Indian J Microbiol (July–Sept 2021) 61(3):262–269
https://doi.org/10.1007/s12088-021-00924-8

REVIEW ARTICLE

Microalgal-Bacterial Consortia as Future Prospect in Wastewater Bioremediation, Environmental Management and Bioenergy Production

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Received: 2 December 2020 / Accepted: 7 February 2021 / Published online: 22 February 2021

Abstract In the recent years, microalgae have captured researchers' attention as the alternative feedstock for various bioenergy production such as biodiesel, biohydrogen, and bioethanol. Cultivating microalgae in wastewaters to simultaneously bioremediate the nutrient-rich wastewater and maintain a high biomass yield is a more economical and environmentally friendly approach. The incorporation of algal–bacterial interaction reveals the mutual relationship of microorganisms where algae are primary producers of organic compounds from CO_2, and heterotrophic bacteria are secondary consumers decomposing the organic compounds produced from algae. This review would provide an insight on the challenges and future development of algal–bacterial consortium and its contribution in promoting a sustainable route to greener industry. It is believed that microalgal-bacterial consortia will be implemented in the near-future for sub-sequential treatment of wastewater bioremediation, bioenergy production and CO_2 fixation, promoting sustainability and making extraordinary advancement in life sciences sectors.

Keywords Microalgal-bacteria consortium · Bioenergy · Environmental management · Wastewater bioremediation · Bioeconomy

Introduction

It is undeniable that microalgae play a significant role in representing the fundamental plant producers and promising feedstock in the biological community. In the recent years, microalgae has been placed in the spotlight as the alternative feedstock for renewable bioenergy production. The awareness of utilizing microalgae as an alternative feedstock has evolved from laboratory research into industrial scale mainly stemming from the economic and environmental benefits that have been reported by numerous studies [1–3]. The ability of these photosynthetic microalgae to absorb carbon as nutrients has mitigated the concerns on carbon dioxide (CO_2) release to the atmosphere and this makes them attractive for the emerging circular bioeconomy comprising of carbon footprint reduction with renewable soruces generation [4]. Considering the impractical cost of typical microalgae cultivation (i.e., using cultivation medium and water), the substitution of medium with wastewater sources through assimilation of nutrients from wastewater sources has shown great prospects [1, 3]. This approach will be more economical and environmentally friendly in the upstream processing by simultaneously bioremediating the nutrient-rich wastewater and maintaining a high biomass yield [5].

Alternatively, ecological studies revealed that specific groups of bacteria have similar association with certain microalgae through synergistic influence to obtain physical and metabolism benefits [6]. The incorporation of algal–bacterial interaction revealed the mutual relationship of

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microorganisms where algae are primary producers of organic compounds from CO_2, and heterotrophic bacteria are secondary consumers that decompose these organic compounds produced [7]. The limitations associated with microalgae cultivation could be addressed by introducing algal–bacterial symbiosis which can provide a positive effect on the upsurge of algal growth, spore germination, pathogen resistance, harvesting process and morphogenesis, making it beneficial for various biotechnological applications [8]. Ongoing researches on algal–bacterial consortia have been recognised for their scientific contribution in promoting sustainability and greener industry for creating advancement and impact to life sciences research [9–11].

The writing and conceptualization of this review was conducted via online databases search to identify similar research studies, where four keywords (i.e. microalgal-bacterial; bioenergy; environmental management and bioremediation) were used to identify related articles (46 results found) to obtain information from peer-reviewed journals, scientific reports and books related to this review topic. Subsequently, this review focused on articles within 5 years (2015–2020) and 43 relevant articles were found. Among these articles, their suitability and relevancy were manually screened before included into the review. The selected articles were categorized into their respective subsections namely bioenergy production, wastewater bioremediation and environmental management. This review will provide insights on the future development of algal–bacterial consortia and its contribution in promoting a sustainable route to greener industry.

