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Review

Recent Trends on Domestic, Agricultural and Industrial Wastewaters Treatment Using Microalgae Biorefinery System

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Abstract: In addition to producing bioenergy and molecules with high added value, microalgae have been recognized as an efficient microorganism for wastewater treatment. However, a major obstacle preventing its widespread use is the high energy cost of pretreatment, cultivation and downstream processes. Different types of wastewaters have been tested as culture mediums for microalgal biorefinery system. This review gives a summary of the most used microalgae strains for wastewater treatment, as well as information on the physical and chemical characteristics of domestic, agricultural, and industrial wastewaters. It also discusses wastewater pretreatment techniques, nutrient uptake and removal, biomass production and biomolecules productivities. There is also discussion on how microalgae remove contaminants from wastewater. Additionally, the problems and restrictions of microalgae-based wastewater treatment are explored, and recommendations are made for additional study and advancement. This literature review demonstrates that microalgae monoculture systems have proven to be beneficial as an innovative wastewater treatment technology, due to its high efficiencies in pollutant removals and biomolecule production; however, the upstream and downstream treatment pose a limit to industrialize the process. Until now, there has been no conventional design of the wastewater treatment process using microalgae in the biorefinery system, which constitutes a huge gap to assess a real life cycle assessment (LCA) and techno economic analysis (TEA).

Keywords: wastewater treatment; microalgae; biomass production; nutrient recovery; biomolecules; biorefinery

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1. Introduction

Nowadays, planet earth is dealing with two significant issues: energy and water crises. According to [1], between 2015 and 2040, the global energy consumption is expected to rise by 28%, while the global use of petroleum-based fossil fuels would rise from 190 to 230 quadrillion British thermal unit. Additionally, excessive fossil fuel use not only depletes natural resources but causes continual increases in the carbon dioxide emissions, which contributes toward global warming [2]. Biodiesel from microalgae has been proposed as an alternative renewable fuel source [3], but the cost of production (160–480 USD BBL^{-1}) is more than the cost of crude oil and over 50% of the overall price is often attributed to the price of freshwater, fertilizers and the harvesting procedure [4].

Freshwater represents only 0.5% of the global water on planet earth, and its consumption increases with the increasing population and industrial activity, which generate

380 trillion L y^{-1} of wastewater in the world [5]. In addition, by 2050, more than 50% of the planet's population is projected to face chronic water shortages, hence the need for wastewater recycling [6]. As reported in this review, domestic, agricultural and industrial wastewaters contain significant concentrations of nutrients, including phosphorus, carbon and nitrogen, which are required for the growth of microalgae. Microalgae-based biorefineries for biofuels and wastewaters treatment have received a lot of interest to tackle the energy and water scarcity [1,5,7]. Consequently, researchers have frequently used wastewater from different sources for microalgae cultivation, in order to determine the potential of microalgae for simultaneous wastewater treatment. Recently, *Chlorella pyrenoidosa* (No. FACHB-863) was employed for its wastewater treatment ability to eliminate contaminants from synthetic tobacco wastewater [8]. The study's findings demonstrated that *Chlorella pyrenoidosa* may grow in this kind of effluent, with a maximum biomass of 540.24 mg L^{-1}. *Arthrospira* has been cultivated in seawater with the addition of anaerobic animal waste effluent to produce biofuels (biogas, biodiesel and biohydrogen) and high added value materials [7]. Although it has been widely studied in previous research, the use of wastewater for a biorefinery system at a low cost is rare on an industrial scale, because this cultivation method still has challenges that limit its application; however, several pieces of research are now underway for its implementation in the future.

In order to identify prospective directions for future research on microalgae-based bioremediation, this review intends to highlight the advances and existing work concerning the use of microalgae in wastewater treatment for a biorefinery system.

Following these guidelines, the available literature was assessed to accomplish the purpose of this review:

1. Wastewater treatment by microalgae: In this section we present the physicochemical properties of domestic wastewater that have been used in domestic wastewater treatment by microalgae, followed by the pretreatment of domestic wastewater before microalgae cultivation, as well as pollutant removals such as chemical oxygen demand (COD), total nitrate (TN) and total phosphate (TP) removals, biomass generation and the productivity of biomolecules after microalgae cultivation, using different species that have been tested in the literature. The same parameters have been explored for both agricultural wastewater and industrial wastewater.
2. Microalgal mechanisms for wastewater bioremediation: As the biodegradation response of microalgae to contaminants varies from one pollutant to another, we focus on the following mechanisms in this section: CO_2 fixation, nitrogen sources assimilation, phosphate sources assimilation and heavy metals biodegradation mechanisms.
3. Economic analysis of microalgae wastewater treatment technologies: In this section we compared microalgae wastewater treatment technologies with co-culture technologies such as microalgae-bacteria, microalgae-fungi, microalgae-yeast and microalgae-Nanoparticle. Furthermore, we discussed a life cycle assessment (LCA) and a techno economic assessment (TEA) of microalgae-based wastewater treatment process.
4. Challenges and prospects: We have proposed strategies to overcome the challenges that the microalgae-based wastewater treatment process is facing.

2. Wastewater Treatment by Microalgae

Different species of microalgae have been used to remediate various types of wastewaters in recent times. In terms of the wastewater employed, Tables 1–12 describe the culture conditions, treatment efficiency, final biomass generated and its biochemical composition.

2.1. Domestic Wastewater

2.1.1. Physicochemical Properties

Domestic effluent is defined as water that has been used by a population and contains all the materials that have been added to it throughout its usage [9]. It is generally classified into two types (Figure 1): black-water and grey-water, and is mostly made up of discharge from domestic and home activities [10]. In some part of the world, this type of wastewater

is disposed into drainage systems, lakes and rivers without any previous treatment, posing challenges to the enhancement of the community's living conditions, because untreated wastewater has a significant negative impact on the environment and human health [9,11]. Black-water may consist of urine, flash water, fecal matter, toilet paper and others water, such as water from cleaning activities [10], and grey-water is wastewater that comes from kitchen sinks, laundromats and showers, or any other domestic activity other than toilet waste [11]. Kitchen wastewater is a type of wastewater that includes a lot of ammonium due to food protein degradation, and its excessive thickness supplements a terrible odor signal that must be treated. The treatment of kitchen wastewater by microalgae has been explored and it appeared that the collected kitchen wastewater had a high organic content due to the existence of oil, grease and food products and was acidic, with chemical oxygen demand (COD) levels ranging from 800 mg L^{-1} to 1400 mg L^{-1}, compared to raw sewage wastewater which has COD levels ranging from 250 mg L^{-1} to 800 mg L^{-1} [12]. To solve this problem and make the kitchen wastewater acceptable for microalgal development, it should be diluted by about 1:1 with water [12].

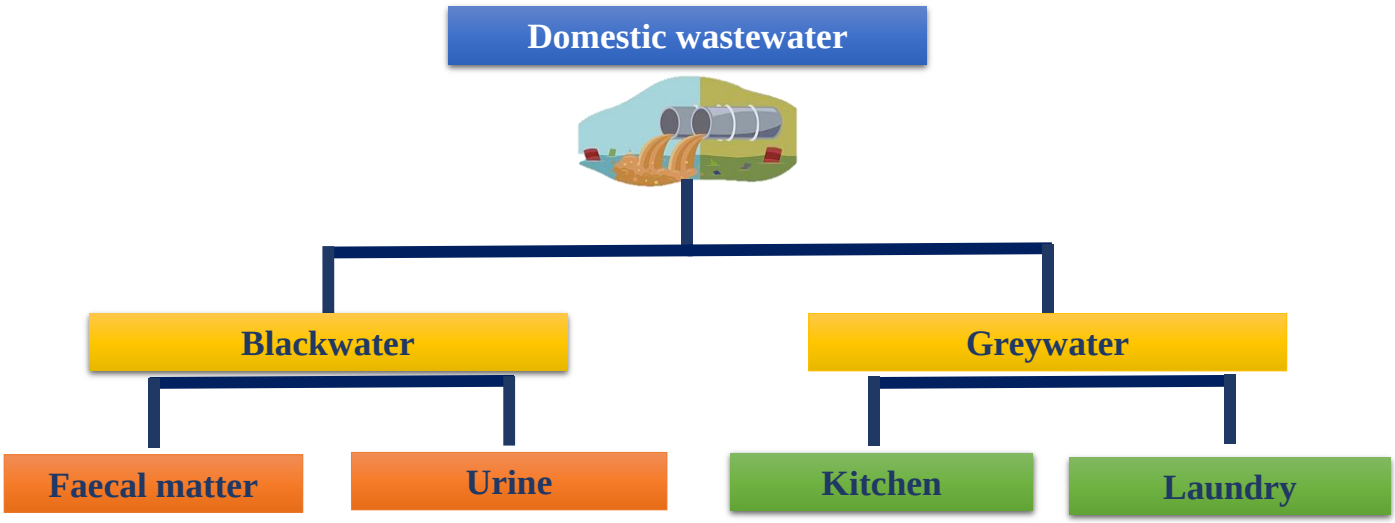


Figure 1. Domestic wastewater types.

