sustainability

Review

Research Progress on the Configurations and Performance of Reducing Pollution and Carbon Emissions by Bacterial–Algal Reactor

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Abstract: Currently, the water ecological environment is severely polluted and traditional bioreactors have issues with high energy consumption and greenhouse gas emissions. However, a promising solution is the bacterial–algal reactor, which is a green bioreactor that can simultaneously treat sewage and fix CO_2. The main configurations of bacterial–algal reactors, including several types, activated sludge, biofilm, batch biofilm–sludge reactor coupled with activated sludge method, and bacterial–algal open reactor, have been reviewed. The performance of these reactors in reducing pollutants and carbon emissions during wastewater treatment has been investigated. Additionally, the technical advantages of coupling a bacterial–algal symbiosis system with a conventional bioreactor have been analyzed. The interaction mechanism of the bacterial–algal system in various reactors has also been elaborated. The bacterial–algal reactor improves pollutant removal efficiency through assimilation and absorption of pollutants by microalgae, and reduces aeration by releasing oxygen through photosynthesis of microalgae. Finally, the existing problems in the practical application of bacterial–algal reactors have been summarized, and future research directions have been suggested, providing theoretical support for the future application of bacterial–algal reactors and directions for optimal design and development of bacterial–algal symbiotic reactors.

Keywords: bacterial–algal system; bioreactor; reducing pollution and carbon emissions; processing efficiency; mechanism

Citation: Lu, Y.; An, H.; Li, C.; Wu, X.; Liu, K. Research Progress on the Configurations and Performance of Reducing Pollution and Carbon Emissions by Bacterial–Algal Reactor. *Sustainability* **2024**, *16*, 1994. https://doi.org/10.3390/su16051994

Academic Editors: Dorina Strieth and Judith Stiefelmaier

Received: 4 January 2024
Revised: 22 January 2024
Accepted: 31 January 2024
Published: 28 February 2024

1. Introduction

Human production and living activities generate approximately 2 billion tons of sewage wastewater daily [1]. This includes industrial, agricultural, and domestic wastewater, which can cause severe pollution to water ecosystems and lead to eutrophication. To address this issue, various bioreactors have been developed for the treatment of sewage wastewater, such as membrane bioreactors (MBR), sequencing batch reactors (SBR), biological carousels, membrane aerated biofilm reactors, and bacterial–algal sequencing batch biofilm–sludge reactors (SBBR). While these reactors effectively remove organic matter, nitrogen, and phosphorus, they still have drawbacks such as high energy consumption and greenhouse gas emissions that do not align with the current low-carbon development requirements. Therefore, it is necessary to develop wastewater treatment reactors that can reduce greenhouse gas emissions and energy consumption while achieving efficient treatment results.

Bacterial–algal symbiosis reactors are gaining popularity as an eco-friendly and energy-efficient wastewater treatment option that can reduce greenhouse gas emissions. In these reactors, microalgae are combined with activated sludge and biofilm to form a bacterial–algal symbiosis system. Microalgae use organic matter, nitrogen, phosphorus [2], and CO_2 in wastewater to sustain themselves while producing oxygen through photosynthesis. This enhances the efficiency of bacterial oxidation and degradation of organic matter [3,4], toxic substances [5], and reduces the need for aeration, which is a major energy cost in wastewater treatment. Studies have shown [6] that external aeration in wastewater treatment accounts for 45–75% of the total energy cost. This process has the potential to achieve "peak carbon" and "carbon neutrality" in municipal wastewater treatment in the future. However, current research mainly focuses on the removal efficiency of pollutants and CO_2 fixation efficiency of the bacterial–algal symbiosis system in the reactor. Xu et al. [7] investigated the purification of biogas by a symbiosis system of microalgae and endophytic bacteria (S395-2), and the optimal purification was achieved when the bacterial–algae ratio was 10:1, and the removal efficiencies of COD, nitrogen, phosphorus, and CO_2 were $88.29 \pm 5.03\%$, $88.31 \pm 4.29\%$, $88.21 \pm 4.51\%$, and $68.13 \pm 1.69\%$, respectively. However, there is a lack of research on the interaction mechanism between the bacterial–algal symbiotic system and the various configurations of bioreactors in the treatment of wastewater and CO_2 fixation process. Furthermore, there is a lack of systematic comparison of bacterial–algal symbiotic systems coupled to bioreactors of different configurations.

This paper offers a detailed performance of the different configurations of mycobacterial–algal symbiotic reactors. There are various reactor types based on mycobacterial–algal symbiotic system. In general, it concludes the closed and open systems and divides into biofilm and non-biofilm form. The paper highlights their effectiveness in reducing pollution and sequestering carbon. Additionally, it discusses the advantages of these configurations of reactors in terms of carbon emission reduction during wastewater treatment, as well as the mechanisms behind bacterial and algal interactions in various reactors. Lastly, the article summarizes existing challenges in practical operation of these reactors and proposes future research directions to address these challenges, providing directions for optimal design and development of bacterial–algal symbiotic reactors.

2. Bacterial–Algal Symbiotic Activated Sludge Reactor

2.1. Bacteria–Algae-MBR Reactor

The bacteria–algae-MBR reactor (Figure 1) is a cutting-edge technology that combines membrane filtration with bacterial–algae activated sludge. This process comprises two main components: the membrane module and the bacterial–algae bioreactor. The membrane plays a crucial role in maximizing the retention of bacteria–algae-activated sludge within the bioreactor, thereby maintaining high biomass levels and improving treatment efficiency by retaining some challenging macromolecules, which extends their residence time. Additionally, this design resolves the issue of easily losing suspended bacteria–algae symbionts. The bacterial and algae bioreactor work together to remove nitrogen, phosphorus, and various types of pollutants through the synergy between bacteria and algae. Activated sludge utilizes microalgae cell life activities that produce O_2, carbohydrates, amino acids, proteins, and other essential nutrients. At the same time, it degrades large organic molecules into smaller CO_2, water, ammonia, nitrogen, nitrate, and phosphate molecules [8]. This makes it easier for the microalgae to be absorbed and promotes the exchange of substances between bacteria and algae. Microalgae produce O_2 through photosynthesis, which can be directly utilized by activated sludge, enhancing the activity of nitrifying bacteria and improving the nitrogen removal rate. In the bacterial–algal symbiotic system, soluble phosphorus removal primarily relies on the anaerobic phosphorus release and aerobic over-absorption processes carried out by phosphorus polymerization bacteria and the assimilation of microalgae.

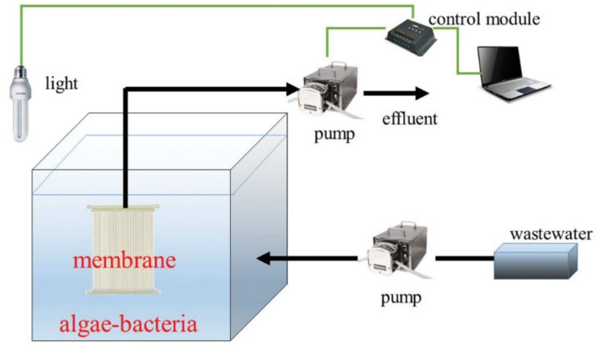

Figure 1. Schematic view of an algal–bacterial MBR bioreactor [9].