Insights of Microalgal-Bacterial Consortia in Wastewater Bioremediation

Wastewater sources such as municipal wastewater, industrial wastewater, rubber effluent and palm oil mill effluent have to be treated before discharging into water bodies as they composed of large amount of contaminants (e.g., ammonium ions (NH_4^+), nitrate ions (NO_3^-) and phosphate ion (PO_4^{3-}) [12]. Microalgal-bacterial consortium has shown its capabilities for bioremediating contaminants, absorbing nutrients, reducing chemical oxygen demand (COD), total dissolved phosphorus (TDP), total dissolved nitrogen (TDN) and biochemical/biological oxygen demand (BOD) as a biological tool for environmental control [13]. The symbiosis interaction between microalgal-bacterial consortium undergoes exchange of O_2, CO_2 and NH_4^+ ions in the wastewater treatment process, where these bacteria oxidize organic carbon compounds in the wastewater sources and convert them into CO_2 (Fig. 1). The produced CO_2 by bacteria was then respirated by these algae for photosynthesis and conversion of CO_2 to algal cell materials [14]. The removal efficiency of nutrient from wastewater sources with symbiosis interaction of microalgal-bacterial will also increase with rise in the biological metabolism of biomass growth. Apart from its utilization for detoxifying organic and inorganic pollutant from wastewater sources, it can recover resources for bioeconomy of both high- and low-value products (i.e. fertilizers, algal-based plastics and fibres and aquaculture feed). Table 1 summarized the microalgal-bacterial consortium used in various wastewater bioremediation.

Insight of Microalgal-Bacterial Consortia in Bioenergy and Bioproduct Production

Microalgae-based biofuels are considered an important energy source due to its availability, rapid productivity and CO_2 fixation in regards to the current world energy crisis [25, 26]. There are various bioenergy and bioproducts production such as biochar, biofuels and even secondary metabolite available from utilizing microalgae. The process "pyrolysis" is to convert algal biomass into biochar which is enriched with carbon to enhance the pH of acidic soil condition. The composition of these algal-based biochar composed of high nutrient content (i.e. nitrogen, phosphorus and inorganic element) to enhance the soil fertility for agricultural purposes. Besides that, algal-based biochar has also been subjected as bio-sorbents for wastewater remediation purposes due to its specific functional group presence on the surface of biochar [27].

As for biofuel production (e.g., biodiesel and biohydrogen), these anaerobic bacteria and microalgae consortia will undergo direct or indirect pyrolysis to produce biohydrogen. It has been proposed that the production of O_2 from microalgae are done through respiration by the bacteria which is beneficial in maintaining an anaerobic environment for biohydrogen production without sulfur deprivation [28]. This finding was supported by Wirth et al. [29] revealing that *Rhizobium* sp. consumed O_2 concentration of 21.0% to 4.5% in 12 h, which simultaneously allowed 1.15 ± 0.01 ml/L of H_2 produced by microalgae biomass in the next 16 h. However, there was no H_2 production by microalgae biomass without the presence of *Rhizobium* sp. in the microalgal culture. On the other hand, the presence of these bacteria enhanced the growth rate of microalgae by providing phytohormones or macro- and micro-nutrients within 10–70% biomass productivity [10]. This was supported by Leong et al. [1] who reported the feasibility of microalgal-bacterial interaction in promoting simultaneous nitrification and assimilation activities for high biomass and lipid production of 1.42 g/L and 0.242 g/L, respectively in municipal wastewater. These are

