Ten years of microalgal biofuels in environmental applications

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Abstract Over the past ten years, microalgae have been investigated as promising sources of renewable energy to replace the diminishing supply of fossil fuels and mitigate the environmental pollution caused by use of fossil fuels. In addition to providing oil-based biofuels, the use of microalgae can potentially reduce environmental pollution because algae can use industrial byproducts (CO_2, NOx, wastewater, and others) as nutrition sources. However, our previous study showed that the unacceptably high cost of biofuels production, especially culturing microalgae, remains the biggest obstacle hindering the large-scale implementation of microalgae biofuels. Therefore, future efforts will likely emphasize biotechnological approaches to improve the economic feasibility of algal biofuel production. This review summarizes the progress made over the last decade in environmental applications of microalgae, combined with data on CO_2 capture, NOx biotransformation, wastewater treatment, and synergistic applications, and discusses future prospects.

Keywords Algal biofuel; Environmental applications; CO_2 capture; NOx biotransformation; Wastewater treatment; Synergistic applications

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1 Introduction

In light of the diminishing supply of fossil fuels, including petroleum, coal, and natural gas, and the environmental pollution associated with them, attention has turned to developing cleaner, renewable energy sources [1, 2]. Microalgal biofuels show great promise as a renewable energy source and have been the focus of extensive research, especially in the past decade [3, 4]. Microalgae are aquatic, simple organisms that utilize sunlight energy to sequester CO_2 and convert it into biomass through photosynthesis [5, 6]. Microalgae have promising applications in various nutritional and industrial fields, including biofuel production, bioremediation of environmental pollutants (CO_2, NOx, wastewater, and others), and production of high added value products (proteins, carbohydrates, pigments, antioxidants, and vitamins) [4, 7—10].

During the past 10 years (2007 to 2017), extensive research has been conducted on microalgae biofuels [8, 11—17]. Unfortunately, research in microalgal biofuels has stalled due to the unacceptably high costs of large-scale implementation [4]. In particular, the high cost of the resources required for microalgal cultivation, including water, inorganic nutrients (mainly nitrogen and phosphate), and CO_2, hinders the

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commercialization of microalgal biofuels [18].

In 2010, the global CO_2 emissions from human activities reached 33 billion tons per year [19]. This increase in greenhouse gases, even based on conservative estimates, could raise the average global temperature by as much as 2.6 ℃ by the end of 2100, and sea levels would rise simultaneously as a result of glacial melting, as well as other environmental problems [20]. Thus, it is critical to reduce our CO_2 emissions.

Nitrogen oxides (NOx) are the main gaseous pollutants in atmospheric smog, which arises mainly from industrial flue gas emissions [21]. Since 2012, this atmospheric haze has become a serious problem in most Chinese cities and has aroused increasing public concern about its impact on the environment and human health [8]. In addition, with the increasing demand for freshwater resources and growing water pollution issues, the reuse of wastewater has become more important for sustainable development [22].

Our previous work suggested that combining the bioremediation of environmental pollutants with microalgae cultivation represents an effective method for achieving environmentally sustainable, cost-effective production of biofuels [4, 23]. Our previous study demonstrated the feasibility of using microalgae for the efficient biological denitrification (DeNOx) of flue gases and for the production of microalgae-based products [8, 24, 25]. Moreover, we recently proposed a method involving the reuse of biomass power plant ash, CO_2 sequestration, and NOx removal from flue gases in the cultivation of *Chlorella*, which would reduce the cost of producing biolipids and other products derived from microalgae [26].

In this review, we summarize the past 10 years (2007—2017) of research on the environmental applications of microalgae, including CO_2 capture, NOx biotransformation, wastewater treatment, and synergistic applications. In addition, we used informatics to systematically analyze these developments to better understand the key questions and possible solutions.

2 Capture of CO_2 from flue gases by microalgae

CO_2 is one of the main greenhouse gases causing global warming. Of the total anthropogenic CO_2 emissions, about 75% are derived from burning fossil fuels [27]. In general, three types of methods have been applied for CO_2 fixation: chemical methods (e.g., alkaline solution adsorption followed by storage [28]), physical methods (e.g., injecting CO_2 into the deep sea [29] or underground [30]), and biological methods (converting CO_2 into organic matter [31]). Fixing CO_2 by physical or chemical means and finding the space to store the adsorbed CO_2 is difficult and includes costs for monitoring, operation, and maintenance. Additionally, CO_2 storage is not permanent, as CO_2 will eventually be released back into the atmosphere [32].