The coupling of bacterial–algal symbiosis technology with MBR can improve the pollutant removal rate of MBR membrane bioreactor. Sun et al. [10]. Mixed algae were inoculated into the experimental bioreactor, namely algal-sludge bacterial-MBR (ASB-MBR), and the dry weight ratio of algae and sludge bacteria was 1:10. Another common activated sludge–membrane bioreactor (CAS-MBR) operated without algae was used as a control system which was regard as. The working volume of each MBR was 6 L and the two MBRs should be maintained at a relatively constant biomass concentration (3300 $\pm$ 150 mg/L), the aeration rate was controlled at 0.15 m^3/h at the bottom of the bioreactor. Sun et al. compared bacterial–algal symbiosis MBR (ASB-MBR) with common activated sludge MBR (CAS-MBR) bioreactor and found that the average effluent concentration of COD in ASB-MBR was 18.3 $\pm$ 1.9 mg/L, which was much lower than that of CAS-MBR 32 $\pm$ 2.5 mg/L. Moreover, the NH_4^+-N and PO_4^{3-}-P removal efficiency in ASB-MBR was increased by 6.71% and 8.15%, respectively, compared with that of the CAS-MBR. The average concentration of EPS in ASB-MBR was 91.35 mg/g VSS, and the introduction of algae reduced EPS by 24.6% compared to C-MBR. The ASB-MBR is simple to operate and occupies less space, which can further reduce membrane contamination and pollution, and achieve high-efficiency and low-carbon treatment. The bacterial–algal symbiosis system reduces EPS secretion through interactions between bacteria and algae, reducing the agglomeration of flocs on the membrane surface. It also slows down the membrane aperture reduction and clogging due to the adsorption and deposition of alternating and organic macromolecules on the membrane pores and surfaces. This slows down the membrane contamination. In a separate study by Sun [11], the algae/sludge inoculation ratios for the four MBR reactors were, sludge only, 1:10, 1:5, 1:1, named R0, R1, R2, R3. The MLSS of each MBR was maintained at 3300 $\pm$ 150 mg/L by sludge discharge, when the transmembrane pressure (TMP) reaches 30 Kpa, the membrane needs to be cleaned. The membrane fouling was observed by monitoring TMP. Obviously, the time required to reach a TMP R2 of 30 kPa is almost three times as long as R0, twice as long as R1, and four times as long as R3. Two studies by Sun showed that the membrane fouling was improved under proper inoculation ratio compared with the conventional MBR, indicating the positive effect of algae system on mitigating membrane fouling in MBR. Similarly, Liang [12] conducted a study which showed that the MLE-MBR with alternating anoxic and aerobic sequencing operations is more effective in removing nitrogen compared to the CAS-MBR. The study also revealed that the biomass from the MLE-MBR has higher levels of heterotrophic and autotrophic bacterial activities, less biofouling and better sludge settling than the CAS-MBR. The results of the study suggest that the process configuration plays a crucial role in MBR operation. Alternating anoxic/aerobic processes can improve nutrient removal, increase bacterial activities, and reduce membrane fouling. Radmehr et al. [13] found that the ASB -MBR can reduce the amount of mechanical aeration by about 60% compared to the ordinary activated sludge MBR reactor, which accounts for about 60% of the total energy demand for the operation of MBRs [14]. This means that the ASB-MBR system can reduce aeration energy consumption and save operating costs by 36%.

2.2. Bacteria–Algae-Sequencing Batch Activated Sludge Reactor

The bacteria–algae-sequencing batch activated sludge reactor (SBR, Figure 2) is a system that involves inoculating microalgae in the activated sludge of an ordinary SBR reactor to form a bacterial–algae symbiosis. This system is designed to perform the functions of homogenization, primary sedimentation, biodegradation, and secondary sedimentation tank. It operates without a sludge return system, allowing sewage to circulate through the water inlet, aeration, sedimentation, and drainage in sequence. The processes within the system can be adjusted depending on water quality and quantity, making it flexible in operation. Moreover, microalgae can absorb the CO_2 produced by bacterial activities and produce O_2 through photosynthesis. Bacteria, in turn, uses O_2 to degrade inorganic and organic pollutants. The bacteria and algae system can also assimilate and absorb nitrogen and phosphorus into their own biomass.

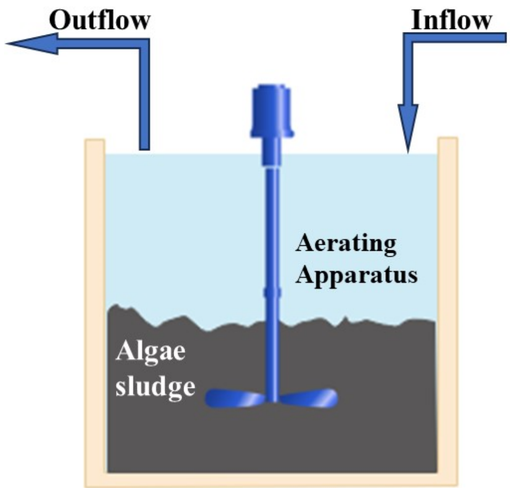

Figure 2. Schematic view of an algal–bacterial SBR bioreactor.