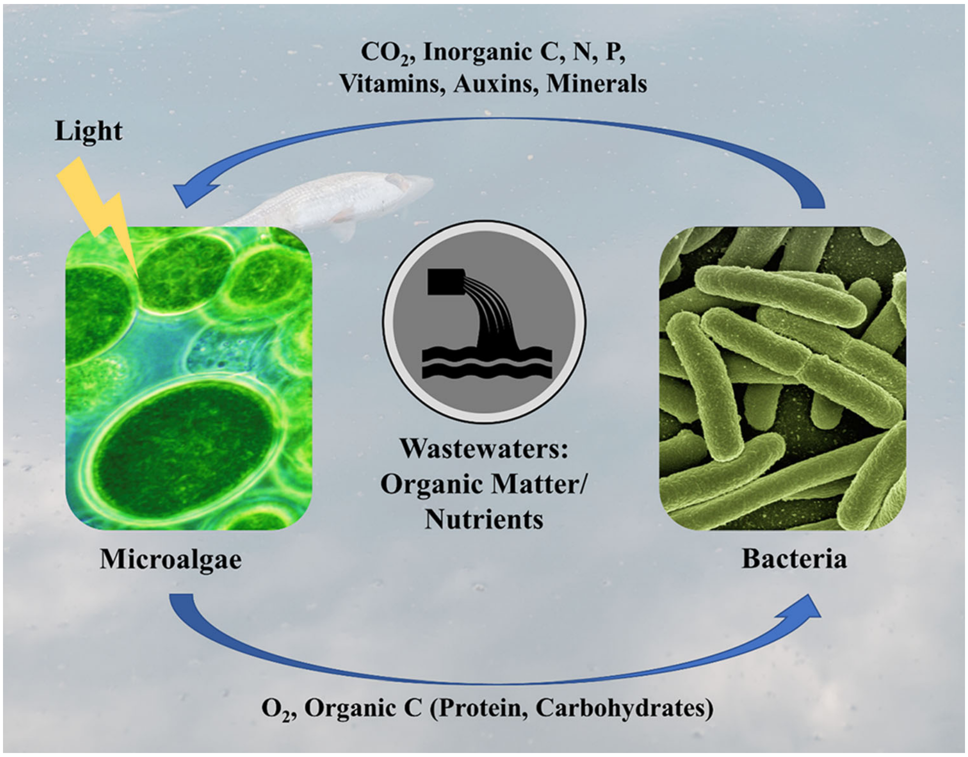

Fig. 1 Symbiosis interaction between microalgal-bacterial interaction in the wastewater treatment

several studies associated to the evaluation of microalgal-bacterial consortia for biofuel production [24, 30–34].

Recent researches have shown the potential of these microalgae as a prospective source of valuable bioproduct for direct human supplement and nutritional product [35]. The transformation of microalgal-bacterial biomass into high value-added commodities would provide a more sustainable and economical process for the downstream bioprocessing industries. For instance, the biosynthesis of polyhydroxyalkanoates (PHAs) derived from microalgal-bacterial consortia and it is considered as a promising green alternative over conventional petrochemical-based plastics [36]. The properties of PHAs obtained from bacterial-based is similar with the conventional plastics, but with added-value such as biodegradability and biocompatibility properties [37]. It has been successfully demonstrated by Fradinho et al. [38] on utilizing microalgal-bacterial consortia for the production of PHA content as high as 20% PHA storage yield per acetate depending on the culture condition [38]. Despite of its advantages, the commercialization of utilizing microalgal-bacterial consortia remains a challenge where external factors that includes the capital cost, market demand, public acceptance, environmental and health risk are needed to be addressed [39].

Insight of Microalgal-Bacterial Consortia in Greenhouse Gases CO_2 Fixation

Carbon dioxide, CO_2 is one of the main contributors of greenhouse effect exhaust from fossil fuel combustion which is directly contributed to global warming. Based on recent study, the CO_2 concentration is over 400 ppm, which is the highest level in over 800,000 years [40]. As mentioned above, microalgae have the capability in consuming high values of CO_2 by converting them into chemical energy with the presence of sunlight; as compared to terrestrial plant, CO_2 fixation efficiency of microalgae are 10 to 50-folds higher [41]. In the microalgal-bacterial symbiotic interaction, the exchange of substrate CO_2 and O_2 are needed for both algae growth and CO_2 fixation. As proposed by Subashchandrabose et al. [42], microalgal-consortium is a more environmentally friendly method towards carbon mitigation. This revealed that photosynthetic microalgae are proficient resources for CO_2 fixation in the framework of a sustainable low-carbon economy [43].

