

REVIEW

Microalgae wastewater treatment: Biological and technological approaches

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Current global environmental issues raise unavoidable challenges for our use of natural resources. Supplying the human population with clean water is becoming a global problem. Numerous organic and inorganic impurities in municipal, industrial, and agricultural waters, ranging from microplastics to high nutrient loads and heavy metals, endanger our nutrition and health. The development of efficient wastewater treatment technologies and circular economic approaches is thus becoming increasingly important. The biomass production of microalgae using industrial wastewater offers the possibility of recycling industrial residues to create new sources of raw materials for energy and material use. This review discusses algae-based wastewater treatment technologies with a special focus on industrial wastewater sources, the potential of non-conventional extremophilic (thermophilic, acidophilic, and psychrophilic) microalgae, and industrial algae-wastewater treatment concepts that have already been put into practice.

KEYWORDS

bioeconomy, bioreactors, extremophiles, microalgae, wastewater treatment

1 | INTRODUCTION

Water is one of the most important natural resources on our planet. However, in addition to an inadequate clean water supply in many developing countries, water quality in industrialized nations has reached a worrying state [1,2]. The pollution of municipal, agricultural, and industrial wastewater with a huge number of organic and inorganic contaminants, such as microplastics [3], xenobiotics [1], heavy metals [4], and high concentrations of nitrates [5], phosphates [6], and carbon (C) compounds [2], puts a strain on the food chain and thus the basis of human life. Wastewater treatment (WWT) is a global issue that cannot be managed by a single technology because of the extremely variable scales, types of contaminants, and regional conditions involved (Figure 1).

Conventional WWT plants focus on the removal of suspended solids (mostly mechanically) and the reduction of biological oxygen demand by activated sludge [7]. This biodegradation involves the breakdown of organic molecules and inorganic constituents (nitrogen [N] and phosphorous [P] compounds), which is of great importance to prevent the eutrophication of downstream waters such as rivers and lakes. The degradation capacity of these conventional technologies is limited, especially with regard to heavy metals, extremely high nutrient loads, and xenobiotics, leading to an increasing accumulation of these substances in groundwater [1–6].

Because of the metabolic flexibility of microalgae, i.e. their ability to perform photoautotrophic, mixotrophic, or heterotrophic metabolism [8,9], they represent promising biological systems for treating a variety of sources of wastewater. In

Abbreviations: ATS, Algal Turf Scrubber; PBR, photobioreactor; RAB, revolving algal biofilm; WWT, wastewater treatment.

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particular, in the context of a circular and bio-based economy and the development of biorefinery concepts [10], microalgae biomass produced from wastewater streams offers a great potential for sustainable bioproducts (dependent on national legislation on reusing microalgae biomass/bioproducts), such as proteins [11], fatty acids [12], pigments [13], biofertilizers/biochar [14,15], and animal feed [16]. Algae-based WWT technologies have in fact been researched since the 1950s, mainly because of their very efficient fixation of inorganic N and P.

The usage of microalgae in WWT plants has two main aims: (1) the direct uptake or transformation of water contaminants, and/or (2) improving the purification performance of bacterial systems (microalgae-bacteria aggregates) by providing additional oxygen from photosynthesis (symbiotic cocultures), thus reducing the total energy costs of direct (gassing performance) or indirect (stirring performance) oxygen supply [17]. Until now, research on algae-based WWT has focused mainly on the conventional microalgae and cyanobacteria such as *Chlorella* ssp. [18], *Arthrospira* ssp. [19], *Scenedesmus* ssp. [20], and *Nannochloropsis* ssp. [21,22] because of their potential to accumulate high levels of lipids and starch. This review provides an overview of these biological systems, with a particular focus on the potential application of extremophilic microalgae (thermophilic, psychrophilic, and acidophilic), the technological systems used for WWT (suspension vs. immobilized systems), and algae

PRACTICAL APPLICATION

This minireview presents the biological and technological approaches concerning microalgae-based wastewater treatment technologies. The biological and technical systems must be adapted to the respective wastewater conditions, since the scale and composition of the wastewater sources can vary greatly. The minireview shows different solution strategies, especially for the treatment of industrial wastewater. The special focus is on the distinction between immobilized and suspended biological systems, the potential of extremophilic microalgae and the presentation of plant concepts that have already been implemented on a technical scale.

based WWT approaches that have already been put into practice.