Carbon is the main element in microalgal cells (36%—65% of dry matter). Microalgae fix atmospheric CO_2 with an efficiency 10 to 50 times higher than that of higher plants [33]. Therefore, bio-sequestration of CO_2 by microalgae has been considered as an environmentally friendly CO_2 remediation strategy. Cultivation of microalgae with CO_2 from flue gases can reduce greenhouse gas emissions. For instance, one gigawatt-electric (GWe) coal power plant operating at an electrical efficiency of 35% and at 75% capacity normally produces 6.77 million tons (Mt) of CO_2 annually. To consume that amount of carbon, a closed microalgae culture system with a CO_2-capture efficiency of about 80% could produce 2.7 Mt of biomass, while an open microalgae culture system (such as a raceway pond) with a much lower CO_2-fixation efficiency of about 50% could produce 1.7 Mt of biomass [34].

CO_2 bio-utilization by microalgae in a closed-culture system requires the capture of the CO_2 from flue gases and absorption by the microalgae, followed by bio-fixation through photosynthesis. However, excess CO_2 may not be taken up by the algae, which would provide no advantage and only increase the cost of biomass production, or it could be assimilated and subsequently elicit a nutritional imbalance leading to a change in biomass quality [35]. The impact of elevated CO_2 on growth rates is highly variable, mostly species-specific, and dependent on energy availability [36]. Thus, although technically challenging and

time consuming, screening for algae species with high CO_2 tolerance is extremely important. Liu et al. [37] established a high-throughput method to rapidly screen and identify high flue gas CO_2-tolerant microalgae strains. Microalgae species reported to tolerate high levels of CO_2 include *Chlorella* sp. [38], *Scendesmus* sp. [37], and *Dunaliella tertiolecta* [39]. Informatics analysis also showed that the main algae genera used for CO_2 capture were *Chlorella*, *Chlamydomonas*, *Scenedesmus*, *Synechocystis*, and *Synechococcus*, and research in this area has focused on CO_2 capture, photosystem II, carbon-concentrating mechanisms, wastewater treatment, and biodiesel production (Table 1).

Table 1 The top 5 algal genera with the proportion of total studies[a)] and research hotspots

Research area	Top 5 algal genera (% of total)	Research hotspots
CO_2 capture	*Chlorella* (32.74), *Chlamydomonas* (23.30), *Scenedesmus* (13.51), *Synechocystis* (12.74), *Synechococcus* (12.40)	CO_2 capture, photosystem II, carbon concentrating mechanism, wastewater treatment, biodiesel production
NOx biotransformation	*Chlorella* (22.69), *Chlamydomonas* (21.96), *Synechococcus* (10.49), *Scenedesmus* (9.43), *Spirulina* (8.79)	photosynthesis, cyanobacteria, flue gas, toxicity, cell growth
Wastewater treatment	*Chlorella* (59.11), *Scenedesmus* (24.35), *Spirulina* (14.54), *Chlamydomonas* (11.45), *Nannochloropsis* (6.49)	biosorption, biodiesel, mixotrophic cultivation, adsorption, harvesting

a) Some studies relate to two or more genera.

Another influencing factor for CO_2 capture using algae is suitable culture conditions. It was estimated that some algal cultivation systems (tubular or flat photo-bioreactor or open ponds) can allow the conversion of large amounts of CO_2 emitted by coal power plants into biomass; this showed that, in principle, algal cultivation could be coupled to production of industrial byproducts to minimize their environmental impact [40]. Another experiment showed that the addition of flue gases to cultures of *Scenedesmus quadricauda* resulted in 85% utilization of the CO_2 in the flue gas; somewhat lower fixation capacities were obtained using *Botyrococcus braunii* and *Chlorella vulgaris* [41].

