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Microalgae cultivation in raceway ponds: Advances, challenges, and hydrodynamic considerations

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ABSTRACT

Microalgae cultivation in raceway ponds represents a significant advancement in the bioeconomy, offering a sustainable solution to the environmental challenges posed by industrialization and population growth. This review explores the historical development, current practices, and future potential of microalgae mass culturing, with a particular focus on the hydrodynamic considerations in raceway ponds. The cultivation process, from early-stage batch cultures to modern raceway pond systems, highlights the importance of optimizing operational parameters such as light, temperature, nutrients, pH, and salinity. The article also examines the challenges of contamination, mixing dynamics, and the effects of shear stress on microalgae growth. Recent advancements in raceway pond design, including improved agitation mechanisms and hydrodynamic models, are discussed to enhance biomass productivity and cultivation efficiency. This review identifies current methodologies, constraints, and areas requiring further research to advance the field of microalgae cultivation in open pond systems, ultimately contributing to a more sustainable bioeconomy.

1. Introduction

The rapid growth of the global human population, along with rapid industrialization, has triggered significant and far-reaching environmental repercussions. Increasing demands for energy, water, and resources, coupled with a surge in carbon emissions, are exerting tremendous pressure on Earth's fragile ecosystems. Depleting natural resources and polluting water bodies pose urgent challenges that require immediate attention and innovative solutions (Moreira et al., 2023). In response, the bio-economy emerges as a groundbreaking and essential paradigm designed to reduce our dependence on finite natural resources and effectively tackle today's pressing environmental issues. This transformative concept embodies a forward-thinking approach that aims to establish a sustainable and harmonious relationship between human activities and Earth's delicate ecosystems (Fernández et al., 2021).

In 1952, the Carnegie Institution of Washington released a publication titled "Algal culture from laboratory to pilot plant" edited by Burlew et al. (1953). In this work, researchers acknowledged the remarkable potential of algae as a distinct product separate from the fermentation industry. They saw algae as offering possibilities for agricultural and chemical commodities. Post-World War II, the initial concept

enthusiastically embraced the idea of using algal biomass as a primary supplement or even a replacement for animal proteins, with the aim of direct consumption by humans. This visionary approach spurred extensive research during the 1960s and 1970s, with significant contributions from research groups in various countries, including the USA, Germany, Israel, Czechoslovakia, Japan, Thailand, and France (Chaumont, 1993).

Particularly, microalgae, which typically range in diameter from 1 to 50 μm , offer a promising alternative for energy production. They encompass a diverse array of microorganisms, comprising both prokaryotic and eukaryotic photosynthetic microorganisms (Singh et al., 2011). The distinctive feature of microalgae lies in their diversity as primary producers, as they thrive in nearly every ecosystem on Earth. They inhabit a broad spectrum of environments, ranging from aquatic to terrestrial habitats, encompassing oceans, freshwater bodies, Arctic regions, alkaline or saline environments, and even hot springs (Guschina and Harwood, 2006).

In a batch culture system, the progression of algal growth typically unfolds through six distinct phases (Fig. 1) (Lee et al., 2015). Which can be summarized as follows (Halim et al., 2012; Huang et al., 2018; Lee et al., 2015):

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- **Lag Phase (1):** Initially, characterized by slow growth as microalgae acclimate to the new environment. The duration of this phase is influenced by factors such as the initial inoculum size and the extent of environmental changes.
- **Exponential Phase (2):** Marked by rapid growth and cell division. This phase is characterized by a significant increase in the number of cells, leading to an accelerated growth rate.
- **Linear growth phase (3):** This phase witnesses a gradual decrease in the pace of microalgae cell division owing to limited access to light. Here, the biomass of microalgae steadily increases until factors like nutrient scarcity start to impede further growth.
- **Declining Relative Growth Phase (4):** As resources become scarcer, specific nutrients essential for cell division become limited, resulting in a decrease in the growth rate.
- **Stationary Phase (5):** Follows the declining growth phase, where growth further decelerates, and the culture reaches a state of equilibrium. During this phase, there is no net increase in the algal population as resources required for growth become increasingly scarce.
- **Death/Lysis Phase (6):** In this last phase, cells start to perish as the vital nutrients in the environment get used up. This gradual decline results in a decrease in the overall number of algae in the population.

Microalgae are renowned for their rapid growth rates, often doubling their population every 24 h, with certain species achieving this feat in as little as 3.5 h during peak growth phases (Chisti, 2007). This exceptional reproductive capacity positions them as highly efficient candidates for numerous applications in biotechnology and sustainable resource production. Three inherent characteristics of microalgae can be utilized for technical and commercial benefits. Firstly, their remarkable genetic diversity results in a wide range of physiological and biochemical characteristics, leading to the natural synthesis of a diverse array of fats, sugars, bioactive compounds, and more. Lastly, their vast and relatively unexplored diversity positions microalgae as a virtually untapped source of valuable products, promising opportunities for further exploration and commercial utilization (Priyadarshani and Rath, 2012).

Nowadays, microalgae find extensive applications (Table 1). Several compounds listed in the table, such as pigments, lipids, proteins, carbohydrates, phenolics, phytosterols, and toxins, have significant economic value due to their wide range of applications in industries such as food, cosmetics, pharmaceuticals, and bioplastics. Microalgae are excellent sources of these compounds due to their rapid growth rates, high productivity, and ability to thrive in various environments, including wastewater.

It is important to note that not all microalgal species produce all

these compounds. Instead, each species serves as a source for specific compounds. For example, astaxanthin, a pigment extracted from microalgae such as *Haematococcus pluvialis*, is widely used in food, cosmetics, and pharmaceuticals due to its antioxidant properties and health benefits. Similarly, lipids extracted from microalgae such as *Chlorella protothecoides* and *Schizochytrium sp.* are used as biofuels, food additives, and health supplements.

In the context of biofuels, microalgae-derived lipids and carbohydrates offer a promising alternative to fossil fuels. Biodiesel and biogas production from microalgae not only helps reduce greenhouse gas emissions but also utilizes resources like industrial flue gas and wastewater to improve cost-effectiveness. With theoretical biomass yields reaching up to 9,100 tons per square kilometer annually in raceway ponds, the scalability of microalgae for energy applications is significant (Banerjee and Ramaswamy, 2017). Furthermore, the integration of anaerobic digestion effluents into microalgae systems creates a closed-loop approach, reducing nutrient loss and boosting energy yields (Romagnoli et al., 2020). Emerging technologies like thermochemical conversion are enhancing the economic viability of algae-based fuels by offering scalable and strain-agnostic solutions for processing diverse types of microalgal biomass, reducing production costs to as low as 1.65 per liter (Hoffman et al., 2017).

In addition to biofuels, microalgae are a valuable source of polyunsaturated fatty acids (PUFAs), including omega-3 oils, which are incorporated into infant formula, nutritional supplements, and therapeutic products. These oils offer a sustainable alternative to fish-derived omega-3, reducing the environmental impact on marine ecosystems by decreasing overfishing and reliance on wild fish stocks. Similarly, pigments such as β -carotene and astaxanthin are widely used as natural dyes in the food and cosmetics industries, providing bioactive and environmentally friendly alternatives to synthetic additives (Benemann, 2013). Proteins derived from microalgae, particularly species like *Spirulina* and *Chlorella*, are also increasingly incorporated into functional foods and animal feeds, addressing the growing demand for sustainable and nutrient-rich protein sources.

Microalgae systems also present opportunities to align with the principles of the circular economy. For example, wastewater treatment integrated with microalgae cultivation can reduce nutrient loads in water systems while generating valuable biomass as a byproduct. This dual-purpose approach not only lowers water treatment costs but also provides an environmentally friendly method to produce high-value compounds (Lage et al., 2021). Furthermore, microalgae's ability to capture CO_2 emissions positions it as a strategic tool for carbon offset programs, enabling industries to achieve emissions targets while producing economically viable biomass that can be utilized for high-value

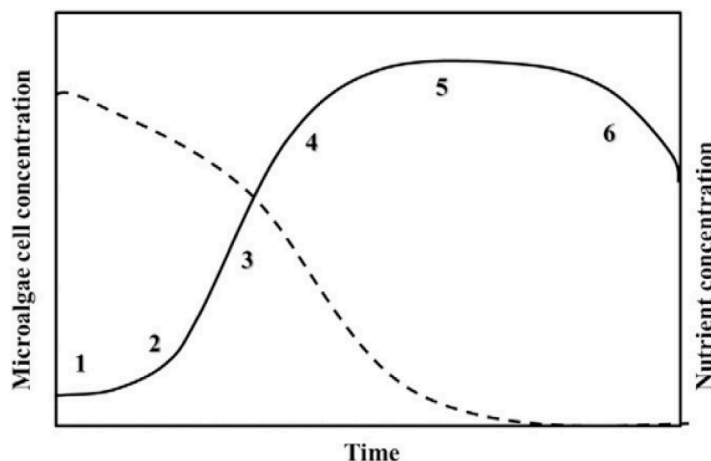


Fig. 1. Stages of growth in microalgae batch culture (solid line) and nutrient concentration ($mg L^{-1}$, dashed line). 1: lag phase; 2: exponential phase; 3: linear growth phase; 4: declining phase; 5: stationary phase and 6: death phase (Lee et al., 2015).

Table 1

Compounds Extracted from Various Microalgae Species and Their Potential Applications (Borowitzka, 2013; Chu, 2012; Koutra et al., 2018; Kumar et al., 2019; Manirafasha et al., 2016; Markou and Nerantzis, 2013; Nwoba et al., 2019; Pagels et al., 2020; Pulz and Gross, 2004).

| Compounds | Applications | Microalgal sources |
|--------------------------------|----------------------------|--|
| Pigments: | Food and nutraceuticals | <i>Aphanizomenon flos-aquae</i> <i>Chlorella sorokiniana</i> <i>Chlorella vulgaris</i> <i>Chlorella zofingiensis</i> <i>Dunaliella salina</i> <i>Haematococcus pluviialis</i> <i>Isochrysis galbana</i> <i>Nannochloropsis gaditana</i> <i>Nannochloropsis gaditana</i> <i>Phaeodactylum tricornutum</i> <i>Spirulina platensis</i> <i>Botryococcus braunii</i> <i>Chlorella protothecoides</i> <i>Cryptocodium</i> <i>Cyanophora paradoxa</i> <i>Glaucocystis nostochinearum</i> <i>Monodus</i> <i>Nannochloropsis salina</i> <i>Neochloris oleoabundans</i> <i>Pavlova</i> <i>Phaeodactylum</i> <i>Phaeodactylum tricornutum</i> <i>Porphyridium</i> <i>Rhodomonas salina</i> <i>Scenedesmus sp.</i> <i>Schizochytrium mangrovei</i> <i>Anacystis nidulans</i> <i>Aulosira fertilissima</i> <i>Chlorella sp.</i> <i>Chlorella vulgaris</i> <i>Gyrodinium impudicum</i> <i>Navicula pelliculosa</i> <i>Nostoc muscorum</i> <i>Porphyridium sp.</i> <i>Rhodella reticulata</i> <i>Scenedesmus acuminatus</i> <i>Schizochytrium sp.</i> <i>Spirulina platensis</i> <i>Synechocystis sp.</i> |
| • Chlorophyll a and b | Feed | |
| • Lutein | Anti-oxidant | |
| • Astaxanthin | Cosmetics | |
| • β -carotene | Pharmaceutical | |
| • Phycobilins | Additives | |
| • C-phycoerythrin | Dyes | |
| • Phycoerythrin | | |
| • Fucoxanthin | | |
| • Canthaxanthin | | |
| • Zeaxanthin | | |
| Lipids: | Biofuels (biodiesel) | |
| • Triglycerides | Food additive | |
| • Hydrocarbons | Feed additive | |
| • Triacylglycerols | Health supplement | |
| • Neutral lipids | | |
| • Polar lipids | | |
| • Phospholipids | | |
| • Glycolipids | | |
| • PUFAs | | |
| Polymers: | Medical | |
| • PHAs | Bioplastics | |
| • EPSS | Biomedical | |
| | Agricultural Films | |
| | Textiles | |
| | Water Treatment | |
| | Food (Dairy Products) | |
| | Cosmetics | |
| Proteins: | UV-screening agent | <i>Aphanizomenon flos-aquae</i> <i>Chlorella ellipsoidea</i> <i>Euglena gracilis</i> |
| • Essential amino acids | Food and feed additives | |
| • Non-essential amino acids | Health supplements | |
| • Mycosporine-like amino acids | Pharmaceutical | <i>Nannochloropsis oculata</i> <i>Porphyridium cruentum</i> <i>Rhodomonas salina</i> <i>Spirulina platensis</i> <i>Dunaliella tertiolecta</i> <i>Isochrysis galbana</i> <i>Nannochloropsis oculata</i> <i>Spirulina platensis</i> <i>Tetraselmis suecica</i> <i>Isochrysis galbana</i> <i>Porphyridium cruentum</i> <i>Spirogyra sp.</i> |
| Minerals and Vitamins | Biofertilizers | |
| | Feed supplements | |
| | Functional food | |
| | Antioxidants | |
| Carbohydrates: | Biofuels | |
| • B1–3- glucan | Animal feed | |
| • Amylose | Functional Foods Additives | |
| • Starch | Immune Modulation | |
| • Cellulose | Cosmetics | |

Table 1 (continued)

| Compounds | Applications | Microalgal sources |
|----------------------|--|---|
| • Alginates | Pharmaceutical and Biomedical | |
| • Laminaran | Prebiotics | |
| • Oligosaccharides | Nutritional Supplements | |
| • Simple sugars | | |
| Phenolics: | Cosmetics | <i>Chlorella sorokiniana</i> |
| • Gallic | Antioxidants | <i>Chlorella vulgaris</i> <i>Desmodesmus bicellularis</i> <i>Desmodesmus communis</i> <i>Dunaliella salina</i> <i>Nannochloropsis salina</i> <i>Nannochloropsis limnetica</i> <i>Phaeodactylum tricornutum</i> <i>Dunaliella tertiolecta</i> <i>Cryptocodium cohnii</i> |
| • Caffeic | | |
| • Salicylic | | |
| • ρ -coumaric | | |
| • Ferulic acid | | |
| Phytosterols: | Functional Foods | |
| • Crinosterol | Nutraceuticals and Dietary Supplements | |
| • Stigmasterol | Cosmetics and Skincare Products | <i>Isochrysis galbana</i> |
| • Isofucosterol | Pharmaceutical | <i>Nannochloropsis gaditana</i> <i>Pavlova lutheri</i> <i>Tetraselmis suecica</i> |
| • Sitosterol | Animal Feed Additives | |
| • Fucosterol | Biopesticides | |
| • Dinosterol | Bioplastics | |
| Toxins: | Health applications | <i>Alexandrium lusitanicum</i> |
| • Ciguatoxin | Antioxidant | |
| • Domoic acid | <i>Gambierdiscus toxicus</i> | |
| • Okadaic acid | | |
| • Gambieric acids | | <i>Nitzschia pungens</i> |

products, thus offsetting production costs.

Lastly, the versatility of microalgae-derived products allows them to target a range of domestic and international markets. Biofuels produced from microalgae can address local energy demands, while high-value products like omega-3 oils, pigments, and proteins cater to global health, food, and cosmetics industries. The rising demand for sustainable and eco-friendly products, coupled with stringent environmental regulations, presents significant opportunities for microalgae-based solutions to penetrate premium markets.

The diverse compounds produced by microalgae, coupled with their integration into sustainable production systems, underline their vast economic and industrial potential. From biofuels and nutraceuticals to wastewater treatment and carbon mitigation, microalgae cultivation offers scalable, eco-friendly solutions for multiple sectors, making it a critical player in the future bioeconomy.

Regardless of the ultimate intended use, it is essential to carefully customize the entire production process to match the specific demands of the application. Attempting to establish a universal technology or process that can effortlessly adapt to all conceivable applications is impractical. Therefore, a tailored approach becomes essential to ensure a precise fit and the successful implementation of the solution in each unique scenario (Garrido-Cardenas et al., 2018).

Since its inception in the 1950s (Burlew et al., 1953), numerous cultivation systems have been devised to facilitate microalgae growth. Microalgae cultivation systems are commonly classified based on various parameters such as size, agitation mode (if applicable), light source (solar or artificial), culture depth, or shape (flat or tubular) (Legrand et al., 2021). This highlights the complexity and non-universal nature of microalgae culture bioprocessing. To achieve optimal outcomes, it is essential to carefully select an appropriate cultivation system, considering factors such as the intended application, geographical location, available resources, and the characteristics of the cultivated strain (Legrand et al., 2021).

In their study, (Legrand et al., 2021) discussed various modeling approaches, distinguishing between models based on variables obtained from experiments and predictive models that incorporate radiative transfer models to predict the distribution of light in PBRs. Additionally, from a commercial standpoint, factors such as the final product price, capital expenditures (CAPEX), and operating expenditures (OPEX) are crucial considerations (Masojídek et al., 2023). Any alterations to these parameters may necessitate the use of a different cultivation system (Legrand et al., 2021). In large-scale production, two primary methods are commonly employed: one involves *open reservoirs*, where the microalgae culture interacts directly with the environment (Masojídek et al., 2023), while the other utilizes *closed or semi-closed vessels*, such as *photobioreactors (PBRs)*, which establish a barrier between the culture and the atmosphere, thus limiting the exchange of gases or pollutants (Grivalský et al., 2019; Masojídek et al., 2023). Open reservoirs and PBRs differ significantly in their operations, leading to distinct growth physiology for microalgae in each system (Grobbelaar, 2009).