2 | CONVENTIONAL MICROALGAE USED FOR WWT

Photosynthetic microorganisms comprise a wide spectrum of photosynthetically active green, red, and brown algae as well

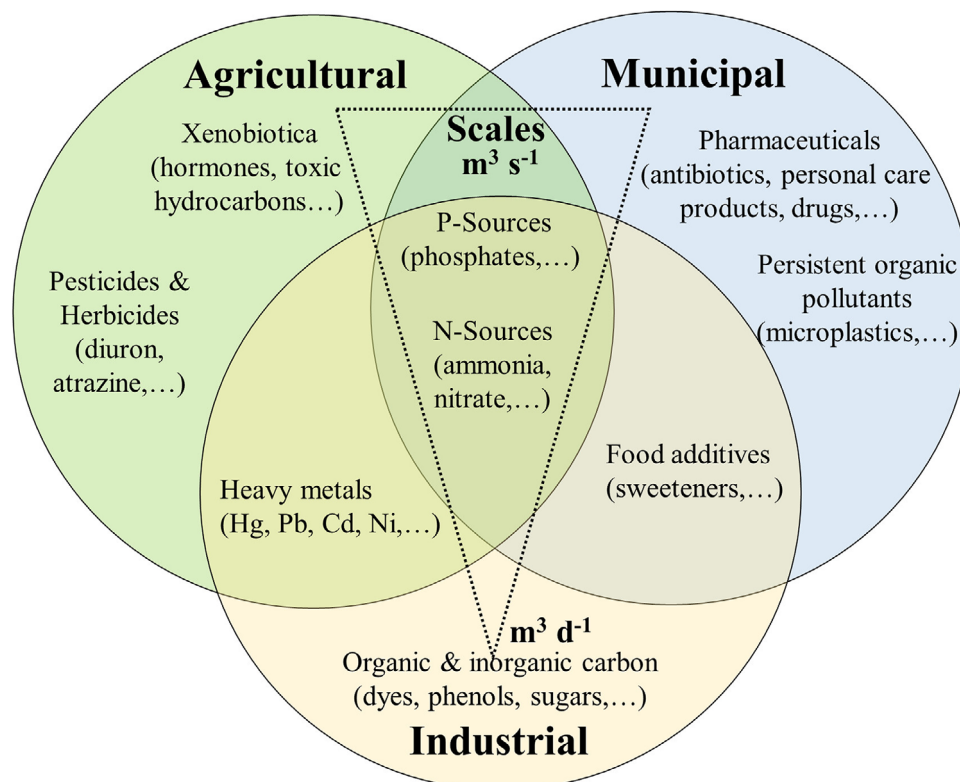


FIGURE 1 Wastewater sources and their typical impurities

as cyanobacteria. Because of their ability to fix carbon dioxide (CO₂) using light as the sole source of energy, they are promising cell factories to produce bio-based energy carriers and products. Along with photoautotrophy, several microalgal species are capable of performing chemoheterotrophic or mixotrophic metabolism, which is of interest for the treatment of industrial wastewater containing a high organic load. Among the most studied conventional microalgal strains is *Chlorella vulgaris*, which has been examined recently for its biomass production from food waste compost [23], sludge extracts [24], corn steep liquor, cheese whey and vinasse [25], textile waste effluent [26], tofu wastewater [27], and industrial dairy effluent [28]. Zhai et al. [19] have demonstrated the high N (81.51%) and P (80.52%) removal efficiency of the widely used cyanobacterium *Arthrospira platensis* using a synthetic wastewater. Hena et al. have evaluated the ability of *A. platensis* to accumulate lipids while undergoing mixotrophic growth on dairy farm wastewater [29], obtaining a total biomass concentration of 4.98 g L⁻¹ and lipid content of 30.23 wt% and thus demonstrating the potential for the production of biofuels. *A. platensis* was also been applied to the treatment of pig-gery wastewater [30], confectionary effluent [31], composite media made of mineral medium, beet vinasse [32], and distillery wastewater [33].

