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ABSTRACT

Microalgae are photosynthetic microorganisms with potential for biofuel production, CO_2 mitigation and wastewater treatment; they indeed have the capacity to assimilate pollutants in wastewaters. Light supply and distribution amongst the microalgae culture is one of the major challenges of photo-bioreactor design, with many studies focusing on microalgae culture systems such as raceway ponds (RWP), widely used and cost effective systems for algal biomass production. This review focuses on possible improvements of the RWP design in order to achieve optimal microalgal growth conditions and high biomass productivities, to minimize energy consumption and to lower the capital costs of the pond. The improvement strategy is based on three aspects: (1) hydrodynamic characteristics of the raceway pond, (2) evaluation of hydrodynamic and mass transfer capacities of the pond and (3) design of the RWP. Finally, a possible optimal design for the RWP is discussed in the context of wastewater treatment.

KEYWORDS: Microalgae, raceway pond, hydrodynamics, mass transfer, wastewater treatment.

1. Introduction

Microalgae are photosynthetic eukaryotic microorganisms, as opposed to cyanobacteria which are prokaryotic photosynthetic organisms. They show a high level of diversity in both their morphological and biochemical characteristics. These microorganisms can form a promising source of bioenergy feedstock (1), lead to the production of high value compounds (2) in various fields such as cosmetic, pharmaceutical, nutraceutical, aquaculture (2-5) or play a role in the environmental field (6).

Biological applications of microalgae date back to the 1950s in California with Pr William Oswald's work; they are based on the high assimilation level of elements such as nitrogen, phosphorus, heavy metals (7) and toxic organic compounds (8) by the microorganisms.

Wastewater treatment using microalgae for low cost biomass production is a highly sustainable and economical process (9-10). This process presents synergistic possibilities (11) in the presence of bacteria. Microalgae can indeed grow relatively fast (12), consume inorganic nitrogen and phosphorus (13) and provide dissolved oxygen to the bacteria that are responsible for the reduction of biological and chemical oxygen demands (14). Wastewater treatment by microalgae is then based on a biological symbiosis between heterotrophic bacteria and photosynthetic microorganisms with gaseous exchanges between both types of microorganisms. During symbiosis, two phenomena are in action: microalgae provide oxygen for bacterial respiration and bacteria produce CO_2 and release some nutrients necessary for microalgae growth.

In wastewater treatment, the inorganic pollutants removal is mainly the consequence of their assimilation through microalgae growth, but chemical elimination of several nutrients may also occur in parallel due to changes in the culture pH. At high pHs, for example, ammonia volatilization and phosphorus precipitation can occur (15). In consequence, compared to chemical techniques, wastewater treatments by microalgae induce lower costs and do not generate any secondary pollution (14).

However, considering economic aspects, wastewater treatments by microalgae can take advantage to be coupled to biomass valorisation processes for the production of high added value molecules. Processes including industrial CO_2 consumption can be proposed too (16-19) although CO_2 consumption is very low.

Domestic sewage treatments include several steps. A preliminary treatment of sewage by flotation removes large solid materials. The primary treatment involves sedimentation to remove the settleable solids. The secondary treatment device consists of biological reactors, fixed film or activated sludge reactors, to reduce the organic matter of pollutants by aerobic oxidation of the biological oxygen demand (14). During the tertiary treatment, biological or chemical processes remove inorganic ions, especially ammonium, nitrate and phosphate ions. Finally, the quaternary treatment aims at eliminating heavy metals, organic compounds and soluble minerals (14). Microalgae culture can provide a promising process for wastewater treatment due to the potential to combine tertiary and quaternary treatments with the production of high valuable products (14). As an additional interest, microalgae can provide oxygen for free in the culture, leading to significant savings as oxygenation is the source of 80% of the costs associated with the sewage treatment (20).

Microalgae cultures have received increasing attention over the last few years. Although microalgal open ponds are generally used in wastewater treatment, microalgae culture systems can be divided into two classes: open systems (natural and artificial ponds), where the microalgal culture is directly exposed to the sun light, and closed photobioreactor (PBR) systems, where the culture is enclosed in a transparent vessel, illuminated by an artificial or natural light source. The closed systems have the advantage of a good control on the physiological and operating parameters such as light, temperature, agitation etc. Moreover, they minimize the risks of biological or non-biological contamination. However, due to the relatively high cost of the photobioreactor systems, their scale-up complexity and some unfavourable phenomena as overheating bio-fouling and toxic oxygen accumulation (21), open systems are often favoured (6, 22). They have received a significant level of attention due to their design simplicity, their lower capital and operating costs (23).

Open systems present a great variety of configurations in relation to their dimensions, construction materials, agitation systems and angle of inclination (24). They can be classified into natural ponds (lagoons) with natural wind agitation systems and artificial ponds, such as circular ponds where mixing is ensured by a central stirrer or raceway ponds (RWP) with paddlewheel agitation systems.

Amongst the open culture systems, the RWPs are the most widely used, thanks to their relatively low construction cost, ease of maintenance, low energy requirement (25-26) and their ease of scalability (27). Several studies have been performed on wastewater treatment by microalgae in RWPs.

According to the general design, suggested more than 40 years ago by Oswald (28), a RWP consists of a shallow pond, divided into two or more channels by wall(s). The agitation of the liquid stream is provided by a mechanical impeller that ensures a turbulent flow inside the pond.

The RWP systems may present several limitations such as low light penetration, poor gas-liquid transfer efficiency (29-31), low control over the operating conditions, high contamination risk and low final microalgal biomass concentration. One of the main disadvantages of a RWP system is that its geographical location imposes environmental conditions, essentially temperature and light levels and quality. Indeed, the RWP performance is highly subject to seasonal changes and weather conditions, making it most unreliable and leading sometimes to undesirable growth conditions for the microalgae (1).