Bacteria–algae-sequencing batch activated sludge reactor is a new type of wastewater treatment reactor with nutrient recovery capacity and more economical. The combination of bacterial–algal symbiosis technology and SBR reactor helps enhance the pollutant removal rate and solves the problem of N and P removal in SBR reactor. The research conducted by NGUYEN et al. [15] showed that the 3:1 ratio of microalgae-activated sludge was proposed to attain simultaneously organic/nutrient removal and biomass production for low COD:N wastewater. The uptake rates for TN, TP, and COD at a 3:1 inoculation ratio were recorded as 43.3 mg/(gbiomass·day), 7.6 mg/(gbiomass·day), and 132.7 mg/(gbiomass·day), respectively. This condition performed sufficient removal of TN (86%), TP (79%) and COD (99%) and total biomass concentration of 1.12 g/L. Microalgae played a pivotal role in nutrient assimilation, while activated sludge contributed to TN assimilation, denitrification, and COD removal. In addition, Tang et al. [16] discovered that TN and TP removal in the ABS system under 0.2 L air/min aeration rate condition increased by 12.13% and 36.00% compared to the CAS system under 0.4 L air/min aeration rate condition; thus suggesting that the ABS system was attractive for achieving higher nutrients removal but lower energy demand than CAS system. Ye et al. [17] compared microalgae inoculated in an activated sludge SBR reactor with a common activated sludge SBR reactor. The removal rates of COD, NH_4^+-N, and TN in the bacterial–algae-SBR reactor were 99.45%, 99.93%, and 90.39% (about 0.02 vvm), while the removal rates of COD, NH_4^+-N, and TN of single activated sludge were 98.36%, 83.51, and 78.96%, at the same aeration intensities. The removal efficiencies of COD, NH_4^+-N, TN, increased by 1.09%, 16.42%, and 11.43%, respectively. Moreover, Wang et al. [18] discovered that 80% of TN was removed by nitrifying–denitrifying bacteria and the rest was absorbed by microalgae in microalgae-coupled short-range nitrification-denitrification SBR reactor. Microalgae photosynthesis supplied 74% of DO, which greatly reduced aeration requirements. SBR reactor activated sludge inoculated with microalgae can reduce the sludge yield, increase the nitrogen content of residual sludge, and improve the value of residual sludge resource utilization. Yasmeen [19] indicated that an algal membrane photobioreactor (MPBR) will be helpful in either supplying the O_2 by recirculating the O_2-rich effluent produced into the MBR or improving water quality by reducing the nutrients before entering into the MBR. Bucci et al. [20] compared the effect of a bacterial aerobic granular sludge SBR and bacterial and algal aerobic granular sludge on the removal of phenol and ammonia nitrogen. They found that the phenol removal rate reached 100% in 24 h and the NH_4^+-N removal rate of bacterial aerobic granular sludge SBR was 100%, while the NH_4^+-N removal rate of bacterial aerobic granular sludge SBR was 0.5%. NH_4^+-N removal was 93 ± 2.3% for bacterial aerobic granular sludge SBR and 100% for bacterial algal aerobic granular sludge SBR, making ammonia nitrogen removal better for bacterial–algal SBR. In addition, the bacterial–algal reactor has a better nutrient recovery capacity. In the study by Liang J. et al. [21], the influent NH_4^+-N was 30 mg/L, under 0.2 L air/min aeration rate condition, for 30 days of reactor operation, the SVIs for the bacterial–algal SBR reactor and the single activated sludge SBR reactor were 50.59 ± 0.39 mL/g and 53.36 ± 0.45 mL/g, respectively. When the bacterial algae SBR reactor and the single activated sludge SBR reactor were operated stably, the mass concentration of MLSS was 2.699 ± 0.093 and 2.704 ± 0.067 g/L, and the sludge and microalgae content in the residual sludge discharged daily were 1.176 ± 71 mg/d, 90.80 ± 14.85 mg/d (bacterial algae SBR), and 1.315 ± 85 mg/d, 0.00 ± 0.00 mg/d (single activated sludge SBR reactor), elemental N content of the remaining sludge were 7.63 w/% (bacterial algae SBR), 7.38 w/% (single activated sludge SBR reactor). This means that the reduction in residual sludge yield of the mycorrhizal SBR counter-reactor can be up to 10.56% compared to a single activated sludge SBR. Increased N content and the presence of microalgae increase the recycling value of sludge. Waste activated sludge extracts were used in Song et al.'s [22] study to examine the growth of microalgae and the accumulation of lipids at various temperatures. Temperatures of 10 and 25 °C were found to yield the highest lipid productivity (80.41 mg/(L·d)) and lipid content (59.13%), respectively, during cultivation.

3. Bacteria–Algae Symbiotic Biofilm Reactor

3.1. Closed Bacteria–Algae-Biofilm Photobioreactor

A closed bacteria–algae-biofilm photobioreactor is a device made of transparent material that contains microalgae. The microalgae are inoculated with a mixture of bacteria that forms a biofilm attached to the reactor wall or surface. Organic wastewater that is rich in nitrogen and phosphorus flows through the biofilm, where there is a substance ex-change taking place. This photobioreactor does not exchange gases and substances with the environment. The bacteria and algae attach to the solid material to form the biofilm of the bacteria and algae, creating a stable microenvironment that minimizes pollution and controls conditions such as pH, temperature, light, and CO_2 concentration [23]. Closed bacterial–algal biofilm photobioreactors use sunlight as an energy source to fix CO_2 in the closed unit and convert light energy into chemical energy stored in the bacterial–algal cells [24]. When treating wastewater, the bacterial algal biofilm is accompanied by the process of carbon sequestration. The microalgae absorb and assimilates the nitrogen and phosphorus in the sewage [25], and the bacteria achieve the degradation of pollutants through the nitrification–denitrification of nitrogen as well as the process of phosphorus over-absorption. This achieves the simultaneous reduction of sewage and carbon. The mycorrhizal biofilm exhibits a superior adsorption capacity. Molinuevo-Salces et al. [26] indicated that 96% of the total biomass was retained after harvesting bacterial algal biofilms from closed bacterial algal biofilm photoreactors.

Tubular algae biofilm photobioreactors are mycobacterial biofilm photobioreactors that use tubes made of transparent, rigid plastic, glass, or plexiglass, with small diameters that are bent into various shapes. These photobioreactors are commonly used for treating animal farm wastewater. De Godos et al. [27] demonstrated that tubular algae biofilm photobioreactors (Figure 3) are highly effective in removing nitrogen (94–100%) and phosphorus (70–90%) from swine wastewater. Similarly, González et al. [28] found that tubular bacterial–algal biofilm photobioreactors are highly efficient in removing pollutants from diluted swine wastewater containing 180, 15, and 2000 mg/L of NH_4^+-N, soluble P and total COD, achieving 99% NH_4^+ removal, 86% PO_4^{3-} removal, and 75% COD removal. When properly designed and operated, closed type PBRs are more efficient in the distribution of gas and light. However, they are generally not cost-effective due to their high installation and maintenance costs. The ideal setup for large- or industrial-scale algal cultivation is inexpensive, energy-efficient PBRs with carefully regulated systems to track the performance of the algal culture [29].

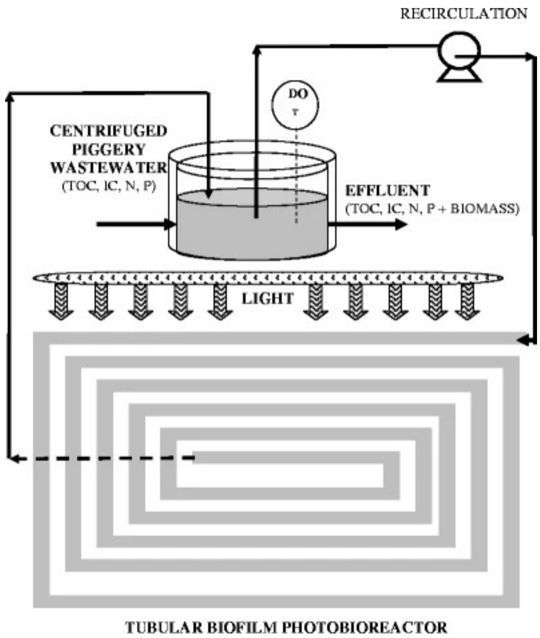

Figure 3. Schematic diagram of the photobioreactor set-up [27].

3.2. Algal–Bacterial Rotating Biological Contactor

Bacteria and algae attach to a plastic disc, forming a biofilm. The disc rotates in the direction of vertical water flow, and around 40–50% of the disc is submerged in sewage that needs to be treated. As the disc rotates, microorganisms such as bacteria–algae in the biofilm are alternately immersed in the wastewater, and organic matter in the wastewater is absorbed or adsorbed on the biofilm. This process absorbs carbon, nitrogen, phosphorus, and other pollutants from the wastewater, and releases CO_2 and absorbs O_2 when exposed to sunlight. As the biofilm grows and develops, it becomes thicker and forms different partitions, like anaerobic, micro-oxygen, and aerobic. These partitions form a rich community structure on the biofilm. When the biofilm is turned out of the water surface, it decomposes the organic matter adsorbed on its surface. The algal–bacterial rotating biological contactor is a highly efficient reactor for the removal of opaque wastewater such as petroleum wastewater and dye wastewater.

