Microalgae-bacteria consortium for wastewater treatment and biomass production

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Abstract

The diversity of microalgae and bacteria allows them to form a complementary consortium for efficient wastewater treatment and nutrient recovery. This review highlights the potential of wastewater-derived microalgal biomass as a renewable feedstock for producing animal feed, biofertilisers, biofuel, and many valuable biochemicals. Data corroborated from this review shows that microalgae and bacteria can thrive in many environments. Microalgae are especially effective at utilising nutrients from the water as they grow. This review also consolidates the current understanding of microalgae characteristics and their interactions with bacteria in a consortium system. Recent studies on the performance of only microalgae and microalgae-bacteria wastewater treatment are compared and discussed to establish a research roadmap for practical implementation of the consortium systems for various wastewaters (domestic, industrial, agro-industrial, and landfill leachate wastewater). In comparison to the pure microalgae system, the consortium system has a higher removal efficiency of up to 15% and a twofold shorter duration. Additionally, this review addresses a variety of possibilities for biomass application after wastewater treatment.

Keywords: Microalgae; Microalgae-bacteria consortium, Nutrient removal; Wastewater treatment.

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1. Introduction

There has been a gradual shift in the role of wastewater treatment from a sole focus on sanitation to also include nutrient removal and recovery. Indeed, conventional activated sludge treatment is highly effective and efficient at removing pathogens and dissolved organic carbon, which is in part responsible for pathogen regrowth. To remove nutrients, additional steps or processes, such as nitrification/denitrification, anammox, and chemical precipitation must be integrated into conventional activated sludge treatment. While these treatment technologies have been widely used, they are complex, expensive and energy-intensive (Nhut et al., 2020; Wollmann et al., 2019). For example, the two key nutrients namely nitrogen and phosphorus can only be removed separately by for example anammox and chemical precipitation, respectively. Inadequate nitrogen and phosphorus removal from wastewater lead to eutrophication and other significant ecological damages (Lin et al., 2021; Vu et al., 2020).

In developing effective and energy-efficient nutrient removal technology, a consortium of microalgae and bacteria has excited the scientific interest of many researchers (Mohsenpour et al., 2021; Udaiyappan et al., 2020; Vuong et al., 2020; Zhang et al., 2020a). Microalgae and bacteria interact in various ways, from symbiotic (i.e. mutualism) to competition (i.e. antagonism) (Fallahi et al., 2021). The symbiotic interactions between microalgae-bacteria include nutrient exchange, cell-to-cell communication, and chemical compound stimulation (Zhang et al., 2020a). Microalgae may also detect quorum-sensing signal molecules, vitamins, and siderophores produced by bacteria, resulting in symbiotic relationships with improved bioactivity, elimination, and tolerance (Zhang et al., 2020a; Zhang et al., 2021). Creating a symbiotic relationship between microalgae and bacteria enhances wastewater treatment efficiency.

As a result, a microalgae-bacteria consortium is a viable option for wastewater treatment and bioenergy generation. On the other hand, the antagonism effect is often negligible compared to the overall beneficial relationship. The antagonistic interactions occur when the decay of dead microalgae competes for oxygen with bacteria (Chen et al., 2019; Qu et al., 2021). Furthermore, microalgae and bacteria can produce a wide range of inhibitory compounds that can harm the partner's growth (Khan et al., 2018; Meyer and Nodwell, 2021). It is noteworthy that most studies to date on microalgae-bacteria interactions have been conducted in a well-controlled condition in the laboratory to avoid cross contamination.

This review recapitulates the critical distinctions in microalgae-bacteria characterisation. The discussion delves into the symbiotic relationship between microalgae and bacteria in the nutrient removal process. While microalgae bacteria consortia interactions have been previously evaluated for their wastewater treatment performance, this review aims to compare the effectiveness of microalgae and microalgae-bacteria consortium for treating various wastewaters (domestic, industrial, agro-industrial, and landfill leachate wastewater) and to highlight the potential for biomass utilisation. Major challenges and future developmental research recommendations are also discussed in this review.

2. Microalgae and bacteria characteristics

Microalgae and bacteria can be found in all habitats, including water and sediment columns in freshwater and marine environments. Through photosynthesis, microalgae utilise energy from sunlight and carbon dioxide from the atmosphere. Then, it is used to synthesise biomass as a source of chemical energy for the overall ecosystem. On the other hand, bacteria are responsible for the decomposition and assimilation of organic materials. There is also some overlap between these two domains. Blue-green algae (or *cyanobacteria*) are strictly bacteria with photosynthesis capability. Thus, they function as microalgae in the ecosystem. When integrated, the biodiversity of microalgae and bacteria offers symbiotic benefits and significant economic-environmental value. Since bacteria have been thoroughly examined for wastewater treatment, the classification below focuses mostly on microalgae.

2.1. Pigment content and habitats

Colour is a convenient visual identification to classify microalgae. Most microalgae derive their primary colouration from *Chlorophylls* that are green. *Chlorophyll a* converts light (photons) to chemical energy. Other *Chlorophyll*s (e.g., *b,* c_1, c_2, and *d*) and *non-chlorophyll* pigments are accessory pigments to absorb a broader light spectrum. The energy is then transferred to *Chlorophyll a* for chemical energy conversion. Fig. 1 shows the wavelength of light absorbance of several classes of microalgae. Carotenoids have yellow-red colours. Lutein and other primary carotenoids act as non-chlorophyll accessory pigments, while secondary carotenoids (astaxanthin and canthaxanthin) are important in cell defence processes. Primary carotenoids are tightly tied to structural and functional components in the cellular photosynthetic machinery. By contrast, secondary carotenoids are produced in large quantities as oily droplets or a coating layer to protect microalgal cells from oxidative stress or intense illumination (Begum et al., 2016; Wang et al., 2015). Carotenoids are beneficial antioxidants to improve the immune system. Microalgae contain a much wider diversity of carotenoids than terrestrial plants. Microalgae are known to produce more than 40 type of carotenes and xanthophylls (Bjornland, 1989).

Phycobilin (e.g. phycoerythrin, phycocyanin, and allophycocyanin) is another group of non-chlorophyll accessory pigment. Unlike chlorophyll and carotenoids, phycobilin is water-soluble. *Cyanobacteria* (or blue-green algae), glaucophytes, red algae, and cryptophytes can all generate phycobilin. Phycobilin absorbs light in the blueish to the red range, which is beyond the range of most chlorophyll. Phycoerythrin captures light energy and directs it to the reaction site through the phycobiliproteins and phycocyanin. Phycocyanin is used as a pharmaceutical agent because of its antioxidant, anti-inflammatory, neuroprotective, and hepatoprotective properties (Sukhinov et al., 2021).