Most of the applications of microalgal CO_2 fixation are carried out photoautotrophically, as this gives higher transformation efficiency than heterotrophic fixation [42]. Interestingly, mixotrophic cultivation of microalgae can effectively bio-transform flue gas CO_2 with the accumulation of microalgae biomass and algal lipids, and the overall amount of CO_2 fixed increases due to higher biomass accumulation under mixotrophic conditions [24]. For example, mixotrophic culture of *Botyrococcus braunii* fed with CO_2 and glucose achieved a CO_2 bio-fixation rate of 75% [43].

As mentioned by Chisti [44], biodiesel production could potentially use the CO_2 from industrial waste to minimize culture expenses and reduce greenhouse gas emissions. Microalgae can fix CO_2 from various sources, such as gaseous CO_2 directly from the atmosphere and industrial flue gases, and dissolved CO_2 in the form of carbonates. Industrial flue gases normally contain 10%—15% CO_2, which could potentially provide the microalgae with carbon at little or no cost [33]. Zhao et al. [45] investigated three oilgae (algae with high oil contents), *Chlorella* sp., *Isochlysis* sp., and *Amphidinium carterae*, and selected *Chlorella* sp. as the dominant species to fix CO_2 from flue gases for energy conversion.

During microalgae cultivation, the supply of CO_2 in the culture solution is a limiting factor for fixation due to its low solubility in water (1.45 g L^{-1} at 25 ℃, 100 kPa) [46]. Most current CO_2 feeding methods for microalgae cultivation rely on direct blowing of pure CO_2 or CO_2 from flue gases. However, because of its poor solubility in water, much of the CO_2 is lost to the atmosphere during the sparge-feeding and results in relatively low carbon utilization efficiency [46]. Also, these direct blowing CO_2 feeding methods have high energy costs, which limits their application for scaled-up production [47]. Chemical fixation of

CO_2 using absorption liquids (e. g. alkaline solutions) to stabilize the CO_2 as carbonate may improve the CO_2 uptake efficiency by the microalgae compared with direct blowing of the CO_2 into the culture media [48], and may also reduce the energy requirements [47]. In this case, it would be necessary to screen microalgae species for high tolerance to the alkaline conditions that the carbonates would produce in the culture media. Hsueh et al. [49] found a microalga from an alkaline hot spring that grows well at over 50 ℃ and at a pH of 11. 5, and its CO_2 mass transfer rate was enhanced by 5-fold with a high performance alkaline absorber and regenerating the alkaline solution through microalgal photosynthesis, as the pH of culture would increase during algal photoautotrophic growth.

3 Biotransformation of NOx from flue gases by microalgae

Flue gases also contain different NOx species, such as NO, NO_2, N_2O, N_2O_2, N_2O_3, N_2O_4, and NO_3, and most of these NOx species must be removed from emissions as they are restricted by legislation [50]. Conventional DeNOx methods are expensive and the secondary wastes produced in the process often require further treatment [51]. As nitrogen is one of the most important nutrients for algal production, NOx species may be used as a nitrogen source for microalgae cultivation [24, 26, 52, 53]. Thus, microalgae may be useful for recycling the nitrogen in flue gases.

As the NOx removal efficiencies of microalgae vary by species, it is necessary to select or genetically modify appropriate algal candidates for this purpose. Some strains of the genera *Chlorella* sp., *Scenedesmus*, and *Dunaliella* have been reported to remove substantial amounts of NOx [54—56], although high levels of NOx tend to depress photosynthesis. Informatics analysis showed that the main algal genera for NOx biotransformation were *Chlorella*, *Chlamydomonas*, *Scenedesmus*, *Synechococcus*, and *Spirulina* (Table 1), and the research in this area has focused on photosynthesis, cyanobacteria, flue gas, toxicity, and cell growth (Table 1).

Up to 95% of the NOx in typical flue gas is NO. In the medium, NO is initially oxidized to nitrite, which is the main component of NOx in aqueous solutions [57]. Nitrite inhibits algal growth because it decreases electron transfer from Q_A to Q_B at photosystem II, and interferes with the donor side of photosystem II [58]. Therefore, screening for nitrite-tolerant microalgae species is crucial for algal DeNOx approaches. In our previous work, we analyzed the acclimatization of numerous *Chlorella* strains to high levels of NOx and the potential utilization of *Chlorella* strains in biological DeNOx of industrial flue gases. We found that the degree of nitrite tolerance was strain-specific, and most *Chlorella* strains could withstand high concentrations of nitrite [25]. Among these strains, *Chlorella* sp. C2 was found to be a promising candidate for biological DeNOx of industrial flue gases.