3 | EXTREMOPHILE MICROALGAE — SPECIALISTS FOR HARSH PROCESSING CONDITIONS

Typically, WWT of municipal and agricultural wastewater by microalgae is performed in outdoor conditions at physiological temperatures and pH. However, the parameters of industrial wastewater can fluctuate widely, ranging from highly acidic (2.0 < pH < 8.0) to extreme temperatures (>40°C for process industries, e.g. fermentation residues of bioenergy industry, <10°C in the food processing industry) and high organic loads (>100 g L⁻¹ in fruit processing), which is not compatible with the physiology of most conventional microalgal species. Microalgal specialists that are adapted to thermophilic, psychrophilic, or acidophilic environmental conditions are therefore necessary to realize the degradation of water impurities on the spot of origin (see Table 1). Some of those extremophiles not only tolerate such conditions but require them for their metabolic activity [34].

Galdieria sulphuraria, also denoted as *Cyanidium caldarium*, is one of the most interesting microalgae with extremophilic growth properties. Gross and Schnarrenberger reported in 1995 that strains of this Rhodophyta (red algae) species are able to grow mixotrophically and heterotrophically on 27 different sugars and sugar alcohols [35,36]. *Galdieria sulphuraria* is able to grow not only in neutral environments

but also in highly acidic environments, down to pH 1.8 [37], and *G. sulphuraria* is able to acidify its environment by an active proton efflux, thus reducing the costs of pH control and the risk of contamination [38,39].

Besides its acidophilic nature, *G. sulphuraria* shows thermophilic growth behaviour up to 56°C [41]. The economic value of *G. sulphuraria* is enhanced by high levels of the phycobiliprotein phycocyanin, which is increasingly being accepted as a natural colorant/nutraceutical in the food industry [49,50], cosmetics industry [51], and as a fluorescence marker in molecular biology [52]. This metabolic versatility, coupled with the ability to produce value-added phycocyanin, makes *G. sulphuraria* a very promising candidate for treating high chemical oxygen demand-loaded, acidic or high-temperature wastewater [53]. Sloth et al. [42] have shown the potential of growing *G. sulphuraria* 074G heterotrophically on hydrolysates of food waste from restaurants and bakeries. In a first field study, Lammers and co-workers [40] have reported that *G. sulphuraria* was able to grow well in primary-settled wastewater while significantly reducing levels of organic carbon (46–72%), ammonium (NH₄-N) (63–89%), and phosphate (PO₄) (71–95%). Further promising acidophilic microalgal strains can be found within the Chlorophyta (green algae). *Chlamydomonas acidophila* has been isolated from an acidic river in a mining area, with pH values ranging between 1.7 and 3.1 [43]. It has been shown that *C. acidophila* can grow mixotrophically without CO₂ by using different carbon sources, especially glucose, glycerol, and starch, at pH 2.5 [43], and its capacity to remove NH₄ [54]. The added value of *C. acidophila* biomass from waste sources is its ability to accumulate high concentrations of antioxidants such as the carotenoid lutein [55].

Chlorella protothecoides var. *acidicola* has been isolated from acidic (pH 2.5–2.6) mine water and has shown good heterotrophic growth on glycolic acid [56], which is part of the wastewater load of fruit and vegetable processing industries. *Chlorella sorokiniana*, a well-studied thermophilic green microalgae, has revealed high photoautotrophic growth rates up to 43°C [57]. Kim et al. [58] have shown efficient P and N removal rates in heterotrophically grown *C. sorokiniana* cultures, which is an essential precondition for many WWT processes. In a following study Kim et al. have described superior removal behaviour for heterotrophic *C. sorokiniana* cultures, compared with photo- and mixotrophic cultures [59]. Cells of *C. sorokiniana* can accumulate high levels of valuable bioproducts, e.g. lutein [60], fatty acids [61,62], and proteins [63], making the sustainably produced biomass a good source for animal feed or biofuel production. The co-immobilization with the microalgae growth-promoting bacterium *Azospirillum brasilense* significantly enhanced the P-removal efficiency of *C. sorokiniana* [64,65].