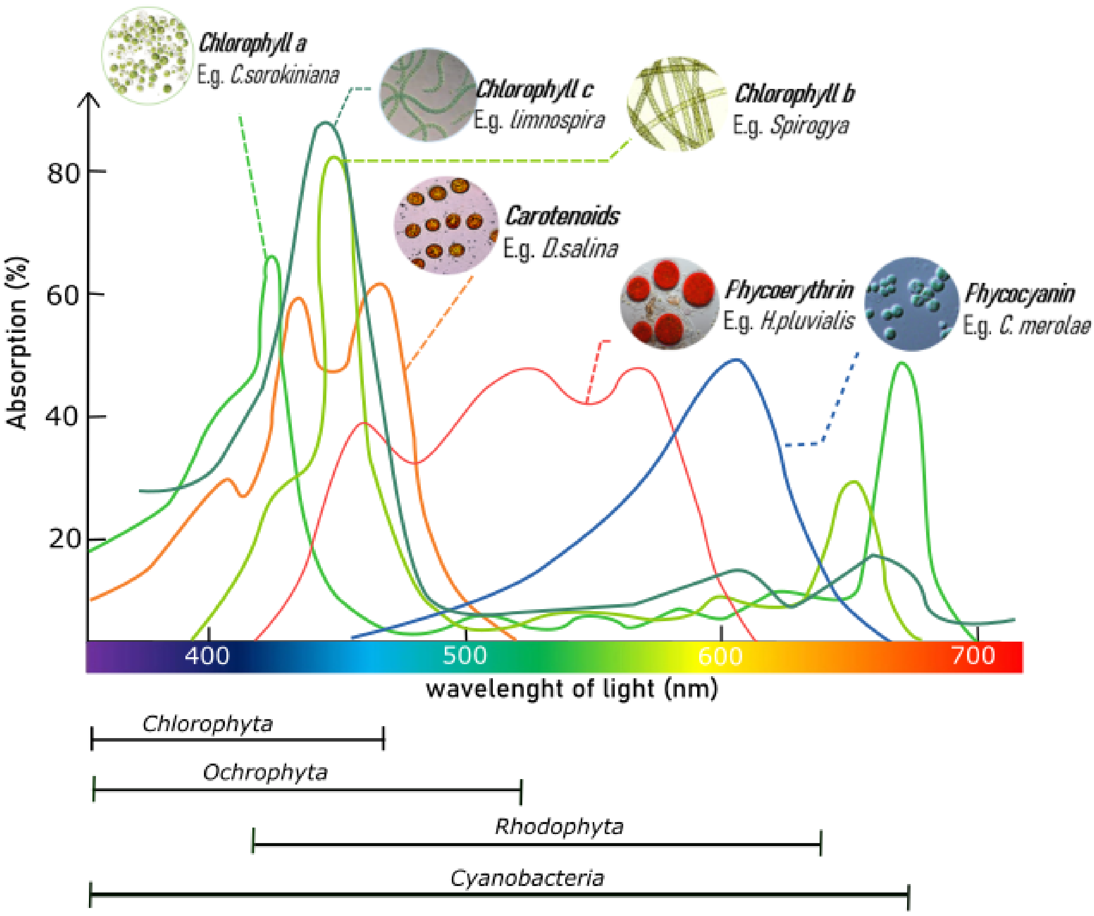

Fig. 1. The microalgae pigments absorbance spectrum of light.

The production of microalgal pigments depends on environmental conditions. For example, low light intensity presents higher biomass pigments content. The light intensity of 27 mol photon/m^2/sec produced a chlorophyll content of 14.7 mg/g, while the light intensity of 54 mol photon/m^2/sec produced a chlorophyll content of 11.6 mg/g (Begum et al., 2016). High salinity causes cell shrinkage and decreases the content of the pigment. The optimum temperature for *S. platensis* chlorophylls and phycocyanin were 25 °C and 28 °C, respectively, while carotenoids remained reactive at up to 60 °C in *N. gaditana* (Chauhan and Pathak, 2010; Macías-Sánchez et al., 2009; Nwoba et al., 2020).

Bacteria do not carry out photosynthesis (with the exception of *cyanobacteria*), and thus, they can produce a broader range of pigments such as melanin, violacein, and prodigiosin. Melanin can potentially be used to visualise the in vivo interaction in the consortia system. Melanised bacteria are also responsible for the anaerobic degradation of the organic compound trinitrotoluene in digested sewage (Wang et al., 2020). Violacein toxin may protect microalgae from omnivorous grazers (Ward et al., 2021). Despite the potential advantages of violacein pigment, its application for protecting microalgae cultivation still needs further investigation (Becker et al., 2021). By contrast, prodigiosin is a natural algicide (Wei et al., 2020; Zhang et al., 2020b). Thus, bacteria producing prodigiosin pigment are not compatible with the microalgae-bacteria system.

Microalgae can thrive in both fresh and saltwater habitats. On the other hand, bacteria can only thrive mostly in a low saline environment. This is because some microalgae can regulate and exchange ions with the environment. Saline water microalgae contain more ion transporters for photosynthetic machinery, nuclear, organellar, and cellular membrane activities than freshwater species (Nelson et al., 2021). Saline water microalgae tend to have a high content of lysine, which is an amino acid for regulating ions in algal cells. In most cases, lysine content in saline water microalgae is double than in freshwater species (Nelson et al., 2021).

2.2.Taxonomy

Microalgae can be either prokaryotic or eukaryotic microorganisms. Prokaryotic microalgae are essentially *cyanobacteria*, which can be strictly classified as bacteria. Eukaryotic microalgae include green algae (*Chlorophyta/Charophyta*), *Euglenophyta, Haptophyta, Dinoflagellates (Dinophyceae),* diatoms *(Bacillariophyceae), Eustigmatophyceae,* and red algae *(Rhodophyta).*

Cyanobacteria have *chlorophyll a* and complexes with light-activated enzymes. They are the only prokaryotic organisms that can undergo oxygenic photosynthesis. *Cyanobacteria* can be found in some of the most hostile and strangest habitats. For instance, after Mount Krakatau's (Indonesia) volcanic activity, *cyanobacteria* (*Anabaena* and *Tolypothrix*) were observed at the surface of volcanic ash (Gaysina et al., 2019).

A notable example of the *Chlorophyta* phylum is *Chlorella*, which is spherical or ellipsoidal, with diameters ranging from 2 to 15 μm. It contains *chlorophyll a* and *b*, as well as starch for reserve material. Among *Chlorophyta*, *C. vulgaris* is a highly utilised strain with high biomass production (Leliaert, 2019).

Euglenophyta is unicellular, motile, free-living microalgae typically found in freshwater. Due to the absence of *chloroplasts*, about two-thirds of *Euglenophyta* are *heterotrophic*. The energy storage product is arranged outside the *chloroplasts*. An example of this genus is *Euglena*. It has been recognised as a promising source of valuable biotechnological metabolites processes, like *paramylon*. (Kottuparambil et al., 2019).

The *Haptophyta* are primarily found in marine environments, with lower numbers found in freshwater and terrestrial environments. *Isochrysis aff. galbana* is a well-known example of *Haptophyta*. Many are characterised by *calcite (calcium carbonate)* scales covering the cell (coccoliths).

Dinoflagellates (*Dinophyceae*) are unicellular *biflagellate* organisms that live in various habitats and are often found in ocean or brackish water. Only half of this taxa can carry out photosynthesis. The rest lives in symbiosis with reef-building corals and is critical in forming coral reef systems. An example of this genus is *Gonyaulax*. *Gonyaulax* belongs to red *dinoflagellates* and commonly causes red tides (Borowitzka, 2018b).

The diatoms or *Bacillariophyceae* organisms can be either unicellular or colonial. The wall of this genus is made up of two valves that overlap and are constructed with *silicon oxide*. The vast majority of diatoms species is benthic microorganisms. *P. tricornutum* is the most well-known diatom (Bowler and Falciatore, 2019).

The *Eustigmatophyceae* cells are *spherical* or irregularly shaped coccoid unicells. They grow individually, but they can also grow in a colony in some cases. *Nannochloropsis* is an example of a species that has drawn economic and academic interest due to its potential (Gaber et al., 2021).

The red algae are a morphologically varied group that lives primarily in marine environments. These microalgae are spherical. They do not have flagella and can form loose colonies in a mucilaginous matrix. This genus species have arachidonic acid and pigments (phycobiliprotein and phycoerythrin) (Borowitzka, 2018a).

