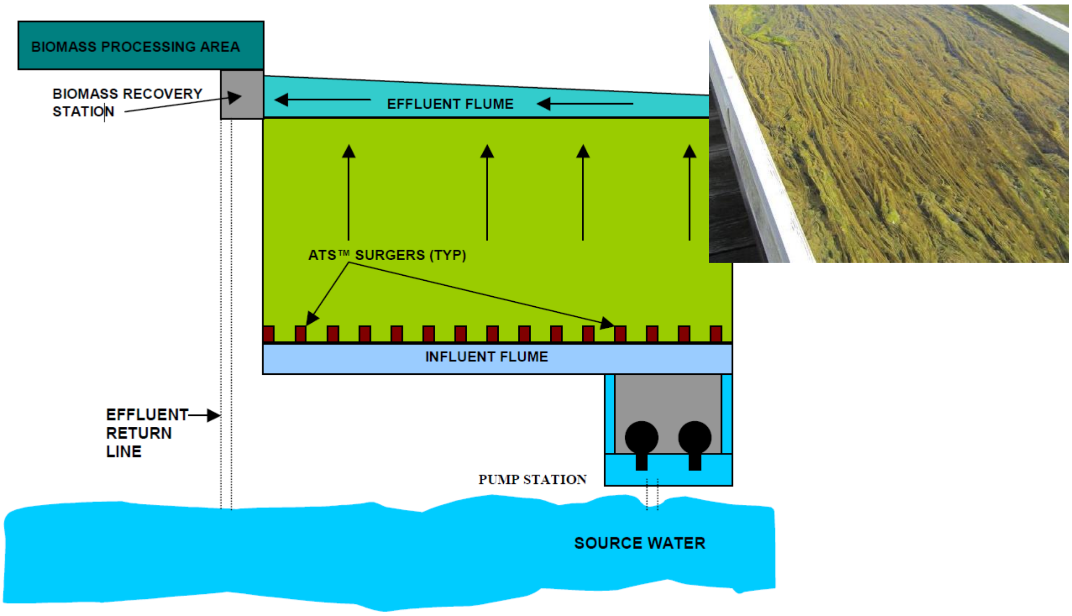

Fig. 6. Algal turf scrubber system (Adey et al. 2013, HydroMentia 2014).

2. Technical considerations

The typical construction of ATS is inclined (e.g. 0.5%-2% slope), lined flow-way covered with mesh (0.5-5 mm). A pump at the base of the flow-way is needed for recirculating the wastewater. For maximizing photosynthesis, the ATS has high surface area and low depth (e.g. 0.01-0.04 m). Addition of CO_2 and water surge motion for enhancing the removal of pollutants and nutrients are recommended. The flow rate is critical. Too high flow rates will shear-off the filaments, lowering the biomass yield and nutrient removal capacity. For obtaining maximal nutrient removal rate, the nutrient loading rate often requires adjustment by diluting the influent with the effluent.

The colonization takes place within three weeks and the communities consist usually of the natural assemblages such as species of *Oscillatoria*, *Navicula*, *Nitzschia*, *Microspora* and *Cladophora*. Due to the natural daily variation of sunlight, the flow rate is reduced at night to a level just enough to prevent desiccation of the turfs and the dissolution of precipitated phosphorus.

3. Operation and maintenance

The system requires harvesting generally once in 1-4 weeks in order to maintain high production rates and nutrient removal, to prevent the growth of macroalgae, macrophytes and grazers (e.g. chironomids) and to remove the pollutants from the system. The harvesting is done by draining the flow-way for 1 h and removing the algal biomass either by scrapers or vacuums. Scrapers is likely more suitable for developing countries as vacuums requires electricity.

4. Applications and feasibility in developing countries

ATS are simple in design and construction and are cost-effective especially at latitudes lower than 40°, where the sufficient solar energy lowers the costs. Also the harvesting is easy in comparison to suspended systems. The fatty acid content is generally low but the harvested biomass can be used for biogas production and as biofertilizers. A typical ATS produces 50 to 100 tons of organic fertilizer per ton of phosphorus recovered (HydroMentia 2014). The optimal hydraulic loading rates for ATS are typically 40-100 times higher than for constructed wetland systems, whereas the land requirement is 90-99% less, e.g. for 38 MLD load rate, only 1 ha of ATS area is needed (HydroMentia 2014).