The composition of different domestic wastewaters, which have been used in the literature for microalgae culture, is given in Table 1. As described in this table, sewage effluent has a pH of 6.6 to 8.81, a chemical oxygen demand (COD) of 97 mg L^{-1} to 1100 mg L^{-1}, a total nitrate content (TN) of 0.22 mg L^{-1} to 265 mg L^{-1}, a total phosphate concentration (TP) of 0.6 mg L^{-1} to 170 mg L^{-1} and other constituents such as chloride and potassium. Kitchen wastewater has a COD content of 560 mg L^{-1}, whereas toilet wastewater has a COD value of 506.8 mg L^{-1}, with TN and TP levels of 203.6 mg L^{-1} and 22.3 mg L^{-1}, respectively. As a reason, using domestic wastewater for microalgae growth is a suitable choice for both wastewater treatment and the generation of biodiesel and other chemicals from the produced biomass.

Table 1. Domestic wastewater composition.

Type	pH	TSS (mg L^{-1})	TOC (mg L^{-1})	COD (mg L^{-1})	NO_3-N (mg L^{-1})	NO_2-N (mg L^{-1})	NH_4-N (mg L^{-1})	NH_3-N (mg L^{-1})	PO_4-P (mg L^{-1})	TN (mg L^{-1})	TP (mg L^{-1})	References
Secondarily Treated Sewage	7.63	-	5.5	-	7.67	0.01	0.17	-	0.02	8.9	0.04	[13]
	7.2	352	-	328	-	-	-	-	-	18	7	[14]
	8.77	740	-	784	30.25	-	-	-	1.7	-	-	[12]
	-	-	310–560	1000–1100	-	-	-	-	-	230–260	15	[15]
	7.80	-	-	702	10.72	-	-	33.1	2.25	-	-	[16]
	7.1	-	-	252	-	-	205	-	-	265	17.1	[17]
	7.8	-	-	104	-	-	26.3	-	-	33	0.6	[18]
	6.6–7.6	-	-	190–230	-	-	-	20–35	-	40–60	4.5–5.6	[19]
	7.82	-	-	426	1.156	-	46.2	-	-	-	3.22	[20]
	7.7	3500	-	286	197	-	992	-	-	-	286	[21]
Raw Sewage	7.86	-	-	618	-	-	54	-	-	80	4.2	[22]
	7.56	-	154	496	2.45	-	12.5	-	7.1	24.45	9.6	[23]
	-	-	208.15	446.25	16.58	-	37.64	-	-	61.47	7.42	[24]
	6.9–7.5	-	-	-	2–5	-	36–47	-	-	-	12–19	[25]
	7.9–8.2	-	-	296–858	1.5–5.6	-	58.2–136.9	-	-	-	7.9–27.7	[26]
	8.81	-	20.58	-	0.07	-	30.02	-	-	30.46	2.6	[27]
	7.2	-	-	129	-	-	-	37	-	48	9	[28]
	7.4–7.6	95.8	201–311	190–310	-	-	45.6	-	-	57.9	4.4	[29]
	8.2	32	22.1	97	10	-	136	-	62	146	-	[30]
	-	-	-	-	-	-	-	-	-	315	10.15	[31]
	8.55	-	343.07	-	-	-	-	-	-	0.22	2.28	[32]
Kitchen Toilet	6.85	980	-	560	52.962	-	-	-	2.037	-	-	[12]
	7.1	-	-	506.8	-	-	157.5	-	16.4	203.6	22.3	[33]

Type	Chloride (mg L^{-1})	Na (mg L^{-1})	F (mg L^{-1})	Fe (mg L^{-1})	Cu (mg L^{-1})	Zn (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Pb (mg L^{-1})	Turbidity NTU	References
Secondarily Treated Sewage	-	65	-	-	-	0.05	3	-	27	-	-	[14]
	58.25	110	-	-	-	-	-	160	135	-	-	[12]
	1200	-	-	-	<0.005	-	14.8	-	-	-	-	[17]
	268	-	-	-	-	-	-	-	-	-	379	[21]
	-	-	-	-	-	-	-	-	-	-	182	[23]
Sewage	173–190	-	-	-	-	-	108–144	300–400	-	-	-	[25]
	410–435	222.5–312.1	-	-	-	0.1–0.18	52.1–65.7	31.1–31.9	8.4–9.8	-	-	[26]

Table 1. *Cont.*

Type	Chloride (mg L^{-1})	Na (mg L^{-1})	F (mg L^{-1})	Fe (mg L^{-1})	Cu (mg L^{-1})	Zn (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Pb (mg L^{-1})	Turbidity NTU	References
	-	-	-	-	-	-	-	-	-	-	-	[27]
	-	-	-	-	-	-	-	-	-	-	-	[28]
	-	-	-	-	-	-	-	-	-	-	140–160	[29]
	-	-	-	0.098	0.0321	0.0218	-	52.2	12.16	0.1707	-	[31]
Kitchen	92.08	130	-	-	-	-	-	180	148	-	-	[12]
Toilet	-	-	-	-	-	-	8.6	23.8	98.2	-	-	[33]

TSS (total suspended solids), TOC (total organic carbon), COD (chemical oxygen demand), NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), NH_3-N (ammonia-nitrogen), PO_4-P (orthophosphate phosphate), TN (total nitrogen), TP (total phosphate), Na (sodium), F (fluorine), Fe (iron), Cu (copper), Zn (zinc), Mg (magnesium), Ca (calcium), K (potassium), Pb (lead), NTU (nephelometric turbidity units) and nr (not reported).

2.1.2. Pretreatment

Table 2 shows three pretreatment procedures that have been mostly used for domestic wastewater: filtration, autoclaving and centrifugation. These pretreatments can remove suspended solids, debris and colloidal particles, which can limit light penetration and microbial contamination from wastewater. According to [33], all of their wastewater samples included significant levels of suspended particles, which might limit photosynthetic performance. As a result, they centrifuged them for 15 min at 5000 rpm before filtering the liquids through 0.45 µm polyester filters. They further sterilized the filtrated samples in an autoclave for 20 min at 121 °C to guarantee that they were axenic [33]. Other authors have filtered and sterilized the wastewater by autoclaving at 15 psi for 30 min to remove particles and microorganisms such as bacteria, fungi and microalgae [34]. The autoclaving has reduced the biological oxygen demand from 159.63 mg L^{-1} to 93 mg L^{-1} and the ammonium concentration from 31.38 mg L^{-1} to 17.19 mg L^{-1}. In contrast, the total phosphate concentration increased from 9.24 mg L^{-1} to 12.8 mg L^{-1} and the nitrate concentration increased from 40.02 mg L^{-1} to 45.1 mg L^{-1} [34]. Even if the centrifugation and sterilization of wastewater is feasible for microalgae culture in the laboratory, it would be impossible to use it on a massive scale due to the increased costs of production, and the most significant barriers being the energy usage and time consumed [1].

Table 2. Pretreatment methods of domestic wastewater before microalgae cultivation.

Wastewater	Pretreatment Method	Microalgae	References
Domestic	Filtered (Whatman filter paper, grade 1), autoclaved	*Chaetoceros* sp. and *Isochrysis* sp.	[35]
Municipal	Settled in flask for two hours and pretreated by passing Whatman filter paper	*Chlorella minutissima*	[23]
Domestic	Filtered using a 0.2 µm nylon membrane filter	*Scenedesmus* sp.	[36]
Domestic	Filtered through a mesh sieve (100 µm)	*Chlorella* sp. and *Scenedesmus* sp.	[24]
Domestic	Pre-filtered using filter cloth (nylon monofilament, pore size 25 µm) and autoclaved at 121 °C for 20 min	*Chlorella variabilis* TH03	[37]
Septic tank	Centrifuged at 5000 rpm for 15 min, filtered by 0.45 µm polyester filters and sterilized by an autoclave for 20 min at 121 °C	*Chlorella pyrenoidosa* (FACHB-9)	[33]
Municipal	Filtered using LLG-filter papers (pore size 5 µm to 13 µm)	*Chlorella sorokiniana* (UTEX 1230)	[22]
Municipal	Filtered with a 2 µm filter	*Phaeodactylum tricornutum*	[28]
Domestic	Filtered using nylon mesh with pore size ~50 µm	*Botryococcus* sp.	[14]
Domestic	Filtered	*Chlorella* sp.	[12]
Domestic	Autoclaved at 121 °C for 30 min	*Chlorella pyrenoidosa*	[19]
Municipal	Filtered and autoclaved at 121 °C for 20 min	*Chlorella zofingiensis*	[31]
Municipal	Filtered through glass microfiber filters with 0.6-µm pores and autoclaved at 121 °C under 15 psi for 20 min	*Dunaliella salina*	[38]
Domestic	Autoclaved at 121 °C for 30 min	*Chlorella pyrenoidosa*	[20]
Municipal	Filtered and sterilized using vacuum filtration unit and autoclaved at 121 °C for 15 min	*Nannochloropsis oceanica*	[32]
Domestic	Filtered and sterilized by autoclaving at 15 psi for 30 min	*Chlorella vulgaris* and *Nannochloropsis oculata*	[34]