The primary objective of a mass algal production process is to maximize the volumetric biomass productivity and minimize the production costs (32). As a low cost device, the RWP microalgae production system was studied by several authors in order to improve its performances in terms of energy consumption, biomass productivity, operating conditions and design (30, 33-35).

By optimizing the RWP system, it is imperative to find the biological and hydrodynamic conditions of the process ensuring its technico-economic viability in terms of biomass productivity, wastewater treatment and energy consumption (Figure. 1).

In particular, the hydrodynamic behaviour of the culture is important to be studied in order to ensure its optimal mixing and homogeneity, improving mass transfer and nutrients availability for microalgae cells. Cell sedimentation may lead to a local nutrient limitation but at the same time allow better light availability for the actively growing suspended cells. Also, the sedimented cells may experience stress phenomena resulting in cell death. Besides, in attempting to achieve well-mixing, excessive shear stresses must be avoided while maintaining a turbulent liquid (culture) flow. In addition, the optimization of the fluid dynamic behaviour inside the pond can reduce the formation of “dead zones”, with anaerobiotic conditions that could increase the risk of contamination.

This paper aims to review the recent research on the effects of hydrodynamics, mass transfer, global shear stress and pond geometry on algal biomass production. Then, the optimization of the raceway pond design in terms of biomass productivity and energy consumption for wastewater treatment, in continuous operating condition, will be discussed while taking in consideration all the mentioned parameters.

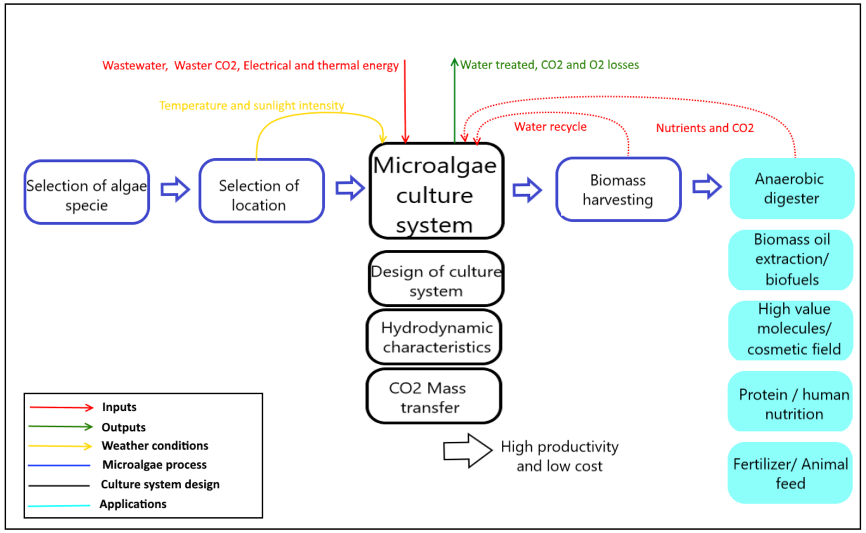

Figure 1. Diagram of the wastewater process.

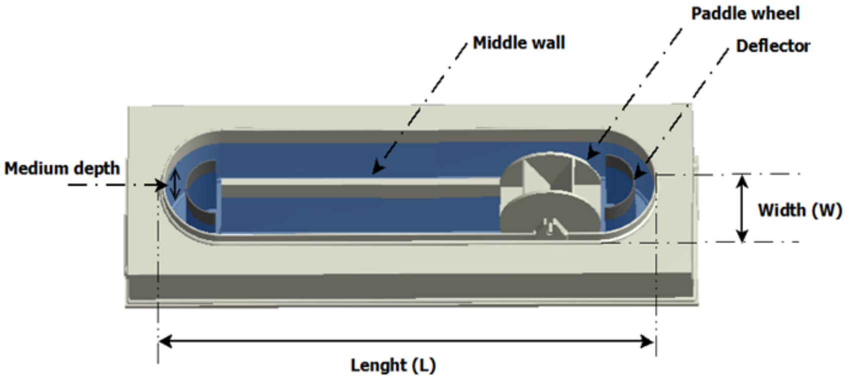

Figure 2. Schematic representation of the raceway pond.

2. Raceway pond (RWP) system: geometry, materials and operation

A RWP, also called high rate algae pond (HRAP), generally consists of a shallow pond with a central middle wall creating two channels arranged in a racetrack closed loop (21) (Figure. 2). The microalgae culture is continuously stirred in turbulent flow around the middle wall. The RWP may be agitated by various devices such as low shear force pumps, air-lifts and paddle wheels (36). The paddle wheel is the most common device in industrial applications (37).

The RWP pond could be excavated into ground or constructed above it (38). The ground level RWP is cost-effective but can lead to insect contamination. Several materials can be used for the raceway wall: concrete, cement, fibre-glass, even epoxy-coated concrete the most common being impermeable linear PVC (38). The choice of material depends on many parameters such as: species of microalgae (potential toxicity of the material), specifications of the process (e.g. the quality of the high value molecule produced), and properties of the material (resistance against corrosion, rigidity, ease of maintenance, costs).

Temperature and lighting are impossible to control in an open pond and strongly depend on climatic conditions; they are critical parameters that must be taken into account during the pond design. A hot geographical location can induce high water evaporation and CO_2 losses. A cold location can strongly inhibit the algae growth.

