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Sustainability and carbon neutrality trends for microalgae-based wastewater treatment: A review

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ABSTRACT

As the global economy develops and the population increases, greenhouse gas emissions and wastewater discharge have become inevitable global problems. Conventional wastewater treatment processes produce direct or indirect greenhouse gas, which can intensify global warming. Microalgae-based wastewater treatment technology can not only purify wastewater and use the nutrients in wastewater to produce microalgae biomass, but it can also absorb CO_2 in the atmosphere or flue gas through photosynthesis, which demonstrates great potential as a sustainable and economical wastewater treatment technology. This review highlights the multifaceted roles of microalgae in different types of wastewater treatment processes in terms of the extent of their bioremediation function and microalgae biomass production. In addition, various newly developed microalgae cultivation systems, especially biofilm cultivation systems, were further characterized systematically. The performance of different microalgae cultivation systems was studied and summarized. Current research on the technical approaches for the modification of the CO_2 capture by microalgae and the maximization of CO_2 transfer and conversion efficiency were also reviewed. This review serves as a useful and informative reference for the application of wastewater treatment and CO_2 capture by microalgae, aiming to provide a reference for the realization of carbon neutrality in wastewater treatment systems.

1. Introduction

Human activities are estimated to have caused global temperatures which increased by approximately 0.8°C–1.2 °C above pre-industrial levels (IPCC, 2018). To strengthen the global response to the threat of climate change, the Paris Agreement on Climate Change required all nations to substantially reduce global greenhouse gas (GHG) emissions to limit the global temperature increase to a value below 2 °C, while simultaneously pursuing efforts to limit the increase to 1.5 °C in this century relative to pre-industrial levels (IEA, 2020; IPCC, 2018). The United Nations Environment Programme (UNEP) recently analyzed the major emission gap to achieve this goal, but it found the expected 2020 decline in emissions only translates to a 0.01 °C reduction of global warming by 2050. Therefore, global warming will rise by 3.2 °C by the end of this century even with full implementation of unconditional nationally-determined contributions under the Paris Agreement (Anne et al., 2020). CO_2 emissions from industry in pathways limiting global warming to 1.5 °C are projected to be about 65–90% (interquartile range) lower in 2050 relative to 2010 (IPCC, 2018). Most models indicated there was only a 50% chance to reach 1.5 °C without significant carbon negative emissions (Minx et al., 2017; Rogelj et al., 2015). Therefore, it is necessary to develop CO_2 removal and negative emission technologies (IPCC, 2018; Lu et al., 2018; Rau et al., 2013).

Although many energy-intensive sectors such as energy, industry, transportation, and building systems have conducted extensive research on emissions reduction and carbon capture, research in wastewater treatment has started relatively late. It is estimated that 380 billion m^3 of wastewater are produced globally each year, and production is expected to increase up to 24% over current levels by 2030 and by 51% in the year 2050 (Qadir et al., 2020). Wastewater is generated throughout all facets of human activity. The energy consumption of wastewater treatment plants (WWTPs) accounts for 3% of global electricity, and this proportion will continue to increase as the wastewater treatment rate increases (Li et al., 2015; McCarty et al., 2011). In addition, WWTPs will directly generate huge amounts of GHG and sludge during wastewater treatment (Fig. 1). It is estimated that the GHG emissions by wastewater treatment account for about 1.3% of global total GHG emissions (Hannah and Max, 2020). Even with an assumed 70% treatment rate and 70% utilization

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potential of municipal wastewater in China, the recovery rate of C, N, and P are only 35.8%, 35.8%, and 35.7% (2.12×10^6, 2.05×10^5, and 2.92×10^4 tons/year), respectively (Li et al., 2019; Sun et al., 2016a). Conventional wastewater treatment technologies have drawbacks including a high energy consumption, GHG emissions, excess sludge discharge, and resource wasting, which are also evident obstacles to match the concept of carbon neutrality in WWTPs (Goswami et al., 2021).

Research on the technology of negative emissions in WWTPs to achieve carbon neutrality has gradually become a hot spot of concern. Great progress has been made to improve carbon capture and recover renewable energy from WWTPs using technologies such as microbial electrolytic carbon capture, microbial electrosynthesis, microalgae cultivation, constructed wetlands, and biochar production (Daneshvar et al., 2022; Lu et al., 2018). Microalgae can be used to purify different types of wastewaters through bioaccumulation, biodegradation, and bio-adsorption. In addition, the pollutants, like C, N, and P from the wastewater can be assimilated by microalgae for biomass synthesis (Ahmed et al., 2022; Nie et al., 2020). Microalgae biomass consists of protein, lipid, and carbohydrate, which can be used as raw materials for the generation of biofuel (e.g., biodiesel, bioethanol, biogas, and bio-hydrogen) and value-added products (e.g., polyunsaturated fatty acids, pigments, vitamins, and numerous other nutritious substances) (Poh et al., 2020; Levasseur et al., 2020; Rani et al., 2021; Sun et al., 2018). Microalgae is estimated to produce 200 times more oil per unit area than conventional oil crops, considered to be the third generation biofuel (Zhang et al., 2010). As prokaryotic and eukaryotic photosynthetic microorganisms, microalgae exhibit faster growth rates and higher annual photon-to-biomass conversion efficiencies (about 3% vs.< 1% for terrestrial plants), and no intrinsic sensibility to seasonality (Levasseur et al., 2020; Perin et al., 2019). Higher photosynthetic efficiency also enables microalgae to capture more CO_2. On average, 1.83 g CO_2 can be fixed to produce 1 g of dry microalgae biomass (Lu et al., 2018; SundarRajan et al., 2019). In summary, microalgae-based wastewater treatment in WWTPs has three benefits: CO_2 capture, wastewater treatment, and resources recovery, which is a promising technology for achieving carbon neutrality in WWTPs (Fig. 2) (Daneshvar et al., 2022; Ji and Liu, 2022).

However, the photosynthetic efficiency and growth of microalgae are limited due to the high pollutant concentration or chromaticity of wastewater (Cheng et al., 2020c; Xu et al., 2020b). The efficiency of microalgae treatment of wastewater is related to the types of wastewaters, nutritional characteristics, photobioreactors (PBRs) type, and cultivation method. As the main carbon source for photosynthetic growth, CO_2 is usually injected into the microalgae suspension in the form of bubbles using a gas aerator (Fu et al., 2019). Therefore, determining how to improve the efficiency of gas-liquid mass transfer and CO_2 biofixation, preventing CO_2 overflow from the microalgae suspension are also critical to achieving carbon neutrality in WWTPs.

This study is intended to give a comprehensive review of the literature regarding the status quo of microalgae cultivation for wastewater treatment. The performance of different types of wastewaters for microalgae cultivation was critically analyzed and evaluated. Different microalgae cultivation systems as well as their potential and further development trends for resource recovery and CO_2 capture were summarized in this paper. Moreover, the latest advances for the enhancement of CO_2 capture by microalgae were also estimated. This review can provide strategies for the development of microalgae-based wastewater treatment technology and the promotion of carbon neutrality in WWTPs.

2. Source of wastewater for microalgae cultivation

Wastewater is the most common waste produced by humans during daily activity. Different wastewater generation processes and discharge systems can significantly affect the composition of wastewater (Bhatia et al., 2021). Wastewater with different compositions has an important influence on the growth of microalgae, the removal rate of the contaminants, and the formation of different intracellular substances (carbohydrate, protein, and lipid). The carbon source, organic or inorganic carbon, macronutrients, nitrogen, phosphorus, micronutrients, vitamins, and trace minerals in the wastewater are essential for achieving optimal growth of microalgae (Ahmad et al., 2016). The wastewater commonly used for microalgae cultivation reported in the literature can be categorized based on its source such as municipal, agricultural. and industrial wastewater (Chiu et al., 2015; Liu and Hong, 2021). Table 1 shows the different types of wastewaters used for microalgae growth and nutrient removal efficiencies.

2.1. *Municipal wastewater*

Municipal wastewater, which can also be defined as domestic wastewater, includes wastewater discharged from houses, kitchens, bathrooms, laundry rooms, etc. The growth of urbanization and the population increase have resulted in heightened municipal wastewater generation. Compared with industrial and agricultural wastewater, municipal wastewater contains lower levels of N (15–90 mg/L) and P (5–20 mg/L) (Chiu et al., 2015).