2.3. Growth forms

Microalgae tend to grow as individual cells a suspension, while bacteria tend to grow in colonies of aggregated cells as biofilm or aggregated flocs. Although less common, some microalgae can also grow in colonies, and some bacteria can grow as individual cells. Some microalgae can grow in a suspension to a certain size and then form a colony. Examples include *Collodaria, Chlorococcum sp.,* and *C. Meneghini. Collodaria* is unicellular microalgae that develop in single cells (up to 1 mm in size) or in colonies of a few centimetres in length (Villar et al., 2018). *Chlorococcum sp.* is a single green microalga that does not establish a colony (Putri et al., 2019). *C. Meneghini* lives as solitary cells or in temporary groups of indefinite form without a mucilaginous envelope (Correia et al., 2020). Colonial forms are constructed from *mucilage* cells bound physically and connecting the cells. The method of colony development and the kind of colony creation is used to split joined cells by *mucilage.*

Cell division and cell adhesion are the two processes that allow colonies to develop. Cells in cell division stay connected after binary fission, while single cells in culture cling to each other in cell adhesion. The ratio of total biomass to cell number, growth rate, bound extracellular polymeric substances (bEPS), zooplankton effects, and species were all found to be significant variations between these two methods (Xiao et al., 2017). In the cell division process, the cell has an additional bound-extracellular polymeric substance (bEPS) surrounding the cells (Xu et al., 2016). Meanwhile, no correlation was found between colony formation by cell adhesion. It can be interpreted that the adhesive polymers in the bEPS coating of a single cell can possibly be activated. Activation of this adhesion implies intercellular communication by a mechanism that has not yet been identified (Xiao et al., 2017). Cell adhesion and cell division mechanisms toward zooplankton resulted in different effects. The direct threat posed by zooplankton grazing leads to colony formation by cell adhesion. This response appears as a self-defence mechanism by microalgae cells because zooplankton has difficulties consuming the colonies (Yang et al., 2006; Yang et al., 2008). On the other hand, zooplankton filtrate causes colony formation through cell division (Yang et al., 2005; Yang and Li, 2007). The distinction between cell division and cell adhesion is illustrated in Figure 2

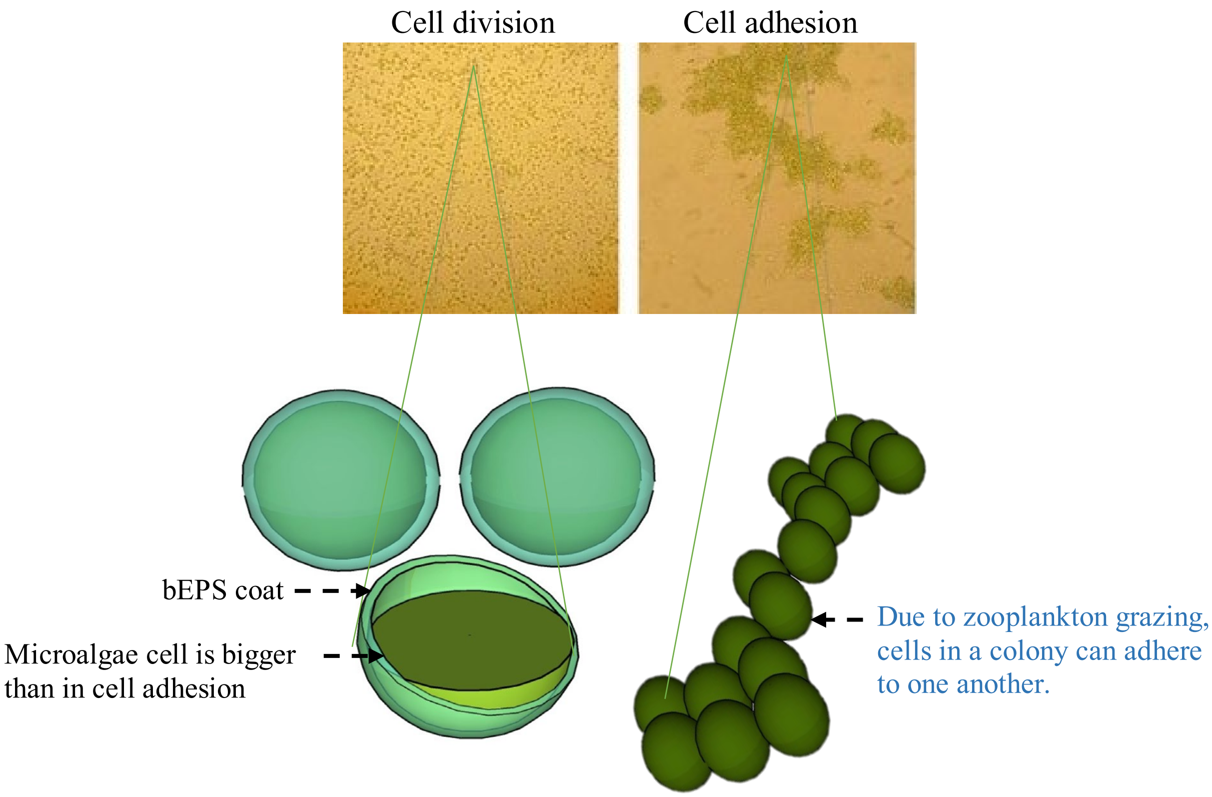

Fig. 2. Cell division and cell adhesion mechanisms of microalgae colony formation.

The kind of microalgae species has an impact on the colony development process. For example, *M. ichthyoblabe* colony formation is mostly based on cell division, while *M. wesenbergii* colony formation is primarily based on cell adhesion (Cao and Yang, 2010). It is possible that cell division and cell adhesion may be stimulated by either environmental stress or a direct danger. For example, colony formation in *M. aeruginosa* was triggered by *Ochromonas sp,* the grazing zooplankton. When microalgae form larger colonies than single cells, zooplankton's ability to graze was diminished (Yang et al., 2009).

The type of colony formation can be divided into two types: *amorphous* and *coenobium*. In the *amorphous* colony, the cell number, size, or shape can vary. All cells are independent and fulfil all functions of an individual. *Cyanophyta, Chlorophyta,* and *Rhodophyta* are the microalgae division belonging to this colony. *Coenobium* is a stalk, most of them can be found in *Chlorophyta* division, in which the cell has a structured arrangement with a specified number of cells. An exemplar of this conformation is in *S. quadriculata* colon-forming. The strain may have 2, 4, 8, 16, or 32 cells arranged linearly inside the umbilicus, with lengths ranging from 8.2 to 9.6 μm and widths varying from 2.4 to 8.2 μm (Queiroz et al., 2020). A new bacteria phenotyping technique allows the identification with an accuracy above 99.4%. This method can be used to examine the form of the colony in the microalgae-bacteria consortium system (Buzalewicz et al., 2021).

3. Microalgae-bacteria consortium for wastewater treatment

Wastewater discharge is a major pathway for nutrients (i.e. phosphorus and nitrogen) depletion in ocean water (Ansari et al., 2017). Each year, around 1 million tonnes of phosphorus and 7.7 million tonnes of nitrogen are released into natural water bodies via wastewater discharge. It causes eutrophication and environmental degradation (Vu et al., 2022). Microalgae based wastewater treatment can recover nutrients toward a circular bio-economy (Chong et al., 2022; Feng et al., 2021; Nguyen et al., 2021). To make microalgae work optimally and efficiently, the combination of internal and external parameters of microalgae should be explored. It includes every aspect from nutrient concentration ratio, percentage of CO_2 supply, the level of pH, the temperature of the growth medium, light intensity to metabolic engineering. Biochemical triggering is another way to stimulate microalgae metabolism. For example, phytohormones and substances, which modify biosynthetic pathways or function straightforwardly as metabolic precursors. Most of these growth-promoting substances can be generated by specific bacteria. A comprehensive understanding of the interaction between microalgae and bacteria is essential to improve the treatment performance, such as increasing the total nutrition removal. Microalgae and bacteria interact in various ways, from symbiotic to competition (mutualism to antagonism). The interactions between microalgal and bacterial communities are based on energy and nutrition exchange, signal transduction, and gene transfer. Key interactions between microalgae and bacteria in the system are summarised in Fig. 3.