An algal–bacterial rotating biological contactor (Figure 4) with microalgae improves ammonia nitrogen removal and can cultivate algae for biodiesel production [30]. The bacterial–algal-biofilm method can increase the biomass yield and reduce the cost of algae harvesting compared to the suspension method, and the bacteria can promote algae attachment [31,32]. Christenson and Sims [31] showed that the algal–bacterial rotating biological contactor had a biomass yield of 20–30 g/($m^2 \cdot d$) and could be harvested to obtain a 12–16% solids concentrated product. Microalgae can accumulate a certain amount of lipids and carbohydrates in their cells. The algal–bacterial rotating biological contactor can be used to produce lipids. The algal–bacterial rotating biological contactor was able to degrade petroleum wastewater efficiently while microalgae promoted oil adsorption and sequestration by the bacterial–algal biofilm. A study by Mukherji and Chavan et al. [5] found that the removal rate could be more than 99% at influent oil concentrations, much higher than the concentration of total petroleum hydrocarbons loaded as high as 31.8 g TPH/(m^2·d) for the use of conventional biofilm rotary discs. Another study by Chavan and Mukherji [33] found that TPH, TCOD removal by the algal–bacterial rotating biological contactor could reach 97–98%, at a diesel concentration up to 0.6% (v/v). The algal–bacterial rotating biological contactor was also able to efficiently degrade high concentrations of azo dyes through bacterial–algal synergism. Zhang et al. [34] found that the algal–bacterial rotating biological contactor was able to degrade more than 95% of acid orange II dye in 24 h. The reactor uses acid orange II as the sole nitrogen source and different concentrations of acid orange II are injected into the reactor. The degradation efficiencies at 200 and 600 mg/L were 97.3 ± 2.2 and 98.25 ± 0.04%, respectively. The removal rate of acid orange II was 592 mg/(L·d) at a concentration of 600 mg/L, reaching the maximum value. Their study also found that organisms in the biofilm, such as rotifers, helped to maintain biofilm activity.

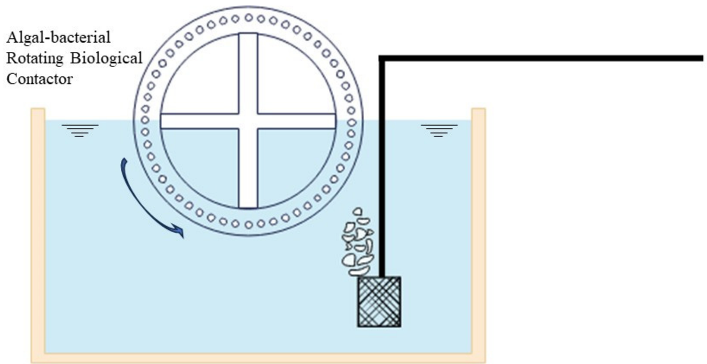

Figure 4. Schematic view of an algal–bacterial rotating biological contactor.

3.3. MABAR-Membrane Aerated Bacterial Algae Biofilm Reactor

A biofilm consisting of bacteria and algae attaches to the aeration membrane components, forming a biofilm reactor. The membrane components serve as carriers for the biofilm while supplying oxygen to the system. The process of algae biofilm formation occurs near the surface of the aeration membrane where oxygen concentration is high. This makes it easier for aerobic microorganisms to gather and multiply. As oxygen diffuses to the outside, the concentration decreases, creating an aerobic anoxic–anaerobic layer on the surface of the membrane module. Pollutants from the sewage diffuse from the external to the internal layer of the biofilm, with pollutant concentration decreasing along the course. The coupling of biofilms and membrane aeration reactors results in complementary advantages and synergistic enhancement.

The MABAR reactor has a high oxygen utilization rate and is less limited by C/N [35]. The integration of bacterial–algal symbiosis and membrane aerated biofilm reactors can enhance the removal rate of pollutants while also mitigating the limitations imposed by C/N ratios in the degradation process. In a study conducted by Zhang et al. [36], the wastewater supply and drainage system, biochemical system, light system, and gas supply system constituted the whole system. The gas supply system is evident, which facilitates the delivery of pure oxygen to the bioreactor via a blower. A pressure gauge has been strategically positioned between the blower and the bioreactor to investigate the relationship between dissolved oxygen and pressure, as well as to determine the oxygen transfer rate across the membrane. The biochemical system is essentially composed of a membrane module, along with an inlet and outlet system. Customarily, the inlet water is propelled by a pump, whereas the outlet water flows freely under the force of gravity. Instead of sunlight, the biochemical system employs self-contained LED lamps for illumination. The combined efforts of the stirrer and aeration system ensure that the reactor maintains a state of completely mixing flow. The biochemical system is the core of the MABAR system, which was made of plexiglass with a total volume of 2.0 L. The material of the membrane used for this test was PTFE with the membrane pore of 0.22 um. The only difference in the bioreactor configuration between the MABR and MABAR is that the MABR system did not contain the light system; the effectiveness of a membrane aerated bacterial–algae biofilm reactor (MABAR) was compared to that of a typical membrane aerated biofilm reactor (MABR). The study found that, when the C/N ratio was 2, 5, and 8, the effluent TN concentration of MABAR decreased by 14.34 mg/L, 0.5 mg/L, and 12.10 mg/L respectively, as compared to MABR. The presence of a bacterial and algal symbiosis system significantly reduces the aeration requirement of the reactor, making MABAR more economical than MABR. Microalgae can produce oxygen through photosynthesis under light, thus increasing the dissolved oxygen content in the wastewater. Li et al. [37] discovered that COD removal and NH_4^+-N in the membrane aerated bacterial algal biofilm reactor could still reach up to 90%, even when the aeration rate was half of the traditional bacterial algal symbiosis system at 24 h. Vanessa et al. [38] show that the longitudinal oxygen gradient has an important effect on both, biomass distribution and effluent total dissolved nitrogen concentration (TDN), whereas the longitudinal substrate exclusively affected the effluent TDN.

4. Algae-Assisted Sequencing Batch Biofilm Reactor

The algae-assisted sequencing batch biofilm reactor (A-SBBR, Figure 5) is a configuration of bacterial–algal symbiosis reactor that is made up of both activated sludge and biofilm methods. In this reactor, a filler is added, and microalgae-activated sludge is inoculated to create bacterial and algal activated sludge. This mixture is then attached to the surface of the filler to form a biofilm that constitutes the A-SBBR. The surface of the filler material is rough and porous, providing a large area for microbial attachment and growth. Based on the filler's operating characteristics, it can be divided into two configurations of reactors: suspended and fixed bed. The suspended filler makes full contact with the wastewater in the aeration period, facilitating a full exchange of substances. When it is floating on the water surface, it does not require aeration, allowing the biofilm to receive more light. The fixed carrier, on the other hand, is fixed on the top of the reactor and can receive more light, while also resisting any hydraulic disturbance caused by aeration.