Open pond cultivation systems are extensively embraced in the industry, primarily owing to their cost-effectiveness in terms of both initial investment and ongoing operational expenses. However, these systems face significant challenges in regulating operating conditions, which could potentially result in decreased biomass productivity. Unfortunately, the practicality of open ponds is confined to only a handful of microalgae species. This limitation stems from the difficulties associated with the limited control over cultivation conditions and the risk of biological contamination (Suh and Lee, 2003). Consequently, open systems prove most suitable for cultivating “robust” microalgae strains, chiefly those belonging to the *Chlorophyta* group, characterized by rapid growth rates, or under highly selective conditions, such as specific microalgae strains like the cyanobacteria *Spirulina (Arthrospira)* or the green microalga *Dunaliella* (Grivalský et al., 2019).

The growth of microalgae is influenced by various factors, some stemming from the environment and others inherent to the organisms themselves. Environmental conditions, including light availability, temperature, nutrient levels, dissolved oxygen content, CO₂ concentration, pH, salinity, and the presence of potentially harmful substances in the growth medium, all play vital roles in shaping microalgae growth. Conversely, factors related to the organisms, such as the presence of microorganisms like bacteria, fungi, and viruses, competition from other algae, the mechanical forces during mixing, the dilution rate, and the method and frequency of harvesting, also significantly impact the dynamics of microalgae growth (Chiu et al., 2009; Fábregas et al., 2004; Hu and Gao, 2006; Moheimani, 2005; Renaud and Parry, 1994; Rodolfi et al., 2009; Shen et al., 2009a; 2009b; 2009c). However, identifying the main factor that has the most influence on algae growth is challenging because all these factors can affect algae growth simultaneously (Abu-Rezq et al., 1999; Zittelli et al., 1999).

This review is divided into five distinct sections, each summarizing recent research on microalgae cultivation with a particular emphasis on raceway ponds, their associated challenges, and limitations. The section Microalgae Mass Culturing: The Early Stage provides a historical overview of microalgae mass culturing, tracing its development from its early stages to contemporary practices. It discusses fundamental growth limitations, including light availability, temperature sensitivity, nutrient requirements, pH levels, stirring and mixing challenges, and contamination issues. The section Limits to Growth explores these growth constraints further, offering a detailed analysis of environmental and biological factors that influence microalgae productivity. This is followed by the section Environmental Impacts of Microalgae Cultivation, which examines the ecological implications of large-scale cultivation systems and highlights opportunities for sustainability improvements.

In the second part of the article, the Raceway Ponds section provides an in-depth discussion exclusively on raceway ponds, covering their design, operation and advancements. It also includes a discussion on the economic aspects of raceway pond cultivation, with an analysis of costs, market trends, and the potential economic benefits of microalgae

products. The section further compares raceway ponds with other open pond systems, such as high-rate algal ponds and thin-layer systems. The subsequent section Hydrodynamic Considerations in Microalgae Cultivation addresses critical factors such as mixing dynamics, including turbulence and chaotic advection, shear stress effects, wave generation, and vortex shedding, all of which are essential for optimizing microalgae cultivation in raceway ponds.

Throughout all sections, the review identifies current methodologies, constraints, and areas requiring further research to advance microalgae cultivation in open pond systems.

2. Microalgae mass culturing: the early stage

Over the past several decades, extensive research efforts have been dedicated to the field of large-scale microalgal cultivation (Lee, 2001). This journey traces its roots back to the late 19th century when Beijerinck conducted pioneering unialgal cultivation experiments, using *Chlorella vulgaris*, as part of his plant physiology studies (Borowitzka, 1999). Fast forward to the 1940s, the Carnegie Institution for Science embarked on cultivation trials with microalgae, specifically exploring the potential for large-scale *Chlorella* cultivation. After 1948, mass cultivation of microalgae became a prominent focus of research at Stanford (USA), Essen (Germany), and Tokyo (Borowitzka, 1999). The foundational work of various research groups in the early phases of microalgae cultivation found its synthesis in the timeless classic book edited by John S. Burlew of the Carnegie Institution in Washington, DC (Burlew et al., 1953). In these early stages, large-scale microalgae cultivation and pilot plant designs primarily centered around closed systems with the key objective of isolating cultures from the natural environment to prevent contamination by other microorganisms (Grivalský et al., 2019).

Commercial large-scale microalgae cultivation began in the early 1960s in Japan, initially focusing on *Chlorella*. By the early 1970s, Sosa Texcoco S.A. established a *Spirulina* facility in Mexico's Lake Texcoco, marking a significant milestone. Subsequently, Dai Nippon Ink. and Chemicals Inc. set up a commercial *Spirulina* plant in Thailand by 1977. By 1980, Asia had 46 factories producing over 1000 kg of microalgae monthly, mainly *Chlorella*. In 1996, Japan alone traded approximately 2000 tons of *Chlorella*. In 1986, commercial production of *Dunaliella salina* for β -carotene began, with facilities in Australia, Israel, and the USA. Concurrently, large-scale production of cyanobacteria started in India. Thus, within a few decades, the microalgal biotechnology industry grew remarkably (Borowitzka, 1999).

The achievement of successful commercial large-scale microalgae production relies on various factors, and a pivotal element is the development of cost-effective large-scale culture systems for these microorganisms. The progression of these systems has been, and remains, an incremental process. Algal biomass production employs both open ponds and closed PBRs. The major operational differences, including advantages and disadvantages, between these two options have been summarized by (Masojídek et al., 2023) in a recent study.

PBRs offer significant advantages, exhibiting substantially higher volumetric algal productivities ranging from 0.2 to 3.8 gL⁻¹day⁻¹, in contrast to raceway ponds which typically achieve productivities of 0.12 to 0.48 gL⁻¹day⁻¹ (Kumar et al., 2015). Closed PBR provide several benefits, including extended gas retention time and improved mass transfer efficiency which contribute to higher microalgae growth rates, increased productivity, better control over growth conditions, reduced contamination risks, and efficient space utilization. Airlift reactors, for instance, stand out for their merits such as high volumetric mass transfer rates of CO₂, effective mixing, light/dark cycling capabilities, and improved light utilization efficiency. Additionally, closed PBRs offer greater control over crucial process parameters, thereby enhancing the overall conditions for cultivation (Kumar et al., 2015). Nonetheless, closed PBRs come with several drawbacks that restrict their application

at a commercial scale. In his review, (Chisti, 2007) emphasizes the superiority of closed PBRs over open ponds in biofuels production, showcasing their advantages in productivity, culture purity, and cell densities, leading to lower harvesting costs and improved overall economics. Researchers in the algae biofuels field widely favor PBRs for these reasons. However, gas exchange limitations (CO_2 in and O_2 out) in PBRs restrict their individual growth units to $\approx 100 m^2$ (the area of each individual growth unit), while raceway-type mixed ponds cover over 10,000 m^2 . This makes closed PBRs impractical for large-scale commodity production, requiring hundreds of hectares and thousands of individual PBRs, making them cost-ineffective even without considering capital costs. Although about a dozen commercial PBR systems ($\approx 1 ha$) were built over the past decades, their high costs, -almost 100 times that of open ponds-resulted in the majority failing within months to years. Only one closed tubular PBR in Israel currently operates commercially, producing high-value *H. pluvialis* biomass ($> \$100,000/t$). Furthermore, PBRs do not provide tangible benefits compared to ponds in terms of productivity when taking into account the actual area occupied, water or energy consumption, or long-term resistance to contamination. Although PBRs might find utility in small-scale seed cultures, their contribution is minimal ($\approx 0.1\%$) to the total system size and does not represent a significant cost factor in large-scale biomass production (Klein-Marcuschamer et al., 2013).

In the early stages of microalgal mass culture, there was a strong focus on closed systems (Burlew et al., 1953). However, by the mid-1950s, the idea of using open outdoor cultures for microalgae cultivation gained traction, especially with the introduction of fast-growing strains that reduced contamination risks. This shift supported the concept of outdoor microalgae culture using open systems. Various studies have compared the productivity and efficiency of outdoor PBRs with open ponds for cultivating microalgae. Summarizing these comparisons, (Sarker and Kaparaju, 2023) highlighted that outdoor PBRs could produce double the amount of *Spirulina* annually compared to ponds. While the protein, lipid, and carbohydrate contents of biomass were similar in both ponds and PBRs, ponds yielded a higher ratio of saturated to unsaturated fatty acids. Outdoor PBRs and hybrid systems were found to offer superior productivity compared to open ponds. Even in less favorable weather conditions, well-designed PBRs effectively reduce photoinhibition, resulting in higher productivity efficiency compared to open ponds. Nowadays, the preference for open-air systems is mainly driven by economic factors, as closed systems are expensive and difficult to scale up, which may limit their widespread commercial application. Moreover, many closed systems require indoor operation with artificial lighting, leading to higher energy costs, whereas open-air systems can take advantage of natural sunlight, offering a more cost-effective solution. In open systems, various types are available, including *shallow big ponds*, *tanks* also known as *unstirred ponds*, *circular ponds*, *mixed ponds*, and *raceway ponds (RWPs)*, each with its unique characteristics. Among these, *RWPs* have emerged as the most widely used option for algal cultivation and wastewater treatment (De Godos et al., 2014).

3. Limits to growth

Understanding the challenges that restrict the growth of algae and the yield of products in microalgal cultures is crucial for creating a sustainable and economically successful large-scale algal process. As highlighted by Richmond and Zou (1999), a critical initial phase in achieving successful microalgal cultivation is pinpointing the physical and chemical factors that might potentially constrain their growth. Within cultivation systems, algal growth is subject to the influence of a diverse array of both "physical" and "biotic" factors (Borowitzka, 1998).

In this section, we will discuss the specific factors that influence optimal algae growth, considering variations in algae strains and desired compositions. Despite this variability, a broad set of conditions is

summarized in Table 2.

3.1. Light, photoinhibition and oxygen

For an accurate prediction of culture performance, it is essential to understand the relationship between the observed light and the process of photosynthesis (Tchernov et al., 2003). As highlighted by Richmond et al. (2004), a central challenge in the mass cultivation of photoautotrophic microalgae lies in the optimization of light utilization to boost photosynthetic productivity, encompassing both cell mass and secondary metabolites. This challenge becomes particularly significant in the context of large-scale outdoor microalgae cultivation, where the efficient utilization of solar energy serves as the cornerstone of this biotechnology's potential. The productivity of algae in photosynthetic cultivation is intrinsically linked to the efficiency of the photosynthetic process itself, exerting direct influence over critical factors such as growth rate, biomass generation, and lipid accumulation (Yousuf, 2020). The amount of light absorbed by a suspended algal cell in a cultivation system is influenced by several factors, including the cell's specific position at a given moment, the density of the culture, and the pigmentation of the cells (Malone, 1982). In situations where the depth and cell concentration of the culture are higher, it becomes necessary to increase light intensity to ensure adequate penetration through the medium. However, caution is essential, as direct sunlight or high-density artificial light may also result in photoinhibition (Yousuf, 2020).

Photoinhibition, as defined in the literature, is the light-induced reduction in photosynthesis, marked by a decrease in the maximum quantum yield of photosynthesis and a decline in the efficiency of photosynthesis light conversion. Moreover, it can notably lower the rate of light-saturated photosynthesis, especially after prolonged exposure to high irradiance conditions (Baker and Bowyer, 1994; Vonshak and Guy, 1992).

It is important to highlight that microalgae depend on a light/dark cycle for efficient photosynthesis. Light plays a crucial role in the photochemical phase, generating energy, while darkness is essential for the biochemical phase, where vital molecules for growth are synthesized (Al-Qasbi et al., 2012).

(Grobbelaar, 1991) pointed out that algal growth can be influenced by three categories of fluctuating light/dark cycles:

- (1) **high-frequency fluctuations** of 100 ms (10 Hz) and less,
- (2) **medium-frequency fluctuations** lasting seconds to minutes,
- (3) **low-frequency cycles** spanning hours to days and years.

Literature has reported that cycles ranging from a few seconds to minutes can enhance the productivity of mass algal cultures (Grobbelaar, 1991). When the light/dark cycle matches the turnover rate of the photosynthetic apparatus (at frequencies of 10-100 msec), it optimizes the efficiency of photosynthesis by ensuring that the photosynthetic machinery is active during the light phase and can effectively utilize the generated energy. Nevertheless, Lee and Pirt John (1981)

Table 2

A broadly applicable set of conditions for cultivating microalgae (abiotic factors) (Lavens et al., 1996).

| Parameters | Range | Optimal |
|--|---------------------------------|-------------------------------|
| Temperature ($^{\circ}C$) | 16–27 | 18–24 |
| Salinity (gL^{-1}) | 12–40 | 20–24 |
| Light intensity ($\mu mol m^{-2}s^{-1}$) | 18.6–186 | 46.5–93 |
| | (depends on volume and density) | |
| Photoperiod | | 16:8 (minimum) 24:0 (maximum) |
| (light: dark, hours) | | |
| pH | 7–9 | 8.2–8.7 |

illustrated that, under certain conditions, the growth rate of algae in alternating short (light) and scoto-periods (dark) was comparable to continuous lighting exposure. Extending the dark period, however, led to a decrease in the growth rate.

Most commercial-scale algal biomass production occurs outdoors, utilizing natural light. This exposes the algae to diurnal changes in irradiation and temperatures as well as shorter-term fluctuations due to cloud cover (Borowitzka and Vonshak, 2017). Throughout the day, these environmental factors oscillate, spanning conditions that might restrict photosynthesis to those that could potentially inhibit it. Lack of synchronization between these environmental factors can impose stress on the photosynthesis process, adversely affecting the growth of outdoor microalgal cultures (Vonshak et al., 2001). As per (Richmond and Zou, 1999), when nutritional needs are met, and the temperature is relatively close to “optimal”, light emerges as a significant limiting factor for productivity and growth. Nonetheless, in open outdoor systems like RWPs, light seldom acts as the sole limiting factor influencing algal growth and biomass production (Dodd, 1986; Richmond and Grobelaar, 1986).

Another factor influencing photosynthetic productivity is biomass density, as it leads to self-shading of the algal cells. There exists an optimum cell density where productivity is at its maximum, which is dependent on the average irradiance received by the cells. Adjusting culture depth, flow rates, and harvesting strategies can help modulate average irradiance and optimize productivity (Borowitzka and Vonshak, 2017).

The challenge posed by the accumulation of oxygen in microalgal cultures stems from its status as a by-product of photosynthesis, often exceeding four times the air saturation level within the culture. Elevated oxygen levels have the effect of limiting the rate of photosynthesis. This phenomenon is evident in both closed PBRs and open ponds, although the latter experiences a comparatively less pronounced buildup of dissolved oxygen due to mechanisms such as diffusion into the atmosphere and the use of mixing devices like paddlewheels. The initial observation of this effect dates back to 1920 when O. Warburg (1883–1970) noted a significant drop in the photosynthesis of *Chlorella* cultures exposed to pure oxygen. (Darvehei et al., 2018). As described by Torzillo et al. (1998), elevated oxygen concentrations not only increase susceptibility to photoinhibition but also result in decreased productivity. Additionally, a decrease in temperature can worsen this situation, intensifying sensitivity to photoinhibition and potentially leading to declines in productivity. (Richmond et al., 1993) noted that under extremely high oxygen concentrations, photooxidative death may occur. This highlights the crucial importance of regulating oxygen levels in algal cultures to ensure their viability and productivity.

3.2. Temperature

Temperature is a crucial factor influencing the growth of organisms. Many microorganisms have adapted to thrive in relatively mild climates and struggle to survive in extreme environmental conditions. Nevertheless, there exist regions on our planet where environmental parameters surpass the typical limits conducive to growth, yet life persists. And even within these challenging environments, certain organisms not only survive but also thrive, successfully completing their life cycles despite extreme temperatures. In 1974, MacElroy coined the term “extremophile” to collectively refer to these organisms capable of enduring extreme conditions, including extreme pH levels, pressure, and salinity. In some instances, these extremophiles exhibit additional attributes, such as their ability to endure high levels of gases like CO_2 or to flourish in the presence of elevated concentrations of metals. Some even exhibit resilience in the face of multiple stresses simultaneously, earning them the classification of “polyextremophiles” (Varshney et al., 2015).

In the context of microalgae, temperature plays a pivotal role in influencing the overall photosynthetic activity of these organisms. This, in turn, has an impact on cellular division and, consequently, the

productivity of microalgae biomass. Extremophilic microalgae emerge as promising candidates for large-scale production due to two key factors; their ability to thrive in extreme growth conditions reduces the risk of unwanted contaminations, facilitating cost-effective cultivation in open photo-bioreactors. As well as, their ability to adapt to and endure harsh environments, often characterized by high oxidative stress. These microorganisms synthesize rare and valuable biomolecules with significant biotechnological potential (Lafarga et al., 2021).

Previous research extensively explores the potential relationship between a species’ origin and its optimal growth temperature (Kong et al., 2007). Microalgae respond differently to temperature fluctuations, significantly impacting various aspects of their growth and physiology (Richmond and Zou, 1999). Each microalgal species typically has a specific optimal growth temperature. Mesophilic species generally achieve maximum growth rates between 20 and 25 °C, while thermophilic strains like *Chaetoceros* and *Anacystis nidulans* can thrive at temperatures as high as 40 °C. In contrast, psychrophilic strains like *Asterionella formosa* prefer lower temperatures, around 17 °C (Ras et al., 2013).

In open-air cultivation systems, where controlling temperature can be economically challenging, prioritizing microalgal species with a broad temperature tolerance is advantageous (Maddux and Jones, 1964; Vonshak et al., 2001). Temperature presents significant challenges in scaling up microalgal cultures for commercial use. Temperature control in large RWPs is difficult and expensive, making it essential to select suitable strains capable of thriving within the specific temperature range at the intended cultivation site is crucial (Borowitzka and Vonshak, 2017). Temperature fluctuations, both diurnal and seasonal, impact growth and productivity. Sub-optimal morning temperatures can cause photoinhibitory damage, reducing productivity, while nighttime temperatures affect dark respiration, leading to biomass losses. Additionally, temperature influences nutrient and gas solubility, impacting CO_2 intake and oxygen removal efficiency. Minimizing temperature-induced damage and optimizing temperature control are essential for maximizing microalgae productivity in large-scale commercial operations.