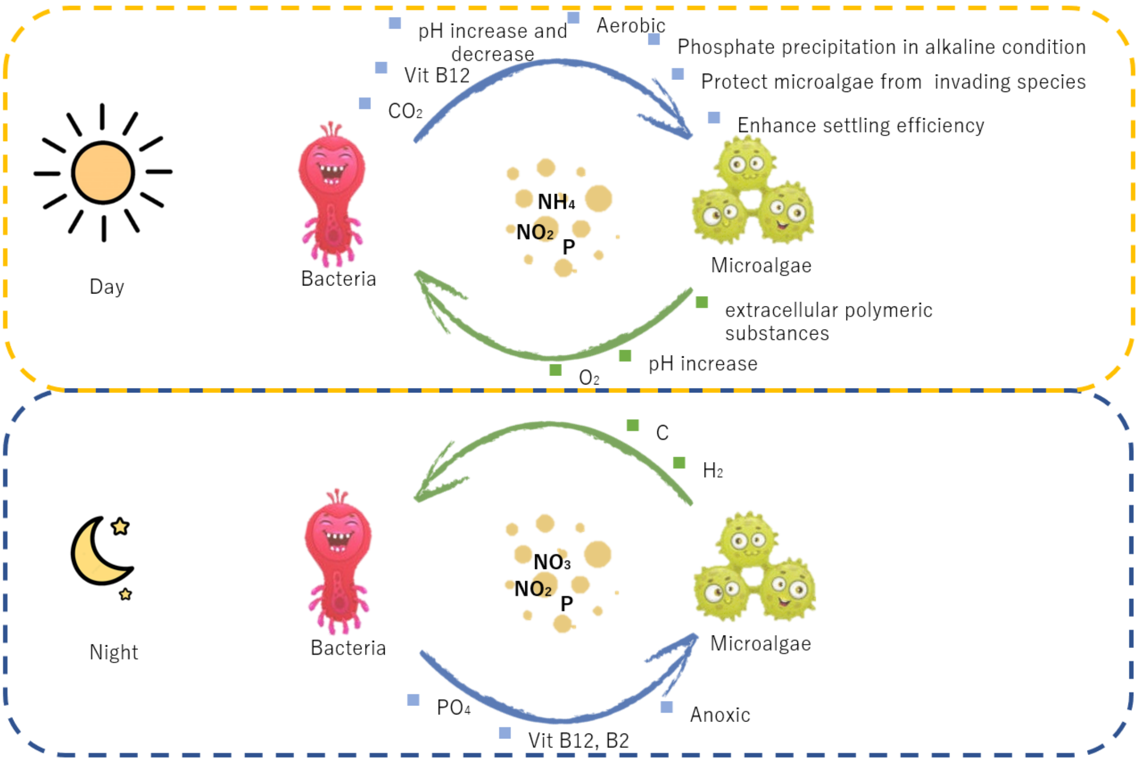

Fig. 3. A generic framework for microalgae and bacteria interaction modalities

Fig. 3 illustrates the exchange of carbon, energy, and key chemicals between microalgae and bacteria. For simplicity, Fig. 3 is presented as a lagoon microalgae-bacteria system that is subjected to a day and night solar cycle. Several co-factors that are important for metabolic processes by microalgae and bacteria are shown in Fig. 3. For example, microalgae produce O_2 for bacteria to utilise as an electron acceptor and energy source to break down organic matter, while microalgae utilise CO_2 bacterial transpiration as the carbon source (Chan et al., 2022; Xiao and Zheng, 2016). The antagonism effect may also occur in a dark condition when microalgae compete for oxygen with bacteria for respiratory (conversion of biomass to energy when energy from photosynthesis is not available) and due to the decomposition of dead cells.

Vitamin B plays a vital role in the symbiotic relationship between microalgae and bacteria (Blifernez-Klassen et al., 2021). The bacterium *A. brasilense* produces vitamin B_2 (riboflavin and lumichrome), plant growth stimulants during the fermentation process. These two substances impacted *C. sorokiniana's* development and metabolism (Lopez et al., 2019). Vitamin B_{12} is produced by bacteria either in the aerobic or anaerobic pathways. Vitamin B_{12} helps control microalgae development and community composition. Photosynthesis by microalgae resulted in an increase in pH (day time), whereas bacteria metabolism produces organic acid to lower the pH (night time).

Nitrogen removal by conventional wastewater is governed by a slow kinetic process involving two stages: nitrification by ammonia-oxidizing bacteria and denitrification by nitrite-oxidizing bacteria and denitrifying bacteria (Huang et al., 2020;

Nhut et al., 2020). Anammox is an alternative process that is faster and more efficient. Still, the anammox process itself cannot remove dissolved organic carbon and must also be integrated with a conventional wastewater process. On the other hand, microalgae assimilate nitrogen by using intracellular nitrate reductase enzymes, nitrate trans-membrane transporters, etc. The main advantage of the consortium system is the combined synergistic metabolism. Microalgae assimilate ammonia and produce oxygen through photosynthesis in the combined synergistic metabolism. Bacteria use oxygen to convert ammonia and nitrite while secreting carbon dioxide (Qu et al., 2021). In comparison to a single microalgae system, the consortium system removed 13.6% more ammonia, it was also 44% more than activated sludge systems (Chen et al., 2019). This synergetic interaction also led to a rapid nitrification process (Bankston et al., 2020). To remove 60-80% of ammonia, the consortium system only required 1 to 2 days of hydraulic retention time, whereas pure-microalgae systems required 2 to 5 days (Maza-Márquez et al., 2018). Inadequate nitrogen leads to an antagonism effect (competition). It would lead to cell death and the release of intracellular ammonium (Chen et al., 2019; Qu et al., 2021).

A microalgae-bacteria consortium system can use two distinct mechanisms for phosphorus removal: microalgae treatment after the enhanced biological phosphorus removal process and phosphate precipitation. In the microalgae treatment after the enhanced biological phosphorus removal process, the orthophosphate and carbon dioxide produced by bacteria can be converted to oxygen by microalgae (Higgins et al., 2018). Phosphate precipitation occurs during the daytime due to microalgae photosynthesis (Xu et al., 2020). Microalgae photosynthesis changes the pH of the culture. Each nitrate ion creates one OH^- ion as it degrades to ammonia (Chai et al., 2021). It allows bacteria to release algaecides. Algaecides have an antagonistic effect on microalgae, causing them to secrete extracellular polymeric substances. This situation encouraged the precipitation of phosphorus in extracellular polymeric molecules (Sells et al., 2018).

Most bacteria associated with microalgae enhanced microalgal bio-flocculation by producing polysaccharides or proteins, making the harvesting process more efficient and cost-effective (Chan et al., 2022). Microalgae provide bacteria with organic carbon and oxygen, whereas bacteria provide fixed nitrogen, micronutrients and stimulate microalgal development (Qi et al., 2021). On the other hand, microalgae can produce a wide range of inhibitory compounds that can interfere with bacteria's growth. For example, microalgae can produce extracellular proteins such as dissolved amino acids and antibiotics, which inhibit bacterial growth (Khan et al., 2018). By contrast, algicidal bacteria can produce harmful microbial substances like cellulase to disintegrate the cell wall of microalgae cells and lyse them (Jia et al., 2014; Meyer and Nodwell, 2021).

It is essential to select suitable species for the microalgae-bacteria symbiotic system. Some microalgae have a higher level of bacterial interaction than others—for example, the cell-to-cell exchange comparison of elements between the microalgae *P. tricornutum*-bacteria and *N. salina*-bacteria. In *P. tricornutum*, 92-98% of cells were attached with bacteria and fixed 64% carbon, while in *N. salina*, only 42-63% of cells had attached with bacteria and fixed just 10% carbon (González-González and de-Bashan, 2021).

The nutrient removal efficiency comparison between an integrated microalgae-bacteria system and single microalgae is described in each type of wastewater origin section, namely domestic wastewater, industrial wastewater, agro-industrial wastewater, and landfill leachate. Studies on microalgae-bacteria interactions have mainly been conducted on the lab-scale since it is more restricted and less contaminated, and the results are easier to interpret. Table 1 summarises and compares nutrient removal and biomass production by a microalgae-bacteria consortium.