In particular, the culture depth has a direct influence on both temperature and lighting. Thus, it must be selected to ensure a good compromise between a favourable medium temperature and a sufficient lighting for algae growth. Besides, it influences the design and the operation of the system, the biomass, the concentration and the harvesting costs (38). Indeed, a deeper pond increases the temperature variations and in same time decreases the available light intensity at low depths of the water. This kind of information concerns only one physical property during the design of the culture system. In terms of microalgae culture system, the attenuations of both temperature and light are strongly dependent to the biological performance of the microalgae specie (growth rate, biomass productivity, physiological stress due to the weather conditions and the capacity to produce biofilm, which strongly reduces the light path on the culture).

The incident light at the surface of the algae culture is progressively attenuated along the light path and finally completely absorbed at the pond bottom resulting in the formation of a dark zone, which depth depends on the microalgae concentration. The result is a gradient of light intensity and wavelength from the culture surface to this dark zone (36); so, a deeper pond leads to a more dilute culture, resulting in an increase in the harvesting costs.

In consequence, a RWP is usually shallow (12 to 40 cm), with an efficient light utilization down to depths of 12 to 15 cm (40). However, the diminution of the pond depth leads to an increase in the required surface for a given culture volume, which intensifies the evaporation losses (41).

The agitation creates a turbulent flow of the culture in the raceway, with a typical liquid velocity about 0.15 to 0.4 m/s (21). This circulation is important to maintain a good culture homogeneity, resulting in an efficient sunlight penetration. It also avoids sedimentation of the cells at the bottom of the pond in the dark zone and thermal and oxygen gradients within the culture medium (22).

In order to enhance biomass productivity and photosynthetic activity of algae, the culture may be aerated by bubbling pure air or air enriched in CO_2 through it. This can be achieved by different devices at the bottom of the pond: gas sparger, plastic sheet with holes under which the gas is pumped. Additionally, the addition of gaseous CO_2 could be used to regulate the pH of the culture around a set point (38).

3. RWP hydrodynamics characterization

A crucial step in the optimization of microalgae biomass productivity is the evaluation of the hydrodynamic characteristics of the raceway. Indeed, an adequate mixing provides a good distribution of nutrients, enhances the use of carbon dioxide, avoids the cell sedimentation and ensures a good exposure of algal cells to light by reducing dead zones (42-43). Besides hydrodynamics has a strong influence on energy consumption and shear stresses that can damage the cells. Several studies focused on the hydrodynamic characterization in an open pond system (26, 44-47).

3.1. Dead zones

Dead zones mainly depend on the geometry of the pond and the mixing efficiency (44). These volumes, also called stagnant zones, are a consequence of imperfect mixing due to the formation of local very large eddies. Beside cell sedimentation, the dead zones can cause anaerobic conditions, inhibiting microalgae growth and resulting in a drastic reduction in the biomass productivity. The anaerobic environment indeed promotes the proliferation of contaminating bacteria and, under certain conditions, the formation of toxic compounds that cause the death of microalgae cells (37). The presence of the stagnant zones increases energy dissipation, reduces the pond effective volume and consequently the hydrodynamic residence time of the fluid (48). They have a negative impact on productivity, especially in continuous culture mode (operating condition on the wastewater treatment), caused by the formation of a non-uniform velocity field leading to uneven cell residence time on the culture system (21). Knowing that in the case of a reactor operated in continuous mode, the residence time of the particles affects the growth rate of the microalgae, this "dead zones" problem is harmful to the pond productivity.

Thus, several researchers concentrated on improving the RWP performance by minimizing the volume of dead zones (44, 46-47); according to most studies, the liquid velocity within the open pond must be higher than 0.1 m/s in order to avoid cell sedimentation (33) (37), but these values probably depend on the algae species and the depth of the pond. The reduction of dead zones is obtained by increasing the velocity of the culture (44, 49). Indeed, a higher turbulent flow leads to a greater homogeneity of the culture and a better distribution of the velocity profile. These studies provide, through theoretical simulations, fundamental information on hydrodynamics characteristics, which are important to obtain high biomass productivity. Many parameters are considered for the optimization design of the RWP such as pond geometry, the velocity and the depth of the medium in order to reduce the impact of dead volumes and shear stress. However, these studies are limited to small production scale. They also need further investigation for large scale raceway design in terms of interaction between hydrodynamics mixing properties of the raceway pond and the availability of light intensity related on the area productivity of the microalgae (biological mechanism for the production of the biofilm)..

Computational fluid dynamics (CFD) can be used to evaluate the hydrodynamic characteristics of the RWP and to calculate the surface fluid velocity as a function of culture depth. By decreasing the culture depth, the volume of the stagnant zone drastically decreases, resulting in the reduction of the sedimented cells quantity (44, 49).

Sompech and her team also propose visualization on the dead zone inside the raceway pond, thanks to computational fluid dynamics simulations. These simulations provide useful information for comparing different raceway configurations of the same scale and for understanding the expected flow behavior in multiple tested configurations. However, these numerical results need to be tested on a large scale raceway design and validated through outdoor experiments. The study needs to correlate the area biomass productivity (related to the selected algae species) and the hydrodynamics characteristics of the pond design.

The ratio of the channel length to width (L/W) is an important parameter for optimizing the pond geometry. Thus, increasing this ratio decreases the dead zones by minimizing eddies at each end of the middle (separating) wall (44, 50).

Ramakant Pandey et al., propose a L/W ratio value for the raceway pond between 6 and 7 with a sufficient mixing with a bottom clearance between 5 and 8 cm and the rotor speed of 20 rpm (51).