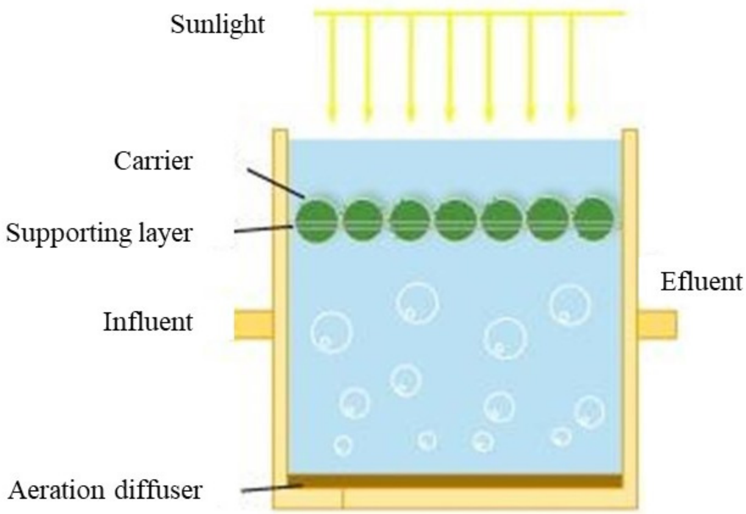

Figure 5. Schematic view of an algal–bacterial SBBR contactor [39].

Compared to the ordinary sequencing batch biofilm reactor (SBBR), the A-SBBR can improve the pollutant removal rate of the reactor. The biofilm composed of bacteria and algae can increase the degree of algae enrichment, which has a positive effect on improving nitrogen and phosphorus removal by microalgae. In a study conducted by Tang et al. [39], it was found that the TN effluent concentration of an SBR reactor and an A-SBR reactor without filler in the initial stage was 26.94 ± 0.84 mg/L and 24.04 ± 1.50 mg/L, respectively, and the removal rate was 45.2 ± 2.71% and 38.5 ± 2.61%, respectively. In the second stage after adding filler, the TN concentration of effluent from the constructed SBBR reactor and A-SBBR reactor was 21.42 ± 2.73 mg/L and 26.38 ± 1.31 mg/L, with the removal rates of 50.8 ± 5.83% and 39.3 ± 3.69%, respectively. The experiment's results showed that the TN removal rate of the A-SBBR reactor was higher than that of the SBBR reactor. Bio-assimilation is the primary phosphorus removal mechanism, and the bacterial–algal symbiosis system significantly enhances this process. In a study conducted by Tang et al. [40], it was found that the anabolic removal of TP was increased by 50.13% compared to the SBBR reactor, and its TP removal rate could reach 94.78%. In addition, a study by Patricia [41] found that a coupled microalgal–bacterial biofilm (CMBB) treatment significantly improved wastewater quality for irrigation with no additional energy cost. CMBB treatment also enhanced the removal of BOD, ammonia and phosphates from the wastewater.

5. Bacterial–Algal Symbiosis Open Reactor

5.1. High-Rate Algae Pond

The high-rate algae pond (HRAP) is an enhanced version of the traditional stabilization pond. It is an open runway configurations pond with shallow water (between 0.2 and 0.5 m deep), using an agitating valve to mix. Compared to a stabilization pond which measures 0.5 to 2.0 m in depth, HRAP has shallower water. The usage of an agitating valve prevents cell settlement, eliminates thermal stratification, promotes the growth of micro-algae, and distributes nutrients uniformly in the water. The retention time in HRAP is usually 3–10 days, substantially shorter than that of a stabilization pond, by approximately 7 to 10 times. HRAP utilizes a bacterial–algal symbiosis system to efficiently treat wastewater. Such enhancements capitalize on algal proliferation to foster an environment optimal for microbial yield and reproduction, leading to a more advanced algal-bacterial symbiosis system. The bacteria use the O_2 produced by microalgae photosynthesis to simultaneously decompose the large molecules in the wastewater into small molecules of ammonia, nitrogen, and phosphate. The CO_2 produced by the bacterial metabolism is absorbed and utilized by the microalgae. The ammonia nitrogen is removed through bacterial nitrification–denitrification and microalgae absorption and assimilation. Phosphate is removed through assimilation absorption and sedimentation by the algae and bacteria.

HRAP is an effective method to treat various types of wastewaters and extract nutrients through the use of algal biomass. A study by De Godos I et al. [42] utilized two HRAPs to treat pig wastewater diluted by 10 and 20 times. The study found that the average removal rates of COD and TKN were 76 ± 11% and 88 ± 6%, respectively, with a biomass yield range of 21–28 g/(m^2·d) in between. Another study by Park et al. [43] showed that by adding carbon dioxide to the HRAP treatment of domestic wastewater, they were able to achieve an average algal production of 9.0 g/(m^2·d) and harvested algal biomass of 7.5 g/(m^2·d). To achieve this, they used a settling device at a hydraulic retention time of 8 days. Selvaratnam et al. [44] indicated that the HRAP systems can integrate technologies which recover energy and recycle nutrients from wastewater to create a sustainable treatment model. While open systems remain prevalent in industrial processes, their technological progress is somewhat constrained. This limitation is largely due to their scale and associated challenges. Open systems are prone to contamination, offer limited control over environmental conditions necessary for culture [45], are susceptible to water loss through evaporation, experience fluctuations in temperature, and are inefficient in homogenization, leading to suboptimal mass transfer rates. Additionally, they often suffer from nutrient limitations and uneven light distribution, which further impedes their performance [46].

5.2. Algal Turf Scrubber (ATS)

The Algal Turf Scrubber (ATS, Figure 6), created by Adey et al. in the 1980s [47], is an innovative artificial riverbed consisting of a two-dimensional solid grid with a layer of biofilm attached to it. This biofilm contains various microorganisms, such as bacteria, fungi, and microalgae, with algae being the primary component of the dominant biofilm. Water flows over an inclined solid surface covered with microalgae and bacterial and fungal aggregates, creating a thin layer of water that flows at a slower rate. This allows the biofilm to remain well oxygenated even at night. The three types of microorganisms within the biofilm—autotrophic algae, heterotrophic fungi, and bacteria—like nitrifying bacteria—work together in harmony. The bacteria not only provide a significant amount of carbon dioxide for photosynthesis but also participate in the degradation of pollutants and nutrients. They convert complex substrates into simpler forms and metabolites, making it easier for the algae to use them.