For microalgae-based NO elimination, the first step is the dissolution of NO gas in the aqueous phase. Nitrite will be oxidized to nitrate in the medium, and then assimilated by the microalgae [57]. However, the solubility of NO in water is low, so the dissolution of NO gas into the medium often limits the rate of nitrogen assimilation and thus is the rate-limiting step for microalgae-based biological DeNOx [55]. To solve this limitation, we previously reported a two-step microalgae-based bio-DeNOx strategy in which NOx-rich flue gases were first fixed, mostly as nitrite, into flue gas-fixed salts (FGFS), which were then used as the sole nitrogen source for the culture of *Chlorella* species [52]. The results showed that 60% of the NOx was removed from the medium with an inoculated cell density of 0. 07 g L^{-1} dry weight and 33% algae lipids were produced when using FGFSs with 5× equivalent nitrogen, as found in BG11 medium, which is used for cultivation of microalgae [52]. We further performed mixotrophic cultivation of *Chlorella* sp. C2 with FGFS and glucose and achieved an overall DeNOx efficiency of 96%, demonstrating the feasibility and efficiency of biological DeNOx with microalgae [24].

SO_x species are also present in most incineration flue gases, and these SO_x mainly consists of SO_2 with a minor amounts (2%—4%) of SO_3. SO_2 and SO_3 are highly soluble in water [50]. SO_2 tends to hydrate to H_2SO_3 and SO_3 hydrates to H_2SO_4; the oxidation of H_2SO_3 can also generate H_2SO_4 and SO_4^{2-}. Therefore, the dissolution of SO_x causes acidification of the medium, and the extent depends on the SO_x

content of the flue gas. The consequence of SO_x dissolution in the growth medium can limit the choice of algae to acidophilic and/or bisulfite-tolerant species [50]. In some cases, chemical scrubbing of SO_x out of the flue gas may be a precondition for any microalgal culture [52]. If pH and toxicity of SO_x-derived solutes are compatible with algal survival, the algae can assimilate substantial amounts of SO_4^{2-} [59], in quantities consistent with the elemental stoichiometry in the growth medium and the stoichiometric constraints of cell growth [60].

4 Treatment of wastewater and other pollutants by microalgae

Large-scale microalgae culture requires huge amounts of fresh water, which can drain the resources needed for terrestrial crops and human activities. This demand, coupled with increasing rates of water pollution, makes wastewater reuse an important component of sustainable development [22]. Algae can recover large amounts of nitrogen and phosphorus, particularly in the forms of NH_4^+, NO_3^-, and PO_4^{3-}, from wastewater [61, 62]. For example, Cabanelas et al. [63] demonstrated the removal of nitrogen and phosphorus from municipal wastewater by *Chlorella vulgaris* cultivation.

Microalgal species with high nutrient removal capabilities and wide tolerance to environmental stresses should be selected for wastewater treatment. Informatics analysis showed that the main genera used for wastewater treatment were *Chlorella*, *Scenedesmus*, *Spirulina*, *Chlamydomonas*, and *Nannochloropsis* (Table 1), and the research in this area has focused on biosorption, biodiesel, mixotrophic cultivation, adsorption, and harvesting (Table 1). Selection for a particular strain of microalgae with additional desirable characteristics, including high photosynthetic efficiency, high CO_2 affinity, and carbon concentrating mechanisms, is also important for the enhancement of both biomass production and nutrient recovery [64]. In a study by Wang et al. [65], co-culturing of *Chlorella* sp. and bioflocculant-producing bacteria was optimized for effective wastewater treatment and efficient harvesting.