In outdoor PBRs, microalgae production faces temperature fluctuations (10°C to 45°C) due to the greenhouse effect, which often exceed the tolerance thresholds of most commercially cultivated algae species (Béchet et al., 2011). Although many microalgae species can perform photosynthesis and cellular division within a broad temperature range (15°C to 35°C), their optimal growth conditions are between 20°C and 25°C (Li, 1980). Lower temperatures can reduce carboxylase activity, leading to potential energy overproduction under constant light conditions, resulting in light saturation. However, some species, such as *Chlorella vulgaris*, can still grow successfully at 5°C, albeit with lower chlorophyll content compared to cultures maintained at 27°C (Maxwell et al., 1994).

Increasing temperatures positively impact photosynthesis and cell division in microalgae by enhancing enzymatic activities linked to the Calvin cycle (Falkowski and Owens, 1980). With each 10 °C rise in temperature, processes like photosynthesis, cell division, and overall growth are expected to roughly double until reaching unfavorable temperature conditions. However, as temperatures exceed the optimal range, microalgae growth rates sharply decrease due to heat stress. Elevated temperatures negatively impact enzyme functionality and alter the structure and function of proteins involved in photosynthetic processes. The decline in growth rate is often depicted as a linear trend, with the decrease occurring more or less abruptly depending on the specific microalgal species (Ras et al., 2013).

3.3. Nutrients

Phototrophic organisms harness light energy to fulfill a significant portion of their nutritional requirements from inorganic compounds. Nutrient limitations profoundly impact the biochemical composition of microalgae, resulting in substantial variations. Determining the minimal

nutritional prerequisites essential for microalgae growth can be achieved using the approximate molecular formula $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ (Grobbeelaar, 2004). A suitable growth medium for microalgae should encompass essential inorganic elements such as carbon (C), Phosphorus (P), Nitrogen (N), Iron (Fe), and others, with their composition possibly adjusting according to the specific species being cultivated. As indicated by the biomass's molecular formula, it is reasonable to assert that carbon (C) accounts for roughly 50% of its content (Grobbeelaar, 2004). Carbon is crucial because it serves as the foundational element for all organic compounds synthesized within cells, including carbohydrates, proteins, nucleic acids, vitamins, and lipids (Richmond et al., 2004). Photosynthesis exclusively relies on carbon as its source, and many algal cultures face limitations associated with carbon availability (Borowitzka, 1998).

Microalgae employ various mechanisms for inorganic carbon assimilation, utilizing diffusion when the pH falls within the range of 5.0 to 7.0 and active transport when the pH exceeds 7.0 (Gonçalves et al., 2017). Maintaining a consistent supply of CO_2 and bicarbonates (HCO_3^-) is crucial for achieving heightened autotrophic production rates (Richmond et al., 2004). Additionally, certain microalgae species, especially those thriving in mixotrophic conditions, can utilize organic compounds such as sugars, acids, and alcohols as alternative carbon sources (Chowdury et al., 2020). In large-scale systems, carbon dioxide (CO_2) can be supplied directly to the culture using gas bubbling or sparging methods. Alternatively, bicarbonates (HCO_3^-) can be added directly to the culture medium to ensure a consistent supply of carbon. Additionally, large-scale microalgae cultivation facilities can be integrated with industrial processes that produce CO_2 emissions. Flue gas or industrial emissions containing CO_2 can be redirected to microalgae cultivation systems, offering a continuous and cost-effective source of carbon.

Nitrogen is another vital component for the formation of structural and functional proteins, ranking as the second most significant element after carbon (Becker, 1994). It constitutes the second-highest proportion in microalgal biomass, ranging from 1% to 14% in dry mass. Nitrogen plays a pivotal role in the formation of proteins, nucleic acids, vitamins, and photosynthetic pigments. Interestingly, microalgal growth rates remain relatively consistent across various nitrogen sources such as urea, nitrite, and nitrate. A deficiency of nitrogen in the cultivation medium promotes the preferential synthesis of lipids and carbohydrates (Yang et al., 2011). When nitrogen is scarce, noticeable changes in cell coloration typically occur, including reductions in chlorophyll and increased carotenoid levels, accompanied by the accumulation of organic compounds like polysaccharides and specific oils (Becker, 1994). Nitrogen compounds such as urea, nitrate, and ammonium salts can be directly added to the culture medium to provide nitrogen to microalgae. Alternatively, microalgae cultivation systems can be integrated with wastewater treatment processes to utilize nitrogen-rich wastewater as a nutrient source.

Phosphorus, another crucial macronutrient, plays a significant role in cellular metabolic processes by contributing to the formation of various structural and functional components essential for the normal growth, development, and reproduction of microalgae. Similar to nitrogen, microalgae also uptake phosphorus through active transport mechanisms (Gonçalves et al., 2017). The availability of phosphorus has a significant impact on the composition of biomass production (Borowitzka, 1988). The balance between internal and external phosphorus supply notably influences the accumulation of lipids and carbohydrates. Additionally, the nitrogen-to-phosphorus (N:P) ratio in the culture medium is of importance, affecting both productivity and the prevalence of dominant species in the culture (Richmond et al., 2004). While a decrease in phosphorus can lead to pigment accumulation in certain microalgae, its impact is generally milder compared to nitrogen deficiency (Becker, 1994). Phosphorus compounds, such as phosphates, can be directly added to the culture medium to provide phosphorus to microalgae. Moreover, microalgae cultivation systems can be integrated with wastewater treatment processes to effectively utilize

phosphorus-rich wastewater as a nutrient source, similar to the approach used for nitrogen. This integration optimizes resource use and reduces the environmental impact of nutrient discharge.

Ensuring an adequate supply of carbon, nitrogen, phosphorus, and other essential nutrients is crucial for maximizing microalgae growth, productivity, and biomass yield. Therefore, careful consideration must be given to selecting the optimal method for providing each nutrient, aiming to optimize cultivation efficiency while minimizing environmental impact. The choice of nutrient provision method depends on various factors, including the specific nutrient requirements of the microalgae species, the scale of cultivation, cost considerations, and environmental impact. Additionally, factors such as nutrient solubility, stability, and compatibility with the culture medium need to be taken into account when determining the most suitable nutrient provision method.

While ensuring an adequate supply of Nitrogen, Phosphorus, and Carbon is pivotal, the growth and metabolic processes of microalgae are influenced by additional nutrients. Elements like manganese and various cations (such as Mg^{2+} , K^+ , and Ca^{2+}) have demonstrated the capacity to obstruct microalgal growth when their availability is limited. Furthermore, trace elements have been shown to be critical for microalgae growth (Moheimani, 2005). For instance, Iron, an essential trace element, plays a key role in transporting electrons during the process of photosynthesis (Hu, 2013). However, nutrients constitute a considerable expense in large-scale microalgae cultivation and careful consideration must be given to their source and composition when scaling up cultivation systems. Although nutrients commonly used in laboratory cultures may be suitable, they are often too costly for commercial biomass production (Borowitzka and Vonshak, 2017). Besides cost, several factors regarding nutrients must be considered (Borowitzka and Vonshak, 2017), such as their impact on medium recyclability, chemical composition, potential impurities, especially when the product is intended for feed and food markets. Additionally, some inexpensive and easy-to-handle nitrogen and phosphorus sources may not be permitted for use. The literature documents various alternative culture media derived from plant sources, swine wastewater, agro waste, industrial wastewater, sewage water, and municipal wastewater (Ahmad et al., 2022; Bauer et al., 2021; Camacho-Rodríguez et al., 2013; Faé Neto et al., 2018; de Medeiros et al., 2020; Nayak et al., 2016; Ribeiro et al., 2020; Singh and Das, 2014; Ummalyma et al., 2020; Viegas et al., 2021), with anaerobic effluents demonstrating significant potential to substitute chemical-based culture media (Bauer et al., 2021; Leca et al., 2023). This approach can mitigate the environmental impact of microalgae cultivation, thereby enhancing its sustainability.

3.4. pH and salinity

pH is regarded as a fundamental factor that exerts control over cell metabolism and the development of biomass in microalgae (Gatamaneni et al., 2018). Its significance in microalgal cultures extends beyond its impact on the microorganisms themselves; it also governs the solubility of minerals and CO_2 within the medium (Qiu et al., 2017). Conversely, several factors, including the medium's composition and buffering capacity, dissolved CO_2 concentrations, temperature, and cellular metabolic activity, can jointly affect the pH of the culture environment (Singh et al., 2011). pH is directly linked to the carbon content in the medium, with carbon dioxide injection serving as a common method to lower pH levels (Bartley et al., 2014). The physiology of microalgae indicates that either the thylakoid or chloroplasts perform crucial functions within specific pH ranges, as the medium's pH significantly influences the photosynthesis process of microalgae. Importantly, both high and low pH extremes reduce the rate of photosynthesis. Elevated pH levels can disturb the absorption pattern of trace metals and nutrients. Similarly, at lower pH levels, enzyme inhibition occurs in the photosynthetic process, and there is an increased risk of contamination of the growth medium by microorganisms (Bakuei et al., 2015). Within moderate pH conditions, a

correlation exists with carbon dioxide concentration-pH incrementally rises as carbon dioxide is consumed. Moreover, pH influences the accessibility of nutrients such as iron and organic acids (Lutzu, 2011). For each distinct microalgae strain, an optimal pH exists that maximizes growth rate (Moheimani and Borowitzka, 2011), typically the favorable pH range spans from neutral to slightly alkaline conditions (pH 7.0-10.0), although certain species exhibit optimal growth at acidic pH values below 3.0 (Lu et al., 2014; Wood and Wang, 1983). While most microalgae demonstrate a degree of tolerance for a wide pH range, deviations beyond this range result in a substantial reduction in yield (Acién et al., 2017). pH fluctuations can be mitigated through the use of buffers in cultures, although this becomes expensive for large-scale systems. As previously mentioned, the pH of the medium decreases due to dissolved CO₂. Introducing atmospheric air, which had an average carbon dioxide concentration of 419.3 ppm (0.0419%) in 2023 according to NOAA's Global Monitoring Lab annual report, could help regulate pH variations in the culture. This, in turn, has the potential to improve microalgae growth by maximizing the utilization of available light. However, the low concentration of CO₂ in the air results in a weak driving force for mass transfer into the microalgal growth medium (Zheng et al., 2018). Thus, relying solely on passive atmospheric diffusion is insufficient to maintain high biomass concentrations or productivities (Zheng et al., 2018). (Jiang et al., 2011) demonstrated that with air aeration, *Nannochloropsis* sp. achieved only one-third of the biomass concentration compared to cultures grown using gas containing 15% CO₂. Various CO₂ supply methods for microalgae cultivation include raw flue gas from fossil fuel combustion, purified CO₂, bicarbonate addition, and CO₂-containing solvents (Zheng et al., 2018).

Salinity is an additional factor that requires attention in the cultivation of microalgae, especially in open cultures where it tends to increase due to significant evaporation, resulting in elevated concentrations in the medium (Chowdury et al., 2020). Each microalgae strain demonstrates a unique ability to adapt to varying salinity levels. Increased salt concentrations impose stress on cell growth and lipid formation. Interestingly, a rise in salinity leads to an increase in lipid expression but comes at the cost of reduced cell growth. Since researchers often seek microalgal strains capable of producing substantial biomass and lipids, those that thrive in saline conditions hold notable significance (Asulabh et al., 2012). The simplest approach to control salinity involves adjusting it through the addition of freshwater or salt, as needed (Moheimani, 2005).

3.5. Stirring and Mixing

Mixing is not stirring (Villiermaux, 2019). In simple terms, mixing is combining two or more substances to achieve a uniform distribution of the components, therefore it is a diffusive process. Stirring is agitating a substance using a tool or a stirring rod to promote even distribution or prevent settling, therefore it is an advective process.

Sufficient fluid movement within microalgae cultures is crucial to minimize gradients in temperature, nutrient concentration, pH, and light intensity, which can otherwise limit cellular performance. However, movement generates velocity gradients essential for nutrient transport and flow dynamics. Gradients in flux and temperature are also vital for maintaining flow dynamics and thermal uniformity within the culture medium. Efficient stirring facilitates nutrient movement, prevents sedimentation, and moves cells between light and dark areas (Brindley Alías et al., 2004). Despite the potential for gradient formation, diffusion smooths out these gradients. Different methods, such as air bubbling, stirring, or using pumps, can create movement in microalgae cultures, but energy input needs optimization to avoid harming cells and impeding growth. Whether using pneumatic or mechanical devices, it is crucial to handle them carefully to prevent exposing microalgae to harmful forces (Barbosa et al., 2004; Merchuk and Wu, 2003). In open ponds, inertial forces often outweigh viscous forces, leading to easy turbulence development. Identifying growth-limiting

factors, such as mass transfer, nutrient gradients, sedimentation, and light exposure, is crucial. It is important to supply energy while minimizing shear forces to prevent mechanical damage to the cells, as every unit of energy introduced disperses across the liquid as shear forces for turbulent flow. Microalgae's susceptibility to shear forces depends on various factors such as microalgae type, cell wall strength, cell size and morphology (especially the presence of delicate flagella), the intensity and nature of shear stress, and the growth conditions experienced by the cells. Energy dissipation rates within the fluid are closely connected to shear stress, shear rates, micro-eddy length scale, and other flow characteristics (Acién Fernández et al., 2013).

The energy input has the potential to cause harm to cells through various mechanisms. Cell damage may occur when bubbles detach from the sparger, during the breakup or coalescence of bubbles within the bulk liquid, and when bubbles burst at the surface of the culture. Extensive research has identified bubble bursting as the primary factor responsible for cell injury in aerated cultures (Chalmers, 1995). It is commonly accepted that smaller bubbles tend to cause more damage compared to larger ones. Additionally, the extent of harm related to bubbles shows an inverse relationship with the aspect ratio of the reactor (i.e., the height-to-diameter ratio). This detrimental effect can be reduced by incorporating surface tension-reducing agents such as carboxymethyl cellulose, which helps reduce stress-induced damage (Camacho et al., 2001).

When utilizing mechanical agitation in the culture, cells experience stress that is influenced by the type of stirrer and the speed employed. A comparable phenomenon takes place in devices responsible for moving the liquid within the system, such as paddlewheels and mechanical pumps, as the liquid moves through the pump cavity (Vandanjon et al., 1999). In open systems employing paddlewheels, the shear rate is determined by the impeller's diameter and the rate of revolutions. In instances where mechanical pumps are employed for fluid circulation, the shear rate within the pump cavity depends on the Reynolds number:

$$Re = \frac{\rho VL}{\mu}, \quad (1)$$

where ρ is the fluid density ($kg.m^{-3}$), V is the fluid velocity ($m.s^{-1}$), L is a characteristic length of the flow geometry, such as the diameter of a pipe or the size of an impeller (m), and μ is the dynamic viscosity of the fluid ($Pa.s$).

As the culture circulates, interactions with the reactor wall may cause cell damage. Wall shear stress, influenced by liquid velocity and Reynolds number, controls this damage. Supplied energy induces turbulence, forming microeddies responsible for energy distribution. If microeddy size matches or falls below cell size, turbulence can damage cells. However, if microeddy size exceeds cell size, cells are carried by the eddy, preventing damage. The energy dissipated per unit mass governs microeddy size and shear rate exposure to cells (Acién et al., 2017).

3.6. Contamination

The most significant challenge algal biomass producers face is the preservation of a monoculture of algae (Moheimani, 2005). The introduction of invasive species and predators brings a variety of unexpected organisms into the microalgae culture environment, obstructing the growth of microalgae, contaminating the culture medium, and depleting essential nutrients. Predators encompass a diverse array of organisms, including fungi, bacteria, insects, and even unwanted microalgae species (Yousuf, 2020).

Open culture systems, particularly, have a significant drawback as they are vulnerable to contamination by undesired species if not carefully managed. Typically, a new open pond is initially seeded with the desired microalgae strain to kickstart growth and establish dominance in the pond's ecosystem. However, with time, the introduction of

undesired species becomes almost inevitable, potentially leading to reduced yields and posing a challenge to the initially seeded species' dominance. Once a significant competitor takes hold in the pond, removing it becomes an increasingly difficult task (Schenk et al., 2008). Nevertheless, specific measures are implemented to effectively maintain the purity of microalgae cultures. The use of customized culture media serves as a protective measure to ensure the uncontaminated status of microalgae cultures (Spolaore et al., 2006). To promote the long-term and reliable cultivation of desired species within open pond systems, it is advisable to consider cultivating extremophiles. As discussed earlier, extremophiles have shown their ability to thrive and outcompete other species under specific environmental conditions, making them a valuable option for cultivation (Singh and Dhar, 2011).

4. Environmental impacts of microalgae cultivation

Microalgae cultivation presents a dual role in environmental sustainability: it offers opportunities for resource recovery and pollution mitigation while posing potential risks to ecosystems if not managed properly. As microalgae systems are adopted for biofuel production, wastewater treatment, and high-value bioproducts, it is critical to evaluate their environmental impacts across multiple dimensions. These include aquatic systems, greenhouse gas emissions, land use, and energy requirements.

This section examines the environmental implications of microalgae cultivation, focusing on its potential benefits—such as carbon sequestration, nutrient recycling, and wastewater remediation—and the challenges, including resource use efficiency, ecosystem impacts, and unintended environmental consequences.

4.1. Aquatic impacts

Microalgae cultivation presents several potential impacts on aquatic ecosystems, stemming from water usage, nutrient management, and wastewater integration. These impacts must be carefully managed to ensure environmental sustainability. The water requirements for microalgae cultivation can exert significant strain on natural water resources. However, exploiting low-grade water sources, such as domestic or industrial wastewater, can mitigate this impact by reducing the demand for freshwater. Globally, approximately 75% of wastewater is discharged untreated into surface waters, leading to severe environmental and public health challenges (UN-Water, 2012). In the UK alone, domestic wastewater production averages 120 liters per person daily, which is processed by nearly 9,000 treatment plants before being released back into the environment (UK, 2002). Integrating wastewater streams into microalgae cultivation not only provides a cost-effective source of water and nutrients but also facilitates wastewater remediation, reducing the environmental burden of untreated discharges.