Table 1. Comparison of nutrients removal and biomass production by microalgal-bacteria consortium on various types of wastewaters (TN: total nitrogen; TP: total phosphorus)

Wastewater type	Wastewater source	Microalgae	Bacteria	Initial concentration	Duration (days)	T (°C)	Nutrient removal efficiency	Biomass yield (g/L)	Biochemical composition	Ref.
Domestic wastewater	Beibei wastewater treatment plant, Chongqing	*Chlorella, chroococcus sp. and Scenedesmus sp.*	*Oscillatoria sp.*	NH_4^+-N: 40 mg/L PO_4^{3-}-P: 10 mg/L	8	22	NH_4^+-N: 99% PO_4^{3-}-P: 100%	1.5	Urocanic acid: 19.45 ± 2 μg/L	(Gou et al., 2020)
	Trento Nord treatment facility	*Chlorella and diatoms*	*filamentous cyanobacteria* and heterotrophic bacteria	NH_4^+-N: 50 mg/L NO_3-N: 1.2 mg/L PO_4^{3-}-P: 2.8 mg/L	182	22.8	TN: 12.6 % TKN: 97% TP: 47%	~0.8	-	(Foladori et al., 2018b)
	Primary treated wastewater from University Rey Juan Carlos (Spain)	*C. sorokiniana*	activated sludge *(Rhodobacteraceae and Rhizobiaceae family)*	NH_4^+-N: 34.1 mg/L NO_3-N: 1.2 mg/L PO_4^{3-}-P: 4.9 mg/L	22	24	NH_4^+-N: 71.4% PO_4^{3-}-P: 68.3%	0.3	-	(Barreiro-Vescovo et al., 2021)
	Local WWTP in Kuala	*S. obliquus (17%)*	activated sludge (83%)	TN: 26 mg/L	30	24	TN: 20%	9.3	-	(Purba et al., 2021)

	Lumpur, Malaysia			TP: 6.2 mg/L			NO_3-N: 72% TP: 5%			
	LBZ municipal WWTP, Wuhan, China	*C. sarokiniana,*	activated sludge *(Nitrosomonas and Dechloromonas)*	NH_4^+-N: 25 mg/L PO_4^{3-}-P: 3 mg/L	30	25	NH_4^+-N: 98% PO_4^{3-}-P: 96%	2.5	-	(Fan et al., 2020)
Industrial wastewater	Textile Industry	*C.sorokiniana DB WC2, Chlorella sp*	*K. pneumoniae OR WB1, A. calcoaceticus OR WB3*	NH_4^+-N: 119 mg/L NO_3-N: 110 mg/L PO_4^{3-}-P: 53.2 mg/L	7	30	TN: 71% PO_4^{3-}-P: 100%	0.67	-	(Goswami et al., 2019)
	Textile Industry	wild sample of a mixed algae	wild sample of a mixed bacteria	TN: 74.1 mg/L TP: 86.4 mg/L	5	37	TN: 53% TP: 50%	0.1-0.5	-	(Raza et al., 2021)
	Vinegar production wastewater	*Chlorella sp*	*B. fluminensis*	TN: 20.5 mg/L TP: 7.4 mg/L			TN: 78.7% TP: 74.8%	5.55	Notable effect on fatty acid composition rather than oil content	(Huo et al., 2020)

	Beer brewing factory	*C.vulgaris MACC360*	Native bacteria from sludge (beer brewing factory)	TN: 60 mg/L TP: 11 mg/L	3	24	TN: ~75% TP: ~75%	-	Total H_2 production: 65%	(Shetty et al., 2019)
	Paper Industry	*C.sorokiniana DB WC2, Chlorella sp*	*K. pneumoniae OR WB1, A. calcoaceticus OR WB3*	NH_4^+-N: 303 mg/L NO_3-N: 187 mg/L PO_4^{3-}-P: 77.7 mg/L	7	30	TN: 89.3% PO_4^{3-}-P: 100%	2.97	The yield of bio-crude oil: 15% (w/w)	(Goswami et al., 2019)
	Leather Industry	*C.sorokiniana DB WC2, Chlorella sp*	*K. pneumoniae OR WB1, A. calcoaceticus OR WB3*	NH_4^+-N: 89.9 mg/L NO_3-N: 162 mg/L PO_4^{3-}-P: 48.3 mg/L	7	30	TN: 55.6% PO_4^{3-}-P: 100%	0.48	-	(Goswami et al., 2019)
agro-industrial wastewater	Unsterilised palm oil mill effluent	*Scenedesmus sp.*	Anaerobic bacteria	TN: ~190 mg/L TP: ~142 mg/L	30		TN: 92% TP: 70%	-	*Actinomycetes* percentage increased	(Udaiyappan et al., 2020)
	Potato processing plant	*C. sorokiniana*	*M. capsulatus*	NH_4^+-N: 19 mg/L PO_4^{3-}-P: 14 mg/L	1	37	TN: 67% TP: 43%	0.21	32% carbohydrates 34.5% lipid	(Rasouli et al., 2018)

Dairy wastewater from Gomati Cooperative Milk Producers' Union, India.	*some of Chlorophyceae, C. variabilis, P. kessleri, P. tricornutum, Chlamydomonas Synechocystis sp.,*	*T. elongatus, M. aeruginosa, Nostocales, Naviculales, Oscillatoriales, Stramenopiles, Trebouxiophyceae, Chroococcales, along with potential bacterial bioremediate*	NO_3-N: 139 mg/L NH_4^+-N: 16 mg/L PO_4^{3-}-P: 63 mg/L	14	25	NO_3-N: 93% NH_4^+-N: 100% PO_4^{3-}-P: 97%	-	18% protein 42% lipid 55% carbohydrates	(Biswas et al., 2021)
Dairy Farm wastewater	*C. sorokiniana DBWC2* and *Chlorella sp. DBWC7*	*K. pneumoniae ORWB1* and *A. calcoaceticus ORWB3.*	NO_3-N: 1730 mg/L PO_4^{3-}-P: 44 mg/L	7	30	NO_3-N: 84.7% PO_4^{3-}-P: 100%	2.87	-	(Makut et al., 2019)
Piggery wastewater	*C. vulgaris*	*R. sphaeroides*	NH_4^+-N: 385 mg/L TN: 469 mg/L TP: 55 mg/L	7	28	NH_4^+-N: 100% TN: 95% TP: 96%	4.09	The combined content of carbohydrate, lipid, and protein was higher than 85%	(You et al., 2021)

	Piggery wastewater (20%)	*S. almeriensis*	*Nitrospira,* and *Nitrobacter*	NO_3-N: 137 mg/L PO_4^{3-}-P: 26 mg/L	4		NO_3-N: 90% PO_4^{3-}-P: 100%		-	(Sánchez -Zurano et al., 2021b)
	Starch wastewater	*C. vulgaris*	*R. sphaeroides*	NH_4^+-N: 878 mg/L TN: 1492 mg/L TP: 154 mg/L	7	28	NH_4^+-N: 100% TN: 95% TP: 96%	0.96	-	(You et al., 2021)
	20% Erin Landfill site, Chesterfield, UK	*C. vulgaris*	*Nitrosomonas*	N-NH_3: 491 mg/L PO_4^{3-}-P: 320 mg/L	8		N-NH_3: 99.2% PO_4^{3-}-P: 100%	2-fold	Increased total organic carbon degradation	(Okurowska et al., 2021)
landfill leachate	10% lagoon in Nicosia	*Chlorophyceae species (Chlorella sp, Scenesdesmus sp, Stigeoclonium sp)*	*Cyanobacteria (Microcystis sp, Oscillatoria sp),*	NH_4^+-N: 256 mg/L NO_3-N: 874.8 mg/L PO_4^{3-}-P: 97.5 mg/L	14	18	NH_4^+-N: 99.8% TN: 99.1 mg/L PO_4^{3-}-P: 98.8%	-	The relative toxicity of the leachate was reduced in relation to the phenol removal.	(Tighiri and Erkurt, 2019)

	Sandtown Land fill in Felton, DE.	wild sample of a mixed algae	wild sample of a mixed bacteria	NH_4^+-N: 5.1 mg/L	366		NH_4^+-N: 83%	-	-	(Sniffen et al., 2018)
	30% dumpsites landfill, Chennai, India	*C. Pyrenoidosa*	bacterial nitrogen fixation	TN: 228.4 mg/L PO_4^{3-}-P: 31.6 mg/L	20	26	TN: 70% PO_4^{3-}-P: 89%	2.8	-	(Nair and Nagendra, 2018)

3.1. Domestic wastewater

Domestic wastewater is a nutrient-rich resource. The concentration of nutrients in residential wastewater varies depending on climate, socioeconomic conditions, and several other factors. Untreated domestic wastewater, on average, contains 59–653 mg/L of total nitrogen and 10-16 mg/L of phosphate (Thomas et al., 2016; Wulan et al., 2022).