Organic nutrients are often found in wastewater and the cultivation of microalgae under mixotrophic conditions using wastewater containing inorganic and organic matter has been reported. Cheng et al. [66] used the alga *Desmodesmus* sp. CHX1 to treat pig farm wastewater and found that mixotrophic microalgae-bacteria systems significantly promoted microalgal growth and the efficiency of nutrient removal, attaining maximal biomass and lipid productivity. Moreover, the co-culture of microalgae and bacteria with wastewater achieved 50%—60% and 68%—81% removal efficiencies of dissolved organic carbon from municipal wastewater and industrial wastewater, respectively [67]. Because of the complex nature of wastewaters, issues including inconsistent wastewater components, contamination with other useless microorganisms, and unstable biomass production have hindered the use of wastewater in large-scale algal cultivation [68].

In addition to being used for flue gases and wastewater, microalgae can also be used for bioremediation of other environmental pollutants. Biomass ash from the burning of coal has been used as a nutrient source for the cultivation of *Chlorella* sp. and was considered sufficient to sustain cell growth and biomass productivity [69]. Our recent work showed that the nutrient-rich ash and flue gases generated in biomass power plants could be used as nutrient sources for the cultivation of *Chlorella* sp. C2 to cost-effectively produce biolipids [26]. Microalgae can also absorb and concentrate certain heavy metal ions. As absorption and intracellular uptake of heavy metal ions usually takes place during the growth phase, absorption mechanisms in living algae are more complex than in non-living algae. Shanab and Essa [70] investigated the effects of different concentrations of Hg^{2+}, Cd^{2+}, and Pb^{2+} on the growth of three freshwater microalgae strains, *Pseudochlorococcum typicum*, *Phormidium ambiguum*, and *Scenedesmus quadricauda*, and found that *S. quadricauda* and *P. typicum* were more tolerant to high concentrations of heavy metals. Lower concentrations of Cd^{2+} and Pb^{2+} (5—20 ppm) even enhanced *S. quadricauda* growth through increased chlorophyll content, and the most efficient heavy metal ion removal rate for *P. typicum* happened within the first 30 min after treatment with culture solutions containing 97% Hg^{2+}, 86% Cd^{2+}, or 70% Pb^{2+}. Using the initial Zn^{2+} concentration of 75 mg L^{-1}, Monteiro et al. [71] found a two-fold

increase in the maximum removal of Zn^{2+} from aqueous solutions by adsorption onto the surface of a strain of *Scenedesmus obliqus* isolated from a heavy metal-contaminated site, compared to a strain obtained from the culture collection.

In addition, organic pollutants can be absorbed and degraded by microalgae. Dyes are a group of persistent compounds that are resistant to conventional bio-degradation methods. Three strains of cyanobacteria, *Phormidium autumnale* UTEX1580, *Synechococcus* sp. PCC7942, and *Anabaena flos-aquae* UTCC64, showed potential for the bio-degradation of three different types of textile dyes (Sulphur Black, Brilliant Blue R, and Indigo) [72]. Another study investigated the effects of pentachlorophenol on strains of *Microcystis aeruginosa* and *Chlorella vulgaris* and found that *C. vulgaris* and *M. aeruginosa* were able to stabilize and effectively bio-remediate the pentachlorophenol added to the culturing medium at concentrations where toxic effects could be observed on the microalgae [73].

5 Synergistic applications of microalgae for bioremediation of environmental pollutants and production of biofuels

The combination of bioremediation of flue gases and nutrient recycling from wastewaters by microalgae provides a promising option to current bioremediation strategies. The nutrients extracted from these industrial byproducts also promote biomass accumulation for the production of biofuels and other metabolic products produced by the algae [74]. For example, Chinnasamy et al. [75] cultured *Scenedesmus bijuga*, *Chlorella minutissima*, and *Chlamydomonas globosa* in wastewater from a carpet factory aerated with 5%—6% CO_2 and attained a biomass productivity of 5.9—21.1 g m^{-2} d^{-1}.