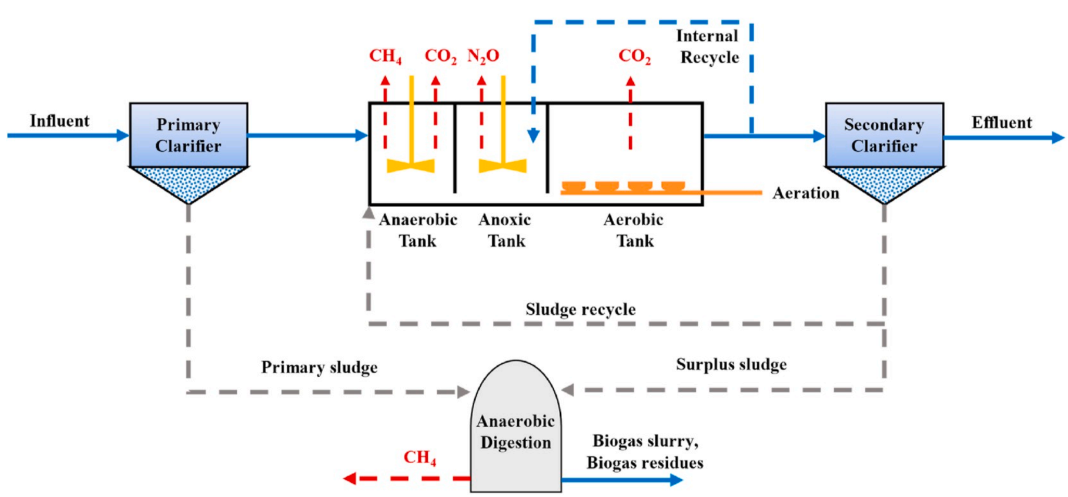

Fig. 1. Conventional WWTPs treatment processes and GHG emissions. The nutrients (C, N, P) in the wastewater are discharged as gas, effluent, and sludge which are not effectively resourced. The red arrows represent the GHG emissions in each process. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

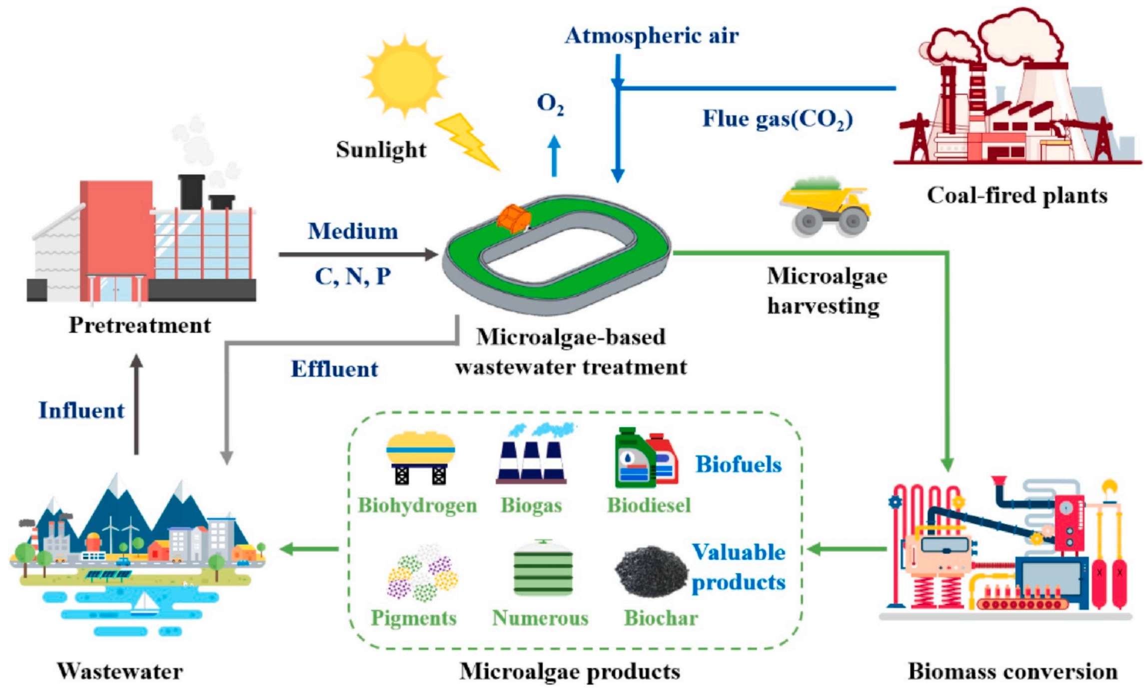

Fig. 2. Microalgae-based wastewater treatment and carbon neutrality of WWTPs. The nutrients (C, N, and P) in the wastewater are absorbed and used by microalgae to synthesize biomass for further resource utilization. The CO_2 in the flue gas can be further fixed in the microalgae culture process to achieve carbon-negative wastewater treatment.

The composition of municipal wastewater varies greatly at different stages of treatment, and it can be divided into four categories: wastewater before primary settling, wastewater after primary settling, the effluent from the aeration tank, and the centrate from sludge centrifugation (Liu and Hong, 2021; Wang et al., 2010). The concentration of N and P in wastewater affects the growth of microalgae and the removal of pollutants. The concentration of nutrients in the centrate of the centrifuged sludge was significantly higher than that of the other three wastewaters. Therefore, the concentration of microalgae cultivated in the centrate was higher. Wang et al. (2010) found that the treatment effect of *Chlorella* sp. on the four wastewaters was positively correlated with the concentration of nutrients. Due to the increased use of chemicals such as pharmaceuticals and personal care products in daily life, more and more emerging contaminants have been detected in municipal wastewater. The presence of emerging contaminants poses a potential threat to microalgae cultivation and the effluent quality. Wang et al. (2021b) investigated the influence of tetracycline on microalgae-bacteria granular sludge cultivated for municipal wastewater treatment. The ammonia nitrogen removed by microalgae assimilation decreased from 19.2 ± 1.69 mg/L to 16.8 ± 0.70 mg/L at a tetracycline concentration of 1 mg/L.

The nutrient composition characteristics of different municipal wastewaters should be fully considered for microalgae treatment. The nutrient concentration and ratio could be balanced by mixing different categories of wastewater to achieve wastewater discharge standards. The influence of emerging pollutants on the performance of microalgae treatment should also be considered.

2.2. Agricultural wastewater

Agricultural wastewater is the wastewater discharged from crop cultivation, livestock breeding, and agricultural products processing, including farmland drainage wastewater, animal manure wastewater, agricultural products processing wastewater, etc. (Beltrán-Flores et al., 2020; Liu and Hong, 2021). Compared with municipal and industrial wastewater, agricultural wastewater (e.g., potato processing wastewater, alcohol processing wastewater, and starch processing wastewater, etc.) typically has a lower concentration of toxic and harmful substances, which is more suitable for the cultivation of microalgae (Hernández et al., 2013; Khalid et al., 2019). For example, using microalgae C. *pyrenoidosa* to treat palm oil mill wastewater, 68% lipid production, and 71% nutrient removal were achieved (Low et al., 2021). Tan et al. (2014) explored outdoor microalgae treatment for anaerobically digested starch processing wastewater. In this study, 5–9% (v/v) CO_2 was used as the inorganic carbon source. During the summer (35–38 °C), the removal rates of COD, TN, and TP reached 65.99%, 83.06%, and 96.97%, respectively. Yang et al. (2015) mixed alcohol with starch-derived anaerobically digested wastewater to enhance the organic carbon source available to microalgae, resulting in a significant increase in biomass as well as the lipid production of microalgae. The removal rates of COD, TN, and TP reached 75.78%, 91.64%, and 90.74%, respectively.

Over the past decades, livestock and poultry farming have increased from the small-scale to the large-scale, which constitutes a major source of agricultural point source wastewater. In China, COD, TN, and TP emissions from livestock and poultry farming can reach up to 10.01, 0.59, and 0.12 million tons of wastewater per year, accounting for 46.67%, 19.61%, and 37.95% of national emissions, respectively (Ministry of Ecology and Environment of China, 2020). The treatment of livestock wastewater by microalgae can achieve the dual purpose of reducing the cost of microalgae cultivation and resource utilization of wastewater. However, the high turbidity and chromaticity of livestock wastewater hinder light transfer, thereby leading to low photosynthetic efficiency of microalgae (Al-Mallahi and Ishii, 2022; Liu and Hong, 2021). To ensure sufficient light transmission, particles and colors need to be removed from the wastewater, which can be done by centrifugation, sedimentation, and filtration (Maurya et al., 2022; Qin et al., 2016). Cheng et al. (2020b) used two types of auto-flocculated microalgae (*Tribonema* sp. and *Synechocystis* sp.) cultured from diluted swine wastewater pretreated with TiO_2 plus intensely pulsed light (T-IPL). The results showed that the pollutant removal rate, microalgae growth rate, and lipid content of the pretreated wastewater were improved.

Table 1
Role of microalgae in different types of wastewaters in terms of nutrient removal efficiency, incubation period, and microalgae biomass production.