Another challenge is the energy-efficient treatment of low-temperature wastewater. Psychrophilic species such as

TABLE 1 Overview on wastewater treatment approaches using extremophilic microalgae

Species	Strain	Cultivation system	Growth conditions	Removal rates	Product	Source
<i>Galderia sulphuraria</i>	CCMEE 5587.1	700 L field scale open system	Mixotrophic on raw primary effluent diluted with media and CO ₂ enriched headspace	After 3 days: BOD ₅ 36 to 13 mg L ⁻¹ N 23 to 2.6 mg L ⁻¹ P 4.5 to 0.6 mg L ⁻¹	Biomass OD ₇₅₀ 1.9	[40]
	074G	3 L bioreactor, 2.5 L culture volume	Heterotrophic on complex media with glucose	After 100 h: NH ₃ 0.31 to 0.15 g L ⁻¹	c-Phycocyanin 250–400 mg L ⁻¹	[36]
	CCMEE 5587.1	Glass tubes, 6 mL culture volume	Heterotrophic in media with primary effluent	After 7 days: NH ₃ 4.85 mg L ⁻¹ d ⁻¹ PO ₄ 1.21 mg L ⁻¹ d ⁻¹	Biomass 2.5 g L ⁻¹	[41]
	CCMEE 5587.1	Closed outdoor reactor, 300 L culture volume	Mixotrophic in media with primary effluent and 1–2% CO ₂ sparged	-	Biomass 2.5 g L ⁻¹	[41]
	074G	500 mL shake flasks, 150 mL culture volume	Heterotrophic bakery and restaurant waste hydrolysates with supplemented N-sources	-	-	[42]
<i>Chlamydomonas acidophila</i>	River water isolates	1 L batch reactor	Mixotrophic on several carbon sources	-	Lutein: 9–10 mg g ⁻¹ Zeaxanthin: 7–8 mg g ⁻¹	[43]
<i>Chlorella sorokiniana</i>	UTEX 2805	1 L batch reactor, 400 mL culture volume	Phototrophic cultivation, cells immobilized in alginate beads, aeriated	After 4 days: NH ₃ from 10 to 0 mg L ⁻¹	-	[44]
	Open pond isolates	Shake flasks, no volume information	Phototrophic growing on post-chlorinated wastewater supplemented with various N-sources	-	Max. 0.220 g L ⁻¹ d ⁻¹ with urea supplementation	[45]
	UTEX 1230	1 L batch reactor	Phototrophic growth on anaerobic digester centrate and final effluent from municipal WWTP supported with diesel engine flue gas	CO 20–30% CO ₂ 30–45% NO _x 95–100%	Biomass 250 mg L ⁻¹ d ⁻¹	[46]
	UTEX 2714	Hanging bags, 80 L culture volume	Phototrophic growth in 10% anaerobic digester effluent fed with cattle waste, aeriated	PO ₄ -P 57.70% TP 64.10% NH ₃ -N 72.17% TN 87.35%	Biomass 13–17 mg L ⁻¹ d ⁻¹	[47]
	Isolated wildtyp	2 L shake flasks	Phototrophic growth on filtered raw sewage	COD 69.38% N 86.93% P 68.24% coliforms 99.78% faecal coliforms 100%	Biomass with 22.36% lipids	[48]

COD, chemical oxygen demand; N, nitrogen; P, phosphorus.

Koliella antarctica have temperature optima below 10°C [66], making them an interesting potential biological system for treating wastewater from fresh fruit processing industries. *Koliella antarctica* has also been shown to produce high levels of EPA, DHA, astaxanthin, and lutein [67].

4 | (PHOTO-)BIOREACTOR SYSTEMS FOR ALGAE-BASED WWT

Activated bacterial sludge processes in stirred ponds are the most widely used WWT technologies, especially for