Microalgae's ability to assimilate nutrients from their aquatic environment is a double-edged sword. While this trait allows them to remediate wastewater by absorbing nitrogen, phosphorus, and carbon, improper management can result in detrimental effects. Excess nitrogen and phosphorus in water bodies can trigger uncontrolled algal blooms, leading to hypoxic conditions that harm aquatic biodiversity. For instance, nitrogen-essential for protein synthesis, chlorophyll production, and the transfer of biochemical energy in the form of adenosine triphosphate (ATP)—can be sourced from wastewater, reducing reliance on industrial fertilizers (Mata et al., 2010). Phosphorus, another critical nutrient, is often limiting in freshwater ecosystems; its overabundance can exacerbate eutrophication (Correll, 1998). Microalgae can play a pivotal role in recovering phosphorus from wastewater, offering an environmentally favorable alternative to conventional recovery methods.

The carbon requirements of microalgae cultivation also have implications for aquatic systems. While photosynthetic microalgae primarily source carbon from atmospheric or dissolved carbon dioxide, utilizing

flue gases introduces pollutants that may harm aquatic environments. In contrast, heterotrophic microalgae rely on organic carbon sources, often derived from wastewater streams. This dual function—carbon assimilation and pollutant mitigation—underscores the environmental potential of microalgae cultivation.

Microalgae-based wastewater treatment systems, such as Waste Stabilization Pond Systems, can remove pollutants, including nitrogen, phosphorus, and organic compounds, from various wastewater sources. Studies have demonstrated the effectiveness of microalgae in nutrient recovery: *Chlamydomonas* species have achieved complete nitrogen removal and partial phosphorus removal, while *Chlorella* species have shown high removal rates for ammonia, total nitrogen, and phosphorus (Wu et al., 2012). Additionally, microalgae can biodegrade or bioaccumulate harmful compounds like heavy metals, pesticides, and endocrine disruptors (Abdel-Raouf et al., 2012). However, the potential for bioaccumulation of toxic substances could limit the downstream use of algal biomass for food, fuel, or pharmaceuticals.

Large-scale microalgae cultivation poses biodiversity risks, particularly due to its potential to induce eutrophication—a phenomenon akin to “controlled eutrophication.” Unregulated nutrient release or accidental water discharge from cultivation systems can exacerbate oxygen depletion in receiving water bodies, harming aquatic organisms and fostering the dominance of invasive species (Kamilli et al., 2013). For example, nutrient-rich marine discharges can damage seagrass ecosystems, critical for sediment stabilization and marine biodiversity (Smith et al., 2010). Open ponds used for cultivation are especially vulnerable to contamination from native species, which can disrupt culture balance. Conversely, the introduction of non-native microalgae species to local ecosystems could outcompete native species, altering ecological dynamics. In arid regions, the water-intensive nature of cultivation could modify local climates, influencing temperature, humidity, and biodiversity by attracting wildlife (NR, 2012).

The water footprint (WF) of microalgae cultivation varies based on system design, water source, and climate. Closed PBRs exhibit significantly lower WF values compared to open raceways, particularly when wastewater or seawater is used instead of freshwater. For example, the WF for microalgae biodiesel in open raceways ranges from 14 to 87 m^3/GJ , whereas closed systems achieve values as low as 1–2 m^3/GJ (Batan et al., 2013). This highlights the importance of wastewater integration in reducing freshwater consumption and enhancing the sustainability of microalgae-based biofuels.

4.2. Terrestrial impacts

The terrestrial implications of large-scale microalgae cultivation are multifaceted, encompassing land use changes, contamination risks, and biodiversity concerns. Microalgae offer distinct advantages over traditional terrestrial biofuel crops, particularly regarding land efficiency and yield. Projections for microalgal biofuel production indicate that oil yields can reach up to 5,775 liters per hectare per year under optimal conditions. When processed into biofuel with an 80% conversion efficiency, this corresponds to a final yield of approximately 4,620 liters of biofuel per hectare per year. Compared to terrestrial crops like corn and soybeans, which require 1540 *Mha* and 594 *Mha*, respectively, to replace 50% of U.S. transportation fuels, microalgae need only 43 *Mha*, highlighting their potential to significantly reduce the land area required for biofuel production (Wigmosta et al., 2011). However, despite this potential, the focus of microalgal biofuels has shifted away from the automobile sector due to cost and scalability challenges, with recent research prioritizing aviation applications where the high energy density of biofuels is critical for sustainable jet fuel development.

However, scaling up microalgae cultivation presents its own challenges. Direct land-use changes involve converting existing land types, such as agricultural fields or pastures, into cultivation systems like RWP or PBRs. This conversion can lead to alterations in soil properties,

disruptions in carbon fluxes, and reduced availability of land for food production. Indirect land-use changes occur when agricultural land is reallocated for biofuels, displacing food crops and causing land elsewhere to be cleared for agriculture. Such shifts can result in deforestation, habitat loss, and increased greenhouse gas emissions. These concerns have prompted regulatory frameworks, such as the European Union's requirement for fuel suppliers to account for indirect land-use change in greenhouse gas assessments (Wigmosta et al., 2011).

To address land-use limitations, marginal and non-arable lands have been proposed for microalgae cultivation. These areas, often unsuitable for traditional agriculture, could provide sufficient space without impacting food security. Regions with high ambient temperatures, such as the southern Mediterranean, parts of Africa, and the U.S., have been identified as potential sites due to their favorable climatic conditions. However, these regions often face freshwater scarcity, a critical limitation for large-scale cultivation (Van Harmelen and Oonk, 2006; Venteris et al., 2013; Wigmosta et al., 2011). Offshore cultivation systems offer a promising alternative, avoiding land displacement altogether. For instance, the Submariner initiative has explored integrating macro- and microalgae cultivation with offshore wind farms in the Baltic Sea, illustrating how innovative approaches can reduce land-use pressures while taking advantage of existing infrastructure (Doan et al., 2011).

The design and operation of cultivation systems further influence terrestrial impacts. Open pond systems, while cost-effective, are vulnerable to contamination from native species and environmental pollutants. Improperly designed ponds can lead to nutrient leaching, groundwater contamination, or salinization, particularly when marine algae are cultivated on land. Closed systems, such as PBRs, minimize these risks but come with their own challenges. Leaks from PBRs, though rare, can still have localized environmental consequences, especially near natural water sources (Wigmosta et al., 2011). Using wastewater or saline water for cultivation mitigates freshwater demands while reducing potential contamination risks.

Biodiversity concerns also arise with large-scale algae cultivation. Construction activities for ponds or reactors may disrupt local ecosystems, causing habitat loss and species displacement. Habitat fragmentation, as observed in large water projects like reservoirs, could reduce connectivity between populations and compromise genetic diversity. For example, a scoping report for the proposed Havant Thicket Winter Storage Reservoir in the UK highlighted several ecological impacts, including the loss of ancient woodlands, damage to habitats from accidental pollution, and species disturbance from human activity (NR, 2012). Similar challenges are likely for large-scale microalgae cultivation facilities, necessitating thorough environmental impact assessments to identify and mitigate potential risks.

4.3. Atmospheric impacts

Large-scale microalgae cultivation presents both opportunities and challenges in terms of atmospheric impacts, with its potential to mitigate greenhouse gases counterbalanced by emissions from the cultivation process itself. While microalgae can significantly reduce carbon dioxide (CO_2) levels via photosynthesis, the cultivation systems may inadvertently release other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), as well as ammonia (NH_3), into the atmosphere. These emissions highlight the complexity of assessing the net environmental benefits of microalgae-based technologies and underscore the importance of managing these systems effectively.

One of the most promising atmospheric contributions of microalgae is their ability to sequester CO_2 . Through photosynthesis, microalgae like cyanobacteria (*A. microcopia Nageli*) demonstrate fixation rates as high as $28 \text{ mgL}^{-1} \text{ min}^{-1}$, far surpassing other species like the diatom *P. tricornutum* ($1.5 \text{ mgL}^{-1} \text{ min}^{-1}$) (Francisco et al., 2010). This capacity has positioned microalgae as a viable solution for mitigating industrial CO_2 emissions. Studies estimate that offsetting just 2.5% of global CO_2

emissions would require about $65,800 \text{ km}^2$ of cultivation area, which represents only 0.43% of global arable land (Bilanovic et al., 2009). Moreover, the integration of microalgae cultivation with industrial facilities, such as ethanol plants, could capture CO_2 cost-effectively compared to chemical methods (Rosenberg et al., 2011). However, the effectiveness of CO_2 sequestration is influenced by environmental and industrial contaminants like nitrogen oxides (NO_x) and polycyclic aromatic hydrocarbons (PAHs), which can inhibit algal growth and reduce productivity (Kumar et al., 2010).

Despite these benefits, the cultivation process may emit methane (CH_4), a greenhouse gas with a global warming potential 84 times that of CO_2 over 20 years. Although methane emissions from microalgae cultivation are not well-documented, research on natural aquatic systems suggests that both aerobic and anaerobic conditions could contribute to CH_4 production (on Climate Change, 2007). Interestingly, methane generation in aerobic environments has been observed in living plants, indicating that even well-aerated microalgae cultivation systems might emit CH_4 (Keppler et al., 2006). This emerging concern underscores the need for further research to quantify and mitigate methane emissions in these systems.

Nitrous oxide (N_2O), another potent greenhouse gas, presents a significant challenge for microalgae systems. With a global warming potential 264 times that of CO_2 over 20 years, N_2O emissions can arise from bacterial denitrification under anoxic conditions or through algal activity in oxic environments. For example, axenic cultures of *Chlorella vulgaris* release N_2O due to intracellular nitrate reductase activity, even in oxygen-rich conditions (Gueysse et al., 2013). Field studies further reveal that nutrient depletion, particularly in open RWPs, can exacerbate N_2O emissions (Ferrón et al., 2012). The environmental impact of these emissions is compounded when microalgae biomass is used as fertilizer, potentially releasing additional N_2O during application and decomposition, which may offset the carbon savings achieved during cultivation (Frank et al., 2012).

Ammonia (NH_3) emissions from microalgae cultivation are primarily driven by the pH levels in open systems. At high pH (> 9), ammonium in the culture medium shifts toward the gaseous NH_3 form, leading to volatilization (Young, 2011). Although theoretical models predict significant ammonia losses, biological factors such as uptake by microalgae and bacterial denitrification often mitigate these emissions in practice (de Assunção and von Sperling, 2012). However, any volatilized NH_3 that enters the atmosphere can contribute to the formation of fine particulate matter (PM_{2.5}) and ammonium salts, which pose risks to air quality, human health, and the environment. Additionally, ammonia deposition can lead to soil acidification and eutrophication, causing long-term ecological damage in sensitive areas. Proper management of nitrogen dynamics is therefore critical to minimizing these impacts.

The atmospheric impacts of microalgae cultivation illustrate a complex interplay of benefits and challenges. While the process offers significant potential for CO_2 mitigation and greenhouse gas capture, the unintended emissions of CH_4 , N_2O , and NH_3 require targeted solutions. Improved system designs, optimized operational strategies, and ongoing research are essential to ensure that the environmental benefits of microalgae cultivation outweigh its atmospheric costs. These efforts will help position microalgae as a sustainable option in global efforts to address climate change and reduce greenhouse gas emissions.

4.4. Energy and nutrient supply

Energy supply is a crucial factor in the sustainability of microalgae biofuel production. For microalgae to be a viable biofuel source, the energy used in its cultivation and processing must be outweighed by the energy produced from the biofuel itself, ensuring a positive energy balance. The greenhouse gas (GHG) emissions associated with energy use are also of significant importance, especially when fossil fuels are employed for energy-intensive activities such as nutrient supply, culti-

vation operations, and the conversion process. The source and quantity of energy used in microalgae cultivation play a pivotal role in determining the environmental sustainability of the technology. Life cycle assessments (LCAs) have been used to quantify the energy demands and associated GHG emissions of microalgae cultivation, though there is no consensus on the precise amount of energy required to produce a specific quantity of biomass. A comparison of eight different LCAs that assessed fossil energy input for biodiesel production from RWPs showed a broad variation in energy requirements (Handler et al., 2012), underscoring the complexity of accurately quantifying energy use in microalgae bio-fuel production. Energy demand for biodiesel production from different feedstocks also varies significantly, with reports ranging from 0.4–4.4 kg CO₂ eq kg⁻¹ feedstock for microalgae, compared to 0.4–0.5 kg CO₂ eq kg⁻¹ for crops like soybean (Campbell et al., 2011; Lardon et al., 2009). This discrepancy reflects the differences in cultivation methods, technologies used, and the energy sources involved. The energy-water nexus presents an additional layer of complexity. The energy required to supply water, especially when clean water is used, can be significant. Estimates show that water treatment for biodiesel production from microalgae can consume between 5.4 and 25.55 kWhm⁻³ (Plappally et al., 2012). For example, a study examining the water requirements for achieving the target of producing 1 million m³ of biodiesel from microalgae suggests that between 1–11 billion m³ of water could be needed, leading to an energy demand of up to 281 TWh. These figures underscore the substantial energy demand for water treatment, making untreated wastewater an attractive alternative, as it can simultaneously address water needs and provide nutrients for algae growth. The energy requirements for microalgae cultivation also depend on whether saline or freshwater is used. While some studies find no clear energy demand difference between the two types of water, the use of freshwater is often limited in many regions due to competing demands from agriculture and domestic use. This limitation makes the cultivation of marine microalgae a more feasible alternative, though saline water still requires management to compensate for evaporation losses. In this regard, untreated freshwater can be used to offset increases in salinity, providing a balance between water quality and algae growth needs (Jorquera et al., 2010).

The choice of cultivation system—whether RWPs or PBRs—also impacts energy consumption. RWPs, when using biogas for power generation, have been shown to be energy self-sufficient, in contrast to PBRs, which require significantly more energy due to the energy-intensive nature of container production and the need for pumping and cooling. A study conducted in Brazil comparing the energy usage of RWPs and PBRs for cultivating *Nannochloropsis salina* found that PBRs consumed over 15 times more energy, particularly for water pumping and cooling processes (Jorquera et al., 2010). Other cultivation technologies, such as algal turf scrubbers and biofilm designs, aim to reduce both energy and water use, presenting an alternative to traditional cultivation systems (Ozkan et al., 2012).

Climatic conditions significantly affect the choice of cultivation system. In tropical regions, where sunlight is abundant year-round and temperatures are favorable, outdoor cultivation systems can operate at lower costs, as there is no need for artificial heating or covering. However, in regions outside the tropics, such as temperate climates, outdoor cultivation faces challenges during colder months, which can lead to decreased productivity. For these areas, heterotrophic systems, where the environment can be controlled more precisely, may be a more economically viable option (Van Harmelen and Onk, 2006).

The availability of nutrients is another critical factor in the sustainability of microalgae cultivation. Nutrient sources, which can include wastewater, agricultural runoff, or industrial byproducts, offer opportunities for reducing the need for synthetic fertilizers and lowering overall environmental impacts. The use of waste streams not only provides essential nutrients for algae growth but also reduces the environmental footprint by minimizing the energy and emissions associated

with the production of virgin resources. Various studies have shown the environmental benefits of using waste resources, such as wastewater or flue gases, as inputs for microalgae cultivation (Clarens et al., 2010).

5. Raceway ponds

Contemporary technology offers various forms of open ponds for microalgal cultivation, including (a) raceway ponds (RWPs), (b) circular ponds, (c) unstirred open ponds, (d) thin layer cascade systems, (e) simple mixed ponds, and (f) High Rate Algal Ponds (HRAPs). Among these, RWPs are the most commonly utilized in open pond systems (Chisti, 2007) and are frequently employed for commercial cultivation of *Spirulina*, *Haematococcus*, and *Dunaliella* (Benemann and Oswald, 1996). Circular ponds, often equipped with centrally positioned rotating arms for agitation, are primarily used in Asia for *Chlorella* production and can achieve productivities ranging from 8.5 gm⁻²d⁻¹ to 21 gm⁻²d⁻¹ (Benemann and Oswald, 1996). Unstirred ponds, commonly used for mass-producing *D. salina*, typically exhibit lower productivities (less than 1 gm⁻²d⁻¹) and are less suitable for most other algal species (Benemann and Oswald, 1996; Borowitzka, 2005). Thin layer cascade systems, comprising slightly angled shallow trays, have the potential to achieve impressive productivities, reaching up to 31 gm⁻²d⁻¹ (Doucha and Lívanský, 2006). Mixed ponds are primarily employed for algae production used in aquaculture feed (Borowitzka, 2005). Lastly, HRAPs represent a cost-effective and energy-efficient approach to wastewater treatment. In these systems, wastewater serves as a nutrient and water source for microalgae, reducing biomass production costs (Uggetti et al., 2018).

Maximizing the air-water interface in open ponds is crucial for optimizing microalgae growth and productivity. In the context of commercial production, it is essential to replicate and enhance natural growth conditions. The choice of the right cultivation system significantly impacts microalgal biomass productivity. This section focuses on RWPs, discussing agitation mechanisms, their advantages, limitations, and recommendations. It also examines recent developments in RWP technology to enhance productivity and efficiency in large-scale microalgal cultivation.

Over half a century ago, Oswald introduced the initial concept of RWPs (Oswald and Golueke, 1960), which was subsequently refined (Weissman and Goebel, 1987), and has since undergone further enhancements (Chiaromonti et al., 2013; De Godos et al., 2014; Mendoza et al., 2013; Sompech et al., 2012). Presently, numerous researchers have achieved successful large-scale mass cultivation of microalgae in RWPs (Bagchi et al., 2021).