To date, ATS have not been deployed in developing countries. Considering the requirements for feasible wastewater treatment in developing countries, the system fails in the low-energy requirement as pumps are needed for circulating the water. Another issue is potential licensing fees due to the patent. Like algal mats, they could be used in the place of HRPs in AIWPS.

4 A model of an algal cultivation system

We built a dynamic model of the potential of wastewater and CO_2 utilization for cultivating algae, based on an AIWPS (Fig. 4). The model inputs are: inflowing water volume, the limiting nutrient concentration (which in our example is N), latitude and cultivation area. Based on the latitude, the solar elevation is calculated, which provides an estimate of available irradiance and a rough estimation of the temperature. Growth, CO_2 uptake and BOD removal was calculated based on literature calculations presented in Appendix 1. The output of the model is: BOD and nutrient removal from the wastewater and the algal biomass production and CO_2 uptake.

Generally, the total amount of inorganic nutrients provided in the wastewater will determine the maximum biomass production possible. This, in turn, determines the CO_2 uptake. The light conditions will set the areal requirements for obtaining the maximum removal of inorganic nutrients. An example of this is presented in Fig 7. In this example, we kept all other things equal, and just varied the cultivation area. Input variables were: inflow: 20 m^3 day^{-1}; N concentration: 50 mg L^{-1}; latitude: 20° N. Using 25 ha, all of the inorganic nutrients are taken up during the whole year. When reducing the cultivation area, not all the available nutrients are taken up during the winter months, and when the cultivation area is 1 ha, the production is reduced for almost 6 months of the year, meaning that the cultivation will not be able to take up all available N (Fig 7). The total annual production is 34% lower in the case with 1 ha compared with 25 ha. However, the areal productivity is almost 16 fold higher as the 25 ha plant would be nutrient limited during summer months. Similarly, increasing the water flow or nutrient concentration will increase the produced biomass up to the point where light availability will not any longer provide the necessary energy to fix all of it into biomass.