A key benefit of the microalgae-bacteria consortium system over a single system is higher efficiency and faster nutrient removal. The photosynthetic activity of *C. vulgaris* provided sufficient dissolved oxygen for nitrifying bacteria, which boosted the ammonia removal rate. Ammonium removal was mostly accomplished by nitrifying bacteria with support from microalgae. As a result, the ammonia removal rate was higher than algae and bacteria monocultures (Fallahi et al., 2021).

The other advantages of the consortium system are flocculation and aeration. An enclosed culture system of microalgae-bacteria to treat municipal wastewater had been reported by Foladori et al., (Foladori et al., 2018b) at a plant of 100,000 person equivalents in capacity at Trento Nord in Italy. Even though real wastewater had significant changes in influent concentrations, this microalgae-bacteria consortium maintained high and stable removal efficiency (Foladori et al., 2018a). Furthermore, dense flocs might be produced by a combination of *Chlorella*, *Diatoms*, filamentous *cyanobacteria*, and heterotrophic bacteria. This system resulted in a self-sustaining therapeutic approach and may not necessitate extra aeration (Foladori et al., 2018a). This behaviour differed significantly from wastewater treatment using pure *Chlorella.* Without adequate mixing, pure microalgae might settle to the bottom and gradually perish, impacting nutrient removal efficiency (Serrano-Bermúdez et al., 2020; You et al., 2022).

Species selection must be considered for optimal performance. For example, *S. obliquus* and activated sludge bacteria were utilised to treat local wastewater treatment plants in Kuala Lumpur, Malaysia (Purba et al., 2021). However, it could only remove 20% of total nitrogen after 30 days. Previous results suggest that *C. sorokiniana* microalgae is more compatible with *Rhodobacteraceae and Rhizobiaceae* family than with the *Nitrosomonas or Dechloromonas* in activated sludge. The *C. sorokiniana* and activated sludge *(Rhodobacteraceae and Rhizobiaceae* family) removed 98% of nitrogen and 96% of phosphorus within 7 hours (Barreiro-Vescovo et al., 2021). While, *C. sorokiniana* and activated sludge *(Nitrosomonas and Dechloromonas)* were only able to remove 71.4% of ammonia nitrogen in 14 days, since the microbial needed about 9 days to achieve steady-state condition (Fan et al., 2020). This comparison indicated that species selection is one of the prerequisites for the effectiveness of treatment, and each species has a different survival rate. The species selection is also important for obtaining the required biomass quality for further use.

3.2. Industrial wastewater

Microalgae-bacteria remediation of industrial-derived wastewater is an alternative treatment method for removing nutrients with reduced chemicals and energy consumption. Industrial wastewater can have a high concentration of specific contaminants. Thus, an axenic (pure) microalgae culture system may not be sufficiently resilient to thrive in industrial wastewater (Hena et al., 2021). Factors such as extreme pH and toxicity from specific contaminants in industrial wastewater can inhibit an axenic microalgae system. In the microalgae-bacteria consortium system, the bacteria could support the microalgae. For example, microalgae used bacteria-produced siderophores as iron replacements in iron-deficient environments. Gaseous exchange (CO_2-O_2) between microalgae and bacteria also helps the consortium to be more resilient to unfavourable environmental conditions (Goswami et al., 2019). The microalgae-bacterial consortium was also more compact than the combination of each individual system (Huo et al., 2020). Their interconnections can share metabolites and the ability to endure periods of nutrient limitation, combating invasion by other species and maintaining microorganism stability, providing robustness to environmental oscillations.

3.3. Agro-industrial wastewater

Agro-industrial wastewater tends to have higher nitrogen and phosphorus concentrations than domestic wastewater (Biswas et al., 2021; Makut et al., 2019; Udaiyappan et al., 2020). Botanical food processing effluent differs depending on the fruit or vegetable used—for example, palm oil mill effluent (POME) wastewater was treated with three native microalgae (*Coelastrella sp*. UKM4, *Chlamydomonas sp.* UKM6, and *Scenedesmus sp.* UKM9) (Udaiyappan et al., 2020). The raw POME contained *Actinobacteria, Bacteroidetes, Planctomycetes, Firmicutes* and *Proteobacteria*. Over 80% of nitrogen was removed from both sterilised and raw POME. A sterilised POME could only remove 10% of the phosphorus, whereas a raw POME could remove up to 70% (Udaiyappan et al., 2020). Bacteria were eliminated in the sterilised POME, which explained the 60% difference in phosphorus removal efficiency. Botanical food processing wastewater is the most environmentally friendly, and it may be utilised as fertiliser, animal feed, and biofuel. The biomass of *P. purpureum* that flourished in POME was rich in essential minerals, including Fe, K, and N. These are crucial nutrients for plant development. Thus, this biomass was appropriate for conversion to biofertiliser (Osman et al., 2020). After sage and potato processing wastewater treatment, the consortium biomass could be used as animal feed (Noguchi et al., 2021; Rasouli et al., 2018). The biomass from coffee processing effluent boosts methane yield by up to 87% and could be easily converted into biofuel (Passos et al., 2018).

Dairy wastewater tends to have higher nitrate content than most other wastewater (Biswas et al., 2021; Makut et al., 2019). Pure microalgae work slowly on this type of wastewater (Arif et al., 2021; Posadas et al., 2014). It is possibly because the ratio between nutrients was insufficient for its metabolism. The pure microalgae culture could only remove about 65% of nitrate (from the initial concentration of 62.7 mg/L) after 6 days of treatment (Hemalatha et al., 2019). On the other hand, the microalgae-bacteria consortium removed more than 85% of 1730 mg/L (Makut et al., 2019). The presence of nitrate-reducing bacteria helps higher nutrient removal. The lipid content of the microalgae-bacteria consortium biomass was more than 45%. This could be due to the nitrogen present mostly in the form of amino acids. It also had a high lactose content. Overconsumption of lactose would be stored as fats. This biomass is a viable candidate for protein supplements for animal feed, biofertilisers and defatted biomass as feedstock for bioethanol production (Gramegna et al., 2020; Talapatra et al., 2021).

S. almeriensis, *Nitrospira,* and *Nitrobacter* removed 90% nitrogen from animal effluent in 2 days (Sánchez-Zurano et al., 2021b). In contrast, pure microalgae (*Scenedesmus sp.*) required 9 days to remove 83% of nitrogen (Svierzoski et al., 2021). The addition of bacteria to the system improved nutrient removal and duration efficiency. However, ammonium toxicity is the main drawback of microalgal growth in piggery wastewater (You et al., 2021). Pre-treatment, such as dilution, filtration, and the addition of chemical solutions, is required to minimise the high-strength ammonium. An integrated system can help build a circular economy in the future. The process begins with the nutrient-rich faeces from animals treated using anaerobic digestion and microalgae. The microalgae biomass are then harvested and fed to the animals (Fuentes-Grünewald et al., 2021).

3.4. Landfill leachate

The main components of landfill leachate, which may harm the environment, are ammonium toxicity and xenobiotics (Tighiri and Erkurt, 2019). Microalgae could be killed immediately if ammonia concentrations exceed 80 mg/L (Nawaz et al., 2020). Due to their high toxicity, lengthy persistence, and low biodegradability, many xenobiotic chemicals negatively influence microalgae. The addition of denitrifying bacteria and phenol-degrading bacteria aided the microalgae's adaptation. The denitrifying bacteria consume nitrogen, whereas microalgae consume phosphorus. As a result, the removal efficiency was higher than pure microalgae treatment (Okurowska et al., 2021; Porto et al., 2021).

In recent decades, the landfill leachate has been diluted to be treated effectively. Landfill leachate has high turbidity and thus low light penetration. A novel tubular photo-bioreactor using a rotating optical reflector has been proposed by Porto et al. (2021). This technique improved removal efficiency by over 21% compared to conventional photo-bioreactors (Porto et al., 2021). The summary comparison of the consortium and pure microalgae system can be seen in Table 2.

Table 2. A comparison of the culture efficacy for wastewater treatment of microalgae and a microalgal-bacteria consortium.

