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Review

Carbon Capture and Resource Utilization by Algal–Bacterial Consortium in Wastewater Treatment: A Mini-Review

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Abstract: This review critically evaluates the algal–bacterial consortium (ABC) as a promising technology for wastewater treatment, carbon capture and storage, while also assessing its challenges and opportunities. The ABC system, characterized by the coupling of algae and bacteria, not only removes pollutants and reclaims resources but also helps in reducing greenhouse gas emissions. This system harnesses algal photosynthesis and bacterial degradation of organic matters to establish a carbon cycle, enhancing biomass production and pollutant removal. Despite its promise, the ABC process is subject to several hurdles, including sensitivity to low temperatures, reliance on artificial illumination, and the potential for algal biomass contamination by toxic substances. To capitalize on its full potential, continued research and technological advancements are imperative. Future investigations should focus on optimizing the system's operational efficiency, developing precise process models, exploring avenues for resource recovery, and broadening the scope of its applications. By surmounting these challenges, the ABC system has the capacity to make a significant impact on sustainable wastewater management and carbon fixation.

Keywords: algal–bacterial consortium; wastewater treatment; carbon capture; light source; low temperature

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1. Introduction

The burning of fossil fuels has led to an annual increase in the concentration of CO_2 in the atmosphere, triggering a variety of environmental issues, including global warming, sea-level rise, and ocean acidification [1]. In response to the urgent necessity of reducing carbon emissions, the Paris Agreement was concluded at the 21st United Nations Climate Change Conference, aiming to limit the temperature increase to below 1.5 °C in this century [2]. Despite global efforts to reduce greenhouse gas (GHG) emissions, global carbon emissions surpassed 450 billion tons in 2021. The energy sector, which includes transportation, heating, and energy production, continues to be the primary source of these emissions, responsible for about 70% of the world's total CO_2 emissions [3]. In aquatic environments, organic pollutants can also be biologically transformed into other GHGs, such as nitrous oxide (N_2O) and methane (CH_4) [4]. Accordingly, energy consumption and endogenous carbon emission within the wastewater treatment process significantly contribute to the global inventory of GHG [5].

To slow down GHG emissions, in addition to mitigating the burning of fossil fuels at their source and adopting clean energy alternatives, utilizing photosynthetic organisms for carbon capture and utilization has emerged as a crucial technology in advancing GHG emission reduction [6]. Microalgae display rapid growth rates, high photosynthetic efficiency, and strong environmental adaptability. They can directly use light for CO_2 fixation while also assimilating nitrogen phosphorus from wastewater [7]. The resulting biomass is rich in proteins, carbohydrates, and lipids, which can be utilized for the production of valuable products [8,9]. Consequently, it is regarded as an ideal candidate for carbon capture and utilization technology.

Microalgae pose persistent challenges in terms of efficient separation due to their small size, low concentration, and tendency to disperse easily, which traditional physical and chemical methods struggle to overcome. Consequently, current research efforts are increasingly directed towards the integration of microalgae with bacteria to establish an algal–bacterial consortium (ABC), a strategy that shows promise for enhancing the separation and recovery of microalgae [10]. Extensive studies have been conducted on the deployment of bacterial and algal biomass for wastewater treatment [11–14], yet the exploration of the carbon capture, storage and utilization potential within ABC systems is a relatively understudied area.

Therefore, the present paper conducts a thorough review of GHG sources emanating from wastewater treatment processes, while also examining the role of the ABC process in the removal of pollutants and the reduction in carbon emissions. Furthermore, the article delves into the limitations and challenges inherent in this technology, providing a comprehensive analysis of the current state of research and the pathways for future development in the field.

2. Carbon Emissions in Wastewater Treatment Processes

The emission of CO_2, CH_4 and N_2O into the atmosphere exerts a significant influence on the environment. Of particular concern are CH_4 and N_2O, which have a greater global warming potential than CO_2 [15,16]. The operations within wastewater treatment plants (WWTPs)—including energy consumption, chemical applications, biological conversions, and sludge management—can lead to direct or indirect GHG emissions [17]. As depicted in Table 1, a substantial volume of GHGs is emitted by WWTPs across both developed and developing nations. To mitigate carbon emissions effectively, it is essential to understand the mechanisms by which carbon reduction can be achieved in WWTPs.

Table 1. Carbon emission for wastewater treatment in different countries.

Country	CH_4 Emission (MMT CO_{2eq}/yr)	N_2O Emission (MMT CO_{2eq}/yr)	Total Emissions (MMT CO_{2eq}/yr)	Ref.
China	-	-	53.0	[18]
U.S.	20.8	21.9	-	[19]
Japan	-	-	3.499	[20]
UK	-	-	5.0	[21]
Australia	-	-	2.97	[22]
Netherlands	-	-	1.95	[23]
Nepal	3.48	3.48	3.83	[24]
Europe	-	-	35.0	[25]
Mexico	11.12	-	12.4	[26]
Iran	3.36	0.49	4.83	[27]

Notes: CO_{2eq}, CO_2 equivalent; MMT, million metric tons.

2.1. CO_2 Emissions

The emission of CO_2 in WWTPs is primarily linked to the oxidation of organic matter and the energy requirements of the treatment process. It has been estimated that around 17% of the organic material is converted into activated sludge, while a larger proportion, approximately 63%, is converted to CO_2 [28]. Furthermore, the treatment of waste-activated sludge contributes to the production of CO_2 [29]. Moreover, energy consumption represents a significant source of carbon emissions in wastewater treatment processes. The carbon footprint associated with energy use, derived predominantly from fossil fuels, has been found to account for 50% to 60% of the total carbon emissions produced throughout the wastewater treatment cycle [30,31]. This highlights the critical need for energy-efficient technologies and the integration of renewable energy sources within WWTPs to reduce their environmental impact.