2.1.3. Microalgae Treatment of Domestic Wastewater

There have been several pieces of research published in the literature that have investigated the feasibility of treating sewage, kitchen and toilet wastewaters with or without dilution using microalgae. Culture conditions, initial nutrients concentrations and removal rates have been gathered in Table 3 for different microalgae and domestic wastewater treatments, while the growth parameters and metabolites production of microalgae culture in domestic wastewater are provided in Table 4. Figure 2 showed that each species of microalgae has a different capacity to reduce pollutants from domestic wastewater, and this ability varies from one wastewater to another.

The maximum potential for total nitrogen (TN) and total phosphate (TP) removals from municipal wastewater were found for *Chlorella variabilis* TH03 at a 96.8% and 100% removal rate [37]. The other microalgae removed between 28% and 95% of total nitrogen and between 12% and 99% of total phosphate. The removal efficiency of chemical oxygen demand was not assessed in the majority of these studies.

Recently, Kumar et al. 2019 [12] explored the treatment of kitchen wastewater (Phosphates: 2.037 mg L^{-1}; Nitrates: 52.962 mg L^{-1}; COD: 560 mg L^{-1}) and sewage wastewater (Phosphates: 1.7 mg L^{-1}; Nitrates: 30.25 mg L^{-1}; COD: 784 mg L^{-1}) by the species *Chlorella* sp. in culture flasks in the laboratory. The nitrate and phosphate removals were 38% and 75%, respectively, for kitchen wastewater, and 67% and 88% for sewage wastewater. The COD content in kitchen wastewater was gradually reduced in the first four days, after which it was kept around the same value and varied in a modest range throughout the culture period. COD reduction efficiency was 32.14% on the final day of culture [12]. In this study, the color of the kitchen wastewater was black during microalgal culture, and they supposed that it was due to the high concentration of ammonia and high turbidity and then concluded that these conditions were not conducive to microalgal development. To solve this problem and make the kitchen wastewater acceptable for microalgal development, they diluted it by about 1:1 with water [12]. Tan et al. 2021 [33] reported that septic tank wastewater can be utilized for microalgae cultivation. They tested diverse types of wastewaters for *Chlorella pyrenoidosa* (FACHB-9) cultivation and demonstrated that the toilet wastewater (TN: 203.6 mg L^{-1}; NH_4-N: 157.5 mg L^{-1}; TP: 22.3 mg L^{-1}; COD: 5200 mg L^{-1}) was the great medium for biomass (1.68 g L^{-1}) and nutrient removal efficiencies (NH_4-N: 90.8%; TP: 62.9%; COD: 61.3%). According to the same study, discharging kitchen or laundry wastewater decreased the biomass production by 50.5–79%, and should be isolated from toilet wastewater. Kumar et al. 2021 [35] compared the remediation capability of the marine diatom *Chaetoceros* with the haptophyte *Isochrysis* microalgae when grown in urban wastewater. Their results demonstrated that the two strains can successfully remediate NO_2-N of 0.63% from 10% of domestic wastewater by *Chaetoceros* and 5.57% from 30% of domestic wastewater by *Isochrysis*, as well as a total phosphorus removal of 83–84% and 84–94% by *Chaetoceros* and *Isochrysis*, respectively. Chemical oxygen demand was reduced more efficiently in 40% of domestic wastewater by *Chaetoceros* (157 mg L^{-1}) and in 100% of domestic wastewater by *Isochrysis* (93%). According to [35], the use of domestic wastewater as a culture medium for *Chaetoceros* sp. and *Isochrysis* sp. has shown their effectiveness as a sustainable food source and a source of biofuels due to their production of total polyunsaturated fatty acids (PUFAs) from 33.5% to 71.6% in the case of *Chaetoceros* and from 20% to 63.4% in *Isochrysis*.

The effectiveness of autotrophic and heterotrophic metabolisms in different microalgae species for wastewater bioremediation and the generation of sustainable microalgal products/coproducts was also evaluated using various culture regimes [27,34,39,40]. For example, Leong et al. 2022 [39] assessed the photoperiod-induced mixotrophic metabolism in *Chlorella vulgaris*. They measured cell biomass growth and lipid content of *Chlorella vulgaris* and conducted organic nutrient removals from municipal wastewater (COD: 145 mg L^{-1}; NH_4-N: 48 mg L^{-1}) with distinct light: dark photoperiod cycles. In their results, the 16:8 (light: dark) photoperiod was shown to be appropriate for producing high biomass (0.89 g L^{-1}) and lipid production (0.16 g L^{-1}), while also removing chemical oxygen demand and ammonium-nitrogen from municipal wastewater with near–complete removal (>94%).

The removal of nutrients from municipal wastewater by *Chlorella vulgaris* and *Nannochloropsis oculata* was examined utilizing mixotrophic culture with glycerol (0 g L^{-1} to 5 g L^{-1}) [34]. The addition of 2 g L^{-1} of glycerol in the municipal wastewater as a medium for *Chlorella vulgaris* enhanced the biomass production to 56 mg L^{-1} d^{-1} and had a total nitrate removal of 64%. However, for *N. oculata*, the best nitrogen removal (80.62%) was obtained with 3 g L^{-1} of glycerol, with COD and TP removals of 96.3 and 60.72%, respectively, using 1 g L^{-1} and 5 g L^{-1} of glycerol. *C. vulgaris* had the highest lipid content (15.11%) when municipal wastewater was supplemented with 5 g L^{-1} of glycerol compared to wastewater without glycerol (7.72%). In the same way, *N. oculata* had a high lipid content (8.91%) with 2 g L^{-1} of glycerol compared to the culture without glycerol (4.59%) [34].

Similar to this finding, [40] demonstrated that combining a municipal wastewater with glycerol for boosting the mixotrophic culture of *C. vulgaris* Wu-G22 was a viable option for

integrating wastewater treatment with energy production from algal biomass. They found that this microalga had the highest removals for COD, TN and PO_4-P from 6195.6 mg L^{-1} to 448.47 mg L^{-1}, from 46.78 mg L^{-1} to 3.39 mg L^{-1} and from 9.79 mg L^{-1} to 0.75 mg L^{-1}, respectively, when domestic wastewater was supplemented with 50 mM of glycerol [40]. In addition, *C. vulgaris* Wu-G22 produced a high lipid content of 15.7% and produced contents of other compounds such as carbohydrates and proteins by about 7.3% and 70%, respectively [40].

A recent study used sodium acetate (NaAc) to enhance the removal efficiency of nutrients from municipal wastewater [27]. *S. obliquus* cultivated in the municipal wastewater grew faster and accumulated more lipids than those cultivated in the BG11 synthetic medium, indicating that the domestic wastewater might be used to replace the synthetic medium for microalgae growth [27]. Furthermore, introducing exogenous NaAc to mixotrophic cultivation significantly increased the algal growth and lipid synthesis [27]. The growth of *Scenedesmus obliquus* was 2.40 times greater (from 0.2 mg L^{-1} to 0.48 mg L^{-1}) with the addition of 1 g L^{-1} of sodium acetate than that in the municipal wastewater without supplement. Furthermore, this concentration enhanced the microalga removals of nitrogen and phosphorus by 1.75 (from 46.85% to 82.2%) and 2.23 times (from 34.18% to 76.35%), respectively, accompanied with a high lipid productivity of 22.08 mg L^{-1} d^{-1} [27].

The dilution approach was investigated as a strategy for improving *Scenedesmus* sp. nutrient recovery and biomass. The author of [41] investigated the impact of different dilutions of fresh leachate (5%, 10%, 15%, 20% and 25%) using treated municipal wastewater on the growth and nutrient recovery potential of *Scenedesmus* sp. They found the highest removal efficiencies of 100%, 94% and 96% in 15% of fresh leachate for nitrite, ammonium, and phosphorus removals, respectively. Musetsho et al. research [42] on *Acutodesmus obliquus* revealed that poultry litter extract (2 g) diluted in municipal wastewater (100 mL) has the potential to be utilized as a nutrient and water source for this species. *A. obliquus* produced the most biomass (1.90 g/L) and had the greatest NO_3-N, NH_4-N and PO_4-P removal rates (79.51%, 81.82%, and 80.52%, respectively). Furthermore, raw poultry litter extract had a slightly greater COD recovery efficiency of 50.80% when compared to poultry litter diluted in municipal wastewater (40.47%), which might be attributed to the proliferation of heterotrophic microorganisms/bacteria in the raw poultry litter extract [42].