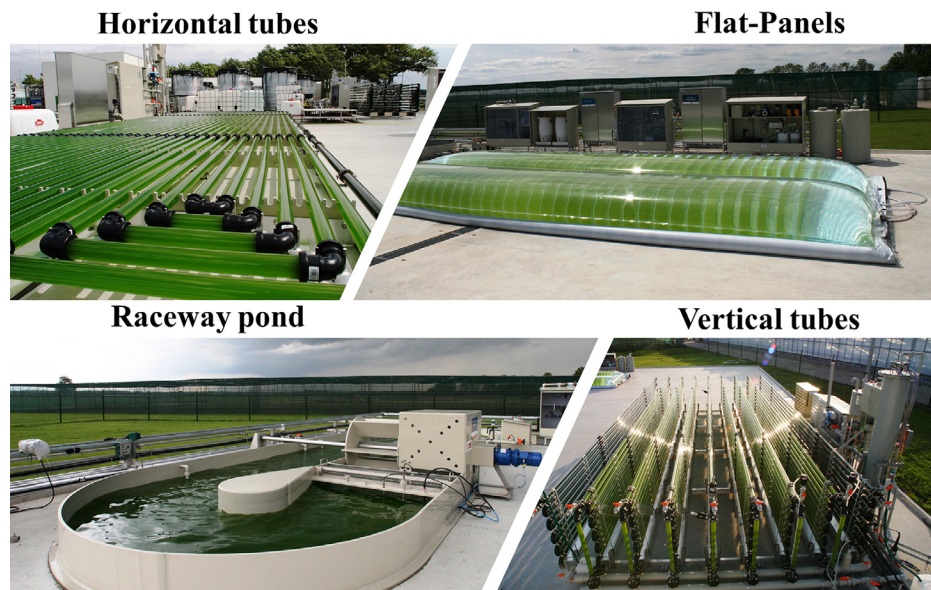


FIGURE 2 Types of photobioreactors (PBR) systems located at the AlgaePARC at Wageningen University and Research. With kind permission of Marcel Janssen [88]

municipal and industrial wastewater. However, as introduced, activated sludge is limited regarding the sufficient N and P removal or elimination of heavy metals without using chemical precipitation [7]. The usage of microalgae in WWT is associated with additional technological requirements regarding photobioreactor (PBR) systems. This is mainly because of the photoautotrophic processes, for which a sufficient supply of light energy and CO_2 is needed. In general, microalgae PBRs are categorized as open and closed systems, which have already been described in several reviews [68,69]. However, for WWT, classification into suspended and immobilized methods provides a more useful comparison of existing technological approaches.

4.1 | Suspended WWT systems

Pond systems are common in bacterial WWT [70]. They are also the most widely applied type of large-scale reactor for microalgae cultivation, because of their simple construction and low investment costs [71]. However, because of a higher light path of >30 cm, resulting in a limited light supply, fluctuating outdoor temperatures, and poor mixing capacity, the biomass yield of pond systems is lower compared to tubular systems or more specific PBRs such as flat-panel PBRs [72,73] (Figure 2). High-rate algal ponds try to bypass some of these problems by enhancing the mixing efficiency via paddlewheel stirrers and gas introduction [70]. The insufficient supply of CO_2 limits algal biomass production because of the unfavourable C:N:P ratio in wastewater [74], but it has been shown that specific aeration and the addition of CO_2 can enhance biomass productivity and removal rates of undesired water constituents. The addition of N or P is

sometimes used to ensure molar ratios of nutrients for optimal algal growth [75,76], and co-cultivation with bacteria can be favourable in relation to heterotrophic oxidation of organic compounds in wastewater by microorganisms that benefit from increased oxygen levels, induced by photoautotrophic algal growth [77–79]. The removal efficiency of total N and P by microalgae from wastewater has been determined to be between 10 and 97% and is highly dependent on culture mode, tank size, type of wastewater, and the microalgae strain [72, 80–83], indicating that there is no single technology/species combination that is able to fulfil every WWT goal.

Alternative PBR technologies, such as tubular or flat-panel PBR systems, are designed to improve light distribution by minimizing the thickness of the surface layer and therefore providing a more efficient light penetration even in highly concentrated suspensions [84]. In combination with a controlled environment and effective aeration, for example with bubble columns or other gas-liquid contractors such as flat-panel airlift PBRs, the growth rates and productivities are usually higher compared with pond-based systems [85,86]. However, the investment and maintenance costs of advanced PBRs significantly exceed open pond systems [71], and therefore such systems do not currently prevail in large-scale WWT but are applied in the production of high-value metabolites or food products, or the generation of sterile inocula for further cultivation in raceway ponds [73,87].