It has also been reported that *Thalassiosira pseudonana* diatom, and heterotrophic bacteria *Pelagibacter* sp. HTCC1062 (SAR11) increases the carbon fixation rate by 20.3% [44]. Moreover, this was supported by Gao et al. [45] who conducted the co-culturing of *Chlorella vulgaris* with activated sludge bacteria and the results exhibited optimal CO_2 removal efficiency of 63.48%. Table 2

Table 1 Microalgal-bacterial consortia utilized in various wastewater bioremediation

Algae	Bacteria	Source of wastewater	Total nutrients removal efficiency	References
Chlorella vulgaris (No. FACHB-8)	*Bacillus licheniformis* (No. 1.7461)	Municipal river in the Yangpu District of Shanghai, China	COD: 86.6% (175.8 mg L^{-1}) TDP: 80.3% (4.97 mg L^{-1}) TDN: 88.9% (31.2 mg L^{-1})	[15]
Chlorella sp.	Heterotrophic bacteria	Municipal wastewater from Trento Nord WWTP	COD: 86.0 ± 2% (37.0 mg L^{-1}) Total Kjeldahl nitrogen, TKN: 97.0 ± 3% (0.5 ± 0.7 mg NH$_4^+$-N/L	[16]
Scenedesmus quadricauda (AG10003)	Activated sludge from local sewage treatment plant in Daejeon, Republic of Korea	Coke wastewater of a steel manufacturing company in the Republic of Korea	NH$_4^+$-N removal: 8.3 mg L^{-1} d^{-1} Total phenol: 27.3%	[17]
*Chlorella vulgaris (*AG 30,007)	*Pseudomonas putida*	Synthetic municipal wastewater	COD: 86.0% (490.0 mg L^{-1}) NH$_4^+$-N removal: 85.0%: (190.0 mg L^{-1}) PO$_4^{3}$-P removal: 66.0% (40.0 mg L^{-1})	[18]
Chlorella vulgaris	*Rhizobium* sp.	Synthetic municipal wastewater	Total organic carbon: TOC 60.8% (127.0 mg L^{-1}) Total nitrogen: 69.1% (21.7 mg L^{-1}) Total phosphate: 98.9% (0.07 mg L^{-1})	[19]
Scenedesmus acuminatus	Filamentous bacteria	Milk whey processing wastewater	COD: 93.0% (982.0 mg L^{-1}) TDN: 88.0% (52.0 mg L^{-1}) Total phosphate: 69.0% (17.0 mg L^{-1}) NH$_4^+$-N removal 88.0% (31.0 mg L^{-1})	[20]
Chlorella sorokiniana (FACHB-275)	Activated sludge bacteria from municipal WWTP, Wuhan, China	Domestic wastewater in Wuhan, China	COD 88.0–90.0% (2500 mg L^{-1}) NH$_4^+$—N removal: 82.0–98.0% (2500 mg L^{-1}) PO$_4^{3}$-P removal: 92.0–98.0% (2500 mg L^{-1})	[21]
Chlorella sp.	*Beijerinckia fluminensis*	Vinegar production wastewater from Hengshun Vinegar Industry Co., Ltd., Zhenjiang, Jiangsu, China	COD: 76.7% (740 mg L^{-1}) Total nitrogen: 78.7% (20.5 mg L^{-1}) Total phosphate: 74.8% (7.4 mg L^{-1})	[22]

Table 1 continued

Algae	Bacteria	Source of wastewater	Total nutrients removal efficiency	References
Selenastrum bibraianum	Activated sludge bacteria from printing and dyeing wastewater treatment plant in Shihezi, China	Printing and dyeing wastewater treatment plant in Shihezi, China	COD: 70.0–85.0% NH_4^+-N removal: 84.9–89.7% Total phosphate: 30.2–37.7%	[23]
Navicula sp.	*Comamonada-ceae* and *Nitroso-monadaceae,* ammonia oxidizing bacteria	Municipal wastewater treatment plant in Tianjin, China	COD: 95% (600 mg. L^{-1}) NH_4^+-N removal: > 99% (50 mg. L^{-1}) Total phosphate: 31.0–42.0%	[24]