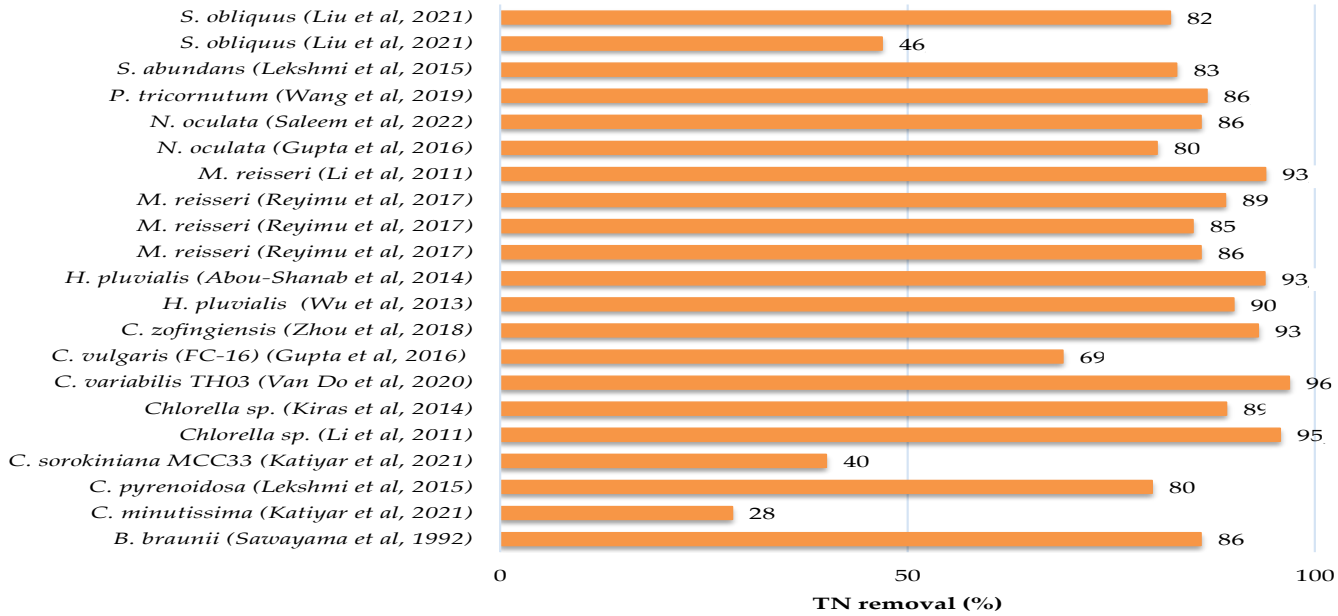


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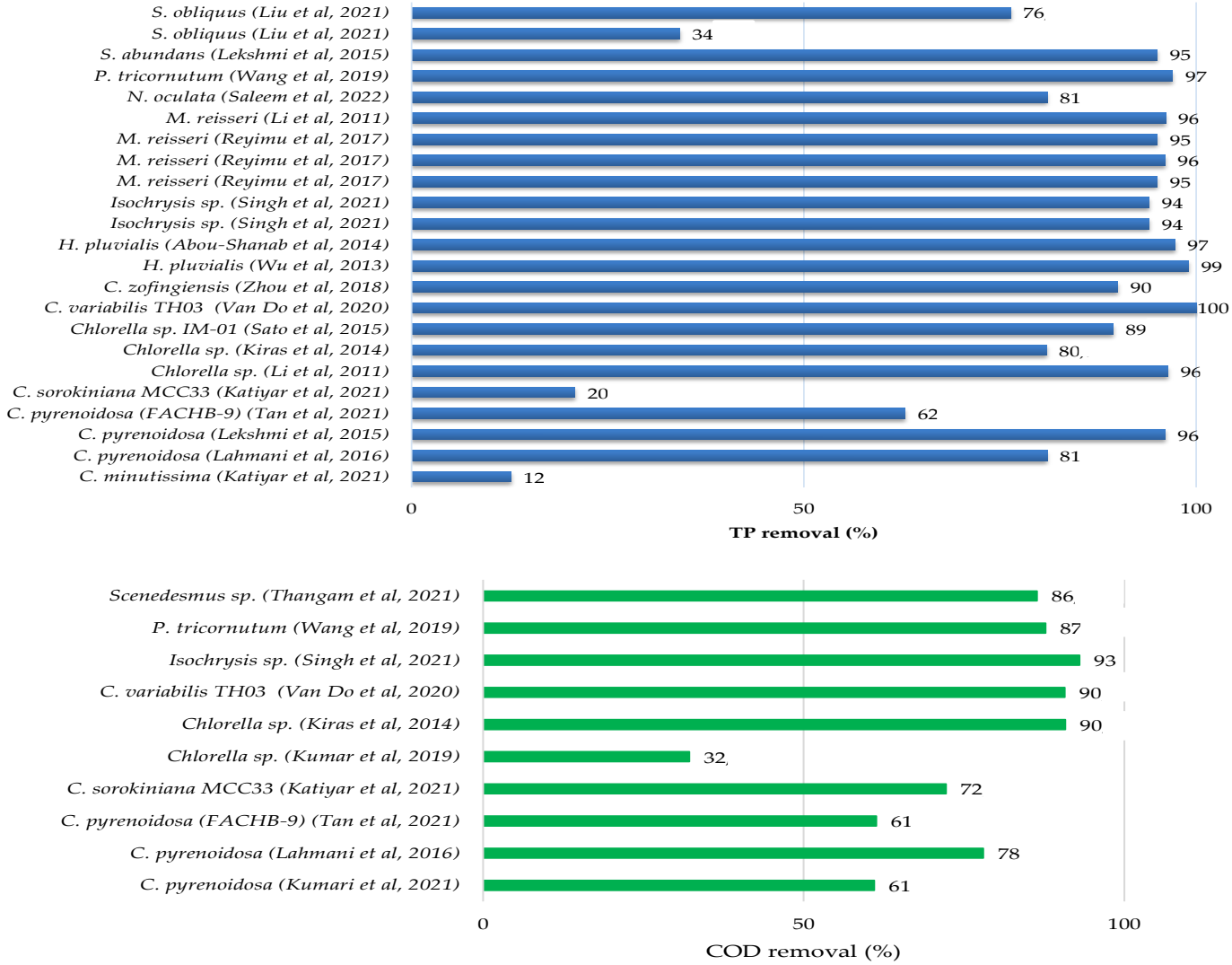


Figure 2. Nutrients and COD removals from domestic wastewater by microalgae [12,13,16,20,21,23,25,27,28,31,33–35,37,41–51].

Table 3. Treatment of domestic wastewater by the cultivation of microalgae.