2.2. N_2O Emissions

The nitrogen removal process in wastewater treatment, a crucial step for environmental protection, predominantly relies on the biological processes of nitrification and denitrification. During these processes, two key pathways can lead to the generation of N_2O: the oxidation of hydroxylamine and the denitrification of nitrite. In the presence of oxygen, ammonium is initially transformed into hydroxylamine and subsequently into nitrite by ammonia-oxidizing bacteria [32]. However, if the level of dissolved oxygen is inadequate, the oxidation of hydroxylamine to nitrite may be incomplete, resulting in N_2O buildup [33]. The nitrite is then typically converted into nitrate by nitrite-oxidizing bacteria. In anoxic conditions, nitrate is sequentially oxidized to nitrite, NO, N_2O and finally N_2 by heterotrophic denitrifiers using organic carbon as an electron donor [34]. The denitrification process involves the stepwise reduction of nitrate to nitrite, NO, N_2O, and finally N_2. When there is a lack of organic carbon, the reduction of nitrate may also result in the incomplete conversion of N_2O to N_2, leading to N_2O accumulation. These findings underscore the importance of carefully managing oxygen and carbon levels in wastewater treatment to minimize N_2O emissions and optimize the overall efficiency of biological nitrogen removal.

2.3. CH_4 Emissions

The wastewater treatment industry is a substantial contributor to anthropogenic CH_4 emissions, accounting for 7–9% of the total quantity [29,35]. Methane is primarily produced in anaerobic conditions, where methanogenic bacteria enable the conversion of acetate, in the presence of H_2 or formate, into CH_4 and CO_2 through anaerobic fermentation [29]. The primary sources of methane emissions within WWTPs are associated with sludge treatment [36], although a smaller proportion is discharged through the facility's piping systems [37].

As methane constitutes a significant portion of the biogas produced [38], and serves as a renewable energy source, it is feasible to generate electricity and heat by recycling methane. This process can partially or completely offset the environmental impact of methane produced during anaerobic digestion [39].

3. CO_2 Capture and Utilization in the Wastewater Treatment Processes

CO_2 capture and utilization in wastewater treatment processes is an innovative approach that combines environmental protection and resource conservation. WWTPs are significant sources of CO_2 emissions, mainly due to the biological degradation of organic matter in wastewater. Implementing CO_2 capture and utilization technologies can not only reduce these emissions but also convert the captured CO_2 into valuable products, creating a circular economy.

3.1. The Methods of CO_2 Capture and Utilization

Biological carbon capture and utilization represent an environmentally attuned strategy for mitigating CO_2 emissions, leveraging the natural processes of photosynthetic organisms such as microalgae, higher plants, and photosynthetic bacteria. These organisms function as a carbon sink, sequestering approximately 55% of anthropogenic CO_2 emissions [40]. In contrast, artificial CO_2 capture technologies, including pre-combustion, post-combustion, and oxygen-rich combustion methods, offer a different approach to carbon management [41].

Artificial CO_2 capture systems, while capable of higher CO_2 absorption rates than biological processes, are not without their drawbacks. They incur a significant energy penalty due to the need for chemicals and electricity (Table 2). Furthermore, their efficiency in capturing CO_2 is notably inferior to that of biological methods. Consequently, in response to the challenges presented by global climate change and its associated concerns, certain countries are favoring natural solutions [42].

Table 2. Comparison between natural and artificial carbon capture methods.

Method	**Cost**	**Advantage**	**Disadvantage**	**Ref.**
Biological method	Low	Energy neutralization	Low capacity, many influenced factors	[40]
Artificial pre-combustion	High, 24–52 Euros/t CO_2	Compact equipment, high CO_2 concentration and energy saving	Secondary pollution	[43–46]
Artificial post-combustion		Simple operation, wide application and least investment	High energy consumption, low CO_2 concentration	
Artificial oxygen-rich combustion		Highest CO_2 concentration	High energy consumption	

Organisms capture CO_2 in the form of organic carbon, which can be readily processed and reused. Conversely, inorganic carbon captured through artificial means requires conversion into useful products [47]. Direct CO_2 utilization has diverse applications across multiple industries, including its role as a refrigerant [48,49], carbonator, preservative, packaging gas, and other functions [47,50], with particularly strong uptake in the food and beverage sector. Additionally, CO_2's use in enhanced oil recovery provides both a direct capture and utilization pathway [51].

3.2. CO_2 Capture and Utilization along with Wastewater Treatment

The objective of wastewater treatment is to remove carbon, nitrogen, phosphorus, and other contaminants from wastewater. Although biogenic CO_2 is not categorized as a GHG, its high abundance and the ease with which it can be recovered in centralized WWTPs make it a valuable target for carbon recovery. This recovery can be achieved without compromising the efficacy of pollutant removal. Furthermore, certain photosynthesis-based wastewater treatment processes offer significant benefits and should be actively promoted and implemented [15].