Table 2 Microalgal-bacterial consortia in CO_2 fixation

Microalgae	Bacteria	Experimental set-up condition	CO_2 removal rate	References
Tetraselmis chuii and *Nannochloropsis gaditana*	Algal pond bacteria	39 L photobioreactor, 1767 µmol m^{-2} s^{-1}, 12 h:12 h light:dark cycles, 24% of CO_2, 76% of N_2 and 498 ± 63 mg m^{-3} of toluene	89.0–97.0%	[46]
Chlorella vulgaris	Activated sludge collected from wastewater treatment plant of Nanjing, Jiangsu, China	16.8 L glass photobioreactor, 200 µmol m^{-2} s^{-1}, 34.69 ± 2.46% (v/v) of CO_2	53.24–63.48%	[45]
Scenedesmus obliquus	Activated sludge collected from wastewater treatment plant of Nanjing, Jiangsu, China	16.8 L glass photobioreactor, 200 µmol m^{-2} s^{-1}, 34.69 ± 2.46% (v/v) of CO_2	51.46–62.29%	[45]
Chlorella vulgaris	Mixed anaerobic sludge collected from the bottom of septic tank	500 mL bubble column photobioreactors, 24 µmol m^{-2} s^{-1}, 12 h using cool white fluorescent, 10 ± 2% CO_2 (v/v)	190.9 ± 8.6 mg $L^{-1}d^{-1}$	[47]
Chlorella vulgaris	Nitrifier-enriched activated sludge from municipal wastewater treatment plant	1 L conical flask, 2000 lx	90% (156 mg)	[48]

summarized the CO_2 removal efficiency by microalgal-bacterial consortia. Based on these published articles and evaluation in this review, microalgal-bacterial consortia will be implemented in the near-future for sub-sequential treatment of wastewater bioremediation, bioenergy production and CO_2 fixation.

Challenges and Perspectives

The algal-bacterial symbiosis has higher proficiency to bioremediate toxic contaminants from the wastewater compared to the single bacterial or algal system because it can compensate in terms of pollutant removal, cost-efficient aeration, and greenhouse gases sequestration. However, consortia involving microalgae and mixed microflora from activated sludge are not usually focused on, and the complexity of the microorganisms in the consortia leads to difficulty in controlling the system stability and this would affect the outcome of wastewater treatment [49]. The screening study of specific symbiotic bacterial strains and subsequent selective establishment of a stable system are essential. Enzymology requires further exploration, particularly the enzymatic mechanism between microalgae and bacteria throughout the wastewater bioremediation process. Moreover, algal-bacterial consortia shows potential for improved biohydrogen production, but it still has low recovery rates and yields, even way before its readiness to industrial application. Strategies such as genetic modifications, cell immobilization, physiological treatments like Mg deprivation, light modulation and oxygen scavengers should be investigated for further improvement of H_2 production. For an economic production of biofuel and final commercialization of microalgal-bacterial bioenergy, techno-economic assessment (TEA) and life cycle assessment (LCA) are important tools in terms of resource availability, economic feasibility, productivity of microalgal-bacterial consortia, environmental sustainability, quality of energy dynamics and renewability. On the other hand, promising biotechnological applications of microalgae-bacterial consortia such as CO_2 fixation are lacking of convincing data from the actual applications based on the current knowledge [50]. This is because these studies are conducted in lab units and has not been applied in scale-up conditions such as different system capacity and external factors like seasonable environmental changes may also affect the algal-bacterial system. Hence, besides studies on community structures and interaction between microalgae and bacteria, future research requires large scale outdoor experiments to evaluate its economic viability and sustainability of these biotechnological applications.

Conclusion

In brief, the system of algal–bacterial consortium can be applied in wastewater bioremediation, bioenergy production and CO_2 fixation. The utilization of algal–bacterial symbiotic system in wastewater treatment technology can result in higher algal biomass and higher contaminant removal, thus minimizing the cultivation of microalgae culture and bioremediation cost for polluted wastewaters. Moreover, anaerobic bacteria and microalgae consortia undergo direct or indirect pyrolysis to produce biohydrogen and they can maintain an anaerobic environment for biohydrogen production since bacteria consumes the oxygen produced by microalgae. Additionally, microalgal-bacterial consortium can increase the carbon fixation rate with much higher efficiency compared to terrestrial plants. The processes utilizing microalgal-bacterial consortia are indeed renewable and sustainable technology to be applied in the current microalgal industry, along with more future research on microalgal-bacterial interaction mechanism, economical analysis for the commercialization and upscaling for further potential applications.

Acknowledgements This work was supported by the Fundamental Research Grant Scheme, Malaysia [FRGS/1/2019/STG05/UNIM/02/2] and MyPAIR-PHC-Hibiscus Grant [MyPAIR/1/2020/STG05/UNIM/1].

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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