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Acutodesmus obliquus	Municipal and poultry litter	25 °C; 80 μE m^{-2} s^{-1}; 16:8 light: dark	PO_4-P: 21.05 mg L^{-1}; NO_3-N: 13.25 mg L^{-1}; NH_4-N: 108.0 mg L^{-1};	NO_3-N: 79.51%; NH_4-N: 81.82%; PO_4-P: 80.52%	[42]
Botryococcus Braunii	Secondary treated sewage	25 °C; 3000 lx; 1% CO_2 (50 mL min^{-1})	TN: 8.9 mg L^{-1}; TP: 0.04 mg L^{-1}	TN:86%; TP:50%	[13]
Botryococcus sp.	Domestic	25 °C; 30 μE m^{-2} s^{-1}; 16:8 light: dark	TN:18 mg L^{-1}; COD: 328 mg L^{-1}; PO_4-P: 7 mg L^{-1}	nr	[14]
Chaetoceros sp.	Municipal	25 °C; 100 μE m^{-2} s^{-1}; 12:l2 light: dark	nr	NO_2-N: 0.63%; TP: 83–84%; COD: 157 mg L^{-1}	[35]
Chlorella minutissima	Municipal	24 °C	COD: 496.0 mg L^{-1}; TN: 24.45 mg L^{-1}; TP: 9.6 mg L^{-1}	TN: 28.46%; TP: 12.68%; COD: 61.69%	[23]
Chlorella pyrenoidosa	Sewage treatment plant	26 °C; 1500 lx	PO_4-P: 2.25 mg L^{-1}; NO_3-N: 10.72 mg L^{-1}; COD: 702 mg L^{-1}	NO_3-N: 99.2%; PO_4-P: 70.1%; COD: 61.0%	[16]
	Domestic	Open pond systems using direct sunlight: 18–31 °C (day) and 6–15 °C (night); the insolation 9 h a day	NH_4-N: 46.2 mg L^{-1}; TP: 3.22 mg L^{-1}; COD: 426 mg L^{-1}	NH_4-N: 95%; TP: 81%; COD: 78%	[20]
	Raw domestic	Continuous illumination of 1800 lx	TN: 197 mg L^{-1}; NH_4-N: 992 mg L^{-1}; TP: 286 mg L^{-1}	NH_4-N: 99%; TP: 96%; TN: 80%	[21]
Chlorella pyrenoidosa (FACHB-9)	Municipal	23.2 °C; 4000 lx; 24:0 light: dark	TN: 33 g L^{-1}; TP: 0.6 g L^{-1}; COD: 104 g L^{-1}	nr	[18]
	Municipal	nr	TN: 50 mg L^{-1}; NH_4– N: 40 mg L^{-1}; TP: 5 mg L^{-1}; COD: 240 mg L^{-1}	nr	[43]
	Septic tank effluents (toilet)	25 °C, 260 μE m^{-2} s^{-1}; 12:12 light: dark	TN: 203.6 mg L^{-1}; NH_4-N: 157.5 mg L^{-1}; TP: 22.3 mg L^{-1}; COD: 5200 mg L^{-1}	NH_4-N: 90.8%; TP: 62.9%; COD: 61.3%	[33]
Chlorella Sorokiniana MCC33	Municipal	25 °C;	COD: 496.0 mg L^{-1}; TN: 24.45 mg L^{-1}; TP: 9.6 mg L^{-1}	TN: 40%; TP: 20.83%; COD: 72.17%	[23]
Chlorella sp.	Kitchen	26 °C; 4000 lx; 12:12 light: dark	PO_4-P: 2.037 mg L^{-1}; NO_3-N: 52.962 mg L^{-1}; COD: 560 mg L^{-1}	NO_3-N: 38%; PO_4-P: 75%; COD: 32.14%	[12]
	Sewage	26 °C; 4000 lx; 12:12 light: dark	PO_4-P: 1.7 mg L^{-1}; NO_3-N: 30.25 mg L^{-1}; COD: 784 mg L^{-1}	NO_3-N: 67%; PO_4-P: 88%	[12]
	Primary effluent treatement plant	20 °C; 16:8 light: dark; 60 μE m^{-2} s^{-1}	COD: 93 mg L^{-1}; TN: 36.1 mg L^{-1}; TP: 4.0 mg L^{-1}	TN: 95.7%; TP: 96.4%	[44]

Table 3. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
	Raw centrate from municipal wastewater	25 °C; 50 μE m^{-2} s^{-1}	COD: 2304 mg L^{-1}; TN: 116.1 mg L^{-1}; TP: 212.0 mg L^{-1}	TN: 89.1%; TP: 80.9%; COD: 90.8%	[45]
Chlorella sp. IM-01	Municipal	27 °C; 2000 lx	NO_2-N 1222.1 mg L^{-1}; NO_3-N: 112.7 mg L^{-1}; NH_4-N: 282.4 mg L^{-1}; TP: 1.51 mg L^{-1}	NO_2-N: 70.42%; NO_3-N: 97.81%; NH_4-N: 98.35%; TP: 89.39%	[46]
*Chlorella variabilis*TH03	Domestic	25.5–35 °C; 12,670 lx to 107,695 lx (outdoor)	nr	COD: 64.7% to 90.7%; TN: 85.1–96.8%; TP: 99.7% to 100%	[37]
Chlorella vulgaris	Municipal	1200 lx; 16:8 light: dark	COD: 145 mg L^{-1}; NH_4-N: 48 mg L^{-1}	(>94% of COD and NH_4-N)	[39]
Chlorella vulgaris (FC-16)	Municipal + glycerol	25 °C, 100 μE m^{-2} s^{-1}; 12:12 light: dark	TN: 45.1 mg L^{-1}	TN: 69.04%	[34]
Chlorella vulgaris Wu-G22	Domestic (unsterilized) + Glycerol (50 mM)	25 °C; 174 μE m^{-2} s^{-1}; 12:12 light: dark 2.5% CO_2	COD: 6195.6 mg L^{-1}; TN: 46.78 mg L^{-1}; PO_4-P: 9.79 mg L^{-1}	COD: 448.47 mg L^{-1}; TN: 3.39 mg L^{-1}; PO_4-P: 0.75 mg L^{-1}	[40]
Chlorella zofingiensis	Municipal + effluent from anaerobic digestion of piggery waste (92% + 8%)	25 °C, 150 μE m^{-2} s^{-1}; 12:12 light: dark; 5% CO_2; (Indoor); 5–6% CO_2 (Outdoor)	TN: 76.34 mg L^{-1}; TP: 16.56 mg L^{-1}	TN: ~93%, TP: ~90%	[31]
Dunaliella salina	75% Municipal + 25% saline water	20 °C; 120 μE m^{-2} s^{-1}	NO_3-N: 40.7 mg L^{-1}; NH_4-N: 0.95 mg L^{-1}; PO_4-P: 3.8 mg L^{-1}	NO_3-N: 84.2%; NH_4-N: 71.0%; PO_4-P: 47.5%	[38]
Haematococcus pluvialis	Raw primary effluent	25 °C, 3000 lx (Green stage)/35,400 lx (Red stage); 12:12 light: dark; 5% CO_2	TN: 20.1 mg L^{-1}; TP: 2.2 mg L^{-1}	TN: 90%; TP: 99%	[47]
	Domestic secondary effluent	25 °C, 55–60 μE m^{-2} s^{-1}; 14:10 light: dark	TN: 7.0 mg L^{-1}; TP: 0.46 mg L^{-1}	TN: 93.8%; TP: 97.3%	[48]
Isochrysis sp.	Municipal	25 °C; 100 μE m^{-2} s^{-1}; 12:12 light: dark	nr	NO_2-N: 5.57%; TP: 84–94%; COD: 93%	[35]
	80% Municipal	25 °C; 100 μE m^{-2} s^{-1}; 12:12 light: dark	nr	TP: 94%	
Micractinium reisseri	Influent (Municipal)	27 °C; 40 μE m^{-2} s^{-1}	TN: 15 mg L^{-1}; TP: 3 mg L^{-1}	TN: 86%; TP: 95%	[49]
	Secondary effluent	27 °C; 40 μE m^{-2} s^{-1}	TN: 13 mg L^{-1}; TP: 2 mg L^{-1}	TN: 85%; TP: 96%	
	Tertiary effluent	27 °C; 40 μE m^{-2} s^{-1}	TN: 11 mg L^{-1}; TP: 1.6 mg L^{-1}	TN: 89%; TP: 95%	
Micractinium sp.	Primary effluent	20 °C; 60 μE m^{-2} s^{-1}; 16:8 light: dark	TN: 36.1 mg L^{-1}; TP: 4.0 mg L^{-1}	TN: 93.9%; TP: 96.1%	[44]
Nannochloropsis oceanica	Municipal sewage	25 °C; 60 μE m^{-2} s^{-1}	TN:0.22 mg L^{-1}; TP: 2.28 mg L^{-1}	nr	[32]
Nannochloropsis oculata	Municipal + glycerol	25 °C; 100 μE m^{-2} s^{-1}; 12:12 light: dark	TN: 45.1 mg L^{-1};	TN: 80.6%	[34]
	75% of treated municipal	24 °C;150 rpm mixing; Continuous illumination	TN: 3.77 mg L^{-1};	nr	[50]
	Municipal	70–100 μE m^{-2} s^{-1}	TP: 4.4 mg L^{-1}; TN: 57.9 mg L^{-1};	TN: 86%; TP: 81%	[51]