Wastewater type	Wastewater source	Microalgae	Cultivation system	Influent (mg/L)			Nutrient removal efficiency (%)			Incubation period (day)	Microalgae production (g/L)	Reference
				COD	TN	TP	COD	TN	TP			
Municipal wastewater	Wastewater before primary settling	*Chlorella* sp.	Erlenmeyer flasks	231	41	6	51	68	83	9	$OD_{680} = 0.6$	Wang et al. (2010)
	Wastewater after primary settling	*Chlorella* sp.	Erlenmeyer flasks	224	39	7	57	69	91	9	$OD_{680} = 0.6$	Wang et al. (2010)
	Centrate from sludge centrifuge	*Chlorella* sp.	Erlenmeyer flasks	2250	132	72	83	83	86	9	$OD_{680} = 2.4$	Wang et al. (2010)
	Effluent of anaerobic digested sludge	*Chlorella pyrenoidosa*	Flat plate PBRs	NA	273 (NH_3–N)	35 (PO_4–P)	–	96 (NH_3–N)	87 (PO_4–P)	14	2.43	Tan et al. (2016)
	Domestic wastewater	*Botryococcus* sp	NA	326	20	2 (PO_4–P)	94	60	37 (PO_4–P)	20	10^7 cells/mL	Gani et al. (2017)
	Domestic wastewater	*Chlorella pyrenoidosa*	Raceways ponds	426	46 (NH_3–N)	3	78	95 (NH_3–N)	81	19	1.71	Dahmani et al. (2016)
	Domestic wastewater	*Chlorella variabilis*	Glass bottles	155	66	6	90	96	100	17	1.72	Tran et al. (2021)
Agricultural wastewater	Treated liquid fraction of pig manure	*Chlorella sorokiniana*	Flat plate PBRs	616	12 (NH_3–N)	50	62	83 (NH_3–N)	58	10	26.3 $mgL^{-1}d^{-1}$	Hernández et al. (2013)
	Ddigested starch and alcohol wastewater	*Chlorella pyrenoidosa*	Erlenmeyer flasks	2597	281	29	76	92	91	9	3.01	Yang et al. (2015)
	Digested starch processing wastewater	*Chlorella pyrenoidosa*	Airlift PBRs	702–1026	240–382	22–40	66	83	97	7	2.00	Chu et al. (2015)
	Digested dairy astewater	*Chlorella vulgar*	Flasks	356	29	9	81	85	66	10	1.23	Choi (2016)
	Soybean processing wastewater	*Chlorella pyrenoidosa*	Erlenmeyer flasks	3000	84	20	78	89	70	5	2.15	Su et al. (2011)
Industrial wastewater	Tannery wastewater	microalgae consortium	Erlenmeyer flasks	814	29	2 (PO_4–P)	50	72	98	20	1.40	Pena e et al. (2020)
	Palm oil mill effluent	*Chlorella sorokiniana*	Glass vessel	832	276	31	64	92	83	15	1.68	Cheah et al. (2018)
	Palm oil mill effluent	*Scenedesmus* sp. and *Chlorella* sp.	Erlenmeyer flasks	2436	277	229 (PO_4–P)	48	86	77 (PO_4–P)	15	0.51	Hariz et al. (2019)
	Industrial park effluent	*Chlorella* sp.	Column PBRs	850	153	11 (PO_4–P)	92	100	96 (PO_4–P)	7	1.52	Yadav et al. (2019)

Note: NA (data not available).

An excessive ammonia nitrogen concentration also affects the electron transfer of photosystem II in microalgae, which inhibits the growth of microalgae (Al-Mallahi and Ishii, 2022; Gutierrez et al., 2016). Traditional strategies for high concentrations of wastewater that inhibit the growth of microalgae include dilution with water (Wang et al., 2015; Yang et al., 2015). Zhu et al. (2013) obtained the best group of COD, TN, and TP concentrations of 1900, 80, and 85 mg/L by culturing *Chlorella vulgaris* with six different concentrations of diluted piggery wastewater, and the corresponding removal rates were 79.84%, 82.70%, and 98.17%, respectively. This process can reduce the cost of diluting livestock wastewater by replacing freshwater with other types of wastewaters, making the livestock wastewater more suitable for microalgae growth. For example, mixing piggery wastewater with brewery wastewater also significantly improved the pollutant removal rate and microalgae biomass concentration (Zheng et al., 2018). In addition, determining how to improve the removal rate of pollutants from undiluted livestock wastewater also deserves further research, which will make microalgae-based wastewater treatment technology more cost-effective (Liu and Hong, 2021). Farm operations require antibiotics and heavy metal-containing feeds to reduce mortality and increase production (Bhatia et al., 2021; Michelon et al., 2021). Most of the antibiotics and heavy metals are excreted and enter the wastewater treatment system (Liu et al., 2020; Yu et al., 2019). The active binding sites outside the microalgae cells can form complexes with antibiotics and heavy metals in the wastewater to achieve pollutant removal (Leong and Chang, 2020; Yu et al., 2021). However, their removal efficiency and underlying mechanisms in the microalgae cultivation system need to be considered (Yu et al., 2021).

2.3. Industrial wastewater

Industrial wastewater is the wastewater produced in the industrial production process, which contains industrial production materials, intermediate products, by-products, and pollutants produced during the production process. According to different processing objects, industrial wastewater can be divided into textile printing and dyeing wastewater, tannery wastewater, paper wastewater, metallurgical wastewater, chemical fertilizer wastewater, pesticide wastewater, etc. Each industrial wastewater varies considerably in terms of physical, chemical, and biological composition (Maurya et al., 2022). Usually, industrial wastewater contains a large amount of oil, heavy metals, antibiotics, and some toxic pollutants, leading to a high content of organic compounds and a low biodegradability (Liu and Hong, 2021; Mohd Udaiyappan et al., 2017). Biological methods such as microalgae cultivation face many bottlenecks in treating this type of wastewater. The factors that are harmful to microalgae need to be fully considered during the treatment of different wastewaters.

Species selection is a crucial step for microalgae cultivation in industrial wastewater. Indigenous microalgae screened in wastewater often achieve a higher pollutant removal rate and exhibit greater environmental adaptability (Jeong and Jang, 2020). Microalgae suitable for treating specific wastewater can also be screened by methods such as microalgae domestication or microalgae mutagenesis (Zhou et al., 2019). Japar et al. (2021) investigated the growth of four acclimatization microalgae (*Chlorella vulgaris*, *Chlorella sorokiniana* UKM3, *Chlamydomonas* sp. UKM6, and *Scenedesmus* sp. UKM9) in anaerobically digested palm oil mill effluent. All microalgae species demonstrated a significant increase in lipid content. The most significant increase was observed in *C. vulgaris* and *C. sorokiniana* UKM3, resulting in an increase of 71.9% and 49.7%, respectively. In addition, genetic engineering to promote the expression of related enzymes in microalgae cells can also effectively improve the wastewater treatment efficiency and biomass accumulation of microalgae (Guihéneuf et al., 2016).

During the treatment of different wastewaters by microalgae, the microorganisms contained in the wastewater interact with the microalgae to form a complex microalgae-bacteria symbiotic system (Sial et al., 2021; Mohd et al., 2020). Microalgae and bacteria can exchange different nutrients like carbon, nitrogen, oxygen, and vitamins during coexistence which helps to improve the microalgae biomass and wastewater treatment efficiency (Leong et al., 2021; Ji and Liu, 2022). The bacteria present in the wastewater can release a specific type of chemical signaling molecules (acyl homoserine lactones) that have also been found to promote the formation of microalgae and bacteria biofilms (Zhang et al., 2020). The antibiotics produced by bacteria have also been reported to protect microalgae against other microbes (Lépinay et al., 2018). Additionally, there are competitive or antagonistic interactions between bacteria and microalgae. First, bacteria can compete with microalgae for nutrients and space. Secondly, the toxins released by bacteria can inhibit the growth of microalgae and even cause microalgae cell lysis (Lépinay et al., 2018). Consequently, when using microalgae to treat different types of wastewaters, the association of the appropriate microalgae species and the dominant bacteria present in the wastewater need to be consistently considered.

3. Microalgae cultivation systems

Microalgae cultivation systems have been used for wastewater treatment since the 1950s (Chisti, 2016). Currently, a wide range of microalgae cultivation systems has been developed to improve wastewater treatment and microalgae production. The properties of wastewater, suitable culture conditions such as adequate illumination, CO_2 concentration, and nutrient exchange are the key factors that influence the production of microalgae (SundarRajan et al., 2019). In addition, the cost of microalgae cultivation such as the land utilized, PBRs manufacturing costs, and culture time are also challenges facing the large-scale application of microalgae wastewater treatment (Rohit et al., 2016). Currently, three cultivation systems are widely used based on their design requirements: open systems, closed systems, and biofilm systems. Different cultivation systems have different advantages and limitations (Table 2). Some common microalgae cultivation systems reported in the literature are shown in Fig. 3.

3.1. Open cultivation system

The open microalgae cultivation system is the oldest and simplest system, which can be divided into natural ponds, raceways ponds, circular ponds, and multi-layer open cultivation systems. This type of cultivation system usually uses sunlight as the main illumination source, requires only a small amount of kinetic energy to maintain effective mixing of the microalgae suspension, and can be kept at a low operating cost. It is the most widely used system for the commercial cultivation of microalgae (Jerney and Spilling, 2020; Ribeiro et al., 2019).

3.1.1. Single layer open cultivation system

The choice of open PBRs depends on the type of microalgae, local climatic conditions, and the cost of land and water. Natural ponds are a natural form of microalgae ponds that are mostly used for natural ecological treatment due to poor controllability, a low concentration of microalgae biomass, and a low carbon sequestration efficiency. Raceways and circular ponds are typically made from poured concrete, or they are simply dug into the earth and lined with a plastic liner. Ranga et al. (2012) found that raceways ponds cultivate higher concentrations of microalgae compared to circular ponds. Currently, most of the large microalgae cultivation facilities utilize raceways ponds, which account for about 90% of global microalgae production (Placzek et al., 2017). To ensure adequate illumination, the pool height of raceways pond systems is generally 40–50 cm, and the depth of the microalgae suspension is 20–30 cm. The microalgae at the bottom may not have an adequate carbon source during operation, so some raceways ponds often have aeration devices installed at the bottom of the pond to provide a sufficient carbon source for the growth of microalgae, while keeping the microalgae in suspension to prevent settling and allowing the

Table 2
Comparison features of various microalgae cultivation systems (Assuncao and Malcata, 2020; SundarRajan et al., 2019; Cheng et al., 2021).