3.2.1. CO_2 Capture and Utilization by Higher Plants

Plants contribute significantly to the carbon cycle by assimilating approximately one-third of the carbon present in the atmosphere [52]. Through the process of photosynthesis, higher plants convert CO_2 into monosaccharides, which are stored within their tissues (Figure 1) [53]. This mechanism enables short-term carbon storage [54]. Following the death of these plants, microorganisms decompose their biomass, transforming the stored simple sugars into organic carbon in the soil. This organic carbon can then be sequestered in the soil for an extended period [55].

Aquatic plants, including emergent, floating, and submerged macrophytes, are key in wastewater treatment for pollutant removal and sediment control [56,57]. Carbon stored by these plants can be used for various purposes, including the production of biochar [58,59]. However, it is essential to manage these resources effectively by ensuring their prompt harvesting and reuse.

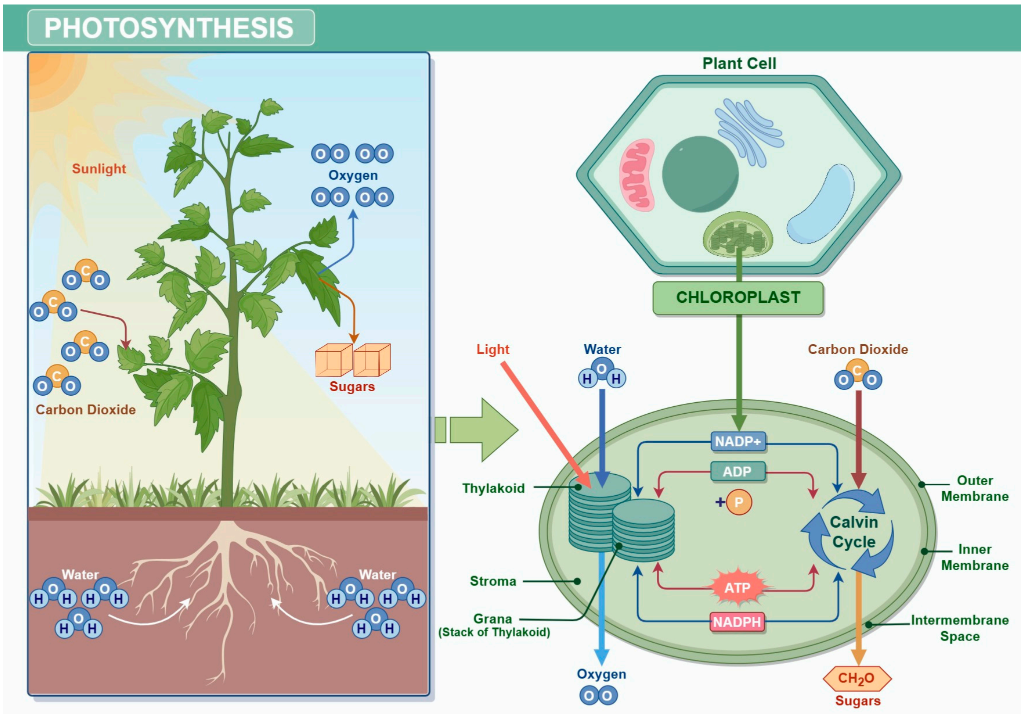

Figure 1. Mechanism of carbon fixation in higher plants (drawn by Figdraw 2.0 software).

3.2.2. CO_2 Absorption and Transformation by Microalgae

Microalgae utilize photosynthesis to absorb carbon dioxide and harness the nutrients within wastewater to facilitate the growth of their biomass (Figure 2). The process of assimilating nitrogen results in the storage of a significant amount of CO_2, ranging from 9.4 to 116 g per gram of nitrogen [15]. Remarkably, the annual carbon fixation potential of microalgae is on par with the carbon emissions produced by an estimated 65,000 power plants, each boasting a capacity of 500 megawatts [60].

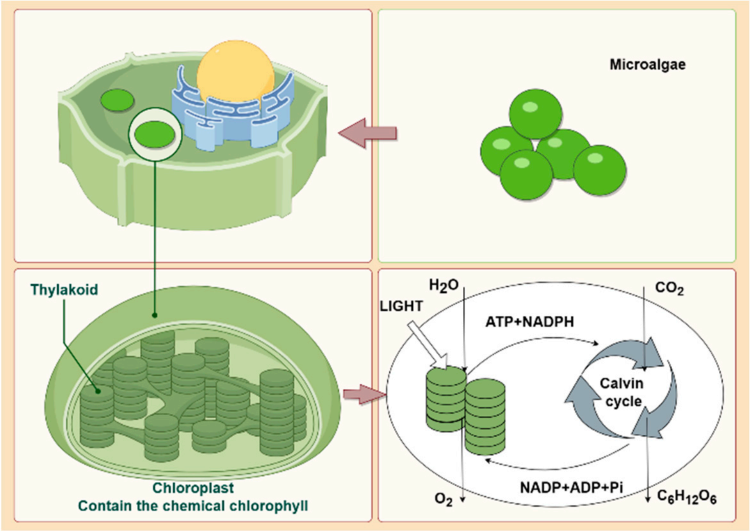

Figure 2. Carbon capture mechanism of microalgae (drawn by Figdraw 2.0 software).

The microalgae-based process, known for its low carbon emissions and high productivity, is used in various sectors, ranging from soil enhancement and animal feed to the production of food, medical supplies [61], and biofuel [62]. These microorganisms are not only valuable but also require a considerable economic outlay for cultivation [63]. A key contributor to the high production costs associated with algae is the substantial demand for water and nutrients [64]. However, wastewater, rich in nutrients, offers an ideal growth medium for algae, thus becoming a valuable resource for their cultivation. To date, algae have been effectively integrated into wastewater treatment, demonstrating exceptional efficiency in nutrient uptake and removal [65–67].