In order to limit the dead zones, it is possible to add solid deflectors at the extremities of the middle wall, which reduces the large eddies formation at the end of the channels. But even with them, uneven flows will still exist along the channel (52). In addition, an increased thickness of the middle wall can improve the uniformity of the velocity profile by strongly reducing the stagnation zone (44, 49). However, this decreases the working volume of the RWP. The implementation of deflectors at each bend is a better solution, allowing a greater uniformity of the velocity flow profile (44-47, 49) without reduction of the working volume. By increasing the length of the straight section of the deflectors in the downstream region (with respect to the fluid flow), the dead zone volume drastically decreases (46). Zhang and his team validate the benefits of the flow deflector and wing baffles, in terms of dead zone and flashing light effect, which are proved by numerical simulation and even with outdoor cultivation experiments on a raceway pond. Indeed, the optimization of the flow deflectors enhances the biomass concentration by 30.11%, reduces the dead volume by 60.42% and the average dark light cycle from 14.05 s to 4.42 s. One potential configuration concerns the fitted size of the paddle with the channel width of the pond and the implementation of the deflector at the end of the bend. Finally, the implementation of three semi-circular baffles and a modified end of the middle wall (by the modification of the thickness of the wall, creating "a solid deposition") leads to the complete elimination of the dead zone volumes (47). Thus, a compromise between dead zone minimization, algae cell shear stress reduction and energy savings should be found, which is to some extent the case with all bioreactors.

3.2. Shear stress

As seen above, in order to optimize the open pond design, it is necessary to take into account the negative effect of liquid velocity on algae by shear stresses. Several authors have determined the average shear rate using energy dissipation (53-54). Increasing turbulence beyond a certain maximal level can damage the cell structure (44). The shear stresses on algae are due to the interaction between free cells and isotropic turbulence eddies based on Kolmogoroff's theory (55-56). The RWP design must consider an adjusted flow velocity, so that the micro-eddies dimension is larger than the cell size (44). The shear stress is induced by the micro-eddies formation with sizes close to the algae cell. By increasing the fluid velocity, the micro-eddies size increases and can approach the cell dimension, leading to cell damage. The shear stress is also affected by the (L/W) ratio. Indeed, lower (L/W) ratio lead to a higher shear stress (44). Thus, the optimum pond design should be realized according to an adequate (L/W) ratio that avoids the shear cell. Given the depth of the culture according to three different layers of flow (upper, middle and lower layer of flow), the shear stress is higher in the middle layer (57). This can be explained by the correlation between share rate distribution with the flow velocity magnitude. In fact, the velocity fluid flow is lower at the lower layer of the suspension due to the friction between the boundary of the domain and the lower layer of the flow. Besides, the velocity of the flow is a little bit higher in the upper layer than in the lower layer, but the suspension is in contact with the air. Singha and her team work on the flow behaviour of the microalgae in an open raceway pond with the total surface area of 98.33 m^2 and a volume of 23.29 m^3. From simulations, the profile of velocity is correlated with the depth, and the cell concentrations are slowly increased in time. Unfortunately, this study needs further investigations with a correlation between shear stress, velocity profile and light distribution and their impact on the biomass productivity.

3.3. Power consumption

Another important parameter for the improvement of the RWP hydrodynamic properties is the quantification of its power consumption. It is indeed crucial for the economy and the productivity of the system (52). Energy consumption is mostly due to the mixing of the culture ant its flow in the channels (44); it depends on the geometry of the pond. Several researchers investigated the influence of the RWP hydrodynamic properties on its power consumption (26, 34-35, 44-45,58-60). One of the challenges of an optimum RWP design is to establish an adequate mixing system with minimal energy input.

The operational energy demand of the RWP system is still at a high level. The total power consumption (the electrical power input to the electric motor) is the sum of the power input for the paddle wheel (shaft power) and the power required to overcome the hydraulic losses of the culture circulation within the pond (hydraulic power) (33). The power consumption of the paddle wheel contributes to approximately 23 % to the total direct energy demand of the culture system (61).

Usually, there are two methods for calculating the power consumption of the paddle wheel. The first method uses the difference between the fluid pressures downstream and upstream of the paddle wheel, determined by using a classic modelling technique for turbulences and fluid dynamics (CFD modelling). The second method estimates the power consumption using Manning’s equation.

The power required for the paddlewheel evidently depends on the hydraulic properties of the fluid, its turbulence dissipation rate and the liquid level (60). The energy demand of the paddle wheel decreases by the reduction of the RWPs depth. Indeed, it results in a smaller total volume of the fluid, and reducing the hydraulic power requirement of the paddlewheel (34). Thus, the power requirement of the paddle wheel is reduced by minimization the head loss pressure of the liquid (culture) (59).

Another important parameter that influences the hydrodynamic behavior of the RWP and its energy demand is its L/W ratio (length/width). The power consumption decreases with increasing L/W ratio (33) (44). So, longer RWPs with narrower channels consume less energy for the same level of mixing.

Reducing the power consumption of the paddlewheel can also be achieved by the installation of deflectors (45, 47,59). They indeed provide a better distribution of the liquid velocity profile through the curvature of the pond, prevent sedimentation at the end of the middle wall (away from the mixing device), and reduce the substantial loss of the fluid kinetic energy and the occurrence of the large eddy currents.

Huang et al focused on the performance of the raceway pond with internal structures (baffles and deflectors). Through numerical prediction and experimental results, this research highlights the importance of using baffles and deflectors on the power consumption, the average velocity, the dead zone, and the areal productivity. Indeed, the RWP with sloping baffles and flow deflectors improves the areal productivity of photoautotrophic *C. pyrenoidosa* culture from 6.24 g m^{-2} d^{-1} and power (272.5 W) in the case of non-optimized classic RWP to 8.61 g m^{-2} d^{-1} and power (255.0 W).