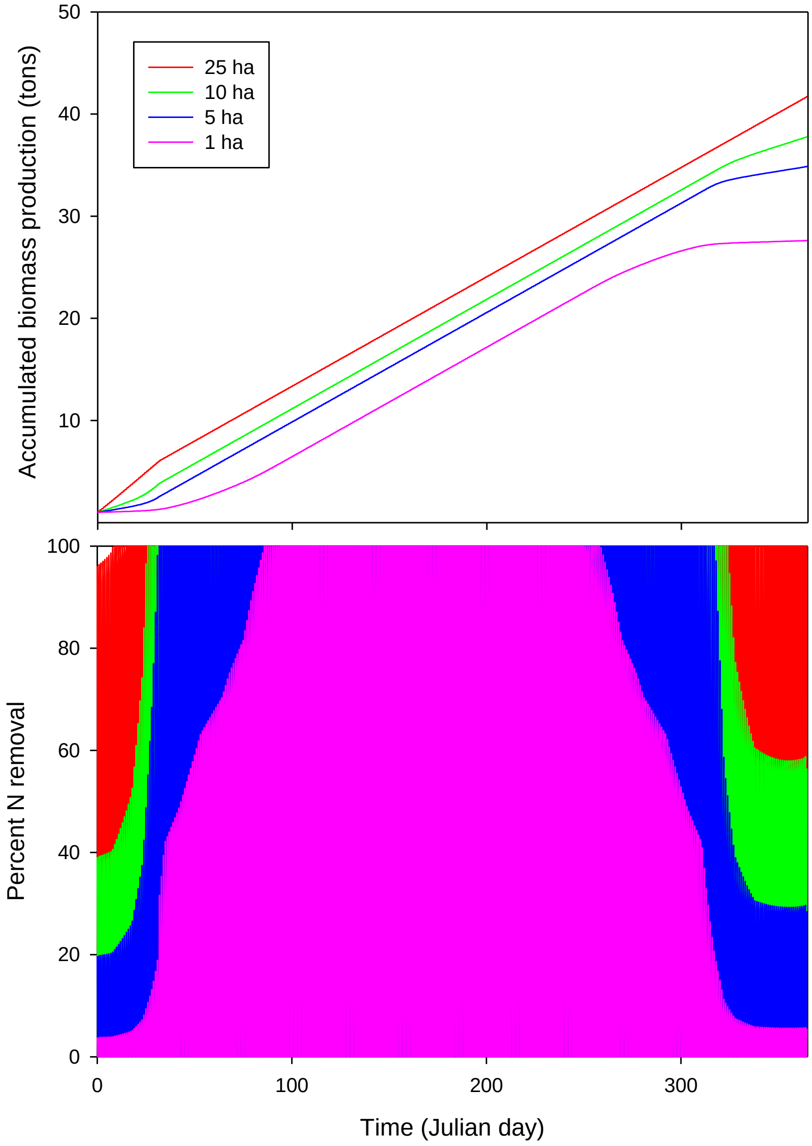

Fig. 7. A model example of how different cultivation area affect the biomass production with all other inputs kept equal (Inflow: 20 m^3 day^{-1}; Nitrogen (NO_3 and NH_4) concentration: 50 mg L^{-1}; Latitude: 20° N). The upper graph depicts the cumulative biomass production with different cultivation area and lower graph how much of the inorganic N that is being removed. See text for details.

This is a simplification as other factors will also influence the production capacity and CO_2 uptake. The concentration of nutrients will in addition to affecting the total nutrients available, also determine the concentration of the algal product. Increasing the concentration will increase algal biomass L^{-1}. This would is beneficial for harvesting step (Fig. 4). However, the concentration can be at a level too high for the algae to tolerate, this is in particular the case of ammonium, which becomes toxic to the algae at high concentration. Very dense algal cultures also have challenges related to shelf shading and the distribution of the light energy becomes critical of obtaining maximum growth per areal unit.

The composition of the wastewater will also have an effect on the applicability to culture algae. Presence of pollutants such as heavy metals and persistent organic pollutants might affect algal growth (which directly affect their ability to take up and fix CO_2) and might also put limitation to the usability of the algal biomass that is produced, because some of these pollutants will be taken up by the algae and will be present in the end product.

5 Conclusion and recommendations

Algal based systems hold high potential for secondary and tertiary wastewater treatment in warm climates of developing Asian countries. This low-cost natural system providing efficient nutrient and CO_2 capture opposed to the conventional systems. In addition, these systems offer economic return in the form of algal biomass that can be used for biogas production or as biofertilizer. If electrical power is needed for operating the system, like in the case with HRPs, the electricity can be generated from the produced biogas, making these systems self-sustaining with concomitant GHG abatement of fossil fuel derived CO_2. As wastewater is generally carbon-limited, the algal production can be increased markedly by adding CO_2 to these systems. Cost-efficient solutions would be to include flue gas from nearby power plants.

Due to their requirement for land area, their optimal use is as decentralized systems in rural areas of developing countries agreeing with the UN-Habitat and Environment and Public Health Organization (ENPHO) promotion on decentralized systems. These systems could be potential options for wastewater treatment for example in India, where the Central Pollution Control Board is promoting technologies based on natural processes. For obtaining sufficient wastewater treatment, algal-based systems are most efficient when it is organized into a series of ponds providing different services like BOD and nutrient removal. Immobilized systems could be more cost-effective than suspended systems since harvesting is significantly easier and algal settling ponds are not required. However, immobilized systems have not been developed to the same extent as suspended systems and would require more R&D.

Similarly to all types of wastewater treatment plants, the successful application of algal based systems requires knowledge on the construction, operation and maintenance of these systems. In addition, motivation is a significant factor determining how well these systems will work, as earlier experiences have shown that even very simple systems such as anaerobic/ aerobic ponds and reed beds, will not work when neglected. The economic return might act as incentive for keeping the algal systems functioning. However, the commercialization of the products has to be done considering local communities, as untreated wastewater has traditionally offered a free fertilizer for poor farmers.