Table 3. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Phaeodactylum tricornutum	Municipal and seawater (1:1)	18 °C; 120 μE m^{-2} s^{-1}; 12:12 light: dark	COD: 129 mg L^{-1}; TN: 48 mg L^{-1}; TP: 9 mg L^{-1}; NH_4-N: 37 mg L^{-1}	COD: 87.7%; TN: 86.7%; TP: 97.0%; NH_4-N: 84.2%	[28]
Scenedesmus abundans	Raw domestic	Continuous illumination of 1800 lx;	TN: 197 mg L^{-1}; NH_4-N: 992 mg L^{-1}; TP: 286 mg L^{-1}	NH_4-N: 98%; TP: 95%; TN: 83%	[21]
Scenedesmus obliquus	Municipal	25 °C; 40 ± 10 μE m^{-2} s^{-1}	TN: 30.46 mg L^{-1}; TP: 2.60 mg L^{-1}	TN: 46.85%; TP: 34.18%	[27]
Scenedesmus sp.	Municipal + 1 g L^{-1} of sodium acetate	25 °C; 40 ± 10 μE m^{-2} s^{-1}	TN: 30.46 mg L^{-1}; TP: 2.60 mg L^{-1}	TN: 82.20%; TP: 76.35%	
	15% Fresh leachate from transfer station	25 °C; 75 μE m^{-2} s^{-1}; 14:10 light: dark	NH_4-N: 507 mg L^{-1}; PO_4-P: 109 mg L^{-1}; NO_2-N: 0.9 mg L^{-1}	NH_4-N: 94%; PO_4-P: 96%; NO_2-N: 100%	[41]
	Domestic	20 °C; 12:12 light: dark	NO_3-N: 2.39 mg mL^{-1}; PO_4-P: 18.53 mg mL^{-1}; COD: 257 mg mL^{-1}	NO_3-N: 71.2%; PO_4-P: 89.6%; COD: 86.38%	[25]
	Primary urban	nr	PO_4-P: 7.9–27.7 mg L^{-1}; NH_4-N: 58.2–136.9 mg L^{-1}	PO_4-P: 0.65 mg m^{-2} d^{-1}; NH_4-N: 99%;	[26]
	Domestic	24 °C; 60 μE m^{-2} s^{-1}; 12:12 light: dark	TP: 98.3 mg L^{-1}; NO_2-N: 303.3 mg L^{-1}; NO_3-N: 131.4 mg L^{-1}	TP: 32 mg L^{-1}; NO_2-N: 2.36 mg L^{-1}; NO_3-N: 18.1 mg L^{-1};	[36]
Tetraselmis suecica	25% of treated municipal	24 °C;150 rpm mixing; Continuous illumination	TN: 3.77 mg L^{-1}	nr	[50]

COD (chemical oxygen demand), NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), PO_4-P (orthophosphate phosphate), TN (total nitrogen), TP (total phosphate) and nr (not reported).

The possible utilization of a combined biogas slurry and municipal wastewater to grow *Chlorella zofingiensis* was studied [31]. They found that putting 8% of a pig biogas slurry in municipal wastewater (TN: 76.34 mg L^{-1}; TP: 16.56 mg L^{-1}) had a considerable impact on *C. zofingiensis* growth, removing 90% of total phosphorus and 93% of total nitrogen and increasing the lipid content by 8% compared to the BG11 medium [31].

Thus, the presented research has demonstrated that different species of microalgae can efficiently clean domestic wastewater, and that it would be much more beneficial if other nutrients such as glycerol and sodium acetate were introduced. Some of this research found that wastewater from the kitchen or laundry has an impact on microalgae growth and biochemical composition and suggested that kitchen wastewater can be diluted with water or anaerobically digested to improve bioremediation. This last procedure can remove organic debris and generate biogas under oxygen-free conditions, but the digestate includes a high concentration of ammonium.

Table 4. Growth parameters and metabolites production of microalgae culture in domestic wastewater.

Algae Used	Wastewater Type	Growth Rate or Volumetric Productivity	Final Biomass Concentration	Production of Target Metabolites	References
Acutodesmus obliquus	Municipal and poultry litter	140.36 mg L^{-1} d^{-1}	1.9 g L^{-1}	Lipids: 38.49 mg L^{-1} d^{-1}; Carbohydrates: 49.55 mg L^{-1} d^{-1}	[42]
Botryococcus Braunii	Secondary treated sewage	nr	0.34 g L^{-1}	Hydrocarbon content: 53%	[13]
Botryococcus sp.	Domestic	200 mg L^{-1} d^{-1}	3.32 g L^{-1}	Carbohydrates: 1.12 g L^{-1}; Lipids: 0.736 g L^{-1};	[14]
Chaetoceros sp.	Municipal	2.79 g L^{-1} d^{-1}	90.6 × 10^5 cells mL^{-1}	Lipids: 0.05 g L^{-1} d^{-1}; Carbohydrates: 1.9 mg g^{-1}	[35]
Chlorella minutissima	Municipal	0.196 d^{-1}	191.66 mg L^{-1} d^{-1}	Lipids: 36.66 mg L^{-1} d^{-1}	[23]
Chlorella pyrenoidosa	Sewage treatment plant	nr	4.5 g L^{-1}	nr	[16]
Chlorella pyrenoidosa (FACHB-9)	Domestic	nr	1.71 g L^{-1}	nr	[20]
	Raw domestic	nr	11.33 mg L^{-1};	nr	[21]
	Municipal	nr	0.54 g L^{-1}–0.67 g L^{-1}	Lipids: 30.61%	[18]
	Municipal	nr	0.6167 g L^{-1}	Lipids: 0.1083 g L^{-1};	[43]
	Septic tank effluents (toilet)	0.54 d^{-1}	1.68 g L^{-1}	Chlorophyll a: 4.3%; Lipids: 11.9%; Proteins: 57.2%; Carbohydrates: 19.3%	[33]
Chlorella Sorokiniana MCC33	Municipal	0.269 d^{-1}	208.35 mg L^{-1} d^{-1}	Lipids: 48.33 mg L^{-1} d^{-1}	[23]
Chlorella sp.	Kitchen	nr	0.45 g L^{-1}	nr	[12]
	Sewage	nr	0.6 g L^{-1}	nr	[12]
	Primary effluent	0.11 d^{-1}	nr	nr	[44]
	Raw centrate municipal	0.677 d^{-1}	0.92 g L^{-1}	FAMEs: 11.04%;	[45]
Chlorella sp. IM-01	Municipal	nr	nr	Carbohydrates: 61–94 µg mg^{-1}	[46]
*Chlorella variabilis*TH03	Domestic	0.41 d^{-1}	1.67–1.85 g L^{-1}	nr	[37]
Chlorella vulgaris	Municipal	0.32 d^{-1}	0.89 g L^{-1}	Lipids: 0.16 g L^{-1}	[39]
Chlorella vulgaris (FC-16)	Municipal + glycerol	nr	0.056 g L^{-1} d^{-1}	Lipids: 15.11%	[34]
Chlorella vulgaris Wu-G22	Domestic (unsterilized) + Glycerol (50 mM)	nr	1.65 g L^{-1}	Lipids: 15.7%; Carbohydrates: 7.3%; Proteins: 70%	[40]
Chlorella zofingiensis	Municipal + effluent from anaerobic digestion of piggery waste (92% + 8%)	0.63 g L^{-1} d^{-1}	2.51 g L^{-1} (indoor), 1.7 g L^{-1} (outdoor)	Lipids: 25.46% (indoor) 21.6% (outdoor); Carbohydrates: 21.2% (indoor) 26.9% (outdoor);	[31]