3.2.3. CO_2 Capture and Transformation by Bacteria

The extensive utilization of bacteria in wastewater treatment is attributable to their remarkable capacity for pollutant removal. Certain bacteria release CO_2 during the treatment process, such as denitrifying bacteria, which heterotrophically release CO_2 and N_2O [68]. Similarly, heterotrophic bacteria produce CO_2 through the hydrolysis and fermentation decomposition of organic matter. Additionally, some bacteria have the capability to absorb CO_2. Apart from cyanobacteria, red and green sulfur bacteria, and other bacteria with photosynthetic pigments, are capable of CO_2 absorption [69]. Furthermore, autotrophic bacteria, including nitrifiers (release N_2O), sulfur bacteria, anaerobic ammonia oxidation bacteria, and iron bacteria, can effectively fix CO_2 as a carbon source (Figure 3) [70].

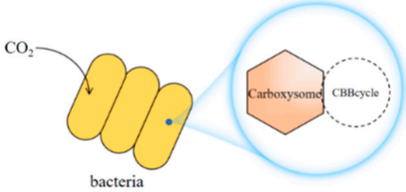

Figure 3. Carbon capture mechanism of bacteria (drawn by Figdraw 2.0 software).

Bacteria assimilate CO_2, nitrogen, and phosphorus, converting them into extracellular polymers (EPS) through a series of enzymatic reactions [52]. These EPS are rich in proteins, lipids, and carbohydrates, making them valuable resources for various applications, such as bioethanol production and animal feed supplementation [71], as well as the production of biofuels [70]. Due to their rapid reproduction rate and high protein conversion efficiency [71], bacteria have certain advantages in carbon fixation compared to higher plants and microalgae. Consequently, they are also considered significant raw materials for carbon utilization.

3.2.4. Carbon Capture in Constructed Wetlands

The constructed wetland leverages the synergistic interactions among plants, soil, and microorganisms to effectively eliminate pollutants from wastewater [72]. It is designed to facilitate nitrification and denitrification, with microorganisms and plant roots in the soil absorbing and degrading some pollutants, while others are removed through these nitrogen-cycle processes [73]. While constructed wetlands are beneficial for wastewater treatment, they do emit CH_4 and N_2O in the short term, which are potent greenhouse gases. However, these emissions can be mitigated by strategies such as modifying the composition of aquatic plants [74], using specific substrates and fillers, and other interventions [75,76]. Over the long term, constructed wetlands have the potential to serve as carbon sinks, with CO_2 storage estimates ranging from 2.7 to 24.0 t/(ha·yr), with a significant portion of CO_2 being absorbed by the plants [15].

Despite their carbon storage potential, the use of higher plants in constructed wetlands can be limited by spatial constraints and complex environmental conditions. In contrast, bacteria and microalgae offer more flexibility in such situations due to their smaller size and adaptability, making them attractive options for carbon capture and utilization where higher plants may not be as effective.

3.2.5. Carbon Storage by Algal-Bacterial Consortium

The ABC process leverages the beneficial relationship between bacteria and algae to enhance wastewater treatment and carbon storage (Figure 4). Within this system, algae employ photosynthesis to absorb carbon, releasing oxygen that aids aerobic bacteria. These bacteria decompose organic material, producing CO_2 that algae then reuse for photosynthesis. This symbiotic cycle not only boosts overall biomass, useful for various applications but also intensifies the bacteria–algae partnership's ability to eliminate pollutants and sequester CO_2 [77]. Moreover, bacteria can stimulate algae to produce EPS, which aids in biomass aggregation, facilitating settlement and removal from wastewater, thereby enhancing treatment efficiency [78].

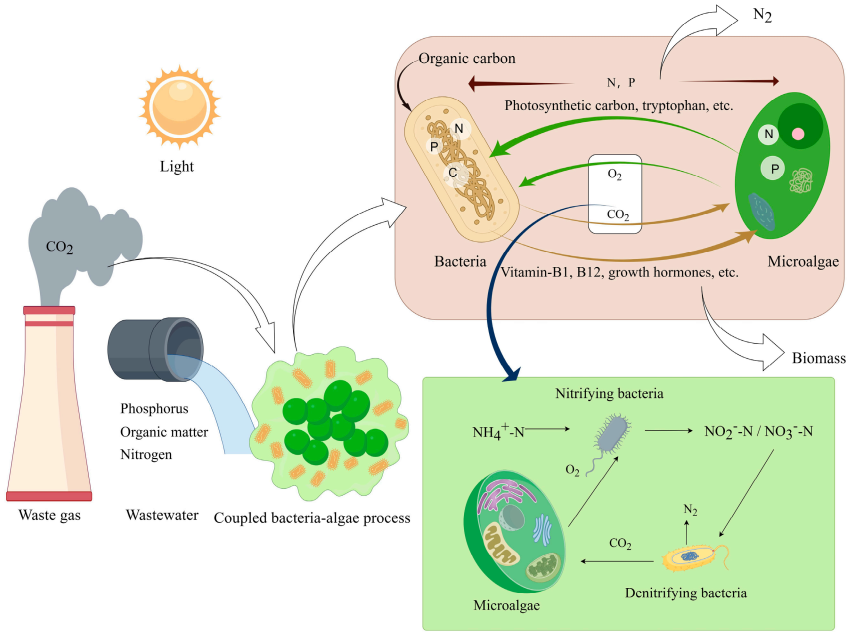

Figure 4. Combined algal–bacterial system for nutrient removal and carbon fixation (drawn by Figdraw 2.0 software).