RWPs are typically constructed as either individual units or interconnected channels. These channels can be fabricated using various materials, including concrete, compacted earth, or lined with plastics (Shen et al., 2009d). The fundamental design of a RWP consists of excavated trenches set in the ground, surrounded by sloping earth embankments. The soil's characteristics determine whether it is necessary to line the walls and floor of the ponds with compacted clay to reduce seepage. In some cases, a crushed and compacted rock surface may be required to prevent erosion, especially at the curved ends (Borowitzka and Moheimani, 2012). However, this construction method has its limitations, primarily concerning flow rates due to erosion risks and the potential for increased suspended particle levels from the pond surfaces. This can result in reduced light penetration and overall productivity. Additionally, these ponds pose challenges in terms of cleaning and maintenance, which can impact long-term culture stability (Borowitzka and Moheimani, 2012).

The act of covering ponds, often using transparent plastic, presents both advantages and drawbacks. Covered ponds generally retain higher temperatures, which can be beneficial in colder climates. However, excessive sunlight in covered ponds may result in excessively high temperatures, constraining the range of suitable algae species. On a

positive note, covered ponds aid in reducing the impact of wind-blown dust and pollutants compared to uncovered ones. Additionally, they facilitate the addition of CO_2 by enriching the air above the cultures (Borowitzka and Moheimani, 2012). Several methods for pond construction offer design flexibility. Choices include excavating ponds with sloping sides and lining, building above-ground ponds using concrete blocks or in-situ cast concrete walls, followed by liner installation. Alternatively, one can choose to construct fully concrete ponds, albeit at a higher cost. However, it is essential to recognize that concrete may not be suitable for saline environments unless coated with epoxy to resist salt, which can considerably increase expenses (Borowitzka and Moheimani, 2012).

In raceway systems, the total area they cover is a crucial factor. The reported sizes of raceways typically vary between 100 and 5000 m^2 (Acién et al., 2017). Achieving larger installations involves increasing the number of ponds. Once the overall surface area is determined, it is divided into either two or four channels for circulating the culture. The lengths of these channels are proportional to their widths, usually falling within ratios of 10 to 20 (Acién et al., 2017). Opting for lower length-to-width ratios is advisable to minimize head losses in the channels. Additionally, it is recommended to minimize the number of bends, as they introduce additional head losses (Acién et al., 2017).

The depths of water channels typically range from 0.1 to 0.3 m . Operating with shallower water layers is preferred, as it enhances light penetration, increases biomass concentration, and promotes culture stability, especially during continuous operation. It is worth noting that the surface-to-total-volume ratio within these systems remains relatively modest, typically ranging from $S/V = 1-10 m^{-1}$. The complete culture volume in the pond can be calculated by multiplying the total area by the depth of the culture layer (Acién et al., 2017). Extensive expertise is available regarding the operation and engineering of raceways. The largest biomass production facility based on raceways spans an expansive area of 440,000 m^2 (owned by *Earthrise Farms* located at Calipatria, CA, USA) (Spolaore et al., 2006).

The initial capital costs of constructing RWP systems are significantly lower than other cultivation systems, largely due to their simple infrastructure. Construction costs currently vary per hectare, depending on material quality, pond design, and local labor costs (Banerjee and Ramaswamy, 2017). For instance, compacted earth and plastic liners are the most economical options but may require higher maintenance, while concrete linings, though more expensive, provide long-term durability. Land acquisition costs further influence capital expenditure. RWP systems require large, flat areas, ideally located in regions with abundant sunlight and moderate temperatures. While arid regions often provide ideal conditions for microalgae growth, water scarcity and land-use competition with other renewable energy projects may drive up land prices in the future. Strategic site selection, such as using non-arable land or coastal regions, can mitigate these costs while taking advantage of favorable climatic conditions.

Operating costs represent a significant portion of the overall expenditure in RWP systems. These costs include energy for pond operation, nutrient and CO_2 supply, water management, and, critically, harvesting and dewatering of the biomass. Energy requirements for paddlewheels and temperature regulation are relatively low compared to enclosed systems, typically consuming 1 – 3 kWh per day per hectare (Chiaramonti et al., 2013). However, the need for temperature management, particularly in regions with high diurnal temperature variations, can increase energy consumption. Models have highlighted the importance of accurate heat and mass transfer assessments to optimize energy usage. Passive solar heating or advanced heat-exchange systems could reduce temperature-related energy expenses by up to 25% over the next decade.

A major contributor to operational costs is the supply of CO_2 and nutrients. CO_2 alone accounts for 40 – 60% of operating costs in RWP systems, with costs currently ranging from \$70 to \$100 per ton

(Valdovinos-García et al., 2020). Industrial flue gases and advancements in carbon capture technology offer promising solutions to lower these costs, potentially reducing CO_2 expenses by 20 – 30% in the next decade. Similarly, nutrient inputs such as nitrogen and phosphorus can cost \$1,000 – \$2,000 per hectare annually, depending on local prices and resource availability (Hoffman et al., 2017). Nutrient recycling from residual biomass has the potential to reduce these costs significantly, while genetically engineered strains of microalgae with lower nutrient demands may further enhance cost efficiency.

Harvesting and dewatering of microalgae remain the most energy-intensive and expensive stages of the production process, accounting for up to 30 – 50% of total operating costs. Biomass concentrations in RWPs are typically low, ranging from 0.5 to 1 g/L , necessitating significant energy input for separation. Conventional harvesting methods, such as centrifugation and flocculation, cost approximately \$5 – \$10 per kilogram of dry biomass. For ponds producing 9,100 tons of biomass per square kilometer annually, this translates to an annual harvesting cost of \$45,000 – \$91,000 per hectare. Emerging technologies, such as electrocoagulation and magnetic harvesting, offer promising avenues for reducing these costs.

The economic feasibility of RWPs is strongly influenced by the productivity of microalgae, which depends on geospatial and climatic factors. Theoretical upper limits for RWP productivity are estimated at 9,100 tons per square kilometer per year (Banerjee and Ramaswamy, 2017). However, real-world productivity varies widely due to differences in solar irradiance, temperature, wind speed, and relative humidity. For example, annual productivity in Algeria has been reported at 6,370 tons per square kilometer, while in the Netherlands, it is significantly lower at 4,150 tons per square kilometer (Banerjee and Ramaswamy, 2017). Advanced geospatial productivity models are instrumental in guiding site selection and optimizing operational strategies to maximize output while minimizing costs.

Looking ahead, the cost of RWP systems is expected to decline due to continued research and development in materials, energy systems, and harvesting technologies. Construction costs could decrease by 15 – 20% through the use of modular or prefabricated pond designs, while operational expenses may be reduced by advances in nutrient recycling and energy-efficient temperature regulation. In the coming decades, harvesting costs could be halved through the adoption of next-generation separation techniques. These technological advancements, coupled with the strategic targeting of high-value markets, position RWPs as a sustainable and economically viable solution for microalgae cultivation over the next ten years.

5.1. Operational parameters for designing RWPs

Once the raceway's geometry is established, a critical parameter to calculate is the power required for liquid circulation within the channels. Power consumption plays a pivotal role in the economic feasibility and overall productivity of algae biomass cultivation (Dodd, 1986). The power consumption is primarily determined by the hydraulic energy necessary to generate liquid velocity within the channel. The specific power requirements for a given raceway are linked to the length of the channel. A longer pond demands more energy to propel water along its length. Additionally, the configuration of bends in the raceway also contributes to the energy needed for water circulation within the channel. Therefore, a comprehensive assessment of power consumption during pond design is of utmost importance (Hadiyanto et al., 2013). Traditionally, Manning's formula (Eq. (2)) has been employed to estimate the power required for liquid circulation within the channels (Weissman and Goebel, 1987).

$$P = \frac{Q\rho g n^2 v^2 L}{R^{\frac{4}{3}}}, \quad (2)$$

where

- P: power consumption (W),
- Q: volumetric flow rate ($m^3 \cdot s^{-1}$),
- ρ : density of liquid ($kg \cdot m^{-3}$),
- n : Manning's friction factor,
- v : mean channel velocity ($m \cdot s^{-1}$),
- L : total length of the pond (m),
- R : hydraulic radius (m).

However, [Acién et al. \(2017\)](#) point out a limitation in its application. According to the researchers, Manning's equation does not account for the pressure drop caused by various accessories present in the raceway, such as bends, sumps, or deflectors. Interestingly, some accessories like bends can have a more significant impact on energy consumption than the pressure drop across the channels themselves. To address these limitations, the classical Bernoulli's equation has been proposed as an alternative approach ([Mendoza et al., 2013](#)). In this case, the power consumption can be determined by considering the system's head loss ΣF ($J \cdot kg^{-1}$) and the overall liquid volume entering the reactor V (m^3) as indicated in [Eq. \(3\)](#). The head loss depends on the reactor's length L , hydraulic diameter D (m), and the Darcy number f_D , which incorporates factors such as turbulence and relative roughness, as shown in [Eq. \(4\)](#).

$$P = \frac{\Sigma F Q \rho}{V}, \quad (3)$$

$$\Sigma F = f_d \frac{LV^2}{2D}. \quad (4)$$

However, this equation has specific application constraints as well, such as a permanent regime, another constraint arises from its derivation, which is based on ideal fluid behavior. Another approach is computational fluid mechanics, which has been widely employed in recent years. Numerous studies ([Drewry et al., 2012](#); [Hreiz et al., 2014](#); [James and Boriah, 2010](#)) investigated the mixing and velocity patterns, dead zones, energy consumption, and the growth kinetics of algae. [Liffman et al. \(2013\)](#) utilized a computational fluid dynamics (CFD) to study flows in different basin configurations. [Hadiyanto et al. \(2013\)](#), also utilizing CFD, established correlations between hydrodynamic flow conditions, power consumption, shear stress characteristics, and the occurrence of dead zones.

Further investigations conducted by [Mendoza et al. \(2013\)](#) identified that various devices with different power requirements can be utilized to attain a desired speed within the pond, thereby rendering it the primary determinant of power consumption.

Consequently, it becomes essential to lower liquid velocity while ensuring the maintenance of culture performance. However, the decrease in liquid velocity can lead to two significant drawbacks. Firstly, it decreases mixing throughout the channel's cross-section, which means that cells spend more time exposed to different levels of light from the surface to the bottom. Secondly, it extends the residence time within the reactor, leading to increased temperature and concentration gradients ([Mendoza et al., 2013](#)). The conventional method of maintaining a constant liquid velocity primarily focuses on preventing cell settling within the channel. Traditionally, it was believed that maintaining a fixed liquid velocity of $0.2 \text{ m} \cdot \text{s}^{-1}$ was sufficient to stop cell settlement along the channel. However, as highlighted by [Acién et al. \(2017\)](#), the settling velocity of microalgae falls within the range of $10^{-7} \text{ m} \cdot \text{s}^{-1}$. This discrepancy arises because microalgae in open raceways typically aggregate, resulting in an increase in their settling velocity to approximately $10^{-4} \text{ m} \cdot \text{s}^{-1}$. As a result, the time required for half of the biomass to settle is reduced to a mere 30 min, aligning with the customary cycling time in large-scale systems.

Other operating parameters and aspect of a RWP include:

• Size and Dimensions:

The typical depth of RWPs ranges from $0.1 - 0.3 \text{ m}$ ([Amini et al., 2016](#); [Chisti, 2007](#); [James and Boriah, 2010](#); [Jiménez et al., 2003](#))

which allows for adequate light penetration and efficient gas exchange. In certain cases, depths can be increased up to 0.5 meters to meet specific cultivation needs ([Brennan and Owende, 2010](#)).

Light penetration depth is crucial for microalgae growth and is linked to microalgae concentration. According to ([Oswald, 1988](#)), light penetration depth (d_p) can be calculated using the equation:

$$d_p = \frac{60000}{C_a}, \quad (5)$$

where C_a is algal concentration in mg dry weight L^{-1} . For typical C_a values of 0.025% (250 mg/L) and 0.25% (2500 mg/L) ([Chisti, 2016](#)), resulting in d_p between 0.24 cm and 0.024 cm . Alternatively, [Borowitzka \(2005\)](#) suggests that:

$$d_p = \frac{2}{3}d, \quad (6)$$

where d is fluid depth.

The aspect ratio (AR), defined as

$$AR = \frac{B}{d}, \quad (7)$$

where B is the channel width (m), impacts hydraulic power requirements. Decreasing the aspect ratio from 15 to 5 led to a 50% reduction in the hydraulic power requirement per unit surface area, emphasizing that deeper, narrower sections with a lower aspect ratio generally demand less power compared to broader, narrower sections ([Ali et al., 2015](#)).

The shape ratio of a raceway establishes a connection between the length and width of the raceway

$$SR = \frac{L}{B}, \quad (8)$$

where L is the channel length (m). SR influences power requirements per unit surface area, with larger SRs typically resulting in lower power demands.

The maximum surface area of an RWP is influenced by factors such as head loss and energy slope. [Oswald \(1988\)](#) recommended a maximum head drop of half the pond's depth for effective mixing. For instance, a pond 6 meters wide and 0.3 meters deep with a fluid velocity of $0.15 \text{ m} \cdot \text{s}^{-1}$ could have a maximum surface area of $32,500 \text{ m}^2$. [Weissman et al. \(1988\)](#) proposed that raceways with a shape ratio of $1 : 20$ and a head difference of 30 cm could accommodate sizes up to $50,000 \text{ m}^2$.

• End Bends and Head Loss:

Head loss in a channel between two locations can be computed using experimental data and by utilizing Bernoulli's Equation:

$$H_L = \left(\alpha \frac{V_1^2}{2g} + d_1 \right) - \left(\alpha \frac{V_2^2}{2g} + d_2 \right), \quad (9)$$

where (see [Luan et al., 2024](#))

$$\alpha = \frac{1}{A} \int_A \left(\frac{V}{\bar{V}} \right)^3 dA,$$

H_L is the head loss (m), V is the average velocity of the section (ms^{-1}), d is the depth of the fluid (m), g is the gravitational acceleration (ms^{-2}), α is the kinetic energy correction coefficient and A is the cross-sectional area (m^2), \bar{V} is the cross-sectional average velocity ($m \cdot s^{-1}$). The subscript number 1 designates the upstream location, while 2 signifies the downstream location.

• Gas Transfer:

Elevating the CO_2 concentration in a CO_2 enriched gas stream,

from 0.25% to 1%, significantly increased biomass yields upon injection into the culture (Ketheesan and Nirmalakhandan, 2011). To produce 1 kg of microalgae biomass in the reactor, approximately 1.65 to 2.2 kg of CO₂ is required (Berg-Nilsen, 2011; Weissman and Goebel, 1987). A straightforward method for carbon supplementation involves bubbling CO₂ enriched gas through the culture, thereby enhancing the transfer of CO₂ into the system and facilitating the release of O₂ out of it (Craggs et al., 2012a; Heubeck et al., 2007).

• Fluid Mixing:

The commonly recommended forward velocity falls within the range of 0.15 to 0.3 ms⁻¹, balancing the requirement to keep microalgae in suspension with the goal of minimizing pumping costs (Borowitzka, 2005; Chiaramonti et al., 2013). It is generally acknowledged that the minimum fluid velocity should exceed 0.1 ms⁻¹; if the velocity falls below this critical threshold, sedimentation of microalgae may occur (Dodd, 1986; Weissman et al., 1988).

Turbulent flow, essential for effective mixing in RWPs, refers to the chaotic movement of fluids and can be characterized by the Reynolds number (Re):

$$Re = \frac{\rho VR_H}{\mu}, \quad (10)$$

where ρ is the density of fluid (kgm⁻³), V is the fluid velocity (ms⁻¹), R_H is the hydraulic radius (m), and μ is the dynamic viscosity (Nsm⁻²). The hydraulic radius of an open channel is given by:

$$R_H = \frac{Bd}{B + 2d}, \quad (11)$$

where B is the width (m) and d is the depth of the channel (m).

Another approach to assess vertical mixing in the system involves evaluating the diffusion coefficient, which is associated with turbulent mixing (mixing induced by turbulence) generated by the shear velocity in the fluid.

The expression for the vertical mixing coefficient is provided by the equation:

$$D = \frac{1}{15} du^*, \quad (12)$$

where D is the diffusion coefficient (m².s⁻¹), d is the fluid depth (m), and u^* is the shear velocity (Chandler, 2012).

The diffusion coefficient D is a measure of how quickly particles diffuse through a medium. In fluid systems, this diffusion can occur due to molecular processes (molecular diffusion) or turbulent processes (turbulent diffusion). In systems with significant turbulence, the mixing caused by turbulent diffusion is much more important than molecular diffusion alone.

5.2. Application for designing and sizing a raceway pond

As presented above, designing a RWP involves several key steps to ensure optimal conditions for microalgae growth. Here, we provide a step-by-step guide to designing an RWP with a target surface area of 10,000 m².