Cultivation system		Mixing	Aeration	Advantages	Limitations
Open	Single layer	High Paddle wheel	Surface CO_2 capture	• Low cost • Large scale • Low energy consumption • Easy to operate and maintain • Less susceptible to photoinactivation	• Large land space • Poor mass transfer efficiency • Low light utilization rate • Low biomass production • Infected with bacteria • High contamination risk
	Multi-layer	Circular flow	Surface CO_2 capture	• Low cost • Suitable for batch assembly • Small degree of wall growth • Moderate mixing and mass transfer • High light utilization	• Strength requirements of support materials • Low biomass production • Infected with bacteria
Closed	Flat plate	Airflow turbulence	Bottom dispersion aeration	• High S/V ratio • Short light path • Moderate biomass production • Low hydrodynamic shear stress • Not restricted to robust microalgae • Low contamination risk	• Difficulty in monomer amplification • Microalgae cell wall attachment • High risk of thermal denaturation • Difficult cleaning and maintenance
	Column	Airflow turbulence	Bottom aeration	• Better mass transfer efficiency • Smaller land space • Small degree of wall growth • Low energy input • Not restricted to robust microalgae • Less susceptible to photoinactivation • Land-saving if compactly packed	• The small diameter of the single reactor makes • High cost for large scale application • Difficult cleaning and maintenance • Low S/V ratio
	Tubular	Circular flow	Injection into medium	• High light utilization • Moderate biomass production • Low contamination risk • Not restricted to robust microalgae • Land-saving if compactly packed	• Photo-inhibition problems • Temperature control required • Poor mass transfer efficiency • Transportation and assembly inconvenience • Difficult cleaning and maintenance • High degree of wall growth • Difficult scale-up
	Plastic bag	Airflow turbulence	Injection into medium	• Low cost • Various forms • Low contamination risk • Land-saving • Multiple application scenarios	• Shorter life span • Easy breakage and leakage • Poor economy of long-term application
Biofilm	Suspension	Carrier flow and rotation of disks	Surface CO_2 capture	• Easy amplification • High mass transfer efficiency • High biomass production • Easy harvesting	• Easy to contaminate bacteria • Full immersion amplification requires built-in light source
	Adsorption	Circular flow	Surface CO_2 capture	• Highest mass transfer efficiency • High biomass production • Low harvesting cost • High light utilization	• Complex inoculation process • Difficult to scale up • High culture cost

microalgae at the bottom to use light effectively. The supply of CO_2 can effectively improve the removal of pollutants in open cultivation systems (Posadas et al., 2015). Chisti (2012) concluded that the highest yield of microalgae biomass from open cultivation systems was 86,700 t/km^2 under suitable conditions. The average yield of microalgae biomass from raceways ponds reported in the literature ranged from 16 to 19 g/(m^2·d) (Kumar et al., 2015b).

Although the raceways ponds are easy to scale up, the depth of the pond is shallow due to the light limitations, and the production scale can only be increased by increasing land space (Kumar et al., 2015b). Therefore, the site selection of raceways pond is an important factor that affects operating costs.

3.1.2. Multi-layer open cultivation system

To improve land-use efficiency and alleviate the high land cost of open microalgae cultivation systems, multi-layer open cultivation systems were developed. The microalgae suspension flows between each layer by gravity and peristaltic pumping, thereby reducing the reactor footprint. At the same time, the reactor depth can be further reduced to improve surface CO_2 utilization. Hu et al. (2013) used a multi-layer open cultivation system to treat the digested piggery wastewater. This preceding study found that the effluent treatment efficiency and microalgae biomass increased, and the protein and lipid content of cultured microalgae increased to 58.78% and 26.09%, respectively.

The theoretical production of microalgae biomass from open cultivation systems can reach up to 40 g/(m^2·d). In other words, they can achieve approximately 14,600 t/km^2 per year. However, this system is susceptible to contamination by bacteria during operation. The bacteria will compete with microalgae for nutrients, thereby disrupting the equilibrium system of microalgae and reducing microalgae biomass production (Brennan and Owende, 2010). The actual biomass production of open cultivation systems has been reported to range from 2000 to 11,000 t/km^2, which is much lower than the theoretical value. Changes in conditions such as water evaporation, temperature fluctuations, and rainfall can lead to low densities of microalgae, usually less than 1 g/L, making enrichment difficult and harvesting costly (Ugwu et al., 2008). The shallow depth and short gas retention time of open cultivation systems result in 80–90% of CO_2 being resolved from the surface (Richmond, 2004). Therefore, determining how to achieve stable operation of open cultivation systems, improve CO_2 utilization, and increase biomass production are still urgent challenges.

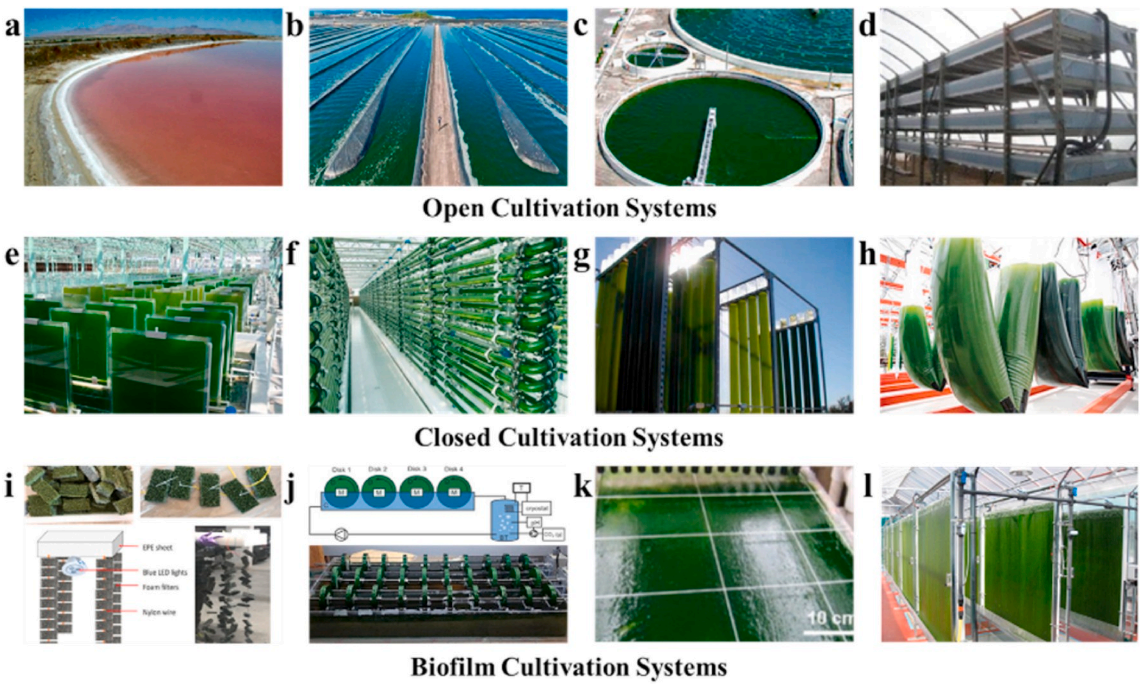

Fig. 3. Different types of microalgae cultivation systems: a) natural pond, b) raceway pond, c) circular pond, d) multi-layer pond, e) flat plate PBR, f) tubular PBR, g) column PBR, h) plastic bag PBR, i) carrier full-immersion, j) carrier semi-immersion, k) horizontal adsorption, and l) vertical adsorption (Blanken et al., 2014; Katam and Bhattacharyya, 2021; Koller, 2015; Martín-Girela et al., 2017; Min et al., 2014; Pires et al., 2017; Savage, 2011; Ozkan et al., 2012; Shen et al., 2009).

3.2. Closed cultivation system

To overcome the problems of the open cultivation system, a series of closed PBRs with different structures were developed, which are made of transparent materials with good light transmission. The manufacturing material needs to meet the transparency and mechanical robustness requirements of PBRs. Such materials that meet these requirements include glass, plexiglass, polyvinylchloride (PVC), acrylic PVC, and polyethylene (Huang et al., 2017a; Wang et al., 2012). Closed PBRs can isolate the microalgae suspension from the external environment, which has the advantages of allowing for controlled culture conditions, ability to culture pure microalgae species, high utilization of light and CO_2, low water evaporation loss, and high production of microalgae biomass. Moreover, these systems can be applied to all kinds of microalgae species. The advantages of closed PBRs include being suitable to produce fine chemicals with high purity requirements from the cultivated microalgae. For example, the production of high value-added products such as biopharmaceuticals, advanced cosmetics, human health food, and biofuels is achievable, which in turn compensates for the cost of microalgae cultivation (SundarRajan et al., 2019). This type of system is normally classified as a flat plate, tubular, column, and plastic bag PBRs (Huang et al., 2017a).

3.2.1. Flat plate PBRs

Flat plate PBRs are simple, compact, and designed in a cuboidal shape. Due to the absorption, scattering, and shading of light by microalgae cells, flat plate PBRs tend to have a small thickness to ensure sufficient illumination inside the reactor. Reduced thickness can reduce light attenuation and increase the surface area-to-volume ratio (S/V). The higher the S/V, the higher the portion of light allowed through the PBRs surface, thereby promoting photosynthetic efficiency and biomass production of microalgae (Assuncao and Malcata, 2020). Flat plate PBRs can be tilted at an angle to obtain the best incident light intensity based on the position of the light source when incubating outdoors. To alleviate the adverse effect of poor light penetrability on microalgae growth, Sun et al. (2016b) manufactured planar waveguides doped with light scattering nanoparticles and introduced them into flat plate PBRs. The S/V was enhanced by 10.3 times, and the biomass production increased by 220%.