The light-dependent reactions of algal photosynthesis occur on the thylakoid membrane within their chloroplasts. Here, algae harness light energy to produce oxygen and convert it into chemical energy in the form of nicotinamide adenine dinucleotide phosphate hydrogen (NADPH) and adenosine triphosphate (ATP) [79]. These energy carriers are vital for the Calvin Cycle, which occurs in the chloroplast stroma and is key to CO_2 fixation (Figure 2). Algae can absorb CO_2 directly from their environment or utilize other inorganic carbon sources after conversion to CO_2 by carbonic anhydrase [80]. Once inside the algae, CO_2 is fixed by the enzyme Rubisco, yielding two molecules of 3-phosphoglycerate (3-PGA) [81]. As shown in Figure 5, the conversion of 3-PGA to 3-phosphoglyceraldehyde (3-PGAL) is driven by NADPH and ATP. 3-PGAL is then transformed into glyceraldehyde-3-phosphate (G3P) and dihydroxyacetone phosphate (DHAP). Some of these compounds contribute to carbohydrate synthesis or enter metabolic pathways like glycolysis and the tricarboxylic acid cycle (TCA) to form proteins, lipids, and other biomolecules. The rest of the glyceraldehyde phosphate and dihydroxyacetone phosphate undergo complex biochemical reactions to regenerate ribulose diphosphate, continuing the cycle of CO_2 fixation [79]. Understanding these mechanisms is crucial for optimizing algae cultivation for wastewater treatment and carbon storage.

Cyanobacteria and specific chemoautotrophic bacteria share the capacity of microalgae to sequester carbon. Despite lacking chloroplasts, these bacteria harbor carboxysomes that contain Rubisco (Figure 3). Rubisco enzymes facilitate the carboxylation of CO_2, reacting with ribulose diphosphate to produce 3-PGA [81,82].

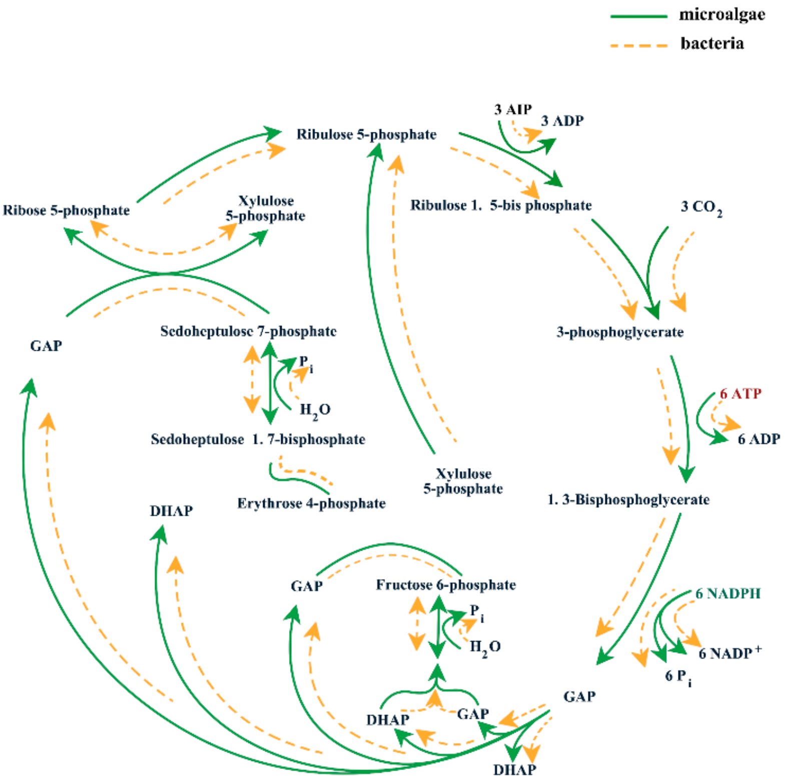

Figure 5. Calvin cycle in microalgae and bacteria (drawn by Figdraw 2.0 software).

4. CO_2 Capture in ABC System

Microalgae, cyanobacteria and chemoautotrophic bacteria serve as the primary carbon-capture organisms within ABC systems. Among these, microalgae are particularly adept at CO_2 capture, storage and utilization (Table 3). The CO_2 uptake by nitrifiers can be influenced by competition with algae, which is in turn affected by the rate of oxygen production during algal photosynthesis. This competition may potentially inhibit bacterial CO_2 fixation. Despite this, the interaction between algae and autotrophic bacteria tends to be one of balance and synergy, contributing to the overall efficiency of the ABC system.

Bacteria within the ABC system can provide essential carbon sources, vitamins, growth hormones, and amino acids, which are crucial for mitigating the toxicity that can arise from high nutrient levels [97–99]. By supplying these nutrients, bacteria effectively enhance the efficiency of photosynthesis and CO_2 fixation [100]. This, in turn, promotes nutrient uptake by the bacteria and nutrient accumulation by algae.