The design of the paddle wheel and the number of the deflectors must then be optimized to minimise energy consumption. Increasing the number of deflectors in the bends leads to a higher liquid velocity and a decrease in the power requirement of the paddlewheel (26). For example, Sompech et al studied a PWR with three semi-circular deflectors on each bend and achieved large energy savings (47).

Other modifications can be performed in the PWR with the same goal. For example, building an asymmetric island attached to the middle wall increases the energy yield by limiting the formation of the stagnation zones (62).

The enlargement of the middle wall width also reduces the power consumption. Indeed, the reduction of the channel width at the curvature and the adjustment of the paddle wheel size in order to match the channel width lead to satisfying hydraulic performance compromise (44).

Most of the energy losses occurring on the bend of the RWP, the improvement of the bend design drastically reduce them by limiting the stagnation zones and enhancing the mixing conditions of the culture. New low-energy bends are designed according to the cosine function variation of the channel width (creation of an asymmetric island in each bend) while keeping the depth uniform across the width (45).

The power consumption of the paddle wheel also depends on the configuration of its blades. By improving the blade design, the area between the blade and the fluid is reduced, which minimizes the energy required for the paddlewheel. Thus, a back-curve blade design, which is crosswise bent and based on a paddle wheel apparatus patent, presents a better energy performance due to a lower blade contact area with the culture (60). Li et al., provides an optimal blades configurations in order to reduce the power consumption in terms of fluid velocity and wheel efficiency in the open raceway pond. However, the numerical and experimental data of flow velocity and wheel efficiency need to be correlated with the biological efficiency of the cell in terms of shear stress and areal biomass productivity.

The conception of an optimum design of the RWP can be achieved by other culture mixing means such as airlift system or pump systems. The airlift is based on the implementation of a CO_2 sparging sump, with baffles that partitioned the sump into two sections: the downcomer and the riser partitions. The gas mixture is injected from the riser (63).

Beyond the advantages of CO_2 (carbon source) supply, high CO_2 uptake efficiency (64) and better gas to liquid mass transfer (65), this system allows a better performance in terms of energy required for the culture systems than with a mechanical mixing systems (58). Additionally, the power consumption minimization in a RWP can be achieved using a propeller or an axial pump, able to be submerged at the bottom of the pond and suitable for low head and high flows (34).

4. Fluid dynamics and mass transfer evaluation

The evaluation of the fluid dynamics of the pond is an essential step to improve algae biomass productivity and wastewater treatment efficiency. The goal of the optimization is to achieve a good mixing and an effective gas transfer while minimizing energy consumption.

4.1. Retention time distribution

A first parameter describing fluid dynamics in the RWP is the residence time of the cells inside the system. As all the cells have not the same residence time, it is necessary to determine the residence time distribution (RTD), leading to the calculation of a mean residence time. Several authors have addressed this issue (66-69).

The determination of RTD allows to compare the hydrodynamic behaviour of the RWP, with ideal reactors: plug-flow (PFR) or continuous stirred tank reactor (CSTR). It also provides information about hydrodynamic parameters such as the total mixing time, the volume of the dead zones or the short-circuit flow rate.

The experimental determination of RTD involves tracer studies; after injection, the tracer concentration in the output flow of the RWP is monitored as a function of time (70). There are various tracer injection methods (71); pulse methods and step methods (called continuous injections) are the most common ones (72). As for the choice of the tracer, it must be easily followed, generally with a suitable probe (pH, conductivity…). For example, in wastewater treatment processes, fluorescent molecules are the most widely used tracers (73), such as Rhodamine WT, which is both non bio-degradable and non-adsorbable on suspended solids (71).

Several studies used pulses with NaCl as a tracer in common RWPs (26, 74) or in RWPs with two agitation systems, a paddle wheel and an air diffuser (75).

For a step impulse the response curve has a sinusoidal shape and it can be modelled by the Vonken equation (1) with two main parameters: Peclet number (P_e) (dimensionless parameter that indicates the heat transfer through two mains characteristics: the convective heat transfer and the conductive heat transfer) and circulation time (T_c), which represents the time interval between the injection and the appearance of the tracer in the output flux.

$$\frac{\partial C}{\partial \theta} + \frac{\partial C}{\partial s} - \frac{1}{Pe}\frac{\partial^2 C}{\partial s^2} = 0 \qquad (1)$$

with C the tracer concentration at time t, s the curvilinear abscissa and θ the normalized time (ratio between time t and circulation time). The RWP has then a macroscopic behaviour similar to the dispersive plug-flow reactor (75-81).

4.2. Mixing degree

The mixing degree strongly affects the RWP performance and the efficiency of the waste treatment process. An efficient culture mixing indeed ensures a good availability of nutrients, satisfactory frequencies of light/dark cycles and avoids undesirabled flow patterns (dead volumes and short circuits). In particular, with a good mixing the algae cells are continuously moved between the enlighted zone (close to the surface) and the dark zone (deeper in the pond), thus reducing photolimitation and/or photoinhibition (1). The flow behaviour of microalgae suspension has been analysed for an open raceway pond system (57). It was proved that the flow velocity is higher in the middle layer of the flow and has a parabolic shape within the straight part of the channel section (57). The biomass productivity of a stirred raceway pond can be up to ten-fold higher than that of an unmixed pond (82-83).

The experimental determination of mixing degree is performed by tracer experiments with determination of the mixing time (time interval after which the variations in the tracer concentration are less than 5 % of the final stable value).