Chlorella vulgaris SDEC-3M was shown to grow well in high concentrations of CO_2 (15% v/v), thereby demonstrating its ability to fix and transform the CO_2 from industrial flue gases into carbohydrates, such as starches for bioethanol production [38]. The green microalga *Scenedesmus* sp. cultured in photobioreactors with flue gas CO_2 optimized at a concentration of 2.5% produced 10.4% carbohydrates and 35.6% bio-lipids, this system also showed a 46.1% increase in biomass productivity when compared to culture with 0.03% CO_2 (the control) [76]. In another study, increased concentrations of CO_2 improved biomass productivity of *C. sorokiniana* and enhanced the composition and structure of the accumulated starch granules for bioethanol production [77]. Lee et al. [78] reported the potential of *Chlorogonium* sp. for the simultaneous recycling of saline sewage discharge and CO_2 sequestration during culture for microalgal bioenergy production, and efficient removal of PO_4^{3-} NO_3^-, NH_3, and total nitrogen, with a CO_2 fixation rate of 58.96 mg L^{-1} d^{-1} and a lipid content of 24.26% of the algal biomass.

Zhou et al. [79] used *Auxenochlorella protothecoides* UMN280 in a mixotrophic culture and demonstrated improved wastewater recycling, nutrient removal efficiency, and microalgal bio-lipid productivity. They achieved a maximal microalgae biomass productivity of 1.16 g L^{-1} and a bio-lipids content of 33.22% (dry weight). At the end of the cultivation, the removal rates of NH_3, total nitrogen, and phosphorus were 100%, 90.60%, and 98.48%, respectively. Industrial solid wastes that are rich in carbohydrates but deficient in nitrogen, and liquid wastes from certain food factories, such as olive mills, could also be used for bio-hydrogen production [80]. To study wastewater purification and algal bio-lipid production in depth, the effects of inorganic and organic compounds on growth and nutrient recovery of a green microalgae *Scenedesmus obliquus* cultured in secondary municipal liquid wastes with 5% CO_2 aeration were tested [81] and resulted in a 577.6 mg L^{-1} d^{-1} biomass productivity and a 16.7 mg L^{-1} d^{-1} bio-lipid productivity. The total carbon, nitrogen, and phosphorus recovery efficiencies were 59.1%, 97.8%, and 95.6%, respectively. These results suggested that *S. obliquus* could be suitable for the simultaneous bio-removal of pollutants (inorganic and organic) and biofuel production. Lu et al. [82] compared the nutrient removal efficiency and biomass productivity of *Chlorella* sp. cultivated in raw dairy wastewater in small-scale laboratory and large-scale outdoor photobioreactors and found a strong potential for large-scale biofuel production using *Chlorella* sp. coupled with raw dairy wastewater purification. A recent study showed that the photosynthetic hydrogen evolution capacity of *C. reinhardtii* cultured in advanced solid-

state fermentation wastewater was improved by more than 700% compared to the control TAP medium [83]. Another series of experiments were designed to test the ability of *S. obliquus* cultured in various concentrations of wastewater to produce sugar-rich biomass for bioethanol production through fermentation, and found that when grown under aerated conditions, *S. obliquus* showed the highest removal efficiency (10%) of both the chemical oxygen demand and the biochemical oxygen demand, with the highest ethanol production efficiency of 20.33% from biomass hydrolysate [84]. Improved bio-methane production in methane digesters was also reported from microalgae biomass harvested from algae-based swine wastewater digestate [85]. However, the industrialization of microalgal biofuel production using wastewater will largely rely on the methods used for microalgae cultivation to address obstacles such as wastewater nutrient recovery under cold climate and outdoor conditions, and other conditions that are adverse to microalgae growth [86].

The prospect of economically viable algal biofuel-based DeNOx of industrial flue gases using *Chlorella* was evaluated in our previous work [52]. In order to address the issue of the large amount of NOx contained in flue gases and the relatively low efficiency for its assimilation in photoautotrophic algae, we further tested the possibility of managing NOx by culturing *Chlorella* strains mixotrophically [24]. After a stepwise optimization, we obtained an impressive DeNOx efficiency of over 96%, along with a biomass productivity of 9.87 g L^{-1} d^{-1} and a high bio-lipid productivity of 1.83 g L^{-1} d^{-1}. Therefore, this approach provided a new strategy for scaling up microalgal biofuel-based bio-DeNOx and practical industrial applications within a limited land area. Furthermore, we evaluated microalgal biofuel production with the co-bioremediation of nutrient-rich ash and flue gas CO_2 and NOx generated in biomass power plants [26].