As a wastewater treatment process, the objective of fostering carbon emission reduction within the ABS system must be pursued without compromising the efficacy of pollutant elimination. The carbon sequestration process inherent to this symbiotic relationship between bacteria and algae is subject to a multitude of environmental constraints, including light intensity, pH levels, and temperature. The provision of appropriate light conditions, a favorable temperature spectrum, and an optimal pH level are essential for sustaining the biological vitality of the bacterial–algal symbiotic system [101]. Within the bounds of these optimal environmental settings, a measured enhancement of these variables can markedly stimulate the growth, metabolic vigor, and carbon sequestration capabilities of the symbiotic assembly [102–104].

To guarantee the enduring stability and efficacy of the bacterial–algal symbiotic system in wastewater treatment, and to robustly advance carbon emission reduction, it is critical to manage the variables influencing the growth of the bacterial–algal symbiotic sludge within an appropriate spectrum. This management is essential for preserving the integrity of the sludge biome and for striking a balance between the photosynthetic conversion efficiency of algae cells and their capacity to sequester carbon dioxide. By achieving this equilibrium, the system’s photosynthetic activity is optimized, which in turn supports the pursuit of carbon neutrality within the bacterial–algal symbiotic ecosystem. This approach not only sustains the system’s operational stability but also underpins its environmental benefits in the context of climate change mitigation.

Table 3. Carbon capture capacity of algae and bacteria.

Species		**Reactor**	**CO$_2$ %**	**Yield g SS/L·d**	**C-Fixation mg CO$_2$/L·d**	**Ref.**
C. Vulgaris	A	BCPBR	2.5	1860	3510	[83]
Chlorella sp.	A	BCPBR	Air	212–216	191–201	[84]
C. vulgaris	A	PBR	8–9	1190–1350	-	[85]
C. vulgaris	A	BCPBR	12	502	919	[86]
N. oculata	A	Raceway	10–14	17,100	31,900	[87]
C. sorokiniana TH01	A	FPPBR	5	284–469	-	[88]
H. pluvialis	A	PBR	5	250	613	[89]
S. platensis	A	PBR	-	68.4–78.4	107.3–122.9	[90]
T. obliquus PF3	A	CPBR	10	310	550–552	[91]
L. sp. *QUCCCM 56*	B	PBR	-	81.8–101	130.7–165.3	[92]
S. sp. *NIT18*	B	PBR	10	22.5	69.4%	[93]
	B	PBR	15	370	71.0%	
C. vulgaris & nitrifier	AB	PBR	Air	531	-	[94]
L. tenuis & C. ellipsoidea	AB	PBR	Air	192.3–201.1	2540–2720	[95]
C. ellipsoidea (A)/ *L. tenuis* (B)	1:1	BCPBR	2	470–610	-	[96]
	1:4	BCPBR	2	570–590	-	
	1:8	BCPBR	2	680–720	-	
	1:16	BCPBR	2	540–560	-	

Notes: A, algae; B, bacteria; BCPBR, bubble column photobioreactors; CPBR, column photobioreactors; PBR, photobioreactors; FPPBR, flat-panel PBR.

5. Environmental and Energy Benefits of ABC Systems in Wastewater Treatment

The ABC process not only effectively removes contaminants from wastewater, but also eliminates the need for additional aeration, conserves energy, and reduces greenhouse gas emissions.

5.1. Removal of Nitrogen, Phosphorus, and Other Pollutants

Nitrogen removal primarily depends on the activities of nitrifying and denitrifying bacteria [105–107]. In recent years, notable advancements have been made in the application of ABC processes for treating biodegradable wastewater from pig farms, households, and aquaculture [108–110]. Table 4 clearly demonstrates that the simultaneous removal of nitrogen and phosphorus can be successfully accomplished during the treatment of wastewater with varying strengths.

5.2. Reducing the Energy Consumption of Aeration

Traditional wastewater treatment methods often rely heavily on energy-intensive processes and the use of chemical agents to achieve effective treatment [123,124]. Aerobic bacteria decompose pollutants under aerobic conditions, making mechanical aeration a critical component of conventional treatment. However, excessive aeration results in high energy consumption. In activated sludge systems used for secondary treatment in most WWTPs, the energy required for aeration typically ranges from 0.25 to 1.89 kWh/m^3 [125–127], which constitutes a significant portion of the total energy usage [31]. Power-related losses are a major source of fossil CO$_2$ emissions during wastewater treatment [17], emphasizing the need to reduce aeration to lower carbon emissions. Algae can produce dissolved oxygen levels that may exceed 100% to 400% of air saturation during photosynthesis, and sometimes even more [128]. Incorporating algae into wastewater treatment provides a sustainable and economical solution for oxygenation, in line with environmental stewardship and resource efficiency goals.

Table 4. Nutrient removal efficiency of algal–bacterial consortium.

Reactor	Wastewater	TN		TP		Ref.
		Inf. (mg/L)	Removal Rate (%)	Inf. (mg/L)	Removal Rate (%)	
UABR-PSBR	Swine	580–951	95.0	10–17	91.0	[111]
MPSR	Rural	56.9	89.9	2.1–4.6	98.2	[112]
PSBR	Aquaculture	6–14	78.4	0.4–0.7	68.2	[113]
PBR	Municipal	70–80	88.8	6–6.5	84.9	[114]
PSBR	Synthetic	30	80.7	5	73.9	[115]
MA/AS	Synthetic	20	87.0	2	99.6	[116]
PBR	Synthetic	31.23	88.9	5.0	80.3	[77]
HRAP	Digested	38.1	73.8	5.0	89.8	[117]
PBR	Brewery	96.2	94.2	8.6	75.2	[118]
PSBR	Secondary	20–40	73.7	3–5	94.4	[119]
PSBR	Synthetic	50–200	71.3	10	-	[120]
PBR	Whey processing	52	88.0	17	69	[121]
PBR	Vinegar processing	20.5	78.7	7.4	74.8	[122]

Notes: UABR, up-flow anaerobic sludge bed reactor; MPSR, micro-pressure swirl reactor; PSBR, photo-sequencing batch reactor; HRAP, high-rate algal pond.