The mixing degree of the pond can be estimated by the Bodenstein Number (Bo), which is connected to the axial dispersion in the liquid phase and is similar to Peclet number (26).

It is then possible to estimate, thanks to the Bodenstein number determination, for each section of the RWP, the mixing degree and the hydrodynamic behaviour in comparison to both ideal reactor models. If Bo is less than 20, the behaviour is close to a perfectly stirred flow, while a value greater than 100 indicates a plug-flow. The paddle wheel, the sump and the bend sections are close to perfectly mixed reactors, whereas the straight channel has a hydrodynamic behaviour of plug-flow. Thus, the dispersion in the system takes place mainly in the three well mixed sections: sump, paddlewheel and (26, 34).

The Reynolds number can be used to quantify the vertical mixing degree. Even in the presence of a highly turbulent flow, despite significant horizontal velocities, vertical mixing can be very limited, resulting in a global insufficient level of mixing (34). Especially in the straight channel section, the poor vertical mixing results in cell sedimentation (26, 84).

The presence of baffles enhances mixing by reducing the formation of the large eddies in the bends, resulting in the diminution of the global liquid velocity of the RWP (84). Prussi et al., investigated on the mixing properties of the raceway pond for microalgae culture. However the optimization concerns only the mixing and not the productivity enhancement. But, in the same time it results in a significant increase of the complete mixing. The positive effect of baffles on mixing is greater when they are set in the paddlewheel section, due to its higher liquid depth (26).

The geometry of the paddlewheel blades also influences the degree of mixing. Using an aligned blade configuration better promotes mixing than non-aligned blades. This is due to the increase in both macro (convection) and micro (turbulence) mixing (21). The mixing efficiency can be also increased using a propeller suitable for low head and high flows (34).

Other devices can be found to enhance vertical mixing: arrays of foils akin to airplane wings (84), up-down chute baffles sequentially generating clockwise and anticlockwise liquid vortices and increasing the liquid velocity between dark and light areas in the open pond (86).

A kinetic model coupling (87) light penetration and photosynthetic activity, under non-ideal mixing culture conditions, was used to optimize a raceway pond system. Lagrangian particle tracking and heterogeneous light distribution were applied to the model to estimate light penetration into the non-homogeneous culture. Another approach concerns a Eulerian multiphase CFD model and spectral radiation model to simulate the flow dynamics of algae suspension and the light transfer in an open pond system with various biomass concentration and culture medium depth (88).

4.3. Mass transfer coefficient

The carbon source is vital in biomass synthesis; inorganic carbon must then be added to increase the biomass productivity.

In consequence CO_2 mass transfer can be one of the limiting phenomena of the whole process due to the reduced contact time between gas and liquid (26) and to the CO_2 losses during gas bubbling through the shallow channel.

The mass transfer volumic coefficient (or k_La) is an intrinsic physical parameter of the reactor that allows to quantify the transfer flux between the gaseous and liquid phases. This transfer coefficient depends on various parameters: CO_2 diffusivity in both phases, temperature, pressure, hydrodynamic conditions which greatly affect the thickness of the diffusion films.

The determination of the mass transfer coefficient is based on a dynamic method. First, nitrogen is injected through a diffuser in order to eliminate dissolved oxygen. Secondly, air is bubbled through the water in the bioreactor until equilibrium is reached. The mass transfer coefficient of oxygen is then determined and this of CO_2 can be deduced afterwards. The oxygen transfer characterization in a RWP has been investigated in several studies using this method (35, 76). Another approach, named the “tracer gas method”, has been developed for the quantification of the atmospheric re-aeration coefficient in rivers (89), with many advantages (90-91). The oxygen transfer coefficient can be obtained through the measurement of a tracer transfer coefficient (76). The tracer gas is injected through the diffuser system of the reactor; the tracer (generally propane) must be naturally absent in water and in air, cheap and easy to analyse. Gas chromatography is used to follow the dissolved tracer concentration during time.

To increase gas liquid contact, the raceway pond can be equipped with devices such sumps, mixing columns (33, 92), baffles, counter-current injection of CO_2 (33).

Enhancement of transfer can also be achieved by decreasing the bubble size with specific diffusers. A good mixing efficiency between gas and liquid phases is in favour of fine bubbles (35).

Increasing the liquid velocity or the volume of the sump, improving the performance of the sparger, increasing the gas flow to the sump (35), implementing up-down chute baffles (86), are various means to improve mixing and then mass transfer.

Oxygen accumulation inside the raceway pond, due to microalgae respiration, is crucial to evaluate, because oxygen is an inhibitor of the Rubisco enzyme complex at the heart of the photosynthetic carbon fixation reactions. Indeed, lower productivities can be observed when pure CO_2 is injected compared to industrial exhaust gases (93). This is strongly depend on the selected microalgae species and their tolerance to the CO_2 level. In fact, the effect of CO_2 concentration on the microalgae biomass productivity depend on the adaption capacity the photosynthetic apparatus (PSA) of the algae cell and, in particular, ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco)—the stromal enzyme that catalyzes the entry of CO_2 into the Calvin– Benson–Bassham (CBB) cycle to the higher CO_2 concentration. To reduce oxygen accumulation, the mass transfer must be enhanced, resulting however in an increase in the energy consumption. Another solution for reducing oxygen accumulation is to harvest continuously the biomass without affecting the efficiency of treatment process (76).

Barceló-Villalobosa et al., investigated on the mass transfer capacity in raceway reactors. This study prove that the dissolved oxygen accumulation can limit biomass productivity in these systems if their mass transfer capacity is not optimized (94).