Step 1: Determine Pond Dimensions

- **Target Surface Area:** 10,000 m²
- **Depth (d):** 0.3 m (recommended range: 0.1 – 0.3 m)
- **Aspect Ratio (AR):** 10
- **Shape Ratio (SR):** 20

Using these parameters, we calculate the pond width (B) and length (L):

$$B = AR \times d = 10 \times 0.3 = 3 \text{ m}$$

$$L = SR \times B = 20 \times 3 = 60 \text{ m}$$

Check the surface area of one raceway:

$$\text{Surface Area} = L \times B = 60 \times 3 = 180 \text{ m}^2$$

To achieve the target surface area, the number of raceways needed is:

$$\text{Number of Raceways} = \frac{10000}{180} \approx 56$$

Step 2: Calculate Light Penetration Depth

- **Microalgae concentration C_a :** 500 mg/L

Using Eq. (5) for light penetration depth:

$$d_p = \frac{60000}{C_a} = \frac{60000}{500} = 120 \text{ cm} = 1.2 \text{ m}$$

This value seems impractically high. Using Eq. (6) for a more practical value:

$$d_p = \frac{2}{3} d = \frac{2}{3} \times 0.3 = 0.2 \text{ m}$$

Step 3: Ensure Adequate Mixing and Flow

- **Forward Velocity V :** 0.2 m.s⁻¹

Check the Reynolds number for turbulence. The hydraulic Radius is:

$$R_H = \frac{Bd}{B + 2d} = \frac{3 \times 0.3}{3 + 2 \times 0.3} = \frac{0.9}{3.6} = 0.25,$$

Assuming the viscosity of the algal solution is approximately equal to that of water:

$$Re = \frac{\rho VR_H}{\mu} = \frac{1000 \times 0.2 \times 0.25}{0.001} = 50,000.$$

The Reynolds number confirms turbulent flow

Step 4: Calculate CO₂ Requirements

- **Biomass productivity:** 1 g/L/day

Calculate the volume of the pond:

$$\text{Volume} = \text{Surface Area} \times \text{Depth} = 10,000 \text{ m}^2 \times 0.3 \text{ m} = 3000 \text{ m}^3.$$

Calculate biomass production:

$$\text{Biomass production} = 3000 \text{ m}^3 \times 1 \text{ g/L/day} = 3000 \text{ kg/day}.$$

Calculate CO₂ requirement :

$$\text{CO}_2 \text{ needed} = 2 \times 3000 \text{ kg/day} = 6000 \text{ kg/day}.$$

Summary of Design Parameters:

- **Depth:** 0.3 m
- **Width:** 3 m
- **Length:** 60 m
- **Number of Raceways:** 56
- **Light Penetration Depth:** 0.2 m
- **Forward Velocity:** 0.2 m.s⁻¹

- **Turbulent Flow:** Confirmed with $Re = 50,000$
- **CO₂ Requirement:** 6000 kg/day

Based on the example calculations and the provided design parameters, we can evaluate the suitability and effectiveness of the designed RWP. Key considerations are:

- The chosen depth of 0.3 m is within the recommended range (0.1 – 0.3 m). This ensures adequate light penetration for efficient photosynthesis.
- The calculated light penetration depth of 0.2 m aligns well with the pond depth, indicating sufficient light exposure to the microalgae.
- The dimensions (3 m width and 60 m length) provide a practical shape for RWPs.
- 56 raceways are required to meet the target surface area of 10,000 m². This is a manageable number, and multiple raceways allow for scalability and redundancy in case of maintenance or failure.
- The forward velocity of 0.2 m.s⁻¹ is within the recommended range (0.15 – 0.3 m.s⁻¹) and ensures proper suspension of microalgae.
- The Reynolds number (50,000) confirms turbulent flow, which is essential for efficient nutrient and gas exchange.
- The calculated CO₂ requirement (6000 kg/day) is substantial but feasible, assuming an adequate supply of CO₂. Proper CO₂ management and delivery systems will be necessary to meet these demands effectively.
- The assumed head loss of 0.1 m is reasonable, and efficient mixing device can help minimize energy consumption while maintaining adequate mixing.

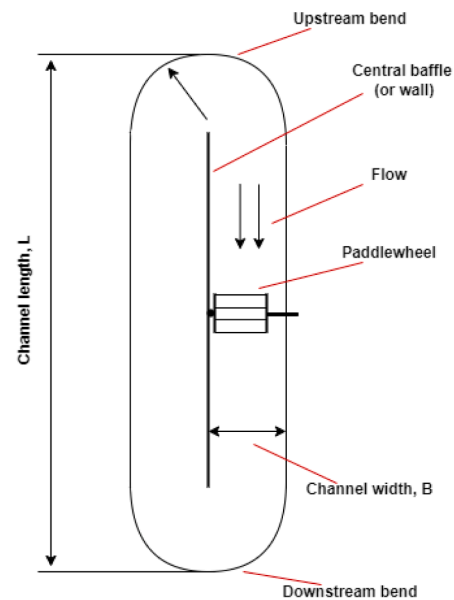
5.3. Agitation mechanisms in raceway ponds

As outlined in the preceding section, the fluid within the raceway is mechanically set in motion at a velocity ranging approximately from 0.15 – 0.3 m.s⁻¹, inducing agitation that facilitates the thorough mixing of the culture medium. Despite the array of devices proposed for the circulation and mixing of the culture medium, paddlewheels have consistently emerged as the most prevalent choice (see Fig. 2 for a schematic representation of a RWP equipped with a paddlewheel) (Hreiz et al., 2014).

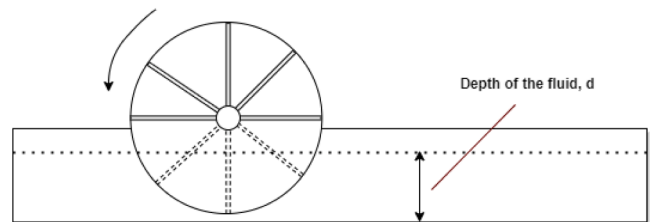
The preference for using paddlewheels in homogenizing RWPs is supported by several compelling factors as discussed by Weissman and Goebel (1987). Firstly, these paddlewheels are well-matched to the pumping needs of RWPs, which are characterized by high volume and low head, indicating a high specific speed. Secondly, their gentle agitation minimizes potential damage to colonial or flocculated algae, thereby facilitating easier harvesting. Thirdly, they are mechanically robust, demanding minimal maintenance. Fourthly, their drive systems can be easily adjusted to accommodate a wide range of speeds, featuring a high turn-down ratio without significantly affecting efficiency. Lastly, they eliminate the requirement for an intake sump, necessitating only a shallow depression for optimal functionality.

The paddlewheel arrangement offers two possible configurations: it can either be situated directly above a flat pond bottom, or, to counteract reverse flow, the paddlewheel can be placed within a recess in the pond floor. This arrangement maintains a small clearance between the blade tips and the channel bottom, as proposed by Dodd (1986). This particular configuration turns the paddlewheel into a positive displacement pump, thereby further enhancing its effectiveness (Weissman and Goebel, 1987). Although there are various paddlewheel designs available, empirical findings suggest that an eight-blade paddlewheel (Fig. 3) typically achieves an optimal balance between efficiency, weight considerations, and construction costs, as indicated by Borowitzka and Moheimani (2012).

Chisti (2013) provides a concise overview on paddlewheel design. In the standard configuration, the raceway channel housing the



(a) Top view of the RWP featuring its paddlewheel



(b) A side view of a RWP featuring a standard 8-blade paddlewheel

Fig. 2. Schematic view of a RWP, (a) Top view, (b) Side view. (L) is length, (B) is width and (d) depth is depth.

paddlewheel maintains a flat flow profile at its base. It is recommended to keep both the bottom and side clearances of the paddlewheel within approximately 0.02 m in this arrangement. To prevent water overflow during rotation, the height of the blades must be carefully calculated. This height is determined by adding the static water depth, the maximum head generated during rotation, and an additional allowance (e.g., 0.1 m). For example, with a typical static water depth of around 0.3 m and a maximum head produced of 2.3×10^{-2} m, the total height of each blade would be approximately 0.42 m, resulting in a paddlewheel diameter of approximately 1 m. Materials such as steel or fiberglass-reinforced plastic can be used for constructing the blades. It is crucial to engineer a robust support system for the blades on the shaft to prevent bending caused by water pressure during rotation.

The speed at which the paddlewheel operates has a substantial impact on the lipid content and biomass of microalgae. When the paddlewheel rotates, it creates turbulence and fluid shear within the culture medium, which can stimulate microalgae to produce more lipids as a defense mechanism against environmental stressors. In a study conducted by Moazami et al. (2012), *Nannochloropsis* sp. was cultivated in enclosed RWPs, and the effect of paddlewheel speed on both biomass yield and lipid content was examined. The results demonstrated that in an indoor open pond, optimizing the paddlewheel speed within the range of 1.4 to 2.1 rad.s⁻¹ led to increased biomass productivity. This enhancement can be attributed to the improved availability of nutrients, CO₂, and illumination facilitated by this specific range of paddlewheel speeds.

The key parameters and measurements related to the performance of the paddlewheel are:



Fig. 3. Conventional 8-Blade Flat Paddlewheel Configuration. Cellana's Kona Demonstration Facility (KDF) on the Big Island of Hawaii.

- **Rotational speed:** Elevated rotational speeds result in a greater head difference across the wheel, leading to increased backflow around the blade. This, in turn, reduces the overall liquid velocity by diminishing the net forward flow. Park et al. (2014) established a cubic relationship between rotational speed and power consumption:

$$P_b = C_D \rho_w A_b v_b^3 \tag{13}$$

where P_b represents the power of a single blade in watts, C_D is the drag coefficient, ρ_w is the density of water ($kg.m^{-3}$), A_b is the wetted area of a blade (m^2), and v_b is the tangential velocity of a blade ($m.s^{-1}$) given by $v_b = R\omega$ where ω is the rotational velocity ($rad.s^{-1}$), and R is the radial distance of the tip of the blade (m) (Fig. 4).

- **The discharge of a paddlewheel:**

Park et al. (2014) proposed a method for estimating theoretical discharge by applying Newton's second law: $F = ma$ where F is the force applied on the fluid by the blade (N), m is the mass of water within a control volume (kg) $m = \rho V$, and a is the acceleration $a = \frac{v_t - v_0}{\Delta t}$ ($m.s^{-2}$).

Therefore:

$$F = \rho V \frac{v_t - v_0}{\Delta t}, \tag{14}$$

Knowing that discharge (Q) is unit volume per unit time ($m^3.s^{-1}$), we get:

$$F = \rho Q (v_t - v_0), \tag{15}$$

If we assume that the initial velocity is 0, then:

$$Q = \frac{F}{\rho v_t}, \tag{16}$$

Finally, according to Park et al. (2014), the theoretical estimation of force involves calculating the drag force exerted on a blade:

$$F = \frac{1}{2} C_D \rho v_b^2 A_b. \tag{17}$$

where v_b is bulk velocity and A_b is cross-section.

- **Losses:**

The losses experienced in a paddlewheel are commonly referred to as slip, indicating the relationship between the wheel's velocity and the fluid. Camp (1955) first introduced the slip factor when investigating the power characteristics of a paddlewheel:

$$v_2 = (1 - k_{slip}) v_b. \tag{18}$$

Later on, the slip factor was approximated to fall within the range of 0.24 to 0.32.

- **Shaft power:**

The power per blade is determined by multiplying the force of the fluid acting on each blade by the blade's speed:

$$P_b = F v_b = \frac{1}{2} C_D \rho v_b^3 A_b. \tag{19}$$

where P_b is the power of a single blade (W).

Park et al. (2014) modified the drag coefficient appropriately, facilitating the computation of the overall power of the paddlewheel $C_{D\theta} = C_D \cos(\theta)$, with θ being the angle of attack. The maximum drag is observed when the blade is perpendicular to the fluid.

- **Efficiency:**

The wheel's efficiency is determined by the ratio of the useful output power (hydraulic power) to the total input power (shaft power transferred from the motor to the wheel):

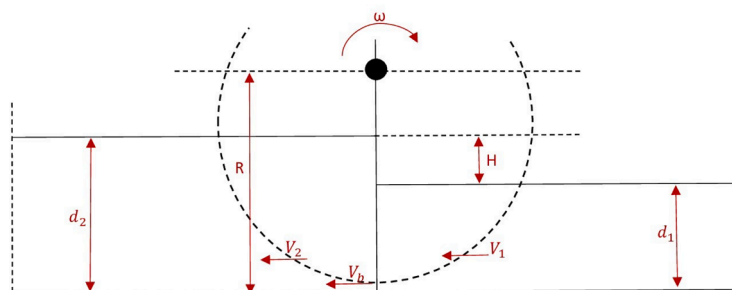


Fig. 4. Side view illustrating the variation in water levels across the paddlewheel, as well as the velocities at the inlet, tip of the blade, and outlet.

$$\eta = \frac{P_h}{P_s}, \quad (20)$$

$$P_h = \rho g H Q. \quad (21)$$

H being the head gained (m), B the channel width and $Q = dBv$.

Enhancing agitation is pivotal for augmenting algal productivity, with a continual focus on minimizing energy consumption for flow and mixing operations (Xu et al., 2014). Despite this objective, the energy consumption associated with paddlewheels remains substantial, particularly in the context of biofuel production (Li et al., 2014). To overcome the constraints linked to conventional paddlewheel setups, an inventive strategy was introduced by Vitale (2012). This approach entailed the creation of a paddle design incorporating a zigzag pattern (Fig. 5), resulting in a notable reduction in energy dissipation.

In addition to pioneering novel paddle designs, researchers have explored the development of RWPs to reduce energy requirements for fluid circulation. Liffman et al. (2013) conducted a study focused on optimizing bend geometries within RWPs to minimize energy consumption. The presence of sharp bends in RWPs is associated with substantial energy losses. To address this challenge, the researchers altered the water flow direction towards the outer edge of the curves by adjusting the curvature radius. They kept the channel width constant while adjusting the depth, transitioning from shallow at the center to deeper at the periphery. This transition utilized profiles like linear, quadratic, or square root functions. Another approach involved maintaining a perpendicular cross-sectional area of the curvature to the culture flow (the area that is exposed to the fluid flow as it navigates through the curved sections of the pond). This was achieved by using a narrow channel width and increasing the channel depth, resulting in a uniform “box-like” design.

Although they tested various bend geometries, the box-like shape proved to be the most effective in reducing energy losses, enhancing mixing, and eliminating low-speed and stagnation areas in the flow. Notably, these inventive bend designs resulted in an impressive 87% reduction in energy consumption when compared to traditional bends. Moreover, this novel design holds the promise of either eliminating or reducing the occurrence of stagnant zones within the flow. Additionally, the enhanced energy efficiency offered by these innovative RWP designs enables the creation of larger ponds with reduced relative capital expenses, potentially leading to a 5% reduction in the overall production cost of algae (Liffman et al., 2013).

Historically, efforts have been made to enhance flow dynamics at

bends by incorporating multi-vane flow rectifiers with the aim of reducing separation regions and mitigating energy loss (Shimamatsu, 1987). An alternative approach involved the implementation of an eccentric curved wall integrated with baffles, as proposed by Dodd (1986).

Alternatively, Hadiyanto et al. (2013) explored the impact of the channel length-to-width ratio (L/B) on the power consumption of a RWP equipped with deflectors. Their study revealed that, when maintaining a constant pond depth, higher length-to-width ratios require less power per unit area in comparison to smaller ratios. However, the relationship between the length-to-width ratio and the required power per unit area is not linear; instead, it reaches a plateau at a ratio above 15. Consequently, opting for a pond design with a larger length-to-width ratio leads to favorable outcomes in terms of velocity uniformity and shear stress. Furthermore, when holding the L/B ratio constant, the power increase exhibits an almost cubic relationship with the superficial fluid velocity ($P = FV$ where $F = f(V^2)$). These findings validate that the power consumption per unit area of a pond is predominantly influenced by the L/B ratio. This observation aligns with (Weissman et al., 1988) assessment of power consumption for two ponds -one with an area of 100 m^2 and the other with an area of 1000 m^2 -revealing consistent power consumption per unit area for both ponds.

Hreiz et al. (2014) introduced an innovative paddlewheel arrangement featuring “non-aligned blades” Their study involved a comparison between blades that were aligned and those that were non-aligned, with an angular offset of approximately 22.5° , to evaluate their impact on mixing efficiency. The research indicated that the aligned blades exhibited superior mixing performance with only a slight increase in power consumption at equivalent flow rates. When operated at similar paddlewheel speeds, both configurations achieved comparable liquid sweep and maintained similar liquid flow patterns. It is worth noting that the dispersion coefficient (m^2s^{-1}) was significantly higher in the aligned blade configuration compared to the non-aligned setup. However, the non-aligned blades demonstrated reduced pulsation effects on the drive train and water flow. Conversely, the aligned blade configuration generated non-uniform flow conditions due to the simultaneous sweeping of substantial water volumes by all paddles.

The efficiency of paddlewheel configurations in open RWPs, incorporating various blade designs, remains an unexplored facet in the existing literature. Li et al. (2014) systematically investigated the effects of blade configurations, filling levels, and rotational speeds on shaft power consumption, fluid velocity, and paddlewheel (of 4 blades) efficiency in an open RWP. The study was conducted in a 2.2 m^2 bench-scale open RWP and explored four different paddlewheel blade configurations: *flat*, *zigzagged*, *back-curved*, and *forward-curved*. The results of this investigation revealed that flat blades exhibited the highest level of efficiency among the tested configurations. Moreover, the study disclosed that increased culture depths were associated with elevated fluid velocity, greater power consumption, and enhanced paddlewheel efficiency, especially when blades were not fully submerged in water. For the same filling level and rotational speed, the ranking of power consumption values, from lowest to highest, was as follows: zigzagged, flat, forward-curved, and back-curved blades. Specifically, the zigzagged blade configuration resulted in higher velocity values at a culture depth of 5 cm , while flat and forward-curved blades exhibited superior velocity values at culture depths exceeding 5 cm . It is noteworthy that the highest paddlewheel efficiency value achieved was 0.50 , which was attained with flat blades at a rotational speed of 11 rpm and a culture depth of 15 cm (Li et al., 2014).