The turbulence of airflow inside flat plate PBRs is also a critical way to improve microalgae cultivation. Increasing airflow turbulence inside the PBRs not only improves gas-nutrient-microalgae mixing but can also flush the PBRs to avoid microalgae from growing against the walls and affecting the incident light intensity. Flat plate PBRs can be divided into two classifications based on the internal airflow turbulence: aeration and circulation flat plate PBRs (Fig. 4a and b). Demirel et al. (2020) investigated the effect of different mixing conditions on microalgae growth in flat plate PBRs. Results demonstrated that a slightly higher amount of saturated fatty acids was detected in bubbling PBRs while a significant increase of mono-and poly-unsaturated fatty acids was found in a combination of bubbling and stirring PBRs. To further improve the CO_2 retention time and light utilization, flat plate PBRs with inclined baffles were developed (Wang et al., 2021a; Xia et al., 2018).

Flat plate PBRs are simple in structure, easy to manufacture, and can effectively improve the carbon sequestration efficiency of microalgae, biomass concentration, and wastewater treatment capacity through the setting of the baffles. However, the large size of the reactor and the high of the hydrostatic pressure make single reactor scale-up difficult (Kumar et al., 2015a).

3.2.2. Column PBRs

Column PBRs are typically shaped as vertical cylinders consisting of transparent vertical tubes that allow for light penetration to improve photosynthesis. The mixing of microalgae within the column PBRs was initially done by mechanical agitation, but the shear force generated by the impeller was destructive to the microalgae cells, which is not conducive to subsequent harvesting and separation (Kim et al., 2015). The turbulent action of the airflow also allows the microalgae suspension to be fully mixed and avoids damage to the microalgae cells by shear forces. A gas sparger is usually installed at the bottom of the PBRs to convert the sparged gas into numerous small bubbles to ensure the microalgae suspension does not settle as well as improve gas-liquid mass

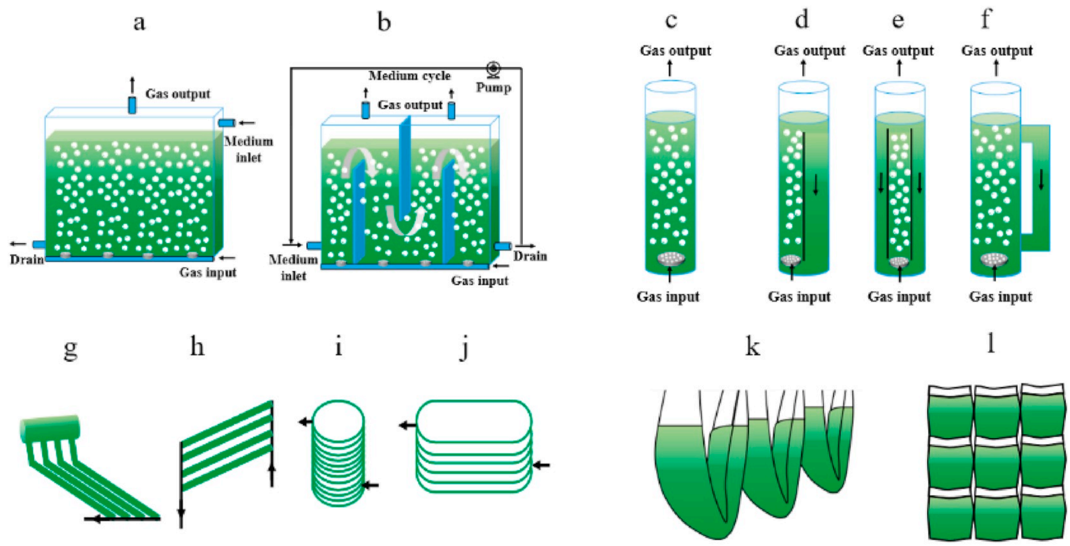

Fig. 4. Configurations of classical closed PBRs employed for microalgae cultivation: a) aeration flat plate, b) circulation flat plate, c) bubble column, d) internal-loop airlift, e) split-column airlift, f) external-loop airlift, g) near-horizontal tubular, h) horizontal tubular, i) helical tubular, j) vertically-stacked tubular, k) hanging plastic bag, and l) mezzanine plastic bag.

transfer, CO_2 uptake, and O_2 emissions (SundarRajan et al., 2019). The top of the PBRs is a gas separation zone.

The column PBRs can be divided into two types based on the flowing and mixing method: bubble column and air-lift column. The bubble column (Fig. 4c) realizes the gas-liquid mass transfer process from the bottom to the top with CO_2 bubbles through the gas sparger at the bottom. Air-lift column PBRs can be considered as the upgraded version of the bubble column. This system has an internal baffle that divides the reactor interior into a rising zone and a falling zone, allowing the microalgae suspension to circulate between the rising and falling zones through changes in gas content and algae density. Air-lift column PBRs can be further classified into three main types (Fig. 4d, e, f) based on their morphology: internal-loop airlift, split-column airlift, and external-loop airlift. Mass transfer efficiency in air-lift reactors has proven superior to bubble columns under the same operating conditions. This is because the microalgae suspension in the air-lift reactor can circulate and prolong the CO_2 retention time, while the microalgae suspension in the bubble column reactor flows in a random mixture and the microalgae receive uneven light exposure. Aeration is critical for proper microalgae growth in air-lift reactors, but aeration must be kept at low levels to minimize shear stress (Kaewpintong et al., 2007).

3.2.3. Tubular PBRs

Tubular PBRs are usually made of small diameter transparent glass or polyethylene tubes (Assuncao and Malcata, 2020). This type of PBRs can be divided into multiple possible orientations: horizontal, near-horizontal, helical, vertically-stacked, and modifications of the aforementioned orientations (Fig. 4g, h, i, j), with a high light conversion efficiency. The tube diameter of tubular PBRs is generally 0.1 m or less, but the length can reach hundreds of meters (Bei et al., 2012). The shape of the tubular PBRs has a “lens effect”, or “focusing effect”, which focuses the incident light on the axis of the tube and increases the radiation intensity (Posten, 2009). The flow of the microalgae suspension in the internal radial direction also reduces mutual shading. Therefore, tubular PBRs have a higher S/V (Assuncao and Malcata, 2020). The sealed piping of tubular PBRs makes it easy to connect with other equipment to automate the whole process, and it is the most popular PBRs for outdoor microalgae cultivation.

The small diameter and long length of the pipe of tubular PBRs lead to its poor internal mass transfer effect, which easily delays the difference of pH and CO_2 concentration in the pipe. If the O_2 produced by microalgae is not discharged in time, it will make the dissolved O_2 concentration too high, which is not conducive to the growth of microalgae. Setting a certain inclination angle of the pipe can increase bubble rise velocities, gas retention time, and gas transfer coefficients. Therefore, near-horizontal tubular PBRs can be a good solution to the problem of poor mass transfer that occurs in horizontal tubular PBRs. Ugwu et al. (2002) found that as the angle of the near-horizontal SBR increases, the gas transfer coefficient and retention time increase, and the mixing time decreases. In the extreme case, this leads to a vertical column. As the angle increases, the cost of the support structure increases, so the maximum angle needs to be maintained at 45° (Assuncao and Malcata, 2020). Microalgae are prone to adhere to the pipe wall inside the tubular PBR, resulting in a rough pipe surface and increased fluid resistance, which further affects the light transmission of the pipe. To avoid the occurrence of microalgae wall adhesion, it is necessary to minimize bending of the pipe, increase the smoothness of the pipe, and install cleaning equipment, which further limits the large-scale application of this type of reactor.

3.2.4. Plastic bag PBRs

To solve the problems of high manufacturing costs, cumbersome transportation, and assembly of closed cultivation systems, plastic bag PBRs have been increasingly used. Compared with other PBRs, plastic bag PBRs offer the advantages of high transparency, low cost, and easy assembly. Therefore, this type of reactor has received more and more attention to achieve scale cultivation. Due to the ease of processing, plastic bags can be shaped and customized in many different manners (Fig. 4k and l). Chen et al. (2018) used 5-L plastic bag PBRs for *Nannochloropsis oceanica* CY2 cultivation, and the biomass concentration reached up to 3.3 g/L. To increase the volume of individual reactors, plastic bags can also be scaled up by fixing them with iron frames or wooden frames. Quinn et al. (2012) used a water floating film hanging bag type microalgae cultivation system, which was placed in a shallow water basin for fixed support and placed in water to avoid a high internal temperature, reduce the production cost, and to some extent solve the problem of high land cost. Although plastic bag PBRs can be used in more application scenarios, they also have many disadvantages. Firstly, the effect of gravity can lead to plastic bag deformation, resulting in the bottom of the reactor not receiving enough light. Secondly, the lifespan of plastic bags is short, they are prone to breakage and leakage, and the difficulty of degradation after disposal, resulting in new pollution.

Closed cultivation systems all have much smaller individual volumes than open cultivation systems, so many reactors will be needed for scale-up, thereby increasing the cost of equipment, and some of them will also have the problem of requiring a large land area. In both open and closed cultivation systems, microalgae are cultured in suspension. It is difficult to harvest due to the microalgae usually having a small cell size (3–30 μm), low biomass concentration (<0.5 g/L), close-to-water density (1.07–1.14 g/cm^{-3}), and electronegative surface charge (−7.5 to −40 mV) (Chen et al., 2021). Conventional harvesting methods for suspended microalgae are centrifugation, filtration, flocculation, and air floatation (Jiang et al., 2022; Mathimani and Mallick, 2018; Singh and Patidar, 2018), which are hampered by high cost, intensive energy consumption, and low efficiency. The cost invested in the harvesting process of suspended microalgae represents 20%–30% of the total cost and may account for 90% of the cost of PBRs (Grima et al., 2003; Mathimani and Mallick, 2018; Nie et al., 2022), which poses a great obstacle to the industrial cultivation of microalgae and its energetic development.