5. Raceway ponds design

The optimal design for a RWP for wastewater treatment might offer the highest productivity, the best treatment efficacy, the minimal power consumption and low construction and operational costs. Thus, the geometry (shape, number of channel, size, channel length to width L/W ratio and mixing system) must allow a good nutrient availability, a good culture homogeneity to minimise photo-limitation due to auto-shadowing, a precise control of temperature and pH and the anaerobic area must be minimised in order to reduce the contamination risk.

A good correlation between the culture pond area, the mixing velocity and the culture depth is given by the Manning's equation, very useful for pond design (52).

5.1. Modification of the geometry

An optimal choice of the channel length to width (L/W) ratio is essential for the RWP design. This optimal choice must allow favourable hydrodynamic conditions: good mixing, minimization of dead zones and short-circuits, low shear stresses, along with a low power consumption. Several studies have analysed the effect of pond geometry on the process performance (48-49, 81, 93).

The value of the (L/W) ratio of the pound is an indication for its hydrodynamic behaviour (77, 95). When this ratio is lower than 8, the pond can be considered as a well-mixed reactor; on the contrary when the ratio is above 8 it behaves like a plug flow reactor.

5.2. Installation of deflectors

The major objective of using one or several curved flow deflectors is to overcome the stagnation zone downstream of the bend by reducing the formation of eddies (96). One optimal configuration is to place semi-circular deflectors at the end of the middle wall.

Several authors have investigated the impact of deflector's installation in the RWP on microalgae productivity, hydrodynamic properties together with performances of the treatment system and energy consumption (26, 44-45). As expected the deflectors have the advantage of improving mixing; their disadvantages are the increase of the shear stresses due to friction effects (44).

5.3. Mixing devices

The mixing efficiency is an important parameter in the design of the pond. As said above a good degree of mixing is important to avoid cell deposition, concentration gradients, thermal stratification and to provide a better availability of nutriments and light to the microalgae (96).

In addition, the mixing device must be chosen to provide a low energy consumption and a sufficient residence time for the algae growth.

Three systems are the most common: paddle wheel, screw pump and airlift system.

The paddle wheel is a mechanical agitation system, driven by an electrical motor; it offers many advantages for mixing RWPs: gentle mixing avoiding damage of flocculated algae, simple and minimal maintenance, good mixing efficiency and flexibility over a wide range of rotating speeds (96). On the other hand, the paddlewheel has some disadvantages: relative high cost of the motor, limitation of head dimension at high velocity and for large RWPs, large size in comparison with other systems (96). The RWP are typically mixed by a single eight-bladed paddlewheel with flat blades to avoid interference between multiple paddlewheels (52). The paddlewheel is considered the most effective and inexpensive means of producing flow in raceways (97).

In order to enhance the performances of the RWP, several modifications of the paddlewheel have been proposed with modifications of the blades: zig-zagged blades, lengthwise bent with right angles, back- and forward-curved blades, crosswise bent and based on a paddle wheel apparatus patent, forward-curved and back-curved, bend following and against the flow direction (60), different orientation of the blades (aligned or non-aligned blades) (21) and inclined configuration (with an inclined angle of the blades) (98) (Fig. 3).

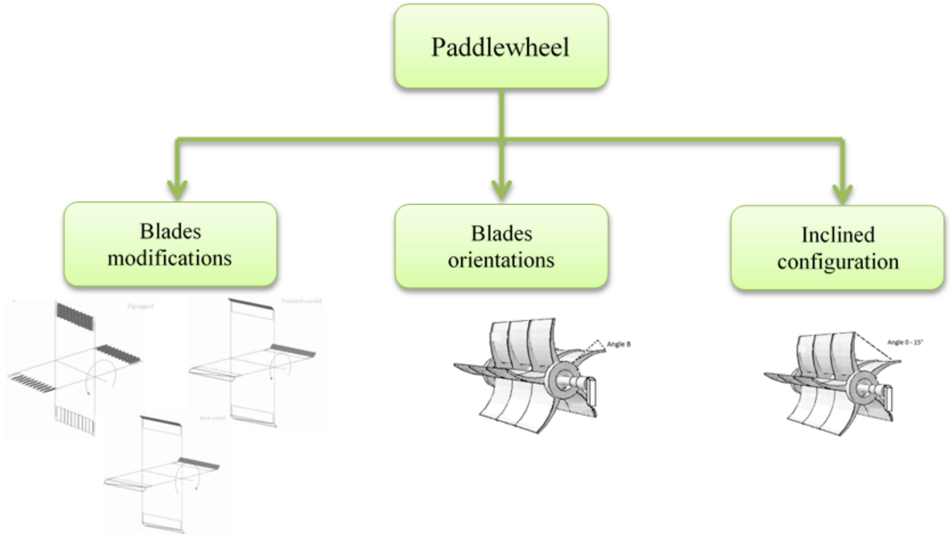

Figure 3. Blades configurations on the paddlewheel [55].

The Archemedes screw pump ensures a good mixing of the pond. However, this agitation system is more expensive than the other ones and requires an intake sump (96). The mixing system using a pump can also lead to significant shear stresses of the flocculated cells (difficulty for cells harvesting).

Another type of mixing is ensured by an airlift gas system. This system is a vertical open sump through which gas is supplied through a sparger located at the bottom of the sump. CO_2 is provided in the sump ensuring at the same time mixing of the culture and its carbonation. In addition, the carbon supply can be used for the pH regulation of the culture. However, this system can lead to a helical flow creating dead zones in the vertical section (99). The air-lift system can be easily constructed and is energetically efficient (26). A baffle can be set allowing the counter-current injection of CO_2 and increasing mass transfer (33); however, using the baffle may considerably increase the power consumption of the pond (60).