5.3. Enhancing Carbon Capture to Mitigate GHG Emissions

The biological treatment of wastewater inevitably produces GHGs as a byproduct of microbial metabolism, which can significantly diminish the net environmental benefits [129]. Completely preventing GHG production during this process is extremely challenging, regardless of the technology used (Table 5) [130]. Conventional WWTPs are known to emit 2 to 15 times more GHGs compared to nature-based systems [131]. This disparity indicates that adopting an ABC system for wastewater treatment could result in a significant decrease in GHG emissions [116,132]. The crucial factor in this reduction is the algae's ability to utilize the CO_2 produced by heterotrophic bacteria [133]. Integrating algae into wastewater treatment not only improves water purification but also reduces the carbon footprint associated with traditional treatment methods, promoting a more sustainable and eco-friendly approach.

Table 5. GHG production of different wastewater treatment processes.

Technology	Species	Aeration	GHG Emission	Ref.
OAC	Bacteria	yes	57.7–60.8% CH_4 329–423 mgN_2O/L 14.5–31.5% CO_2	[134]
AAO	Bacteria	yes	CH_4, N_2O, CO_2	[17]
MBR	Bacteria	yes	CH_4, N_2O, CO_2	[135]
SBR	Bacteria	yes	CH_4, N_2O, CO_2	[26]
CWs	Plants and bacteria	yes	582 mg $CO_2/m^2{\cdot}h$ 22 mg $CH_4/m^2{\cdot}h$ 37 mg $N_2O/m^2{\cdot}h$	[74]
Raceway	Algae	no	CO_2	[136]
PBR	Algae and bacteria	yes	CO_2	[137]
MA/AS	Algae and bacteria	no	2% CO_2	[116]
HARP	Algae and bacteria	no	0.7 kg CO_2/m^3	[131]

Notes: OAC, open-type anaerobic system; AAO, anaerobic-anoxic-oxic; MBR, membrane bio-reactor; CWs, constructed wetlands; MA/AS, microalgae and activated sludge.

6. Valuable Biomass and Energy Generation from ABC Sludge

6.1. Separation of Lipids, Carbohydrates, and Proteins

ABC systems effectively convert inorganic nutrients into biomolecules, including proteins, carbohydrates, lipids, and more (Table 6) [136,138]. The generated biomass can be processed to produce valuable products [139]. Microalgae's lipid content, which can reach 50% to 70% of their mass as triglycerides, is particularly significant. These lipids, predominantly in the form of triglycerides (TAGs), can be extracted using solvent extraction and other techniques. Subsequently, they can be subjected to high temperature and pressure conditions in the presence of alcohols, such as methanol. This reaction converts microalgal fats and the alcohol (e.g., methanol) into fatty acid methyl esters. The resulting fatty acid methyl esters are the primary components of biodiesel. This high lipid content makes microalgae a promising feedstock for biodiesel production, boosting biofuel generation potential [140,141]. Additionally, following the process of mechanical cell disruption, centrifugal separation, filtration, and extraction, microalgal proteins are used in the food industry for producing biscuits, snacks, and as animal feed, expanding their application across various sectors [142,143].

Table 6 illustrates that microalgae have a notably higher protein content than higher plants, generally ranging from 30% to 50%. Cyanobacteria are exceptional with a protein content of 55% to 60% [144,145]. In microalgae, carbohydrates are primarily starch, cellulose, and polysaccharides, less abundant than proteins but essential for biohydrogen and bioethanol production through fermentation and distillation processes [146]. Microalgal pigments like carotenoids and phycobilin find use as food colorants and in pharmaceuticals, such as astaxanthin for human health [147,148]. Symbiotic systems combining bacteria and algae demonstrate increased biomass production compared to single-culture systems, suggesting an improved resource utilization efficiency [149].

Table 6. Lipids, carbohydrates, and proteins produced by microalgae and bacteria.

Species	Yield Rate mg/L·d	Lipid %	Protein %	Carbohydrate %	Ref.
Chlorella	126.9	10.6	17.3	25.1	[95]
Leptolyngbya	52.8	10.0	15.2	22.0	
Leptolyngbya & *Chlorella*	196.7	18.1	20.4	30.7	
Chlorella & *Ettlia*	500	11.0	40.0	19.5	[96]
Ettlia	260	11.8	51.1	13.3	
Chlorella	440	11.8	34.0	20.3	
S. sp. NIT18	24.9	6.4	19.7	33.7	[93]
S. obliquus FACHB-416, *C. vulgaris* FACHB-32 & *O. tenuis* FACHB-1052	6.8–14.2 $g/m^2 \cdot d$	12.5–19.8	35.3–42.6	28.7–33.1	[136]
C. sp. *46-4*	26	21.1	-	-	[150]
BGS or ABGS	145.4–173.3	5.5–8.1	34.4–39.3	-	[151]