3.3. Biofilm cultivation systems

Biofilm cultivation systems use solid filler or substrates as a carrier for microalgae growth. The microalgae adsorb on the surface of the carrier to form a biofilm and grow continuously. This type of cultivation system has the advantages of high operational stability and high concentration of microalgae biomass compared to suspended microalgae cultivation. The support carrier is the essential element for the biofilm cultivation systems. The choice of support carrier usually depends on roughness, hydrophilicity, surface energy, hardness, biotoxicity, etc. (Schnurr et al., 2014; Dalirian et al., 2021). Generally, porous, rough, and hydrophilic support carriers are more likely to form microalgae biofilms. Common support materials used in microalgae biofilm systems are usually non-degradable, and not biotoxic (e.g. cellulose, acetate/-nitrate membrane, polycarbonate membrane, and cotton) (Gross et al., 2016; Rosli et al., 2020; Zhuang et al., 2018). The materials such as copper or cardboard were not suitable for the microalgae biofilm formation and growth, owing to their biotoxicity or degradation in liquid (Zhuang et al., 2018). The biofilm PBRs can be divided into suspension biofilm PBRs and adsorption biofilm PBRs according to the different forms of carriers.

3.3.1. Suspension biofilm PBRs

Suspension biofilm PBRs are a conventional suspended microalgae cultivation system with adsorption carriers that allow microalgae to grow on the surface of the carriers suspended in the reactor. This type of reactor can be further divided into full immersion and semi-immersion based on the different manners of carrier immersion.

Full immersion biofilm PBRs are similar to moving bed biofilm reactors and usually use a filler with a large specific surface area as a carrier for the attachment of microalgae. The specific gravity of the carrier is close to that of water, and the carrier is circulated through the PBR by aeration. Zhuang et al. (2014) proposed a novel suspended-solid phase PBR. In this PBR, solid carriers (cotton, mohair, and linen) were added and kept suspended by aeration. Part of the microalgae could attach and grow on the carriers. When the concentration of microalgae biomass adsorbed on the carrier reached a certain value, the carrier can be taken out for harvesting of microalgae biomass, and the harvested carrier can be put back into the PBRs for reuse. Compared with the control group, the microalgae biomass could achieve a maximum increment of up to about 30% when the carrier of linen was 4 g/L. In addition to the increase in biomass, the lipid content of microalgae biomass attached to polyurethane foam carriers was found to be 4 times higher than the suspension cultivation (Rosli et al., 2020). The full immersion reactor could face the same problem as the suspended microalgae cultivation system, i.e., the efficiency of CO_2/O_2 exchange.

Most semi-immersion biofilm PBRs are rotating systems. Blanken et al. (2014) designed a rotating biological contactor PBRs for microalgae biofilm cultivation. The vertical rotating disks were partially submerged in the microalgae culture medium, and the microalgae adsorbed onto the disks to grow and form biofilms. When the disks rotated, the microalgae alternated between suspension and air, allowing the microalgae to take full advantage of the nutrients, CO_2, and light. When the microalgae on the disks reached a certain concentration, microalgae could be harvested by the scraping method, and the residual on the disks could be used as microalgae species to continue cultivation. This kind of PBR could easily take up CO_2 and release O_2, but it might have the risk of microalgae cell dehydration (Liu et al., 2013).

3.3.2. Adsorption biofilm PBRs

Microalgae cultivation by adsorption biofilm PBRs is a way for microalgae to adsorb onto the porous support media (e.g., filter paper or glass) to form a biofilm and grow by absorbing nutrients from the inner side. Adsorption biofilm PBRs could be classified as vertical or horizontal by the orientation of the support media.

The adsorption biofilm PBRs have the advantages of requiring less water and space, as well as exhibiting a higher water treatment potential and higher biomass productivity compared with other microalgae cultivation systems (Zhuang et al., 2018). Liu et al. (2013) cultured microalgae for attachment on the surface of vertical artificial supporting material to form microalgae films. The carrier of the reactor consists of glass support in the middle and a filter membrane on both sides. Microalgae are grown on the surface of the membrane and receive nutrients from the culture medium and CO_2 through the membrane. The reactor avoids light attenuation in the culture solution and the shading effect of the microalgae, allowing the microalgae to receive sufficient illumination. Results showed that the microalgae biomass production outdoors could reach up to 50–80 g/(m^2·d), or 400–700% higher than the open pond cultivation system. The corresponding photosynthetic efficiency was 5.2–8.3%. Adsorption biofilm PBRs also have a higher contaminant removal rate. Choudhary et al. (2017) selected non-woven spun-bond fabric (70 GSM) as the porous support and assessed the biomass productivity and treatment potential using livestock wastewater. The adsorption biofilm PBRs had higher COD, NO_3–N, and TP removal rates of 87%, 91%, and 93%, while the suspended microalgae cultivation PBRs were only 80%, 87%, and 83%, respectively. The hydraulic retention time of the adsorption PBRs was only half that of the value of the suspension PBRs.

4. Enhancement of CO_2 capture by microalgae

Microalgae cultivation can be divided into photoautotrophic, heterotrophic, and mixotrophic based on the nutrient supply. The photoautotrophic process of microalgae determines the CO_2 capture efficiency and refers to the conversion of CO_2 and H_2O into organic compounds powered by ATP and NADPH through photosynthesis (Fig. 5). Microalgae autotrophy achieves CO_2 capture through the three phases of the Calvin cycle, i.e., carboxylation, reduction, and regeneration (Calvin, 1997; Zhou et al., 2017). Briefly, in the carboxylation phase, CO_2 is combined with ribulose-1,5-bisphosphate (RuBP) catalyzed by ribulose-1,5-bisphosphate carboxylase (RuBisCo) to produce 2 molecules of 3-phosphoglycerate (3-PGA). Then, in the reduction phase, 3-PGA is phosphorylated by ATP catalyzed by 3-phosphoglycerate kinase to form 1,3-diphosphoglycerate, which is then reduced by NADPH catalyzed by glyceraldehyde phosphate dehydrogenase to produce glyceraldehyde 3-phosphate (G-3-P). Finally, in the regeneration phase, RuBP regenerates and re-enters the carboxylation phase through a series of reactions. Finally, in the regeneration phase, G-3-P undergoes a series of reactions into ribulose-5-phosphate, which then regenerates RuBP under the action of ribulose phosphate kinase and re-enters the carboxylation phase (Calvin, 1997).

During heterotrophic growth of microalgae without external inorganic carbon sources, all CO_2 produced by the heterotrophic pathway is

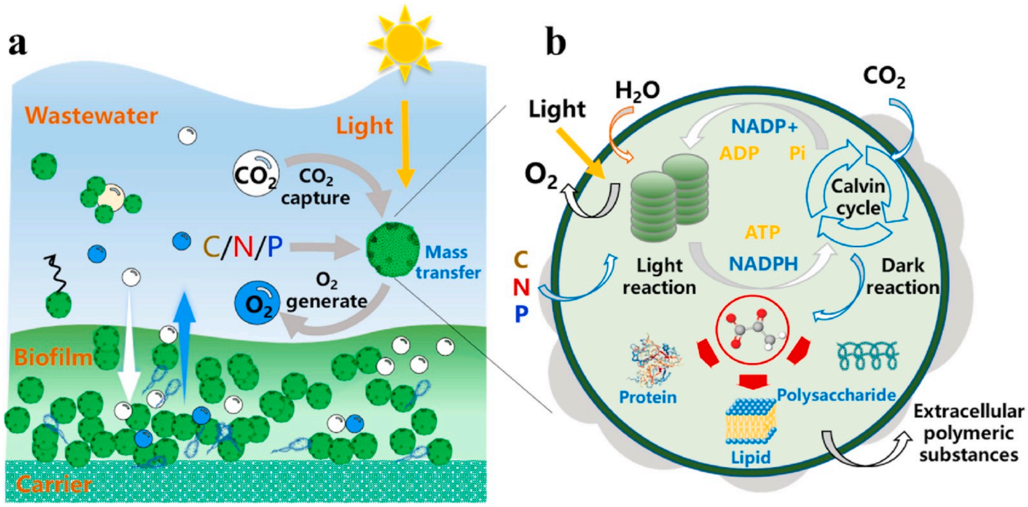

Fig. 5. Schematic diagram of photosynthetic carbon capture coupled with wastewater treatment by microalgae: a) nutrient uptake and gas-liquid mass transfer processes of microalgae in the PBR, b) photosynthesis and CO_2 capture processes in microalgae cells.

internally recycled for photoautotrophic growth (Manhaeghe et al., 2020). Under mixotrophic cultivation conditions, internal CO_2 and O_2 exchange can lead to higher biomass growth than photoautotrophic and heterotrophic growth (Smith et al., 2015). Manhaeghe et al. (2020) found that photoautotrophic growth is the preferential growth mechanism under mixotrophic conditions, but a high concentration of O_2 produced by the photoautotrophic pathway can activate the heterotrophic growth of microalgae to avoid photorespiration. Therefore, appropriate supplementation of inorganic carbon sources can promote the utilization of organic carbon sources in wastewater by microalgae and increase the biomass of microalgae at the same time (Cecchin et al., 2018; Zhang et al., 2017).