Sawant et al., investigated on the hydrodynamics of modified RWP with side entry axial flow impeller and provide that, even with high flow rate, increase in agitation speed showed reduction in the dead zones at the bottom of the pond, enhance the mass transfer, reduce the power consumption per unit volume and improve the biomass productivity compared to a classic RWP (100).

6. Discussion

The above survey highlights the main factors that play a role in the performance of a RWP. In this section, we are going to use all this information to suggest a general optimal design of a RWP dedicated to wastewater treatment (all the information is summarized in the table 1). The biggest constraint of such a system is to present low capital and operational costs. In addition, it must be a low-energy system, efficient in terms of wastewater treatment: a significant reduction in the levels of BOD, COD, TSS, nitrogen, phosphorus and heavy metals must be reached, thanks to a good distribution of nutrients and an acceptable residence time. But it does not necessarily provide high biomass productivities.

Table 1. Optimized RWP design information's for wasterwater treatment (process with flow rate of flow rate of 1 m^3/h).

Parameters	**Technical solutions**
Type of construction	Wall without membrane
Wall material construction	Corrugated asbestos-cement panels
RWP geometry	Asymmetric island in each bend of middle wall
Additional device RWP	Three semi-circular deflectors at each bend
Paddlewheel material	Fiberglass
Blades form	Back- and forward-curved blades
Paddlewheel flow velocity	0.2 m/s
Length	50 m
Width	2 m
Culture depth	0.2 m
Gas supply device	Airlift system (sparger for CO_2 injection)
Optimization device	Control system of pH culture (by CO_2 injection)

Concerning the RWP construction material, the design of the raceway pond can be simplified by a “hole in the ground” construction, with a plastic membrane liner. This type of construction offers a low cost and a simple design but is faced to a short service life and many other operational limitations (risk of contamination and the loss of the entire culture, loss of the liner due to the wind effect especially when the culture depth is reduced). One promising construction design, in terms of operational and economical conception properties for both straight and curved wall, concerns a vertical free-standing walls constructed of corrugated asbestos-cement roofing panels set into a shallow concrete filled trench. Sealing is maintained by using a bead of silicone sealant between the panel joints. Concerning the design of the paddlewall, fiberglass is preferred due to its robustness of the material structure and light weight for the microalgae performance growth. Optimal mixing and mass transfer must be performed whilst avoiding an excess of shear stresses to the cells.

The improvement of the pond performance is achieved by optimisation of the design, of the hydrodynamics of the algae culture, of the growth conditions and the minimisation of energy requirements. For the industrial wastewater treatment with a flow rate of 1 m^3/h, the optimal configuration of the raceway pond depends on the adequate choice of the L/W ratio (which must be as high as possible) to minimize the total head losses, the energy requirement of the system and the presence of the stagnation zones. Thus, the dimension of the pond concerns a length of 50 m and a width of 2 m. The culture depth of raceway pond is fixed to 0.2 m in order to ensure the best compromise between the light penetration of the microalgae culture and the energy requirement for the culture mixing. The proposed depth of 0.2 m depends strongly on the microalgae specie and the optimization of the biomass productivity needs to integrate the weather conditions and especially the light inhibition in the case of higher sunlight intensity. In the case of *Arthrospira Platensis* culture, a lower depth culture provides a better energetic consumption performance, but can reduces the biomass productivity due to the high risk of the inhibition effect by light intensity. Thus, an economic process of microalgae needs to conjugate many applications like a wastewater treatment and production of high value molecules. For this reason, the depth of the culture needs to consider the best compromise between volume/surface of biomass produced and raceway design performance for the wastewater treatment. The culture depth (optical cross section) must be as low as practically possible to decrease the occurrence of dead zones, the energy required for the mixing device and to minimize the attenuation effect of sun-light for a dense culture. Considering the culture mixing on the raceway pond, the paddlewheel is the most widely used device for such processes, with low-energy mixing (generally between 0.15 and 0.3 m/s). The mixing efficiency is linked to the liquid velocity, however, the liquid velocity must be optimized in order to achieve a sufficient culture mixing whilst avoiding high shear stress on the algae. Thus, a flow velocity of 0.2 m/s is proposed. As detailed in the section 5, the paddlewheel with modified blades (the back- and forward-curved blades) is a solution for avoiding excessive shear stress. This is achieved by minimizing the contact area between the blade and the culture. This blade modification also minimizes the energy requirement of the system. As detailed in the section 4, The implementation of an air-lift system for the CO_2 supply enhances the algal production and the algal biomass recovery and separation. This can additionally act as a mixing device, by injection of the CO_2 in counter-current conditions through a sparger to produce small gas bubbles. The increased gas liquid mass transfer efficiency allows a better nutrient distribution and helps to avoid stratification and the pH gradients formation.

This system can be even more energy effective by using the CO_2 to control the pH of the algae culture.

As detailed in the section 3, the optimal configuration for a RWP involved the modification of the middle wall by an asymmetric island in each bend and by the implementation of three semi-circular deflectors at each bend. This configuration drastically reduces the presence of the dead zones and the energy requirement of the system.

To conclude, the optimization approach of the RWP for wastewater treatment described in this review is a first step to understand how to improve the hydrodynamics characteristics and the fluid dynamics of the pond. However, the performance of the RWP is strongly depending on the seasonal weather conditions, ultimately affecting algae growth, the algae specie predominance and the occurrence of biological contamination.

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