Based on these studies, we propose a cyclic strategy for using industrial solid, liquid, and gaseous wastes to nourish the microalgae used for biofuel production (Figure 1). Besides its obvious environmental benefits, implementation of this strategy could eventually enable carbon-negative biofuel production.

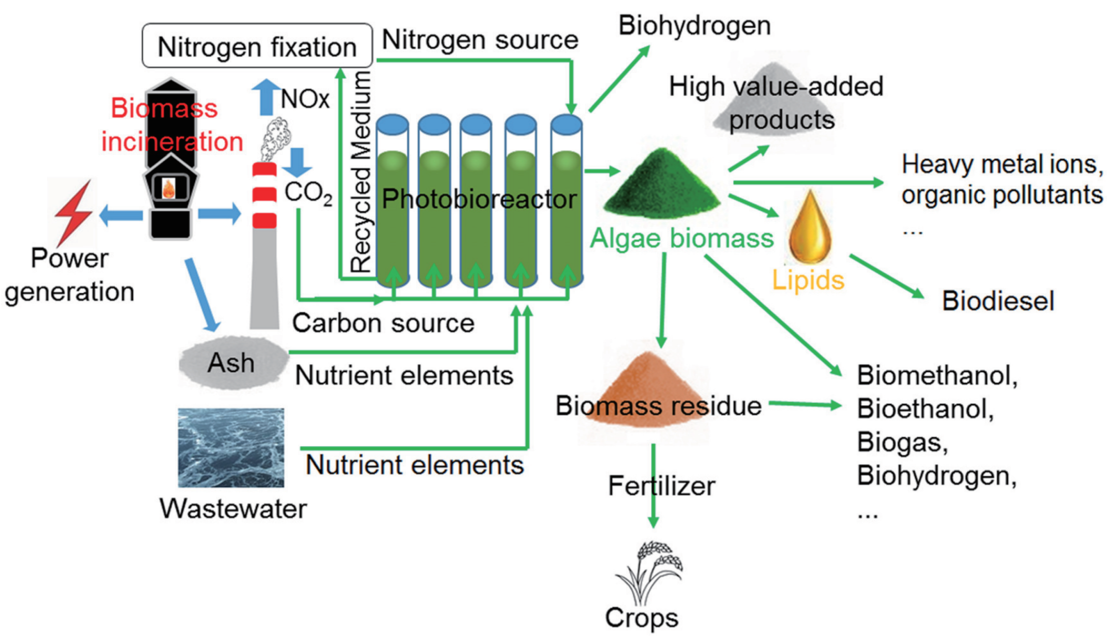

Figure 1 Flow chart of the synergistic applications of prevention and remediation of environmental pollution and the production of biofuels.

6 Existing problems and future research and development

Informatics analysis showed that the applications of microalgae in environmental bioremediation have increased markedly since 2010 (Figure 2). However, the technologies for algal cultivation and biofuel production are still underdeveloped, and our knowledge of basic algal biology remains inadequate. For

example, it is difficult to separate the algae from the culture medium after the wastewater treatment.