According to the assessment of Cheng et al. (2021), the apparent CO_2 removal efficiency of C. *vulgaris* in an open system and closed systems reached 40.64% and 73.07%, respectively. Enhanced CO_2 capture by microalgae can effectively improve microalgae biomass production, wastewater treatment efficiency, and reduce the cost of CO_2 aeration. The transfer of CO_2 molecules from the gas phase to the microalgae cells goes through two main stages: the gas phase to the liquid phase and the liquid phase to microalgae cells. (1) The CO_2 molecules have to cross the gas-liquid interface and diffuse into the wastewater. (2) The dissolved CO_2 is further captured by microalgae and transported to the chloroplast for the Calvin cycle (Carvalho et al., 2006; Fu et al., 2019). The gas-liquid mass transfer coefficient is influenced by the bubble diameter, air-liquid contact area, and retention time of bubbles in the microalgae suspension. To enhance gas-liquid mass transfer for CO_2 capture of microalgae, optimization of parameters such as aeration distribution, gas flow rate, stirring, gas retention time, etc. need to be considered. The performance comparison of various CO_2 capture enhancements for microalgae is shown in Table 3.

4.1. Reducing bubble diameter

The bubble diameter depends mainly on the structure of the aerator, and different types of aerators have been developed to enhance CO_2 transfer (Fig. 6a, b, c, d). Cheng et al. (2020a) proposed a three-stage shear-serrated aerator to generate smaller bubbles (Fig. 6a). The biomass production increased by 46.8% in a raceway reactor. However, the diameter of the generated bubbles was still large (2.4 mm), and the mass transfer efficiency was only improved by 25.5%. Jet aeration is also a commonly used method for generating microbubbles, and it produces a mixing effect that can improve the mass transfer efficiency. In a novel jet-aerated tangential swirling-flow plate PBR (Fig. 6b) with a bubble diameter of 0.37 mm, the mass transfer coefficient was increased by 4.6 times, and the microalgae biomass production increased by 49.4% (Cheng et al., 2019a).

The reduction of bubble diameter by mechanical vibration or fluid shear often requires higher energy consumption. Currently, with the development of membrane technology, microporous membranes are also being applied to aerators to further reduce the bubble diameter. Huang et al. (2017b) designed an optimized round gas distributor with an inner diameter of 0.5 mm and a spacing of 1.5 mm (Fig. 6c) based on bubble dynamic behaviors. The biomass production achieved 2.88 g/L, amounting to an increase of 83.44%. Cheng et al. (2019b) prepared a novel microporous aerator by a microporous fibrous-diaphragm (Fig. 6d) with an average pore diameter of 28 μm, which further reduced the bubble diameter and increased the gas retention time. The mass transfer efficiency and biomass production have been increased by 40% and 38.5%, respectively. However, the smaller membrane pore size is prone to clogging by microalgae cells, and membrane cleaning and long-term operational issues need to be considered (Fu et al., 2019).

4.2. Increasing bubble retention time

Increasing the bubble retention time could allow more CO_2 molecules inside the bubble to cross the gas-liquid interface and promote CO_2 dissolution (Cheng et al., 2006). Bubble retention time depends on the rising pathway and velocity of bubbles in PBRs and the solubility of CO_2. Prolonging the bubble retention time will improve the gas-liquid mass transfer efficiency. Xia et al. (2018) used flat plate PBRs with inclined baffles (Fig. 6e) to culture microalgae and found that the CO_2 retention time was extended from 0.448 s to 256 s. The concentration of microalgae and the CO_2 fixation rate were increased by 26.0% and 26.2%, respectively. The baffles' angles and the baffle opening distance-to-reactor width ratio were the key parameters determining the swirl flow and light regime performance. By optimizing the internal inclined baffles using a computational fluid dynamics model, Wang et al. (2021a) increased the microalgae biomass production to 45.7%. A spiral-ascending flow pattern of CO_2 bubbles can further enhance the CO_2 dissolution rate and bubble retention time. Xu et al. (2020a) designed a helical baffle and central hollow tube in the CO_2 dissolver (Fig. 6f) to improve microalgae growth. This novel CO_2 dissolver dramatically increased the bubble retention time by 190.2% and enhanced the mass transfer coefficient by 69.2%. This led to an increased microalgae biomass production by 40.8% with 15% CO_2 in the horizontal tubular photobioreactor. The cascade of PBRs can also effectively improve the bubble retention time of CO_2 and realize the gradient utilization of CO_2. Dasan et al. (2020) found the CO_2 fixation

Table 3
Performance comparison of various carbon capture enhancement for microalgae cultivation.

Type	Enhancement methods	Microalgae	Mass transfer coefficient	Cultivation system	Culture medium	vol% CO_2	Gas flow rate	Biomass yield (g/L)	Biomass increment	Reference
Reducing bubble diameter	Gas aerator (bubble diameter)									
	Rubber hose (6 mm)	*Nannochloropsis oculata*	≈0.05	Raceway pond	Sea water	11–14%	150 m^3/h	Na	25.0%	Cheng et al. (2015)
	Oscillating (1.14 mm)	*Chlorella mutant py-zu1*	0.15	Raceway pond	Brostol's solution	15%	250 ml/min	1.20	19.0%	Yang et al. (2016)
	Round distributor (1.8 mm)	*Chlorella pyrenoidosa*	≈20	Column PBR	Brostol's solution	5%	0.25 vvm	2.88	83.4%	Cheng et al. (2019c)
	Fibrous-diaphragm (1.18 mm)	*Arthrospira*	2.6	Raceway pond	Zarrouk medium	100%	0.0375 vvm	1.60	38.5%	Cheng et al. (2019b)
	Jet aerator (0.37 mm)	*Chlorellapy-zu1*	48.9	Flat-plate PBR	Modified bristol's medium	15%	0.1 vvm	1.33	49.4%	Cheng et al. (2019a)
	Three-stage shear-serrated (2.4 mm)	*Arthrospira*	3.24	Raceway pond	Zarrouk medium	100%	250 ml/min	1.40	46.8%	Cheng et al. (2020a)
Increasing bubble retention time	Internal structure									
	Perforated inverted arc trough	*Chlorella vulgarisfachb-31*	NA	Flat-plate PBR	Modified BG11	15%	0.02 vvm	3.35	20.9%	Xia et al. (2018)
	Spiral-ascending air dissolver	*Chlorellapy-zu1*	27.9	Horizontal tubular PBR	Modified SE medium	15%	0.1 vvm	5.13	40.8%	Xu et al. (2020a)
	Inclined baffles	*Haematococcus pluvialis*	NA	Flat-plate PBR	Bold's basal medium	Air	0.1 vvm	1.70	25.8%	Wang et al. (2021a)
	Lantern-shaped draft tube	*Chlorella py-zu1*	8.46	Column PBR	Artificial waste-water	15%	0.12 vvm	1.80	50.0%	Ye et al. (2018)
	Baffles	*Chlorella pyrenoidosa*	NA	Flat-plate PBR	Modified F–Si medium	2%	0.6 vvm	0.89	32.8%	Huang et al. (2015)
Chemical absorption of the CO_2	Absorbent solution									
	50 mg/L MEA	*Scenedesmus* sp.	NA	Tubular PBR	BG11 medium	5%	0.1 vvm	2.20	14.0%	Choi et al. (2012)
	0.2 mM MEA	*Spirulina* sp. LEB 18	NA	Tubular PBR	Zarrouk medium	NA	0.05 vvm	NA	31.4%	Rosa et al. (2015)
	50 mg/L MEA	*Chlorella fuscaleb* 111	NA	Column PBR	BG11 medium	Air	0.3 vvm	2.01	3.0%	Rosa et al. (2019)
	5 mM triethanolamine	*Scenedesmus accuminatus* AG10316	NA	Column PBR	BG11 medium	5%	0.1 vvm	2.75	30.5%	Kim et al. (2013)
	2 mM diethanolamine	*Scenedesmus accuminatus* AG10316	NA	Column PBR	BG11 medium	5%	0.1 vvm	2.42	10.0%	Kim et al. (2013)
	1.64 mM diethanolamine	*Spirulina* sp. LEB 18	NA	Tubular PBR	Zarrouk medium	Air	0.1 vvm	1.99	6.4%	Cardias et al. (2018)
	1.64 mM K_2CO_3	*Spirulina* sp. LEB 18	NA	Tubular PBR	Zarrouk medium	Air	0.1 vvm	2.04	9.1%	Cardias et al. (2018)
	1.64 mM diethanolamine and 0.41 mM K_2CO_3	*Spirulina* sp. LEB 18	NA	Tubular PBR	Zarrouk medium	Air	0.1 vvm	2.10	12.3%	Cardias et al. (2018)

efficiency by microalgae in the sequential-flow PBRs system was 3.78-fold higher than a single column PBR.

The enhanced carbon capture by reducing the generation diameter and increasing the retention time of the bubbles in the PBR is suitable for synthetic gas or flue gas sources with a low CO_2 concentration. Due to the limited carbon capture rate of microalgae, high CO_2 concentrations will cause most CO_2 molecules to be released from the liquid phase. This method of optimization for PBRs is highly universal for microalgae species. However, it is usually suitable for closed PBRs with high depths, and the upgrading efficiency is poor in open PBRs.

4.3. *Chemical absorption of CO_2*

To improve the carbon capture efficiency by microalgae, a novel approach that can capture CO_2 to microalgae in a single step was proposed. As shown in Fig. 6g, CO_2 is absorbed from a combustion flue gas into a potassium carbonate solvent which is then pumped through PBRs. The CO_2 desorbs into the microalgae culture medium and the depleted solvent is returned to the absorber (Zheng et al., 2016).