Parameter	Pure microalgae treatment	Microalgal-bacteria consortium treatment
N removal (of 40-50 mg/L NH_4^+-N)	58% (Li et al., 2019)	99% (Gou et al., 2020)

P removal (of 60 mg/L PO_4^{3-}-P)	10% (Udaiyappan et al., 2020)	70% (Udaiyappan et al., 2020)
Dissolved oxygen (mg/L)	< 3 (Udaiyappan et al., 2020)	< 2 (Udaiyappan et al., 2020)
Duration (to remove >83% of 137 mg/L NH_4^+-N)	9 days (Svierzoski et al., 2021)	2 days (Sánchez-Zurano et al., 2021a)
Biomass production	2 fold (Udaiyappan et al., 2020)	4 fold (Udaiyappan et al., 2020)
Lipid productivity	17% (Hernandez-Garcia et al., 2019)	42% (Biswas et al., 2021)
Operation cost	Need additional aeration and more space because the water level must be maintained below 15 cm (You et al., 2022)	Costless (may not necessitate extra aeration) (Foladori et al., 2018a)

4. Microalgae-bacteria consortium biomass utilisation

Biomass from the microalgae-bacteria consortium can be utilised for various applications, including biochemical production, animal feed, biofertiliser, and biofuel (Chia et al., 2022; Chong et al., 2022; Dang et al., 2022). The cultivation process ultimately dictates potential applications of the produced biomass. Nutraceuticals, cosmetic products, and food ingredients can be made from microalgae; however, these applications are unsuitable for a consortium system due to wastewater input and the bacterial component. Thus, only compatible applications are discussed below when considering the type of microalgae for each desirable end-product.

4.1. Biochemicals

Microalgae can be an excellent source of biochemicals, given the high content of lipids, carbohydrates, proteins, and other specific biochemicals. Some microalgae contain up to 40% of their overall mass in fatty acids, such as *C. reinhardtii* 49.9% (Yaakob et al., 2021) and *I. galbana* 47% (Zarrinmehr et al., 2020). These fatty acids might be used for nutritional and therapeutic purposes (Michelon et al., 2021). *C. stigmatophora* (~55%) and *C. vulgaris* (>52%) are examples of microalgae with high carbohydrate contents (de Souza et al., 2019). Carbohydrates from microalgae, apart from alcohol, could be converted to bioplastic and can be produced using wastewater (Rocha et al., 2020). *Cyanobacteria* also produce *exopolysaccharides* which could be utilised as a gelling agent, thickening, stabilising agent, bio-lubricants, and anti-inflammatory agents (Michelon et al., 2021; Xiao and Zheng, 2016). Protein in microalgae is generally found in the form of amino acids. *S. maxima* and *S. platensis* had all the necessary amino acids in quantities acceptable for diabetes and obesity treatment (Ramos-Romero et al., 2021; Soletto et al., 2005). *Cholecystokinin* may be activated by proteins from microalgae or plants, which can lower cholesterol levels. They also play an important role in the human enzymatic process (Yaakob et al., 2021). Fig. 4 compares the biochemical composition of common microalgae strains (Dosta et al., 2008; Levasseur et al., 2020; Rodolfi et al., 2009; Sajjadi et al., 2018).

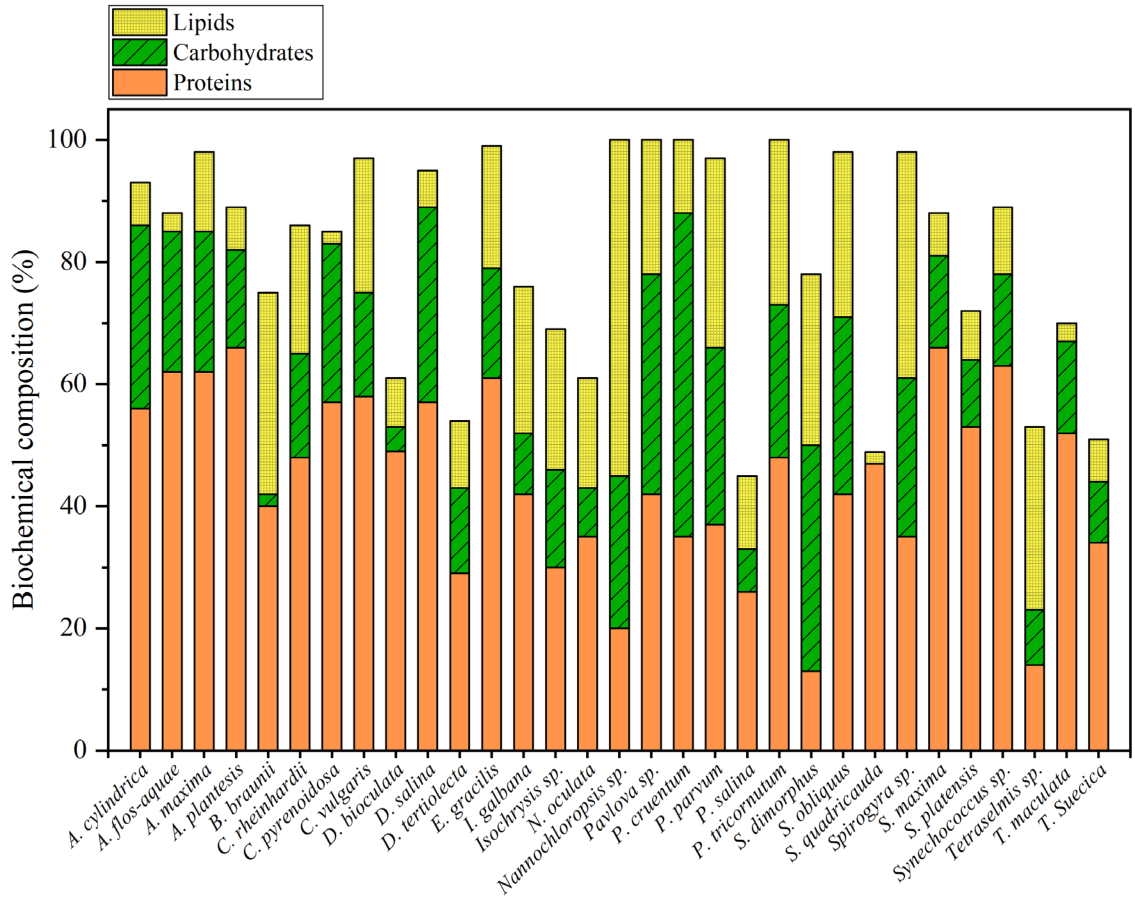

Fig. 4. Macromolecule organic compounds composition in common microalgae.

Adding bacteria to microalgae culture changes the biochemical composition significantly. Microalgae-bacteria consortium of *A. brasilense Cd* and *A. protothecoides UTEX 2341* improved the protein up to 40-60% (Peng et al., 2020). The consortium system of *M. capsulatus* and *C. sorokiniana* enhanced carbohydrates by 42% and lipid by 15% (Rasouli et al., 2018). The pigment levels also increased rapidly (Vuong et al., 2020). However, due to the interaction with bacteria, the lipid enhancement could be in the form of extracellular polymeric compounds.

4.2. Animal feed

Microalgae is a treasure trove for dietary supplements for aquaculture and live-stocking. For instance, feeding ornamental goldfish (*Carassius auratus*) with microalgae had improved colouration (Kiran and Venkata Mohan, 2021). *Nannochloropsis sp.* used in finfish hatcheries had showed enhanced DPA/EPA levels. When poultry birds (chickens, ducks, turkeys, and quail) were fed microalgae, their body weight rose dramatically (Ekmay et al., 2014; Saadaoui et al., 2021; Vethathirri et al., 2021). When chickens were given *H. pluvilais, N. gaditana*, and *Spirulina sp*., they had more muscle pigmentation, antioxidant components in the liver, and carotenoid colouration in egg yolks (Wu et al., 2019). Astaxanthin is a red pigment that contains antioxidants and other health advantages (Torregrosa-Crespo et al., 2018). It helps treat various cancers, prevent heart disease, and many others. Astaxanthin is found in many sea species, such as lobsters, salmons, shrimps, and crabs. In fact, sea species such as wild salmons have pink flesh as they eat plankton containing astaxanthin. Farmed salmon has a light flesh which is appealing to customers. In the past, synthetic astaxanthin was fed to farmed salmon to recreate the natural pink colouration similar to wild fish. Synthetic astaxanthin contains impurities that may pose a health problem to the consumers; thus, they are banned in several countries such as Australia and New Zealand. Here, the *H. pluvialis* microalgae can offer a perfect solution to farmed salmon. They offer a natural source of astaxanthin to farmed salmon. They were 90 times more effective at providing the pink colour to salmon flesh than synthetic astaxanthin without any toxicity effect. Additionally, the microalgae-bacteria consortium system can produce stronger aromas than pure culture, enhancing its attractiveness as a feed for animals (Sakarika et al., 2020). The consortium system, however, frequently occurs in flocs. Hence, using such flocs as feed could harm the animals' health by obstructing shrimp gills and even cause death. Agro-industrial wastewater is the most suitable wastewater for producing animal feed using the microalgae-bacteria consortium.