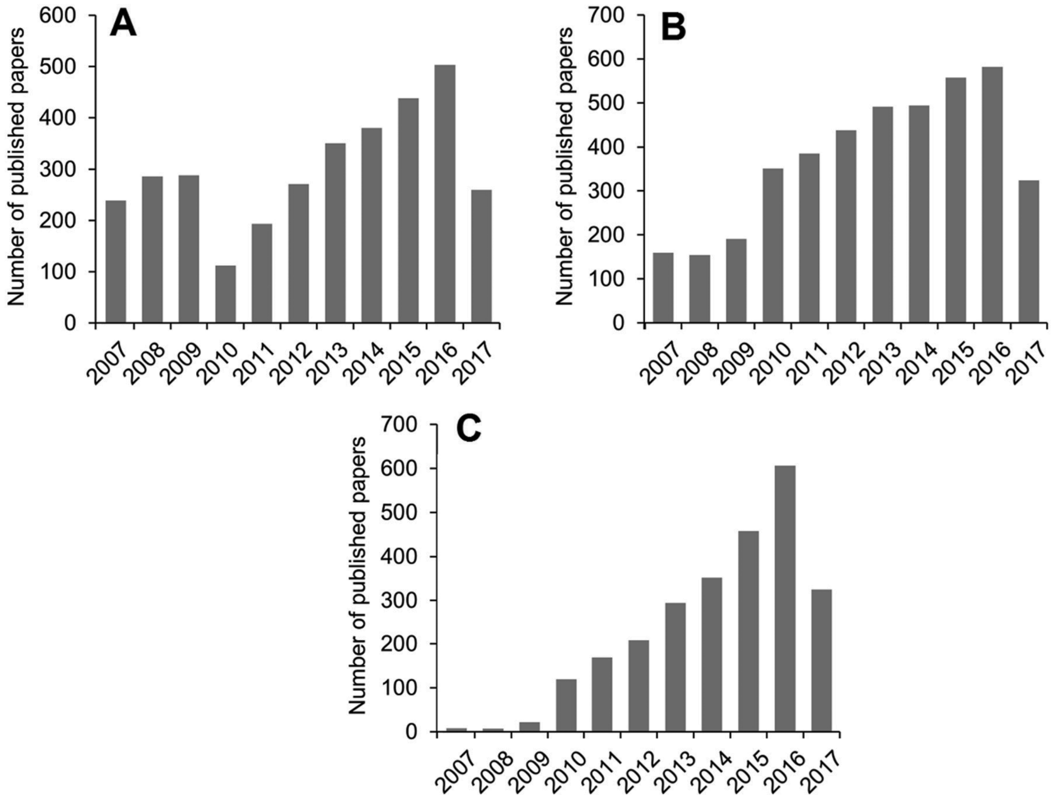

Figure 2 Annual number of published manuscripts related to the use of microalgae for environmental applications from 2007. A, CO_2 capture; B, NOx biotransformation; C, wastewater treatment. The data for 2017 in the current and following figures show only manuscripts published between January 1 and August 28.

As microalgal utilization of CO_2 and NOx varies tremendously among algal strains and species, it is essential to collect, screen, and select suitable microalgae candidates for different applications. Besides CO_2 and NOx, the possible effects of many other flue gas compounds, such as SO_x, O_2, H_2O, N_2, CO, halogen acids, heavy metals, unburned carbohydrates (C_xH_y), and particulate matter, on microalgae needs to be addressed, along with the tolerance of microalgae strains to various flue gas compounds, and the interaction between the flue gas compounds and the microalgae. Thus far, most of the studies on microalgae cultivation with wastewater have been carried out in small-scale experiments. Large-scale and longer-term production will help to optimize the cultivation methods and improve the economic viability of real-world applications of microalgal bioremediation of environmental pollutants. A better understanding of cultivation parameters, such as physico-chemical conditions, contact times, and initial concentrations, are also needed prior to implementation of microalgae for bioremediation. Moreover, before actual implementation, energy-intensity analysis, techno-economic analysis, and life-cycle assessment of any microalgae system must be precisely determined. Coupling the culture of oil-producing microalgae for the production of biofuels with bioremediation of environmental pollutants is a promising strategy to improve the economic viability of biofuel production.

7 Future prospects

With diminishing supplies of fossil fuels and the threat of climate change due to the use of fossil fuels, the development of microalgal biofuels is of paramount importance. Great progress has been made in the application of microalgae for biofuels in the past 10 years; however, due to a poor understanding of basic algal biology and technological shortcomings, the widespread availability of microalgal biofuels cannot yet be realized.

More efforts need to be made to reduce the costs of cultivation and to resolve the technical bottlenecks of large-scale implementation for promoting rapid development of the microalgal biofuels industry. Breakthroughs in algae-based environmental applications are required for comprehensive utilization of algal resources in modern industrial technology, and must provide an effective route to control production costs of algal biofuels for the realization of the potential of this technology.

Future studies should focus on the following: 1) putting more funds and efforts on fundamental research to provide a better understanding of the object, 2) screening microalgal strains for high tolerance to pollutants, and broad adaptability, and 3) synergistic coupling of flue gas bioremediation and wastewater treatment with the production of microalgae-based biofuels and other products. To sum up, although the large-scale industrial implantation of microalgal biofuel in bioremediation still faces great challenges, it has a bright future.

Notes

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