4.2 | Immobilized WWT systems

Because of the typically low biomass concentrations at photoautotrophic growth conditions, harvesting and downstream processing are still the most costly steps in microalgae

cultivation [84,85]. The small cellular size and high water content of most microalgae further exacerbate the problem of keeping processing costs acceptable. Therefore, microalgae immobilization offers a promising approach to obtaining both processing goals: metabolic conversion of wastewater components and easy and cost-efficient harvesting of the produced biomass [91].

The technological implementation can be realized in different ways. For pond systems, the Algal Turf Scrubber (ATS) process uses an immobilized community of bacteria, algae, and cyanobacteria in the form of periphyton for the removal of N and P from agricultural and municipal wastewater, inspired by natural wetland ecosystems. It is based on a raceway with a slight slope, covered with a liner as a substrate for periphyton attachment [92]. The water is streamed through the growing biomass while the pollutants are degraded or filtered. To maintain higher growth rates and removal efficiencies, mechanical harvesting is applied periodically [93].

Immobilized systems can be divided into two groups. Fixed-bed systems rely on a stationary matrix for biomass immobilization, using different types of construction, usually based on porous matrices, fibers, or surfaces. High surface-to-volume ratios are crucial for effective growth conditions [74]. Hydrophobicity and micro- or macro-structured surfaces promoting stable biofilm formation and material selection seem to be important for biofilm adhesion strength, and therefore in terms of growth potential and removal rates [75,93,94]. Sukčová et al. were able to demonstrate removal rates of up to 92% by using naturally occurring algae and cyanobacteria on a horizontal flat-panel PBR made from a concrete slab [95]. The revolving algal biofilm reactor, presented in the study of Gross et al. provides an example of another application, with growth rates higher than in suspended culture for *Chlorella* and an easy harvesting technology [96].

Fluidized bed systems immobilize biomass on a floating substratum that increases the surface-to-volume-ratios even more and enhances light distribution because of an improved mixing capability, adjustable by the movability of the immobilized cells. Examples of common applications include the use of alginate, chitosan, or carrageen beads to fix the biomass. The cells penetrate the porous matrix of the bead and also grow inside it. Fluidized bed systems integrate well with other reactor concepts, such as bubble columns, stirred tanks or ponds, and allow benefit from synergizing characteristics. Growth rates and removal rates can be similar to suspension systems, and sometimes higher. However, in general a direct comparison of removal rates for nutrients or heavy metals is difficult because of the strong dependence on cultivation system, organisms used, immobilization matrix, and pollutant composition. Chevalier et al., Lau et al., and Travieso et al. have reported N removal rates of 100, 95, and 82%, respectively [97–99]; all reported that the rate of phosphate removal was not as high as N, because of the lower demand

for cell growth and N:P ratio in cells. However, the experiments of Fierro et al. showed an opposite trend in relation to nitrate and phosphate [100], and Lau et al. demonstrated slightly higher growth constants for carrageen-immobilized cells of *C. vulgaris* and the same nutrient-removal rates as in suspended cultures [101]. As described in previous studies, the chlorophyll content of immobilized microalgae was higher than in suspension, because of the self-shading effect inside the bead matrix [101–103].

The long-term stability of bead-immobilized algal cultures still has to be improved to maintain the high removal rates achieved so far [104], thus knowledge of biofilm formation is needed. As in suspended cultures, a mixture of microalgae and bacterial growth can be beneficial for removal rates, particularly of organic compounds [105,106]. Su et al. successfully co-cultivated algae and bacteria from activated sludge and reported removal efficiencies for N and P of more than 90% [79]. Plant growth-promoting bacteria such as *Azospirillum* spp. were also tested to support microalgae cells in attached biofilm cultivations. In immobilized cultures, an increase in growth capacity, higher pigment content or N:P, and changing physiological parameters have been detected, showing a distinct relationship between these bacteria and microalgae populations of different *Chlorella* species [107–109]. It has been shown that a bacterially overgrown surface can promote biofilm formation or exopolysaccharide production [110,111]. Covarrubias et al. were able to demonstrate a protective function of immobilization in alginate beads. A surface-attached biofilm of bacteria protected algal cells inside the gel matrix against indigenous natural wastewater micro-fauna [112].

5 | MICROALGAE-BASED WWT APPROACHES THAT HAVE BEEN PUT INTO PRACTICE

During the last decade, several companies, mainly from the US, UK, and Australia, have started working on algae biomass production using wastewater sources. Despite the limited information on the microalgal species used by these companies, a brief overview of the technological approaches is given here.