Table 4. *Cont.*

Algae Used	Wastewater Type	Growth Rate or Volumetric Productivity	Final Biomass Concentration	Production of Target Metabolites	References
Desmodesmus sp.	Municipal (Ultrasound pretreatment)	nr	75 g L^{-1}	Proteins: 97%; Carbohydrates: 89%; Lipids: 73%;	[52]
	Municipal (Ozone pretreatment)	nr	25 g L^{-1}	Carbohydrates: 85%; Lipids: 48%; Proteins: 25%;	
	Untreated Municipal	nr	nr	Lipids: 3.8%; Proteins: 8.23%; Carbohydrates: 37%	
Dunaliella salina	75% Municipal + 25% saline water	nr	169.5 mg L^{-1}	nr	[38]
Haematococcus pluvialis	Raw primary effluent	0.34 d^{-1}	nr	Astaxanthin: 3.26 mg L^{-1}	[47]
	Domestic secondary effluent	27.8 mg L^{-1} d^{-1}	207 mg L^{-1}	Lipids: 43%	[48]
Isochrysis sp.	50% Municipal	0.022 g L^{-1} d^{-1}	110.5 × 10^5 cells mL^{-1}	Lipids: 0.02 g L^{-1} d^{-1}; Carbohydrates: 2.6 mg g^{-1}	[35]
Micractinium reisseri	80% Municipal	1.27 g L^{-1} d^{-1}	nr	Lipids: 1.11 g L^{-1} d^{-1}	[49]
	Municipal (Influent)	1.15 d^{-1}	0.22 g L^{-1}	Lipids: 23%	
	Municipal (Secondary effluent)	1.04 d^{-1}	0.19 g L^{-1}	Lipids: 30%	
	Municipal (Tertiary effluent)	1.01 d^{-1}	0.14 g L^{-1}	Lipids: 40%	
Micractinium sp.	Primary effluent	0.11 d^{-1}	nr	nr	[44]
Nannochloropsis gaditana	Municipal	0.167 g L^{-1} d^{-1}	2.33 g L^{-1}	Carbohydrates: 17.7%	[53]
	Treatment plant	0.15 mg L^{-1} d^{-1}	72 mg L^{-1}	nr	[54]
Nannochloropsis oceanica	Municipal sewage	21.78 mg L^{-1} d^{-1}	nr	Lipids: 26.91%	[32]
Nannochloropsis oculata	Municipal + glycerol	nr	0.044 g L^{-1} d^{-1}	Lipids: 8.91%	[34]
	75% of treated municipal	0.5430 d^{-1}	1.285 g L^{-1}	Carbohydrates: 2.39%	[50]
Phaeodactylum tricornutum	Municipal	nr	406 mg L^{-1}	nr	[51]
	Municipal and seawater (1:1)	1.01 d^{-1}	0.97 g L^{-1}	Lipids: 54.76 mg L^{-1} d^{-1}	[28]
Scenedesmus abundans	Raw domestic	nr	7.23 mg L^{-1}	nr	[21]
Scenedesmus obliquus	Municipal	nr	0.48 mg L^{-1}	Lipids: 9.02 mg L^{-1} d^{-1}	[27]
	Municipal + 1 g L^{-1} of sodium acetate	nr	0.2 mg L^{-1}	Lipids: 22.08 mg L^{-1} d^{-1}	
Scenedesmus sp.	15% Fresh leachate from transfer station	0.17 d^{-1}	133 mg L^{-1} d^{-1}	nr	[41]
	Domestic	nr	0.95 g L^{-1}	Lipids: 30.5%	[25]
	Primary urban	nr	22.2 g m^{-2} d^{-1}	nr	[26]
	Domestic	nr	0.84 g L^{-1}	Lipid productivity: 8.6 mg L^{-1} d^{-1}	[36]
Tetraselmis suecica	25% of treated municipal	0.4778 d^{-1}	0.76 g L^{-1}	Carbohydrates: 4.24%	[50]

nr (not reported).

2.2. Agricultural Wastewater

2.2.1. Physicochemical Properties

A potential alternative growing medium for microalgae has been presented as the wastewater produced by agricultural activities. The properties of this type of wastewater are determined by the effluent's source. There are four primary sources of agricultural wastewater (Figure 3), which are livestock, aquaculture, digested agricultural waste and drainage agricultural wastewater [55]. Organic carbons, volatile fatty acids, nutrients and metal ions are among the substances found in these sources [55]. Table 5 summarizes the physicochemical properties of agricultural wastewater used as a growth medium for microalgae that have been found in the literature. As described in this table, raw poultry litter extract had a pH of 7.45, chemical oxygen demand of 482.2 mg L^{-1}, 13.25 mg L^{-1} of NO_3-N and 108 mg L^{-1} of NH_4-N [42]. This composition is significantly different from anaerobi-

cally digested poultry litter wastewater, which is characterized by a high concentration of ammonium (2000 mg L^{-1} to 3000 mg L^{-1} of NH_4-N) and total nitrogen (2900 mg L^{-1} to 3200 mg L^{-1} of TN) [56]. Swine wastewater contained a high concentration of chemical oxygen demand (419.88 mg L^{-1} to 85,600 mg L^{-1}), total nitrogen (163.40 mg L^{-1} to 5685 mg L^{-1}) and total phosphate (26.2 mg L^{-1} to 284 mg L^{-1}), and the pH was reported at 6.83–8.1 [30,57–62]. The mass cultivation of fish necessitates a large volume of freshwater and produces a large amount of aquaculture wastewater [5]. Bioremediation of aquaculture wastewater by microalgae was reported in the literature [60,63–65]. The pH was at 7.82–8.5, COD was at 30.30 mg L^{-1} to 367.39 mg L^{-1}, TN was at 4.12–60 mg L^{-1} and the TP was at 0.16 mg L^{-1} to 6.8 mg L^{-1} for aquaculture wastewater physicochemical composition [60,63–65]. In addition, Table 5 showed that agricultural wastewater contains a high content of suspended particles (32.15 mg L^{-1} to 32,951.5 mg L^{-1}) and different metal ions such as Zn, Cu, Mg, Ca and K, with concentrations depending on the wastewater source.

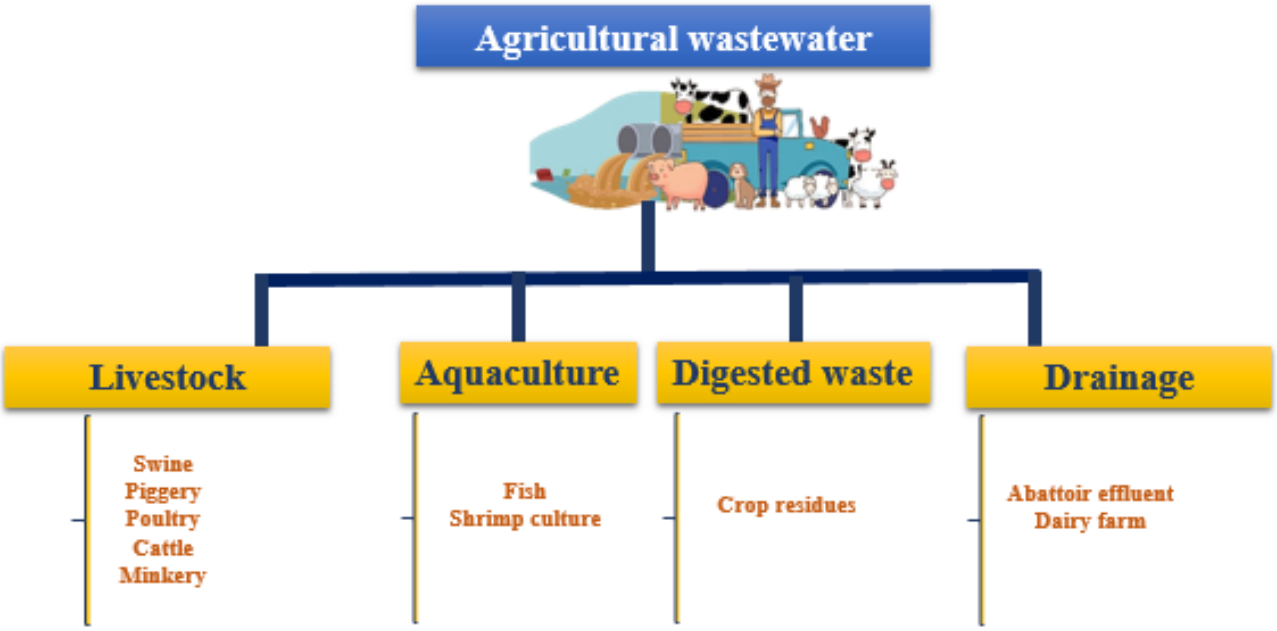


Figure 3. Agricultural wastewater types.

Table 5. Agricultural wastewater composition.

Type	pH	TSS (mg L^{-1})	TOC (mg L^{-1})	COD (mg L^{-1})	NO_3-N (mg L^{-1})	NO_2-N (mg L^{-1})	NH_4-N (mg L^{-1})	NH_3-N (mg L^{-1})	PO_4-P (mg L^{-1})	TN (mg L^{-1})	TP (mg L^{-1})	References
Raw Poultry Litter Extract	7.45	34.40	-	482.2	13.25	-	-	108.0	21.05	-	-	[42]
Anaerobically Digested Poultry Litter	9–10	-	500–1000	400–900	-	-	2000–3000	-	-	2900–3200	20–25	[56]
Pretreated Piggery	7.5–9.3	-	1409–3935	430–11,100	2–352	10	70–644	1388	129	981–1356.75	20–168	[66–70]
Swine	6.83–8.1	2375–7120	20,075	419.88–85,600	1.19–334	-	260–5351	578.27	36.7–6608	163.40–5685	26.2–284	[30,57,58,60–62]
Nejayote	9.80	9060	-	9153.30	-	-	-	-	-	120.69	41.16	[62]
Cattle	6.11	-	-	674	3041	-	22,358	-	760	-	-	[71]
Dairy Farm	6.05–8.18	32.15–65.65	- -	119.21–2593	1.45–5.44	-	0.75–181.50	-	4.33–7.01	283	115.90	[72,73]
Swine Lagoon	5.5	-	-	2386	4.33	-	336.2	-	-	348.2	26.62	[74]
Aerated Swine Lagoon	8.9	-	-	2328	103	-	22.3	-	-	177.9	19.48	[74]
Minkery	8.84	-	-	1200	10	10	3250	-	-	-	1400	[75]
Paddy-Soaked	6	7255	2900	2250	-	-	-	265.30	211.50	-	-	[76]
Shrimp Culture	8.18	32,951.5	-	73.5–367.39	12.9–73.67	7.58	8.07–109.91	-	15.59	21.9	<0.4	[63,64]
Fish Farm	7.82–8.5	-	-	30.30–112	3.93–12	0.08	5.6	-	-	4.12–60	0.16–6.8	[60,65]
Anaerobically Digested Abattoir Effluent	7.1–7.4	-	-	302–514	0–8	0–7.5	-	200–210	70–80	-	-	[77]