Solvent selection is one of the most important elements to improve CO_2 absorption efficiency. In recent years, different solvents, such as phase-change solvents and blending solvents, have been developed due to their potential for CO_2 absorption (Liang et al., 2016; Zhang et al., 2019). In the microalgae medium containing 300 ppm (4.92 mM) monoethanolamine (MEA), the solubility of CO_2 could be increased almost 6 times compared to the blank group. The carbon capture rate of microalgae was 539.6 mg CO_2/L/d, which increased by 63%. However, excessive amounts of MEA (>400 mg/L) inhibited microalgae growth,

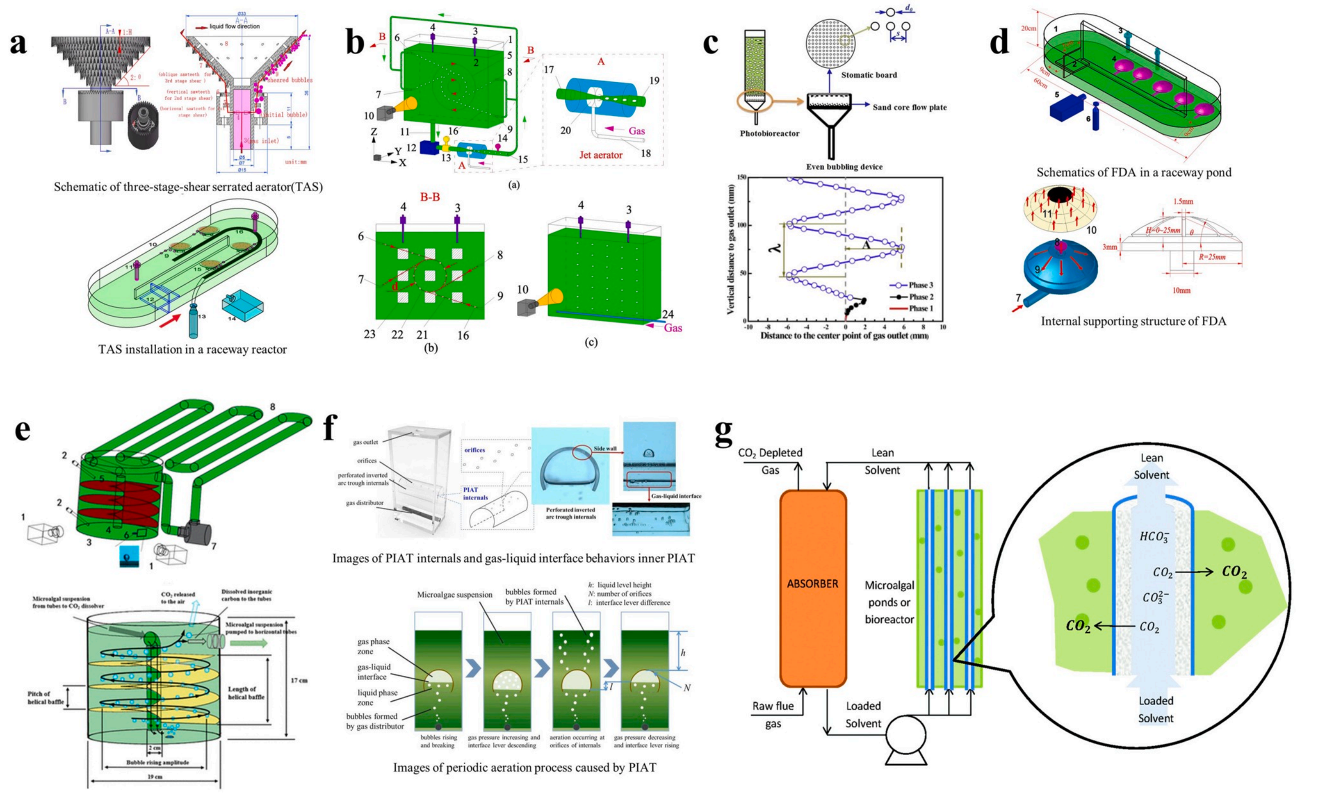

Fig. 6. PBRs design to enhance CO_2 capture by microalgae: a, b, c, d) different types of aerators. e, f) different ways to increase bubble retention time. g) typical reactor for chemical absorption of CO_2 (Cheng et al., 2019a, 2019b, 2020a; Huang et al., 2017b; Xia et al., 2018; Xu et al., 2020a; Zheng et al., 2016).

probably due to the toxicity of carbamate intermediates (Choi et al., 2012). Rosa et al. (2015) also found that the addition of MEA increased the microalgae biomass production by 31.4%, and the carbohydrate content in microalgae cells was almost 96.0% higher. Zhang et al. (2016) developed an effective CO_2 absorption system of a spraying absorption tower combined with a raceway pond for microalgae cultivation. The concentration of HCO_3^- generated in the spraying absorption tower was adjusted to maintain a constant pH in the raceway pond. The CO_2 capture efficiency by microalgae with the spraying tower reached 50%, while the bubbling method only achieved 11.17%.

The chemical absorption method avoids the problem of secondary emissions caused by the slow dissolution and absorption of CO_2 in the microalgae medium, and it is suitable for the fixation of a high concentration CO_2 flue gas. This method is suitable for microalgae species where HCO_3^- is the primary carbon source. This carbon replenishment process is suitable for PBRs with no requirements. Almost all kinds of microalgae cultivation systems can be used with this method for enhanced carbon capture.

5. Prospects and suggestions

Microalgae cultivation provides a sustainable solution for carbon neutrality in WWTPs. Although the use of different wastewater sources has been extensively studied, microalgae-based wastewater treatment technology is mostly conducted at the lab-scale or pilot scale, and there are still many problems that need to be solved to achieve large-scale applications.

The vast diversity of nutrients in different types of wastewaters has an important influence on the growth of microalgae. Research should be focused on utilizing various sources of wastewater as a well-balanced nutrient medium for microalgae cultivation. It is also necessary to identify and select a dominant microalgae species or consortium of multiple microalgae which are resistant to specific wastewaters. Furthermore, due to the cooperative relationships between microalgae and bacteria, microalgae-bacteria consortia can achieve the desired results (e.g., high nutrient removal, high biomass production, short hydraulic retention time, etc.). Ongoing research should focus on the selection and synthesis of viable microalgae strains to achieve consortium fortification in specific wastewater. Subsequent studies should focus on the optimization of community functions through bioaugmentation, genetic engineering, microalgae mutagenesis, etc.

The design and development of systems or PBRs that can be used for large-scale culture is a key task to realize microalgae-based wastewater treatment applications. To improve the treatment performance, the optimization of cultivation conditions in combination with some new technologies (micro-nano aeration, quantum planar waveguides, novel biomaterials, etc.) can be considered. The performance may be different after the system is scaled up to a large scale, so future research should focus on the large-scale treatment of real wastewater with microalgae to assess its feasibility and economics.

Enhancing carbon capture by microalgae will cause an increase in operating costs. For example, reducing the bubble diameter size will increase the energy consumption of aeration, and the implementation of a chemical absorption method will increase the chemical cost. Therefore, attention should be placed on finding a balanced relationship between the carbon capture efficiency of microalgae and cost control in the future. In addition, changes in aeration conditions (size, number, and pathway of bubbles) can directly affect the collision and attachment efficiency between microalgae cells and bubbles, which can promote the floatation separation of microalgae. Future studies should combine the cultivation of microalgae with flotation separation to reduce the concentration of suspended microalgae, and then reduce the subsequent harvesting cost (flotation reagents and energy consumption).

Effective systems or PBRs design and processes control require process models. However, when microalgae growth is combined with nutrient removal of wastewater, none of the existing models can effectively describe all the processes involved. More efforts are needed to establish uniform and accurate models to improve the adaptability of microalgae-based wastewater treatment technology to different application scenarios. The majority of current models in the literature are based on laboratory data. However, the goal of microalgae in wastewater treatment is the large-scale application, so focusing on laboratory data has significant limitations. By shifting modeling studies from short-term laboratory data to long-term large-scale data, some issues can be resolved or ameliorated.

6. Conclusions

Microalgae-based wastewater treatment technology showed significant benefits in comparison with the conventional wastewater treatment technology. It is also in conformity with the trend of process carbon neutrality in WWTPs, such as nutrient recovery, low energy consumption, and negative carbon emissions. Prior knowledge of the nutrient conditions of different types of wastewaters helps to build the pre-treatment strategy for microalgae cultivation. Although a range of microalgae cultivation systems has been developed, there are no systems that can be widely used. An ideal cultivation system should be designed depending on microalgae species and application scenarios. Modification of aerators and installation of deflectors are easily implemented in wastewater treatment facilities and further enhance the efficiency of carbon capture by microalgae. The chemical absorption method may hamper the subsequent resource valorization of microalgae due to the introduction of pharmaceuticals. Overall, there are still many challenges in large-scale applications that deserve further research.

Credit author statement

X.G.Y, conceived of the manuscript, wrote the manuscript with the participation of all authors, developed the figures. **L.B.Y**, conceived of the manuscript, wrote the manuscript with the participation of all authors, received the funding. All authors were involved in the discussion and manuscript revision. **X.F.Z**, conceived of the manuscript, received the funding. All authors were involved in the discussion and manuscript revision. **Y.L.Z**, conceived of the manuscript.

Declaration of competing interest

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

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