The algae WWT plant of Algal Enterprises (Australia) can be applied to the whole spectrum of wastewater sources: municipal, industrial, and agricultural. Photosynthetically active radiation is used as the main energy source by local algae species in a closed PBR system. The algal biomass produced is co-digested anaerobically to obtain a methane-rich biogas that is further converted to electricity [113].

The RNEW® technology of Microbio Engineering (US) uses mechanically mixed, CO₂-gassed open raceway ponds to

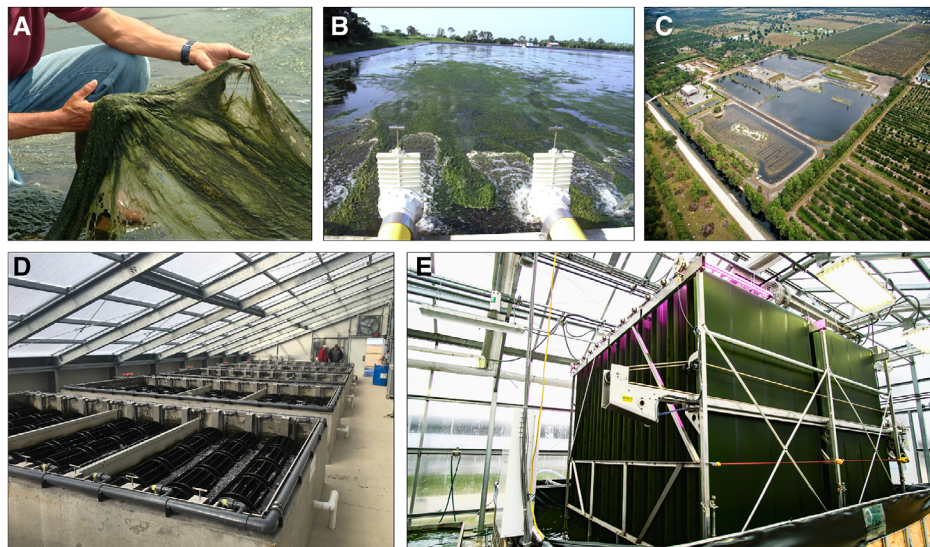


FIGURE 3 (A–C) Images of the Algal Turf Scrubber® of *HydroMentia*, kindly provided by Mark Zivojnovich; (D) AlgaeWheel® system of *OneWater Inc.* kindly provided by Daniel Johnson and Steve Kingsland; (E) Revolving algal biofilm (RAB) system of *Gross-Wen Technologies* kindly provided by Martin Gross

treat N- and P-rich municipal wastewater to produce feedstock biomass for biofuel production [114–116]. Solimeno et al. predicted the proportion of algal and bacterial biomass within the open raceway ponds to 58–68% and 23–30% of total suspended solids, respectively [117]. In a following study the algae microbiome of the high-rate algal ponds was found to be dominated by species of *Micractinium* ssp., *Scenedesmus* ssp., *Chlorella* ssp., and pennate diatoms [118]. Oswald Green Technologies has developed the Advanced Integrated Wastewater Pond System (AIWPS®), also known as Energy Ponds™, which works with a symbiotic bacterial algal consortium to capture both organic and inorganic pollutants of municipal, agricultural, and industrial wastewater [119,120]. In a first pretreatment step, the wastewater solids are removed by anaerobic ponds or gravity settlers, followed by the assimilation of organic and inorganic matter by the microalgae in high-rate algae ponds. The captured algal biomass from the Energy Ponds™ is processed as fertilizer, animal feed and raw material for plastics and biofuel.

Another approach is offered by *AlgaeSystems*. This US company has developed a low-cost offshore floating PBR system that is applied in environmental light and CO₂ conditions to take up nutrients downstream from their original source [121]. The offshore PBR was demonstrated to treat 50 000 gal day⁻¹ of raw municipal wastewater with removal efficiencies of 75% (total N), 93% (total P), and 93% (BOD). After one year of operation, the originally inoculated pure culture of the genus *Scenedesmus dimorphus* shifted towards a stable operating polyculture of *Chlorella* ssp., *Scenedesmus* ssp., and *Cryptomonas* ssp. [122]. The raw algal biomass is processed onshore by hydrothermal liquefaction to yield renewable fuels and fertilizers [122].