The ATS is an efficient way to remove nitrogen and phosphorus from wastewater. The results of a study by Gan et al. [48] showed that with elevated, dissolved oxygen and pH values, the maximum removal rates of TP and TN were 8.3 mg/(L·d) and 19.1 mg/(L·d), respectively. Within seven days, 99% of TP and 100% of TN were removed. The ATS not only removes nutrients from the effluent but can also be harvested for biodiesel production from bacterial and algal biofilms. The biofilm of ATS consists of three parts: bacteria, fungi, and algae. The symbiosis of bacteria and microalgae facilitates the bio-aggregation of algae, and the surface of algae and fungal hyphae with opposite charges adsorb each other [49]. Under suitable cultivation conditions, the oil content of several microalgae can account for 50–70% of the dry weight of the cells [50]. A study by Marella et al. [51] on the treatment of an ATS system to treat municipal wastewater for simultaneous biodiesel production showed that the lipid content of the harvested algae ranged from 9.3% to 22.2%, with 10.8 g/(m^2·day) achieved in the summer season when the highest yield was obtained. This means that the ATS reactor can be used to produce lipids.

Generally, bacterial–algal symbiosis in open reactors carries inherent disadvantages. For instance, without proper control of the reactor parameters, algae can proliferate excessively, leading to ecological and environmental hazards due to the overgrowth and potential escape of these microorganisms.

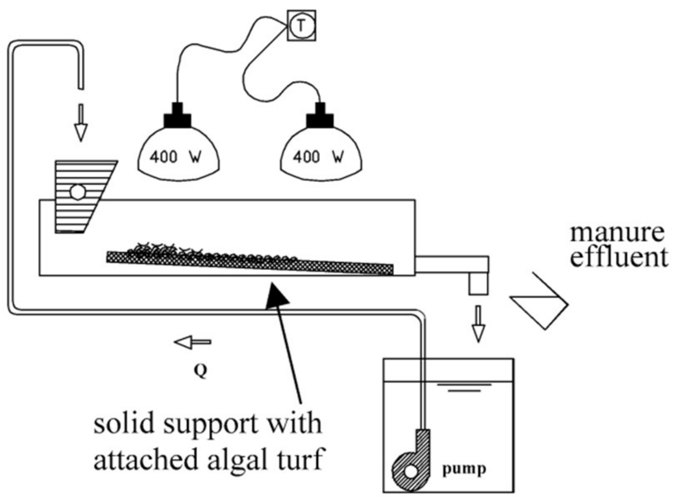

Figure 6. Diagram of an Algal Turf Scrubber [52].

6. Summary and Outlook

The serious pollution of water environment, high energy consumption of traditional bioreactors, and the large amount of greenhouse gas emissions are major concerns that need urgent attention. The solution to these issues is the bacterial–algal symbiotic reactors, which can effectively remove nitrogen and phosphorus pollutants from wastewater while reducing the emission of greenhouse gases. There are various configurations of bacterial–algal symbiotic reactors that can be used for wastewater treatment. These include bacterial–algal-MBR and bacterial–algal-SBR (sequencing batch activated sludge reactor) systems. There are also bacterial–algal symbiotic biofilm reactors such as the closed bacterial–algal-biofilm photo-bioreactor, the algal–bacterial rotating biological contactor, and MABAR. In addition, there is the bacterial–algal SBBR coupled to activated sludge-biofilm method. Finally, there are bacterial–algal symbiosis open reactors, like the high-efficiency algal ponds and Algal Turf Scrubber, that can be used. The efficacy of these reactors has been summarized based on their configurations for pollution reduction and carbon reduction. In theory, the ability of the CO_2 sequestration of algae is 1.83 kg of CO_2 per kilogram of algal biomass production. For these bacterial–algal symbiotic reactors, according to our investigation, it is much lower and with a larger range from 0.14 to 0.43 kg CO_2/d, since the CO_2 sequestration will be influenced by so many factors such as different kinds of algal, temperature, hydrodynamic conditions, etc. Moreover, the advantages of synergistic carbon emission reduction in wastewater treatment of bacterial–algal symbiotic reactors have been introduced, and the mechanism of interaction between bacterial–algal symbiotic systems in each reactor has been elaborated.

There are still several challenges in using bacterial–algal symbiotic reactors for practical applications. Industrial wastewater is often too dark and not transparent enough, which reduces the efficiency of microalgal photosynthesis. Moreover, the cultivation and performance of microalgae present several constraints and challenges. For instance, the difficulty in precipitating microalgae results in biomass loss within the reactors. Furthermore, controlling the growth of microalgae can be challenging, often leading to overgrowth.

To increase the effectiveness of wastewater treatment and the utilization of biomass in mycobacterial–algal symbiotic reactors, we can take the following steps: (1) during the design or improvement of the reactor, it is important to consider light distribution to improve energy conversion and light utilization. (2) Develop new, efficient, and reliable bacterial and algal symbiotic catalysts, which can help to reduce the costs associated with operation, maintenance, and recycling of the reactor. With the advancements in chemical and material sciences, there are now a wide range of artificial and natural materials available that can be used as catalysts for efficient pollution and carbon reduction in mycobacterial–algal symbiosis reactors. In summary, the research and development of bacterial–algal symbiotic reactors will lead an effective promotion on the practical applications of bacterial–algal symbiotic technologies, which still need much works to do.

Author Contributions: Writing—original draft preparation, Y.L.; Writing—review and editing, H.A.; Data curation, C.L.; Conceptualization, X.W. Formal analysis, K.L. All authors have read and agreed to the published version of the manuscript.

Funding: H.A. acknowledges support from the National Natural Science Foundation of China (Grant No. 51508263). C.L. acknowledges support from the Major Science and Technology Demonstration Projects of Carbon Peak and Carbon Neutra Technology Innovation in Jiangsu Province (No. BE2022861).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: Author Hao An was employed by the company China MCC5 Group Corp. Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

ASB-MBR	Algae-sludge bacterial-membrane bioreactor
A-SBBR	Algae-assisted sequencing batch biofilm reactor
ATS	Algal Turf Scrubber
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
C-MBB	Coupled microalgal–bacterial biofilm
C/N	Carbon/nitrogen
CAS-MBR	Common activated sludge-membrane bioreactor
EPS	Extracellular polymeric substances
HRAP	High-efficiency algae pond
MBR	Membrane bioreactor
MLE-MBR	Modified Ludzack–Ettinger-membrane bioreactor
MPBR	Membrane photobioreactor
MABR	Membrane aerated biofilm reactor
MABAR	Aerated bacterial–algae biofilm reactor
SBR	Sequencing batch reactor
SBBR	Sequencing batch biofilm–sludge reactors
TPH	Total petroleum hydrocarbon
TCOD	Total chemical oxygen demand
TDN	Total dissolved nitrogen
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TMP	Transmembrane pressure
VVS	Volatile suspended solids
Vvm	Air volume/culture volume/min