4.3. Biofertilisers

Microalgae cultivated in wastewater can be used as a biofertiliser or soil additive (Das et al., 2019). Soil nitrogen and phosphorus levels and several other plant-required trace elements (Ca, K, Fe, and Mn) can be improved by microalgal biomass. When combined with soil phosphorus solubilising organisms, microalgal fertilisers exhibited a greater phosphorus release in non-sterile soil (Solovchenko et al., 2021). The biomass derived from landfill leachate can be directly converted into biofertiliser. The biomass should be blended with palm oil to be used as a biofuel, since this biomass contains low monounsaturated acids (Tighiri and Erkurt, 2019).

Microalgae (including *cyanobacteria*) application to tomato plants showed a considerable increase in the biochemical and metabolomics connected to the plant's defence systems (Garcia-Gonzalez and Sommerfeld, 2016; Rachidi et al., 2021; Yan et al., 2022). Another research found that utilising filamentous microalgae strain as bio-fertilizers enhanced the dry weight of wheat plants by 30% and its biochemical composition (Renuka et al., 2016; Umamaheswari and Shanthakumar, 2021). The symbiotic system between microalgae and bacteria can easily transform organic and inorganic chemicals into plant-digestible molecules, making them efficient biofertilisers (Ferreira et al., 2019).

4.4.Biofuel

It is widely accepted that the third generation of biofuel is a fuel produced from microalgal biomass. Microalgae cultivation does not compete with the production of food on arable land. Microalgae grow much faster than land-based energy crops and can double their biomass within a few hours (Okoro et al., 2019). Microalgae lipid yield is 15–300 times greater than traditional oil crops, and since it is an aquatic plant, it does not compete for land with food crops (Zullaikah et al., 2019). Around 0.7–30.6% of free fatty acids and 4.1–77.5% of triglycerides were contained in microalgae lipid (Kim et al., 2021; Yao et al., 2015). Microalgae also contain unsaponifiable matter (0.4–20.9% of hydrocarbons, 0–83.2% of phytol, and 7.8–90.0% of sterols) and *Chlorophyllides* (5.8–16.8%) (Yao et al., 2015). This unsaponifiable matter can be readily converted to biodiesel and aviation fuel (Mofijur et al., 2021; Siddiki et al., 2022). Biodiesel production from microalgae to blend with or completely replace jet fuel has been demonstrated in recent years (Mofijur et al., 2021). The addition of bacteria can double lipid content and productivity by the *indole-3-acetic acid* released by plant growth-promoting bacteria (Chen et al., 2019). The high lipid content may also relate to nutritional deficiency caused by microbial competition between microalgae and bacteria. This technique is advantageous for large-scale biofuel production (Biswas et al., 2021). Domestic wastewater is a viable option for microbial biofuel production since it can be grown continuously on a large scale.

Sustainable aviation fuel from microalgal lipids can be produced by transesterification and hydro-processing. The lipid quality depends on microalgae strains. For example, *T. maculata* had a less than 4.5% total lipid concentration. In contrast, *Schizochytrium sp.* had a total lipid content of more than 80% (Siddiki et al., 2022), The unmodified biofuel *Chlorella sp. NT8a* could meet several aircraft fuel standards (Mofijur et al., 2021). The current method of converting microalgae to jet fuel costs 2 to 8 times more than regular jet fuel. Although several technological innovations have been created, they have not been able to significantly reduce the aviation industry's carbon footprint (O'Malley et al., 2021; Peter et al., 2021). In the future, proper planning optimisation and simulation are required to reduce operational expenses. Immediate reductions can be achieved via improving multi-stakeholder collaboration, including biofuel producers, aircraft manufacturers, operators, and the government.

4.5.Future direction

A thorough examination of the microalgae-bacteria interaction mechanisms in wastewater treatment and how such interactions aid in the formation and maintenance of long-term systems are currently lacking. A significant concern is to utilize microalgae-bacteria consortia system in large-scale wastewater treatment. To maximise the performance of the microalgae-bacteria consortium, many aspects should be examined and investigated further. However, information about the microalgae-bacteria interactions at molecular level are still limited. This can be accomplished using microbiological and biochemical analysis techniques (Fallahi et al., 2021). Future studies should investigate on what actually happens in in-vivo that allows bacteria to continuously secrete lytic enzymes that cause microalgal cell structures to degrade (Wang et al., 2020). For example, by using melanized bacteria. Another promising approach is to predict and manage interactions across various microorganisms using genome-scale modelling. however, the amount of information available on this technique is still limited (Zuñiga et al., 2020). Future study also should examine light/dark cycle effect on the consortia system since it has an effect on microalgae and denitrifying bacteria. Moreover, the distinction between microalgae-bacteria consortium metabolites and interactions should be investigated extensively to improve the microalgae-bacteria wastewater treatment process.

Modification of photo-bioreactor configuration is necessary to optimise microalgal-bacterial wastewater treatment, preventing biomass detachment and minimising external disturbance. For example, adding an optical reflector and the tubular photo-bioreactor rotating horizontally improved the removal efficiency by over 21% (Porto et al., 2021). Suitable operating techniques could also improve extracellular polymeric substances production or cell attachment and minimise the duration (Wang et al., 2022).

Finally, techno-economic evaluation should be a primary concern to establish a clear vision of commercialisation efficiencies. Since the current method of converting microalgae into biofuel are still not economically feasible (Aron et al., 2021). A comparative life cycle assessment research must examine the whole process chain's energy balance and possible environmental implications. For example, creating an integrated system by leveraging a low-cost CO_2 source from flue gas, nutrient-rich wastewaters, and bacteria harvesting methods reduces energy usage. Some software packages, such as BIO ALGAE, could be used to test the suggested system while also lowering costs. BIO ALGAE help estimate the simultaneous effects of various parameters on pollutant removal pathways and improve bioreactor design and parameter control. This mechanistic model tool can reproduce the pattern of the experimental data (Andreotti et al., 2020).

5. Conclusions

Data corroborated from this review highlights the potential of the microalgae-bacteria consortium for wastewater treatment and nutrient recovery. The review consolidates the current understanding of microalgae characteristics and their interactions with bacteria in a consortium system. Microalgae and bacteria can thrive in a variety of conditions, and interact in various ways, from mutualism to parasitism. This review discusses the comparison of recent studies on the practical implementation of pure and consortium systems in various wastewater treatments (domestic, industrial, agro-industrial, and landfill leachate wastewater). It highlights the ability of a microalgae-bacteria consortium to utilise nutrients from wastewater and produce valuable microalgae-based products. This review also discusses the potential of wastewater-derived microalgal biomass as a promising feedstock for animal feed, biofertilisers, biofuel, and many valuable biochemicals. The applications of wastewater-derived microalgal biomass are discussed, and examples are presented in this study. This review also examines major challenges and future developmental research recommendations.

CRediT authorship contribution statement

Lisa Aditya: Conceptualization, Writing - original draft. T.M.I Mahlia: review & editing; Luong N. Nguyen: review & editing; Hang P. Vu: review & editing. Long D. Nghiem: Supervision, Conceptualization, Writing - review & editing

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