In an effort to enhance the efficiency of microalgae cultivation in open RWPs, Zeng et al. (2016) introduced an innovative paddle design featuring blades inclined at a 15 -degree angle. In a comparative study of microalgae cultivation under identical environmental conditions, their research demonstrated superior growth rates of *Chlorella pyrenoidosa* in the novel RWP equipped with inclined blades compared to the

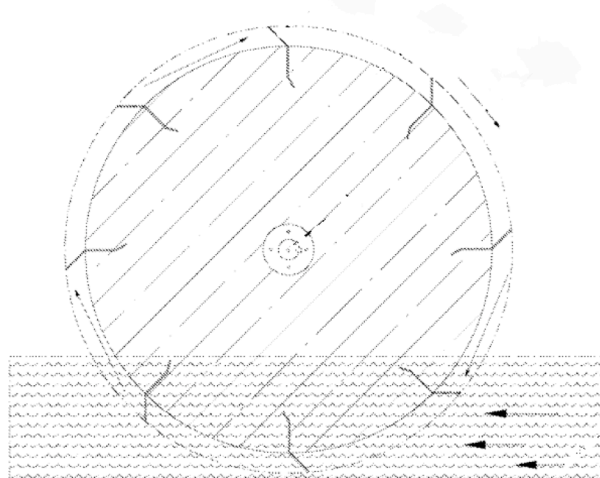


Fig. 5. A cross-sectional depiction of the paddlewheel segment of the device deployed in a water body, illustrating the rotational direction (Vitale, 2012).

traditional reactor. Furthermore, the areal productivity in the novel RWP exhibited a 17% increase, reaching $11.89 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in contrast to the traditional RWP's productivity of $10.18 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Additionally, it was observed that the power consumption of the conventional RWP exceeded that of the new PBRs by 30%.

Various strategies have been investigated to improve mixing patterns within RWPs, including the integration of flow deflectors, rectifiers, gilded vanes, and modifications to island or bend designs (Hreiz et al., 2014). For instance, propellers have shown the potential to cut energy costs by around 50% compared to traditional paddlewheel-driven RWPs. Importantly, research has shown that propellers do not harm the cells during operation (Chiaramonti et al., 2013). Flow deflectors are another example. They are simple, small, and elegant passive devices that can be positioned at multiple locations within RWPs (e.g., at bends). Designed to reduce velocity and convert it into additional torque to generate more energy, deflectors operate without requiring any external power source (Sawant et al., 2019). By incorporating flow deflectors, the settling of cells and the formation of large eddies can be eliminated, resulting in a reduction of the dead zone in RWPs. Additionally, they can significantly increase the exposure of microalgae cells to light, thereby enhancing the light exposure time and the ratio of light exposure time to the L/D cycle (Chen et al., 2016).

Ketheesan and Nirmalakhandan (2011) introduced an airlift-driven raceway system and demonstrated its superior energy efficiency in comparison to traditional paddlewheel-driven raceways for algal cultivation. Simulation results indicated that the power consumption required to maintain typical raceway velocities ranging from 8 to 14 $\text{cm}\cdot\text{s}^{-1}$ could be reduced by approximately 80% in the proposed system as compared to the conventional paddlewheel design. Moreover, in their study, Ketheesan and Nirmalakhandan (2012) investigated the cultivation of *Scenedesmus* sp. using a 23-L airlift-driven raceway reactor under controlled laboratory conditions and artificial lighting, both in batch and continuous modes (Fig. 6). In batch mode, they achieved a maximum volumetric biomass productivity of $0.085 \text{ dry g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}$ through sparging at a CO_2 -to-air ratio of 1%. Additionally, a maximum CO_2 utilization efficiency of 33% was attained with a CO_2 -to-air ratio of 0.25%. Transitioning to continuous mode, the reactor displayed an even higher maximum volumetric biomass productivity of $0.19 \text{ dry g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}$. Remarkably, the biomass productivities per unit power input achieved in this specific reactor setup (ranging from 0.60 to $0.69 \text{ dry g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}$) were comparable to, or even surpassed, those reported in the literature for various PBR designs (ranging from 0.10 to $0.51 \text{ dry g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}$). This impressive demonstration of energy-efficient productivity and significant CO_2 utilization efficiency suggests that the

proposed airlift-driven raceway design could offer a promising avenue for cost-effective algal cultivation.

Moreover, a patented jet-type circulation system for algae ponds has been developed (Parshah et al., 2014) and was employed in large raceway-type ponds by Aurora Algae in Australia.

Nevertheless, these approaches often bring escalated operational costs and restricted operational flexibility, despite their relatively favorable efficiency outcomes (Rogers et al., 2014). Furthermore, in addition to the typically elevated construction and operational expenses associated with these systems, they all generate higher shear forces in comparison to paddlewheels. Therefore, they are not suitable for many algae species, especially *flagellates*, which are susceptible to damage caused by such circulation systems (Borowitzka and Moheimani, 2012). Potential alternatives could include the removal of mechanical mixing by incorporating large-scale open ponds with "sloped" or "corrugated" designs (Rogers et al., 2014).

Kumar et al. (2015) analyzed current design trends in RWPs, highlighting a focus on optimizing CO_2 absorption. One effective approach involves incorporating a sump within the channel to enhance CO_2 absorption capacity. By introducing gas at the bottom of the sump, deeper contact is achieved, extending interaction time and improving mass transfer between gas and liquid phases (De Godos et al., 2014). This counter-current CO_2 injection method, particularly in the deeper region of the sump, significantly enhances CO_2 utilization efficiency while minimizing CO_2 loss into the atmosphere (Craggs et al., 2012b). According to De Godos et al. (2014), sump-assisted RWPs achieved an areal productivity of $17 \text{ g}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and a CO_2 capture rate of 66% of the inlet carbon within the biomass, with a carbon transfer rate of $10 \text{ g}\cdot\text{C}\cdot\text{min}^{-1}$. High liquid-to-gas ratios were found to enhance CO_2 removal efficiency. Baffles within the sump further improved performance, dividing it into two sections resembling an airlift reactor, albeit with an undetermined efficiency (Kumar et al., 2015). However, the introduction of a sump baffle may increase energy consumption, reduce flow velocity, and diminish mixing efficiency (Mendoza et al., 2013). Alternative approaches, like external carbonation columns, have been proposed but result in higher power consumption due to the need to circulate the culture through the absorption unit (De Godos et al., 2014; Putt et al., 2011).

The literature also features studies on closed RWPs. Li et al. (2013) developed a model that achieved an impressive CO_2 fixation efficiency of 95% through intermittent gas sparging. Their innovative approach involved the deployment of a closed RWP design (Fig. 7), where they placed a specialized transparent cover directly over a standard open RWP, ensuring direct contact with the microalgal culture medium's surface. This cover effectively contained the supplied CO_2 , preventing its

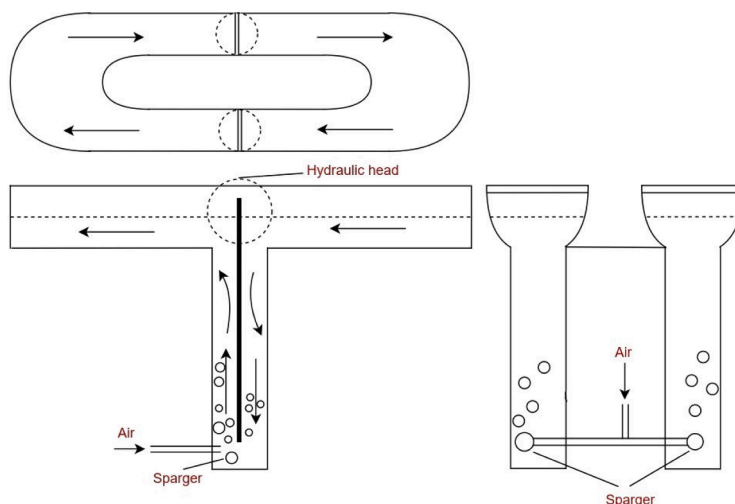


Fig. 6. Airlift-driven raceway reactor (adapted from the original publication by (Ketheesan and Nirmalakhandan, 2012)).

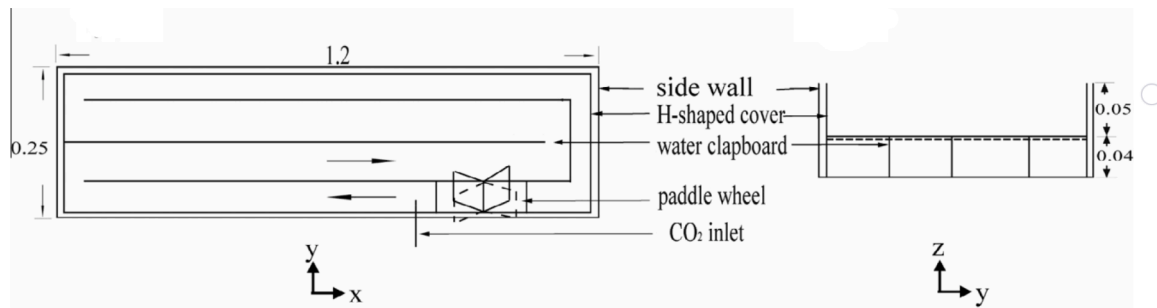


Fig. 7. Schematic representation of the closed RWP: Top view (on the left), Side view (on the right) (Li et al., 2013).

escape into the atmosphere and thereby extending the retention time of CO_2 . Additionally, this method provided the advantages of reducing water loss due to evaporation and preventing culture dilution caused by precipitation and rain (Kumar et al., 2015). The utilization of hybrid RWPs represents another innovative approach. This hybrid cultivation system offers a synergistic strategy that combines the advantages of both PBRs and RWPs while addressing challenges such as the high production costs associated with PBRs and contamination issues in RWPs (Adesanya et al., 2014). Notably, a privately funded program with a budget of US \$20 million successfully developed, constructed, and managed a commercial-scale modular production system covering 2 hectares. This system employed a two-stage process that combined PBRs with open ponds for the cultivation of *Haematococcus pluvialis* for biodiesel production. The achieved annual average rate of microbial oil production reached $420^{15} J/m/year$, surpassing even the most optimistic estimates for biofuel production from terrestrial “energy crops” plantations (Huntley and Redalje, 2007).

6. Hydrodynamic considerations in microalgae cultivation

Understanding fluid dynamics is paramount for successful microalgae cultivation in open ponds. It plays a pivotal role in optimizing operational efficiencies and achieving desired outcomes in biomass production. Key fluid dynamics mechanisms such as shear layers, shear stress, and vortex shedding exert profound influences on growth processes, impacting mixing, mass transfer, and nutrient distribution within the pond. By comprehensively studying and modeling these hydrodynamic factors, insights can be gleaned to enhance pond design and operational strategies, thereby maximizing microalgal productivity.

Turbulence, for instance, is pivotal in ensuring uniform nutrient distribution and mitigating stratification that can adversely affect microalgae growth. Shear layers, arising from velocity differentials, influence the spatial distribution of microalgae and nutrients, necessitating precise management to minimize cell stress. Shear stress, generated by inter-fluid friction, promotes nutrient diffusion but must be carefully regulated to prevent detrimental effects on microalgae. Moreover, bubble-induced shear represents another consideration in optimizing cultivation conditions.

Vortex shedding, induced by fluid flow around obstacles, introduces localized disturbances that affect nutrient availability and light exposure across different pond regions. These factors collectively underscore the complexity of hydrodynamic interactions in open pond systems and highlight the need for tailored approaches to enhance microalgal biomass production.

In the next section, we will discuss the physical mechanisms that come into play when growing or cultivating microalgae in raceway. These environments often present various hydrodynamic challenges that impact algal growth, prompting extensive research.

6.1. Mixing dynamics: turbulence and chaotic advection

It is widely agreed upon that the mixing process is intricate and

multifaceted. However, there’s no unanimous agreement on the underlying causes of these complexities, as they vary across different domains (Aref et al., 2017). Given the widespread occurrence of mixing in various fields and applications, it is improbable that a single explanation can cover all aspects of this complex phenomenon. Yet, it is beneficial to tackle the issue broadly and generally. This brings us to the basic question: *what contributes to the complexity of mixing?*

Traditionally, real-world mixing problems have been challenging to model due to the highly complicated nature of fluid dynamics. This difficulty is exacerbated by the complex rheological properties of the fluids involved, especially at small length scales and with non-uniform fluids. As a result, addressing mixing problems on a case-by-case basis has been the usual approach. However, advancements in experimental studies, coupled with the integration of kinematics with dynamical systems and chaos theory, are providing a more comprehensive framework for analyzing mixing.

As explained by Villermaux (2019), mixing is a dynamic process that shifts a system from an initial state characterized by segregation and simplicity to a final state of uniformity, marked by simplicity. This process, often termed the homogenization of a scalar impurity or “tracer”, happens through intentional actions like stirring, mixing, or diffusion mechanisms, which also contribute to mixing and lead to the final state of mixing at a given time. These actions result in thorough stirring and impurity dispersion throughout the entire medium, ensuring uniform composition and properties. This process can lead to various patterns influenced by factors like medium deformation and interactions between constituents, resulting in the dissipation of patterns. Consequently, mixing stands out as a compelling example of an irreversible phenomenon.

However, there is a tendency in the literature for inconsistent terminology in describing mixing and stirring, often using these terms interchangeably. To distinguish between the two, it is helpful to define stirring as the mechanical stretching of material interfaces while mixing involves the diffusion of substances across these interfaces. Mixing can be intimately associated with the stretching and folding of material surfaces.

To illustrate the complexities of stirring and mixing, we can refer to Eckart (1948)’s comprehensive analysis of mixing as interpreted by Le Guer (2005). Eckart (1948) divided the homogenization process of two fluids A and B, into three distinct phases, covering all space-time scales of the flow:

- **Initial Phase:** At this initial stage, one or more interfaces act as boundaries between fluids A and B. The concentration within each fluid stays relatively constant, and the concentration gradient approaches zero. At the interface where A and B meet, there is a noticeable concentration gradient. However, due to the confined nature of these interfaces, which cover only a small area, the resulting concentration gradient is typically of moderate magnitude on average.
- **Stirring Phase:** In this phase, fluid A experiences mechanical manipulation, which includes stretching, folding, and rolling within

fluid B. This process results in a notable increase in concentration gradients within the mixture.

- **Mixing Phase:** In this final phase, concentration gradients disappear gradually due to the fine striations, and the two fluids become completely homogeneous. The mechanism behind this progressive mixing is molecular diffusion, where the random motion of molecules causes thorough blending and uniformity of the two fluids.

The stirring and mixing phases, however, occur simultaneously within the flow.

To comprehensively address the topic of mixing, it is imperative to situate it within the broader framework of turbulence research. In various practical scenarios, the primary objective revolves around optimizing the rate at which a fluid undergoes mixing. In its simplest form, this entails minimizing the time required for molecular diffusion to thoroughly homogenize an initially non-uniform distribution of a scalar tracer. Without the presence of advection, molecular diffusion alone necessitates a considerable amount of time to achieve uniformity, even within relatively compact containers. Accordingly, the introduction of advection becomes crucial to expedite this process. The conventional and widely recognized approach for achieving this acceleration is through the induction of turbulence. However, it is important to note that efficient mixing doesn't necessarily require turbulent flows; rather, it can also be achieved through gentle (laminar) mixing, which combines stationary solutions in a chaotic manner.

Advancements in statistical theories, particularly the work of Kolmogorov (1941) and Obukhov (1941), have revealed the concept of universality in turbulent flows. This suggests consistent behavior across diverse turbulent systems, independent of flow-specific details. The Kolmogorov-Obukhov theory proposes a universal energy cascade in turbulence, transferring energy from large-scale eddies to smaller scales, which is then dissipated as heat at the Kolmogorov microscales. From a mixing perspective, turbulence rapidly generates small-scale structures in the spatial distribution of advected fields, subsequently smoothed through diffusion.

The concept of chaos is a relatively recent addition to fluid dynamics, contributing to a better understanding of turbulent phenomena. Despite lacking a universally accepted definition, the work of Aref (1984), particularly the article "Stirring by chaotic advection," laid the foundation for chaotic mixing studies. Aref (1984) connected dynamic systems' ability to generate chaotic trajectories with fluid mixing. Simultaneously, Ottino (1989) linked stretching and folding properties of fluid filaments to chaotic mixing. Chaotic flows create zones of thorough mixing through effective stretching and folding, along with areas of material separation, as described by Ottino (1994). Chaotic advection, proposed by Aref (1984), rapidly transforms smooth distributions into complex patterns, converging towards a geometric, fractal structure. The subsequent definition of chaotic advection by Aref et al. (2017) characterizes it as a process generating small scales within a flow through chaotic dynamics. Chaotic advection offers advantages over turbulence, requiring less energy input. It finds applications in microfluidics, where achieving a high Reynolds number is impractical. The insights and possibilities presented by chaotic mixing could also be utilized to enhance the design of microalgae culture systems, especially open ponds.

6.2. Shear stress and micro-eddy induced damage

Shear stress, a hydrodynamic force resulting from the interaction of mixing and aeration, emerges as a crucial factor in the cultivation of microalgae across various scales. Its importance is twofold: firstly, concerning aeration and mixing, both essential for microalgal cultures and particularly critical for large-scale microalgal farming. Secondly, an excess of shear stress can lead to adverse effects such as reduced cell growth and productivity, significant cell damage, and, in extreme cases, cell lysis (Rodríguez et al., 2009). Nevertheless, the sensitivity to shear is

contingent upon strain, shear conditions, and the environment. Microalgae and cyanobacteria exhibit significant variability in shear sensitivity. In certain instances, the sensitivity to shear undergoes alterations throughout the cell cycle, as observed in the case of *Haematococcus* (Scarsella et al., 2012). Striking the appropriate balance becomes essential—ensuring that mixing and aeration facilitate optimal cell growth without compromising cell integrity. This intricate balance poses a significant challenge, especially for species highly sensitive or ultra-sensitive to shear stress (Wang and Lan, 2018).

The shear stress experienced by microalgal cells can be approximated using the following equation, $\tau = \lambda\mu$, where τ represents shear stress (Pa), λ denotes shear rate (s^{-1}), and μ stands for apparent viscosity (Pas) (Wang and Lan, 2018).