Our literature review can be summarized in the following recommendations for developing an integrated wastewater treatment and CO_2 capture by microalgal cultivation:

- Algal based systems have a potential for integrating CO_2 capture with wastewater treatment, but the areal footprint will be large and it will be most suitable for decentralized operation.
- For the purpose of CO_2 uptake, algal cultivation should be integrated with wastewater treatment in open ponds.
- Wastewater with high Biological Oxygen Demand (BOD) should be treated in a facultative pond before the algal cultivation, and a maturation pond might be required to reduce harmful pathogens.
- High BOD provide a lot of CO_2 during oxidation, and would reduce the CO_2 uptake from external CO_2 sources.
- Recycling of process water is needed to some extent, depending on availability of inflowing wastewater sources and loss processes (mainly evaporation).
- The R&D need is lowest for utilizing the algal biomass produced in biogas production as wet biomass can be used directly, i.e. the dewatering needed for most other applications is technically challenging at a large scale.
- Careful planning is needed to accommodate cultivation to the local conditions, key parameters for calculating the CO_2 uptake potential is: light availability, land availability, source and amount of wastewater, chemical composition of the wastewater (nutrient concentration, BOD and presence of toxic compounds).

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7 Appendix 1 – Model input

Calculating the position of the sun based on the position on the earth, day of the year and time of the day.

Fractional year g in degrees:
g = (360/365.25)*(N + hour/24)
where:
N = day number --> January 1 = day 1, January 2 = day 2, etc.

The hour is the local hour and it is expressed in fractions of hours, that is 10h 35m = 10 + 35/60 = 10.58333. Do not use Daylight Saving Time (DST)

The declination of the sun:
D = 0.396372-22.91327*cos(g)+4.02543*sin(g)-0.387205*cos(2*g) + 0.051967*sin(2*g)-0.154527*cos(3*g) + 0.084798*sin(3*g)

Time correction for solar angle:
TC = 0.004297+0.107029*cos(g)-1.837877*sin(g)-0.837378*cos(2*g) - 2.340475*sin(2*g)

Solar Hour Angle (SHA)
SHA = (hour-12)*15 + Longitude + TC

Longitude in degrees (this figure should be negative West of Greenwich and positive East of Greenwich).

If SHA is greater than 180, then you must add (-360) to the result and if SHA is lower than -180, then you must add 360 to the result.

Sun Zenith Angle (SZA):
cos(SZA) = sin(Latitude)*sin(D)+cos(Latitude)*cos(D)*cos(SHA)

SZA = arccos(cos(SZA))

SZA is the complementary angle of the Sun Elevation Angle or Altitude(SEA), therefore SEA = 90-SZA

Azimuth Angle (AZ):
cos(AZ) = (sin(D)-sin(Latitude)*cos(SZA))/(cos(Latitude)*sin(SZA))

AZ = arccos(cos(AZ))

BOD removal

BOD removal in the facultative pond was calculated according the equation:

BOD_input/(1+(1000/Water_input)*(0.3*1.05^(temp-20)))

Where BOD_input is the BOD in mg L-1, Water_input is in liters and temp is temperature in n°C.

In addition there is some BOD removal in the cultivation pond and this was calculated using the same equation as above only with the output BOD from the facultative pond as the input BOD and multiplied with 0.5 as the BOD removal is generally not as effective in the cultivation unit as the facultative pond.

Light to growth conversion

At 90 ° solar elevation and with a dry atmosphere the available irradiance is approximately 2000 µmol photons m^{-2} s^{-1} and with this amount of light biomass growth of 50 g m^{-2} d^{-1} has been obtained in open cultivation. Production less than 50 g m^{-2} d^{-1} is often the case, but for the model exercise we used 50 g m^{-2} d^{-1} as a best case scenario. For calculating productivity, we used a simple linear regression with decreasing solar elevation from 50 g m-2 d-1 at 90 ° to no production at 0 ° solar elevation.