6.2. Anaerobic Digestion for Energy Generation

The ABC sludge can be utilized in fermentation to produce methane or hydrogen as renewable energy sources [152]. This renewable energy, with its versatility, can be harnessed for power generation, transportation, and a multitude of other sectors. By doing so, it significantly diminishes our reliance on fossil fuels, paving the way for a more sustainable and environmentally friendly energy landscape. Although the typical carbon-to-nitrogen (C/N) ratios for microalgae and bacteria (6 to 8) are lower than the optimal C/N ratio (20 to 25) for efficient biogas production [153–157], ABC sludge has a methane production rate of about 20% higher than that of activated sludge [158]. To improve the biodegradability of ABC sludge, pretreatment methods such as alkaline treatment, sonication, thermal processing, and microwave application have been implemented. Additionally, co-digesting the pretreated sludge with high-carbon substrates can further increase methane yield [159]. Biogas is a promising clean energy source that can generate substantial heat and electricity, aiding in the reduction in greenhouse gas emissions [160]. The concentrated CO_2 from biogas can also be used as a raw material for industrial products [161].

6.3. Anaerobic Digestion for Nutrients Recycling

The sludge generated by the ABC system is rich in nitrogen and phosphorus, making the digested liquid and solids ideal for use as fertilizers. This organic biofertilizer, derived from algal residue via high-temperature pyrolysis, is commonly known as biochar. It boasts a range of functionalities, serving as a soil quality enhancer [162], and a carbon-based catalyst [163]. Its multifaceted application makes it a valuable asset in environmental and agricultural practices. This closed-loop approach supports waste management and resource utilization. Additionally, phosphorus, a non-renewable resource at risk of depletion [164], highlights the importance of the wastewater treatment industry as an intermediate link in the nitrogen and phosphorus cycle, with significant potential for nutrient recycling.

7. Overcoming Environmental and Technological Challenges of the ABC Process

The large-scale implementation of the ABC process and the effective management of ABC sludge are still in the nascent stages of development and confront a range of challenges that demand focused attention and resolution.

7.1. Addressing Low-Temperature Suppression

There is an urgent requirement to enhance the performance of ABC processes. It is crucial to investigate the synergistic interactions between algae and bacteria, as well as understand how various factors such as nutrient levels, light availability, pH, and temperature impact their activity and pollutant removal efficiency [165]. Especially, the low-temperature resilience of algae and bacteria significantly affects their growth and metabolic activities.

Future research should focus on selecting cold-tolerant species or developing techniques to enhance the cold adaptability of the algae–bacteria coupling process. Additionally, optimizing bioreactor design with thermal insulation can expand the ABC system's applicability. However, it is crucial to balance the energy input for insulation with the system's resource recovery potential. The energy expended on temperature control should be offset by energy-rich products, such as biofuels and bioplastics, the recovered biogas energy, and the heat generated by solar greenhouses. Further research is needed to investigate methods for efficiently harvesting algae and extracting valuable compounds such as lipids for biodiesel production, proteins for animal feed, and carbohydrates for bio-based materials. This can help in making the wastewater treatment process more economically viable and sustainable. This ensures that the overall energy efficiency and sustainability of the system are maintained.

7.2. Addressing the Discrepancy between Light Source and WWTP Footprint

The ABC process, known for its energy-saving potential by reducing aeration needs, heavily depends on light for microalgae growth. While artificial light sources are commonly used in laboratories, large-scale applications in WWTPs should maximize sunlight utilization. Structural designs optimizing natural light capture are essential for practical ABC implementation in WWTPs, aligning with energy reduction and sustainability goals. However, ABC-based WWTPs require extensive space for light exposure. Future research should focus on compactness through multi-layered configurations and innovative natural light storage techniques to optimize space utilization and reduce the footprint of ABC-based WWTPs.

7.3. The Puzzle of Harmful Substance Accumulation

Given algae's capacity to adsorb heavy metals and persistent organic pollutants during wastewater treatment, the inability to eliminate these substances can lead to the buildup of toxins. Consequently, individuals in management positions should prioritize the effective management and regulation of wastewater sources to reduce the introduction of these harmful substances. Furthermore, the development of more sophisticated post-treatment technologies is essential to guarantee the safety and environmental soundness of the final product, achieving a thorough removal or reduction of biomass toxins, heavy metals, and recalcitrant compounds.

7.4. The Importance of Accurate and Reliable Process Models

Effective control and optimization of ABC systems require the development of mathematical models that capture the complex interactions between algae, bacteria, and their environment. These models can aid in predicting system behavior, optimizing operational parameters, and identifying potential bottlenecks. Additionally, the development of advanced control strategies, such as real-time monitoring and adaptive control algorithms, can further enhance the stability and efficiency of the treatment process.

8. Conclusions

The ABC process represents a novel approach to wastewater treatment, offering the dual benefits of removing carbon, nitrogen, and phosphorus contaminants while converting biomass into valuable products such as biofuels and animal feed, thereby minimizing waste. This process harnesses sunlight and utilizes fossil CO_2 to cultivate algae, presenting an energy-saving and carbon-neutral solution that reduces operational expenses and advances sustainability. Despite its promise, the ABC process requires optimization, the creation of scalable systems, and a thorough evaluation of the economic feasibility of its byproducts. With continued research and technological advancement, the algal–bacterial consortium holds significant potential for widespread adoption, poised to make substantial contributions to water conservation, pollution reduction, and the pursuit of a more sustainable global future.

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