Given the complexities of microalgal cultivation, various processes in the system can give rise to shear stress. These operations fall into three categories, namely: 1) mechanical stirring, 2) aeration, and 3) pumping (Wang and Lan, 2018). However, in open pond systems like RWPs, paddlewheels are commonly used for agitation. The modest levels of agitation in these ponds usually result in minimal shear stress from mixing, making it generally unproblematic. Due to the shallow depth of the ponds and the larger size of air bubbles compared to microalgal cells, shear stress related to aeration is generally regarded as negligible in most cases (Wang and Lan, 2018).

Nevertheless, research has indicated a direct relationship between shear stress and the rotational speed of paddlewheels, extending to exceptionally high speeds ($> 23 \text{ rpm}$) (Ali et al., 2015). Once this threshold is surpassed, there is a notable surge in shear stress, thought to be linked to the creation of high velocity gradients at such elevated rotational speeds (Ali et al., 2015). Elevated velocity gradients contribute to intensified particle interaction within the fluid, resulting in higher strain rates. This increased shear stress in the fluid has the capacity to inflict damage on the biomass. Furthermore, turbulent flow undergoes shear stresses due to its non-uniform nature, where various particles within the fluid travel at different velocities. The interplay of these particles among themselves gives rise to shear forces within the fluid. The hydrodynamic shear in turbulent flow, explained by Kolmogorov, is associated with eddies of different sizes, where the energy content decreases as the size diminishes. Eddies that are nearly equal to or slightly smaller than particles or aggregates have the potential to induce damage, while larger eddies would simply carry them through convection (Henzler, 2001). Hence, the dimensions of micro-eddies are influenced by both the kinematic viscosity and the local energy dissipation rate.

6.3. Generation of waves

One drawback of using paddlewheels is that they produce waves downstream, but these waves do not effectively push the fluid forward. Instead, they create a circular motion as the waves rise and fall. Depending on the type of wave generated (linear, nonlinear, impulsive, etc.), fluid particles are prompted to move beneath the surface to a specific depth in complex patterns, including backward and upward, forward toward the crest, forward but downward, and backward to their original position. If the wave breaks, the stored energy turns into forward velocity. Additionally, when the wave breaks, it is likely to enhance gas transfer potential due to the significant turbulence it generates. Waves continue to move until their energy is dissipated by rubbing against the sides of the raceway. When a wave breaks, it rapidly converts energy into both forward speed and turbulence. Whether waves break or not depends on the fluid depth, which can be deep or shallow.

Waves can be effectively used to create vertical mixing in RWPs. The turbulence and energy from breaking waves facilitate vertical mixing, improving the distribution of nutrients and gases throughout the cultivation system.

6.4. Vortex shedding

Vortex shedding refers to the generation of vortices caused by the vortex motion in the downstream region behind a cylinder through which fluid is passing (Dhar, 2016) (Fig. 8a). The defining characteristic of this phenomenon is expressed through a non-dimensional parameter known as the Strouhal number (St) and defined as follow:

$$St = \frac{fD}{v_{\infty}}, \quad (22)$$

where:

- f represents the frequency of vortex emission, conventionally defined as the reciprocal of the period measured consistently across analogous situations,
- D corresponds to the characteristic length (the diameter of the wire in Strouhal's experiments),
- v_{∞} denotes the velocity of the undisturbed flow.

Considering the limitations of the RWP cultivation systems, numerous investigations, encompassing both experimental and numerical approaches, have aimed to enhance the algae's growth conditions. Specifically, various efforts have been undertaken to implement cost-effective alterations to the current RWP configuration. These modifications aim mainly to induce vertical mixing in the straight sections and improve gas transfer at the free surface (Leman et al., 2018).

Researchers have employed diverse vortex generators to optimize growth. Notably, Laws et al. (1983) achieved a 2.2-fold increase in algae growth by utilizing airfoils. In another study, Cheng and Dugan (1995) introduced square and triangular plates into the flow. While their focus wasn't on algae growth effects, they established that these vortex generators enhanced mixing induced by turbulence with minimal impact on power consumption.

The Hydraulics Group research team at Utah State University has directed their efforts toward augmenting biomass growth through the incorporation of Delta Wings (DWs) (Blakely, 2014; Godfrey, 2012; Lance, 2012; Vaughan, 2013; Voleti, 2012). DWs are flat geometrical structures resembling isosceles triangles (Fig. 9). When strategically positioned within the raceway, DWs induce significant downstream circular movements, referred to as trailing vortices. These trailing vortices are responsible for producing the intended mixing effect (Blakely, 2014). Positioned to confront the oncoming flow, (DWs) are set at a 40-degree angle of attack, generating substantial downstream vortices. These trailing vortices contribute to heightened vertical mixing, subsequently enhancing the growth of algae (Blakely, 2014).

Inostroza et al. (2023) in a CFD study, showcased the advantages of incorporating vortex generators in a raceway. These benefits encompass elevated vertical mixing, enabling microalgae cells to efficiently absorb photons and utilize them before commencing a new cycle. Additionally, there is an increased frequency of changing the position of particles

traversing the photoinhibition zone, thereby minimizing damage caused by excessive light exposure. However, this improvement involves a compromise in terms of energy consumption (Leman et al., 2018). Vaughan (2013) reported a 1.5 W increase for a single delta wing generator, and, in practical applications, an array of delta wing generators would be necessary to achieve sufficient mixing. Additionally, Godfrey (2012) observed turbulence levels exceeding critical thresholds for various algal strains, which could potentially damage algae cells due to shear forces from the smallest turbulence scales. Meng et al. (2015) also highlighted a drawback, manifesting as a slight decrease in horizontal velocity.

In a recent investigation, Akca et al. (2023) examined the potential use of vortex-induced vibration (VIV) systems to improve vertical mixing. The researchers noted that these systems do not necessitate extra energy input and do not introduce obstructive fixed structures into the flow path.

Vortex-induced vibration is a type of flow-induced motion where a body becomes excited, emitting vortices from its surface (Akca et al., 2023). Starting from a low Reynolds number of approximately 50 and extending to the highest recorded values, the presence of bluff bodies in external flow and the attachment zones of the cylinder within the flow create three-dimensional structures. These structures lead to an unstable wake, resulting in the formation of a regular pattern and intricate downstream vortices distinct from those generated directly by the cylinder, known as the Karman vortex street (Fig. 8b) (Triantafyllou et al., 2016).

The Karman vortex street is comprised of an arranged series of vortices emerging at a frequency denoted as f , adhering to the Strouhal law (expressed in Eq. (22)). In cases where D represents the cylinder diameter and v is the current speed, the Strouhal number is $St = 0.20$ for subcritical flows exceeding $Re = 150$, and for supercritical flows, the Strouhal number assumes slightly higher values (Triantafyllou et al., 2016). The formation of the Karman vortex street occurs spontaneously, arising from the instability present in the separated flow behind bluff bodies. This instability is analogous to an unstable pole in finite-dimensional systems and can be triggered by even the smallest perturbations.

According to Triantafyllou et al. (2016), the Strouhal number can be considered primarily as a wake parameter, implying a closer association with the width of the wake (h) rather than the cylinder diameter. In this context, the Strouhal number can be expressed as

$$St_h = \frac{fh}{v}, \quad (23)$$

leading to the derivation of a nearly universal value applicable across all Reynolds numbers (Triantafyllou et al., 2016). For instance, with a water velocity of 0.5 m s^{-1} and a diameter of 5 cm , we obtain a Reynolds number of 25,000 (using a kinematic viscosity of $10^{-6} \text{ m}^2 \text{ s}^{-1}$), resulting in a Strouhal number of 0.2.

In their investigation, Akca et al. (2023) implemented a

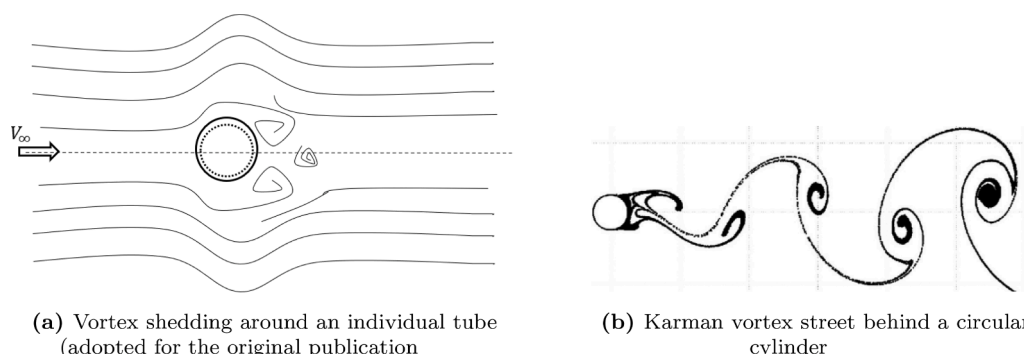


Fig. 8. Illustrations depicting vortex shedding.

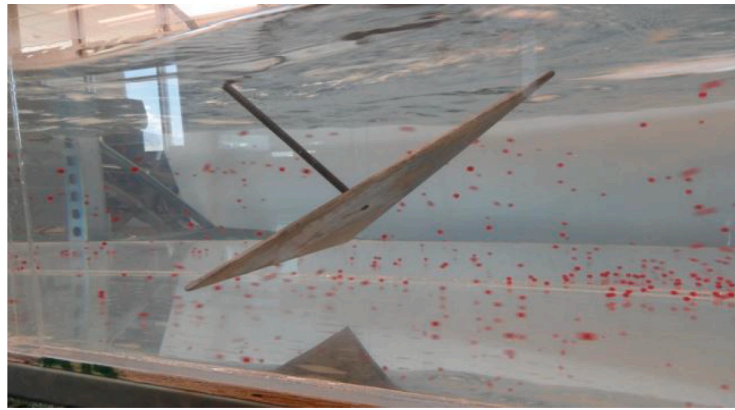


Fig. 9. Delta Wing (DW) with a width of 14.5 inches installed in the experimental raceway utilized at USU (Blakely, 2014).

Vortex-Induced Vibration (VIV) system, which operates without the need for additional energy input, within a 0.3 m deep RWP. Fig. 10 provides a comprehensive illustration of the system and its specific details. They successfully achieved continuous cylinder oscillation appearing downstream of the cylinder, with experimental results showing a cylinder oscillating frequency of 1.24 s^{-1} and an amplitude of 6.5 cm for a flow velocity of 0.3 m s^{-1} . Vertical flow motion resulting from the cylinder oscillation reached an enhanced velocity magnitude of 0.3 m s^{-1} , covering approximately two-thirds of the pond depth.

Moreover, the VIV system's impact on biomass growth was substantiated through a comparative study of *Chlorella vulgaris* cultivation under outdoor conditions. The results indicated that the VIV system-installed reactor enhanced biomass production capacity by over 20% compared to the control pond.

It is worth mentioning that while vortex shedding and turbulence-inducing devices show promise in enhancing algae growth, their implementation in large-scale cultivation systems requires a careful assessment of their impact on production and the associated construction and maintenance costs. Additionally, the increase in energy consumption, particularly in the case of Delta Wings, should be carefully evaluated against the potential benefits in algae production. It's essential to consider not only the improvements in mixing and biomass

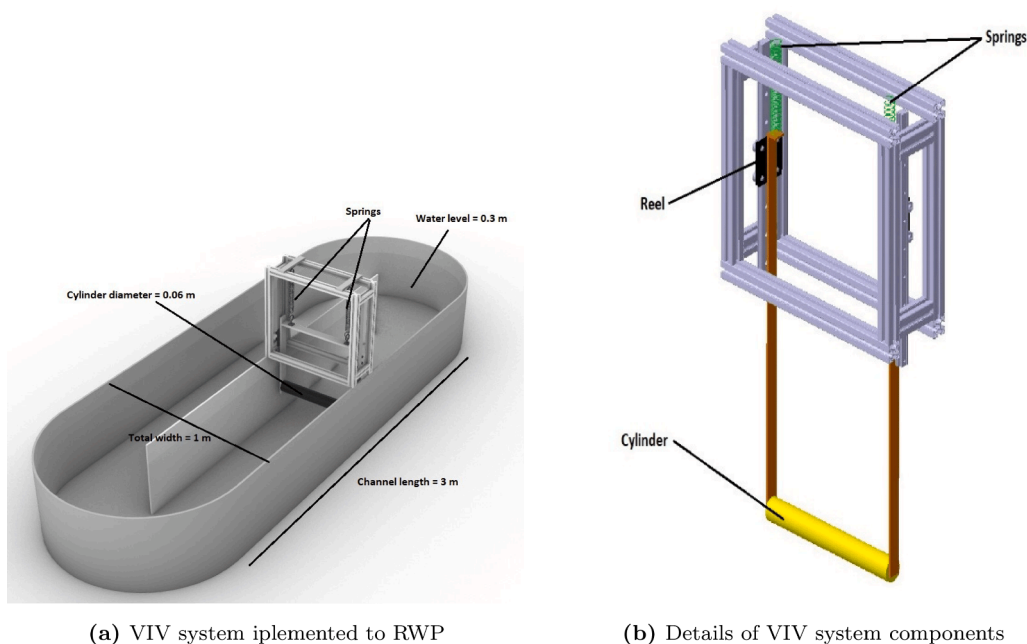
growth but also the long-term sustainability and cost-effectiveness of these solutions in large-scale operations.

7. Conclusion and future perspectives

The cultivation of microalgae in RWPs represents a significant advancement in sustainable biomass production, offering solutions to pressing global challenges. The evolution of RWPs from basic paddle-wheel systems to sophisticated designs incorporating advanced fluid dynamics principles demonstrates the industry's commitment to innovation and efficiency.

Throughout this analysis, we have explored the critical factors influencing microalgal growth and productivity in RWPs, including light availability, temperature regulation, nutrient balance, pH and salinity management, and contamination control. The complex interplay of these factors underscores the need for a holistic approach to system optimization, balancing productivity with cost-effectiveness and environmental sustainability.

Recent innovations in paddlewheel configurations and alternative circulation systems, such as airlift-driven and jet-type systems, have shown promising results in enhancing energy efficiency and scalability. These advancements, coupled with ongoing research into fluid dynamics



(a) VIV system implemented to RWP

(b) Details of VIV system components

Fig. 10. A comprehensive illustration of the VIV system and its specific details (Akca et al., 2023).

and computational modeling, pave the way for more efficient and sustainable large-scale algal cultivation practices. The integration of these technological improvements with a deeper understanding of hydrodynamic principles offers a path forward for the industry. By optimizing mixing patterns, reducing energy dissipation, and improving nutrient distribution, these advancements can significantly boost productivity while minimizing environmental impact.

Looking ahead, the microalgae cultivation industry faces both challenges and opportunities and the continued pursuit of innovation and interdisciplinary collaboration is essential for realizing the full potential of microalgae cultivation. Despite significant advancements in the cultivation of microalgae in RWPs, several areas require further investigation to optimize productivity and sustainability. First, enhancing our understanding of the hydrodynamic conditions within RWPs remains critical. Future research should focus on the development of more sophisticated computational fluid dynamics (CFD) models to better predict the interactions between flow patterns and microalgae growth rates. Additionally, these models should be integrated with real-time monitoring systems to adjust operational parameters dynamically, thereby maximizing biomass yield.

One promising avenue involves the development of microalgae strains with enhanced productivity and resilience through genetic engineering and selective breeding. Genetic engineering tools, such as CRISPR/Cas9, allow for precise modifications to specific metabolic pathways, thereby optimizing traits critical for large-scale cultivation. For example, genetic modifications can increase lipid production, improve photosynthetic efficiency, and enhance stress tolerance-traits vital for maximizing productivity in both controlled environments and open ponds.

Additionally, genetic engineering can enable microalgae strains to better tolerate fluctuating environmental conditions, such as variations in light, temperature, and salinity, as well as stresses caused by contaminants or nutrient deficiencies. These modifications can make microalgae more resilient in the face of challenges typically encountered in commercial-scale operations, such as rapid changes in the growth environment or exposure to pathogens.

Selective breeding programs, especially those using adaptive laboratory evolution (ALE), further complement genetic engineering by stabilizing these enhanced traits over successive generations. ALE allows for the selection of microalgae strains with superior performance under stress, which are then passed down, ensuring their reliability and consistency under large-scale, real-world conditions. This combination of genetic engineering and selective breeding holds the potential to generate strains that are not only more productive but also more robust to environmental stressors, reducing the need for costly interventions and improving the overall sustainability of microalgae production.

Furthermore, integrating these advanced strains with optimized RWP designs could lead to significant operational benefits. For example, enhanced strains could thrive in challenging hydrodynamic conditions typically found in RWPs, while also utilizing nutrients more efficiently. This would reduce nutrient waste, lower operational costs, and minimize the environmental impact of microalgae cultivation. Additionally, research into extremophilic strains-those adapted to extreme environments-could offer a solution to contamination risks in open pond systems. These strains are more likely to withstand microbial competition and environmental stress, making them ideal candidates for commercial cultivation in outdoor systems.

Research is also needed to improve the cost-effectiveness of nutrient supply, particularly by integrating microalgae cultivation with waste treatment processes. This could reduce the reliance on chemical fertilizers while enhancing the sustainability of large-scale operations. Moreover, advancements in the use of alternative carbon sources, such as industrial CO₂ emissions, could further lower operational costs and reduce the carbon footprint of microalgae cultivation.

Finally, the environmental impact of large-scale microalgae cultivation needs to be better understood. Studies should investigate the

long-term effects of RWPs operations on local ecosystems, including water consumption, land use, and potential pollution. Addressing these research needs will be crucial for the future scaling of microalgae cultivation as a sustainable solution for bioenergy and bioproducts.

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Imane Skifa: Conceptualization, Writing – original draft, Writing – review & editing. **Nicolas Chauchat:** Supervision, Writing – review & editing. **Pierre-Henri Cocquet:** Supervision, Writing – review & editing. **Yves Le Guer:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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