Besides the approaches using suspended cultures for WWT, there is a trend in using microalgal biofilms, immobilized microalgae, or microalgae–bacteria co-cultures, such as those of *HydroMentia*, *OneWater*, and *Gross-Wen Technologies* (Figure 3). The Algal Turf Scrubber® (ATS) of *HydroMentia* consists of a flow-way that is pulsed in waves with the treated wastewater [123,124]. Periphytic algae, which are harvested periodically from the surface of the flow-way, fix excess nutrients and CO₂ from the wastewater. Kangas and Mulbry found a non-linear relationship between daily operation time and ATS productivity [125]. The N and P removal rates for an agricultural drainage ditch were accounted to 125 mg N m⁻² d⁻¹ and 25 mg m⁻² d⁻¹ [125] at the highest flow characteristics and continuous ATS operation. Later, the ATS system was further validated in a couple of studies dealing (waste-)water originated from an oyster aquaculture facility [126,127], a Chinese drinking water reservoir [128], and rivers [129]. The authors found a high variability in the ATS community structure (~182 species at 28 m² growing area) and seasonal biomass productivities (peak production during July/August). The ATS produced algae biomass serves as soil-enhancing compost and livestock feed but is also intended as a resource for biofuel production [124]. The technological approaches of OneWater and Gross-Wen Technologies are based on immobilized cells in rotating parts of the WWT plant. OneWater has developed the AlgaeWheel® system, an advanced algal-fixed film technology. The biofilm ecosystem attached to the AlgaeWheels® comprises a diverse group of algae and bacteria, and the synergetic effect of both types of microorganism enhances the treatment efficiency of the overall system [130]. The microalgae use sunlight to fix CO₂, which is released by the bacteria. The polysaccharides,

which are produced by photosynthesis, act as both bacterial nutrient source and solid settlement. In turn, the bacteria are able to use the photosynthetically produced oxygen, resulting in a stable self-regulating and ecological WWT system [130].

The revolving algal biofilm (RAB) system of Gross-Wen Technologies is made of an algae biofilm attached to vertically oriented rotating conveyor belts. While performing photoautotrophic growth at the gaseous phase, the attached microalgae fix N and P from the nutrient-rich liquid [96]. The algal biomass of the RAB system can be easily scrapped from the surface of the RAB system avoiding expensive harvesting operations [96]. Gross and Wen presented the results of a year-round operation of the RAB WWT pilot plant at a greenhouse facility at Iowa/USA [131]. The authors found a 302% increased biomass productivity compared to control raceway ponds yielding a biomass productivity of 18.9 ash free $\text{g m}^{-2} \text{d}^{-1}$, which was further increased to 46.8 $\text{g m}^{-2} \text{d}^{-1}$ by using a trough-based RAB configuration [132]. Zhou and co-workers validated the RAB system processing sulphate-loaded mining wastewater at low pH conditions obtaining a sulphate removal efficiency of 46% with a rate of 0.56 $\text{g L}^{-1} \text{d}^{-1}$ [133]. A further RAB validation study at pilot scale was performed at supernatant from sludge sedimentation yielding removal rates of 80% (total P) and 87% (total N), respectively. Actually, the biomass produced is sold as fertilizer or feedstock for bioplastics [134].

6 | CONCLUDING REMARKS

Clean water has become a limiting resource in many regions of the world. The most efficient approach to reduce the pollution of water resources with nitrates, phosphates, and high organic loads is to remove these components at the point of origin, i.e. at the processing sites. However, conventional biological WWT systems are often unable to fulfil this cleaning task because the pH values, high organics, or temperatures are often non-compatible to microbiological physiology. Extremophilic microalgae offer a potential means, so-far largely unexplored, to solve this problem. Microalgae in general, conventional and extremophile can play an important role in a circular bio-economy by providing high-quality products, such as proteins, lipids, and colorants, within the biomass produced by the WWT cleaning process. Some selected examples of algae-based WWT technologies have been reviewed here, with a special focus on concepts that have been validated at technical scale.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest

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