References

1. Bustamante, M.; Liao, W. A self-sustaining high-strength wastewater treatment system using solar-bio-hybrid power generation. *Bioresour. Technol.* **2017**, *234*, 415–423. [CrossRef] [PubMed]
2. Biswas, T.; Bhushan, S.; Prajapati, S.K.; Chaudhuri, S.R. An eco-friendly strategy for dairy wastewater remediation with high lipid microalgae-bacterial biomass production. *J. Environ. Manag.* **2021**, *286*, 112196. [CrossRef] [PubMed]
3. Ramanan, R.; Kim, B.H.; Cho, D.H.; Oh, H.M.; Kim, H.S. Algae-bacteria interactions: Evolution, ecology and emerging applications. *Biotechnol. Adv.* **2016**, *34*, 14–29. [CrossRef] [PubMed]
4. Su, Y.; Mennerich, A.; Urban, B. Municipal wastewater treatment and biomass accumulation with a wastewater-born and settleable algal-bacterial culture. *Water Res.* **2011**, *45*, 3351–3358. [CrossRef]
5. Mukherji, S.; Chavan, A. Treatment of aqueous effluents containing non-aqueous phase liquids in rotating biological contactor with algal bacterial biofilm. *Chem. Eng. J.* **2012**, *200*, 459–470. [CrossRef]
6. Razzak, S.A.; Hossain, M.M.; Lucky, R.A.; Bassi, A.S.; Lasa, H.d. Integrated CO_2 capture, wastewater treatment and biofuel production by microalgae culturing—A review. *Renew. Sustain. Energy Rev.* **2013**, *27*, 622–653. [CrossRef]
7. Xu, M.; Xue, Z.; Sun, S.; Zhao, C.; Liu, J.; Liu, J.; Zhao, Y. Co-culturing microalgae with endophytic bacteria increases nutrient removal efficiency for biogas purification. *Bioresour. Technol.* **2020**, *314*, 123766. [CrossRef] [PubMed]
8. Zhang, Y.L.; Su, H.Y.; Zhong, Y.N.; Zhang, C.M.; Shen, Z.; Sang, W.J.; Yan, G.; Zhou, X.F. The effect of bacterial contamination on the heterotrophic cultivation of *Chlorella pyrenoidosa* in wastewater from the production of soybean products. *Water Res.* **2012**, *46*, 5509–5516. [CrossRef]
9. Yang, J.X.; Shi, W.X.; Fang, F.; Guo, J.S.; Lu, L.H.; Xiao, Y.; Jiang, X. Exploring the feasibility of sewage treatment by algal-bacterial consortia. *Crit. Rev. Biotechnol.* **2020**, *40*, 169–179. [CrossRef]
10. Sun, L.; Tian, Y.; Zhang, J.; Li, L.P.; Zhang, J.; Li, J.Z. A novel membrane bioreactor inoculated with symbiotic sludge bacteria and algae: Performance and microbial community analysis. *Bioresour. Technol.* **2018**, *251*, 311–319. [CrossRef]
11. Sun, L.; Tian, Y.; Zhang, J.; Li, H.; Tang, C.C.; Li, J.Z. Wastewater treatment and membrane fouling with algal-activated sludge culture in a novel membrane bioreactor: Influence of inoculation ratios. *Chem. Eng. J.* **2018**, *343*, 455–459. [CrossRef]
12. Liang, Z.; Hu, Z. Start-Up Performance Evaluation of Submerged Membrane Bioreactors Using Conventional Activated Sludge Process and Modified Luzack-Ettinger Process. *J. Environ. Eng.* **2012**, *138*, 932–939. [CrossRef]
13. Radmehr, S.; Rissanen, T.; Kallioinen-Manttari, M.; Mänttäri, M. Reducing mechanical aeration in membrane bioreactors by inoculation of algal cells into activated sludge biomass. *J. Water Process Eng.* **2022**, *49*, 103047. [CrossRef]

14. Barillon, B.; Ruel, S.M.; Langlais, C.; Lazarova, V. Energy efficiency in membrane bioreactors. *Water Sci. Technol.* **2013**, *67*, 2685–2691. [CrossRef] [PubMed]
15. Nguyen, T.T.D.; Nguyen, T.T.; An Binh, Q.; Bui, X.T.; Ngo, H.H.; Vo, H.N.P.; Lin, K.Y.; Vo, T.; Guo, W.; Lin, C.; et al. Co-culture of microalgaeactivated sludge for wastewater treatment and biomass production: Exploring their role under different inoculation ratios. *Bioresour. Technol.* **2020**, *314*, 123754. [CrossRef] [PubMed]
16. Tang, C.C.; Zuo, W.; Tian, Y.; Sun, N.; Wang, Z.W.; Zhang, J. Effect of aeration rate on performance and stability of algal-bacterial symbiosis system to treat domestic wastewater in sequencing batch reactors. *Bioresour. Technol.* **2016**, *222*, 156–164. [CrossRef] [PubMed]
17. Ye, J.; Liang, J.; Wang, L.; Markou, G. The mechanism of enhanced wastewater nitrogen removal by photo-sequencing batch reactors based on comprehensive analysis of system dynamics within a cycle. *Bioresour. Technol.* **2018**, *260*, 256–263. [CrossRef] [PubMed]
18. Wang, M.; Yang, H.; Ergas, S.J.; van der Steen, P. A novel shortcut nitrogen removal process using an algal-bacterial consortium in a photo-sequencing batch reactor (PSBR). *Water Res.* **2015**, *87*, 38–48. [CrossRef] [PubMed]
19. Yasmeen, N.; Sanghyun, J.; TorOve, L. Nutrient utilization and oxygen production by *Chlorella vulgaris* in a hybrid membrane bioreactor and algal membrane photobioreactor system. *Bioresour. Technol.* **2017**, *237*, 64–71.
20. Bucci, P.; Garcia-Depraect, O.; Montero, E.J.M.; Zaritzky, N.E.; Caravelli, A.; Muñoz, R. Phenol and nitrogen removal in microalgal-bacterial granular sequential batch reactors. *J. Chem. Technol. Biotechnol.* **2023**, *98*, 2274–2282. [CrossRef]
21. Liang, J.; Wang, L.; Jia, Q.; Wang, Z.; Ye, J. Study on Treatment of Simulated Domestic Sewage by SBR Based on Algae-Bacteria Symbiotic System. *Technol. Water Treat.* **2019**, *45*, 116–120,130.
22. Song, X.; Kong, F.; Liu, B.F.; Song, Q.Q.; Ren, N.Q.; Ren, H.Y. Combined transcriptomic and metabolomic analyses of temperature response of microalgae using waste activated sludge extracts for promising biodiesel production. *Water Res.* **2024**, *251*, 121120. [CrossRef]
23. Singh, R.N.; Sharma, S. Development of suitable photobioreactor for algae production—A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2347–2353. [CrossRef]
24. González-Fernández, C.; Molinuevo-Salces, B.; García-González, M.C. Open and enclosed photobioreactors comparison in terms of organic matter utilization, biomass chemical profile and photosynthetic efficiency. *Ecol. Eng.* **2010**, *36*, 1497–1501. [CrossRef]
25. Posadas, E.; García-Encina, P.A.; Soltau, A.; Domínguez, A.; Díaz, I.; Muñoz, R. Carbon and nutrient removal from centrates and domestic wastewater using algal-bacterial biofilm bioreactors. *Bioresour. Technol.* **2013**, *139*, 50–58. [CrossRef] [PubMed]
26. Molinuevo-Salces, B.; Garcia-Gonzalez, M.C.; Gonzalez-Fernandez, C. Performance comparison of two photobioreactors configurations (open and closed to the atmosphere) treating anaerobically degraded swine slurry. *Bioresour. Technol.* **2010**, *101*, 5144–5149. [CrossRef] [PubMed]
27. De Godos, I.; González, C.; Bécares, E.; García-Encina, P.A.; Muñoz, R. Simultaneous nutrients and carbon removal during pretreated swine slurry degradation in a tubular biofilm photobioreactor. *Appl. Microbiol. Biotechnol.* **2009**, *82*, 187–194. [CrossRef]
28. Gonzalez, C.; Marciniak, J.; Villaverde, S.; León, C.; García, P.A.; Muñoz, R. Efficient nutrient removal from swine manure in a tubular biofilm photo-bioreactor using algae-bacteria consortia. *Water Sci. Technol.* **2008**, *58*, 95–102. [CrossRef]
29. Chang, J.S.; Show, P.L.; Ling, T.C.; Chen, C.Y.; Ho, S.H.; Tan, C.H.; Nagarajan, D.; Phong, W.N. 11—Photobioreactors. In *Current Developments in Biotechnology and Bioengineering*; Larroche, C., Sanromán, M.Á., Du, G., Pandey, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 313–352.
30. Han, S.F.; Jin, W.B.; Tu, R.J.; Wu, W.M. Biofuel production from microalgae as feedstock: Current status and potential. *Crit. Rev. Biotechnol.* **2015**, *35*, 255–268. [CrossRef]
31. Christenson, L.B.; Sims, R.C. Rotating algal biofilm reactor and spool harvester for wastewater treatment with biofuels by-products. *Biotechnol. Bioeng.* **2012**, *109*, 1674–1684. [CrossRef]
32. Hodoki, Y. Bacteria biofilm encourages algal immigration onto substrata in lotic systems. *Hydrobiologia* **2005**, *539*, 27–34. [CrossRef]
33. Chavan, A.; Mukherji, S. Effect of co-contaminant phenol on performance of a laboratory-scale RBC with algal-bacterial biofilm treating petroleum hydrocarbon-rich wastewater. *J. Chem. Technol. Biotechnol.* **2010**, *85*, 851–859. [CrossRef]
34. Zhang, H.; Zhang, K.; Gao, M.; An, Z.; Tang, C.; Yan, X. Degradation efficiency of the azo dye acid orange 2 and microbial community characteristics in a rotating algal biofilm reactor. *J. Water Process Eng.* **2022**, *50*, 103233. [CrossRef]
35. Zhang, H.; Gong, W.J.; Bai, L.M.; Zeng, W.C.; Chen, R.; Li, G.B.; Liang, H. Membrane aeration enhances the performance and stability of the bacterial-algae biofilm reactor. *J. Civ. Environ. Eng.* **2021**, *43*, 145–154.
36. Zhang, H.; Gong, W.J.; Zeng, W.C.; Chen, R.; Lin, D.C.; Li, G.B.; Liang, H. Bacterial-algae biofilm enhance MABR adapting a wider COD/N ratios wastewater: Performance and mechanism. *Sci. Total Environ.* **2021**, *781*, 146663. [CrossRef]
37. Li, J.B.; Ou, R.; Liao, H.Y.; Ma, J.X.; Sun, L.; Jin, Q.; He, D.; Wang, Q.L. Natural lighting enhancing the algae proliferation and nitrogen removal in membrane-aerated bacterial-algal biofilm reactor. *Sci. Total Environ.* **2022**, *851*, 158063. [CrossRef] [PubMed]
38. Vanessa, A.A.; Susanne, L. Membrane Aerated Biofilm Reactors—How longitudinal gradients influence nitrogen removal—A conceptual study. *Water Res.* **2019**, *166*, 115060.
39. Tang, C.-C.; Tian, Y.; Liang, H.; Zuo, W.; Wang, Z.W.; Zhang, J.; He, Z. Enhanced nitrogen and phosphorus removal from domestic wastewater via algae-assisted sequencing batch biofilm reactor. *Bioresour. Technol.* **2018**, *250*, 185–190. [CrossRef]
40. Tang, C.C.; Tian, Y.; He, Z.; Zuo, W.; Zhang, J. Performance and mechanism of a novel algal-bacterial symbiosis system based on sequencing batch suspended biofilm reactor treating domestic wastewater. *Bioresour. Technol.* **2018**, *265*, 422–431. [CrossRef]

41. Akao, P.-K.; Singh, B.; Kaur, P.; Sor, A.; Avni, A.; Dhir, A.; Verma, S.; Kapoor, S.; Phutela, U.G.; Satpute, S.; et al. Coupled microalgal–bacterial biofilm for enhanced wastewater treatment without energy investment. *J. Water Process Eng.* **2021**, *41*, 102029. [CrossRef]
42. De Godos, I.; Blanco, S.; García-Encina, P.A.; Bécares, E.; Muñoz, R. Long-term operation of high rate algal ponds for the bioremediation of piggery wastewaters at high loading rates. *Bioresour. Technol.* **2009**, *100*, 4332–4339. [CrossRef] [PubMed]
43. Park, J.B.K.; Craggs, R.J. Wastewater treatment and algal production in high rate algal ponds with carbon dioxide addition. *Water Sci. Technol.* **2010**, *61*, 633–639. [CrossRef] [PubMed]
44. Selvaratnam, T.; Pegallapati, A.K.; Montelya, F.; Rodríguez, G.; Nirmalakhandan, N.; Lammers, P.J.; Voorhies, W.A. Feasibility of algal systems for sustainable wastewater treatment. *Renew. Energy* **2015**, *82*, 71–76. [CrossRef]
45. Fernández, F.G.A.; Sevilla, J.M.F.; Grima, E.M. Photobioreactors for the production of microalgae. *Rev. Environ. Sci. Bio-Technol.* **2013**, *12*, 131–151. [CrossRef]
46. Naik, S.N.; Goud, V.V.; Rout, P.K.; Dalai, A.K. Production of first and second generation biofuels: A comprehensive review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 578–597. [CrossRef]
47. Adey, W.H.; Kangas, P.C.; Mulbry, W. Algal Turf Scrubbing: Cleaning Surface Waters with Solar Energy while Producing a Biofuel. *Bioscience* **2011**, *61*, 434–441. [CrossRef]
48. Gan, X.; Klose, H.; Reinecke, D. Optimizing nutrient removal and biomass production of the Algal Turf Scrubber (ATS) under variable cultivation conditions by using Response Surface Methodology. *Front. Bioeng. Biotechnol.* **2022**, *10*, 962719. [CrossRef]
49. Gultom, S.O.; Hu, B. Review of Microalgae Harvesting via Co-Pelletization with Filamentous Fungus. *Energies* **2013**, *6*, 5921–5939. [CrossRef]
50. Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25*, 294–306. [CrossRef]
51. Marella, T.K.; Datta, A.; Patil, M.; Dixit, S.; Tiwari, A. Biodiesel production through algal cultivation in urban wastewater using algal floway. *Bioresour. Technol.* **2019**, *280*, 222–228. [CrossRef]
52. Kebede-Westhead, E.; Pizarro, C.; Mulbry, W.W. Treatment of swine manure effluent using freshwater algae: Production, nutrient recovery, and elemental composition of algal biomass at four effluent loading rates. *J. Appl. Phycol.* **2006**, *18*, 41–46. [CrossRef]