Type	Chloride (mg L^{-1})	Na (mg L^{-1})	F (mg L^{-1})	Fe (mg L^{-1})	Cu (mg L^{-1})	Zn (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Pb (mg L^{-1})	Turbidity NTU	References
Anaerobically Digested Poultry Litter	-	-	-	0.085	0.085	-	-	0.044	1314.24	-	-	[56]
Pretreated Piggery	52,524	139.55	-	1.62	0.026	0.14	54.75–81	28.55–105	400.75	0.0025	-	[66,67,70]
Swine	154.7	66.24–583.8	-	0.52–0.728	0.0015–0.94	0.087–1.7	8.3–37.49	3.89–63.88	229.9–666.7	-	-	[58,59,61,62]
Dairy Farm	-	121–165	-	0.02–0.03	0.004–0.007	0.001–0.003	-	-	-	-	-	[72,73]

TSS (total suspended solids), TOC (total organic carbon), COD (chemical oxygen demand), NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), NH_3-N (ammonia-nitrogen), PO_4-P (orthophosphate phosphate), TN (total nitrogen), TP (total phosphate), Na (sodium), F (fluorine), Fe (iron), Cu (copper), Zn (zinc), Mg (magnesium), Ca (calcium), K (potassium), Pb (lead), NTU (nephelometric turbidity units) and nr (not reported).

2.2.2. Pretreatment

The high suspended particles concentration in agricultural wastewater, similar to domestic wastewater, necessitates the use of a first treatment procedure prior to the cultivation stage. The same pretreatment methods (filtration, autoclaving and centrifugation) as for domestic wastewater were used for agricultural wastewater pretreatment, with other pretreatments such as flocculation, acid precipitation, digestion and stripping, as described in Table 6. Previous research has used the filtering approach to pretreat wastewater, utilizing filters with varying pore sizes depending on the wastewater source and the materials that need to be removed. Khatoon et al. [78] filtered aquaculture wastewater using a 22 µm pore size filter, followed by a 1.2 µm pore size filter. For swine wastewater pretreatment, a recent study used an 8 µm pore size filter after the centrifugation technique [30]. The centrifugation method was used by the majority of these studies, with different durations and forces, for instance, 8000 rpm for 10 min [79], 7000 rpm (8656× *g*) for 5 min [30], 10,000× *g* for 10 min at 4 °C [52], 3000× *g* for 5 min [64] and 3000× *g* for 10 min [65,69]. However, once more, these methods can only be used at lab-scale.

An air-stripping method was used in the study of Kim et al. [66] for decreasing the concentration of free ammonia, that affect the growth of microalgae, from piggery wastewater. The results showed that the concentration was reduced from 644 mg L^{-1} to 14.1 mg L^{-1} [66]. For chemical oxygen demand reduction, acid precipitation was used by Teràn Hilares et al. and Musetsho et al. [42,80]. Teràn Hilares et al. [80] discovered that by adjusting the pH of the poultry slaughterhouse from six to four using H_2SO_4, almost 80% of the COD was eliminated as sludge [80].

Table 6. Pretreatment methods of agricultural wastewater before microalgae cultivation.

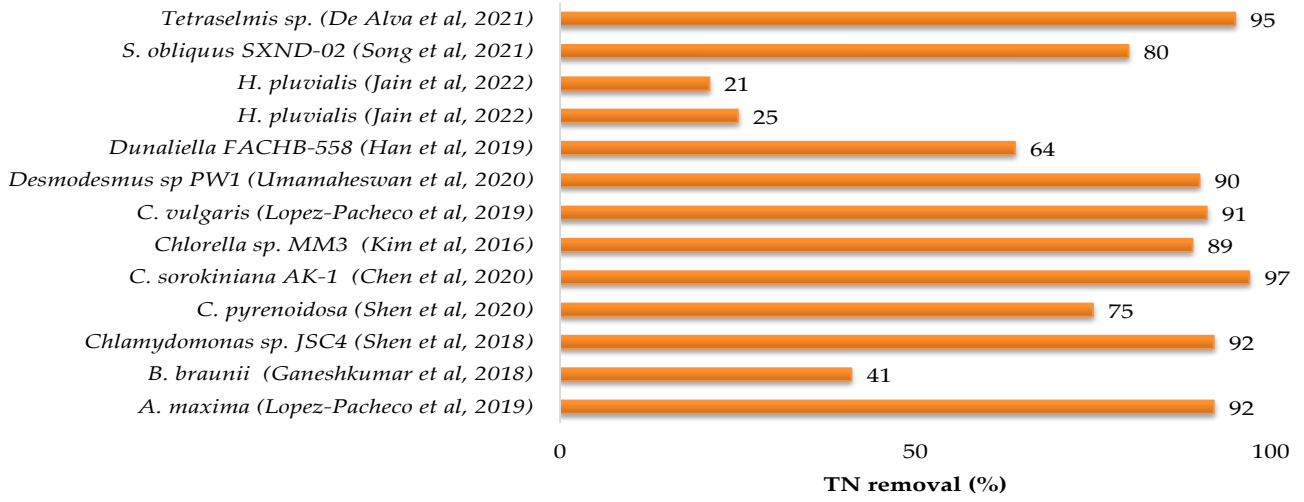
Wastewater	Pretreatment Method	Microalgae	References
Swine	Settled for 24 h, then centrifuged at 8000 rpm for 10 min	*Chlorella* sp. HL	[79]
Swine	Centrifuged at 7000 rpm (8656× *g*) for 5 min, filtered with filter of pore diameter 8 µm	*Scenedesmus* sp.	[30]
Cattle	Filtered using Whatman filter paper 42	*Chlorella thermophila* (MF179624)	[71]
Poultry litter extract	Acid pretreatment using 5 M of HCl or H_2SO_4	*Acutodesmus obliquus*	[42]
Swine	Natural precipitation method for 1 day; and added with 5% sodium hypochlorite for 1 day.	*Chlorella vulgaris* MBFJNU-1	[57]
Aquaculture	Filtered using a filter pump (pore size: 22 µm), then filtered with GF/C Whatman glass microfiber filters (pore size: 1.2 µm).	*Tetraselmis* sp.	[78]
Fishery	Sterilized in an autoclave at 121 °C and 150 kPa for 30 min.	*Thalassiosira pseudonana* and *Isochrysis galbana*	[81]
Poultry slaughterhouse	Acid precipitation (H_2SO_4) at pH 4	*Chlorella vulgaris*	[80]
Swine	Sedimentation for 2 days, and anaerobically digested at 55 °C for 10 days	*Chlorella pyrenoidosa*	[59]
Swine	Filtered with a sieve of mesh number 140 (100 µm)	*Chlorella sorokiniana* AK-1	[58]
Anaerobic digested swine	Sterilized in an autoclave at 121 °C and 150 kPa for 30 min.	*Chlorella zofingiensis*	[60]
Fishery	Sterilized in an autoclave at 121 °C and 150 kPa for 30 min.	*Chlorella zofingiensis*	[60]
Piggery	Centrifuged at 10,000× *g* for 10 min at 4 °C and pre-autoclaved at 121 °C for 20 min	*Chlorella* sp. GD	[59]
Minkery	Filtered through a filter cloth then filtered using 1.5 µm glass microfiber filters, autoclaved at 121 °C and 15 psi for 20 min.	*Haematococcus pluvialis*	[75]
Aquaculture	Centrifuged at 3000× *g* for 5 min.	*Chlorella Sorokiniana* MB-1-M12	[64]
Piggery	Sedimented and sterilized by passing through a 0.45 µm filter	*Chlorella pyrenoidosa*	[62]
Piggery	Flocculated and filtered through 0.2 µm cellulose acetate membranes followed by stripping with air using an acrylic column (ID 5 cm × H 100 cm)	*Acutodesmus obliquus*	[66]
Aquaculture	Centrifuged at 3000× *g* for 10 min	*Chlorella* sp. GD	[65]
Aquaculture	Filtered using 0.45 mm Whatman GF/C filter papers followed by autoclaving	*Chlorella* sp.	[82]
Piggery	Autoclaved for 30 min at 121 °C then centrifuged (3000× *g* for 10 min)	*Chlorella* sp. GD	[69]

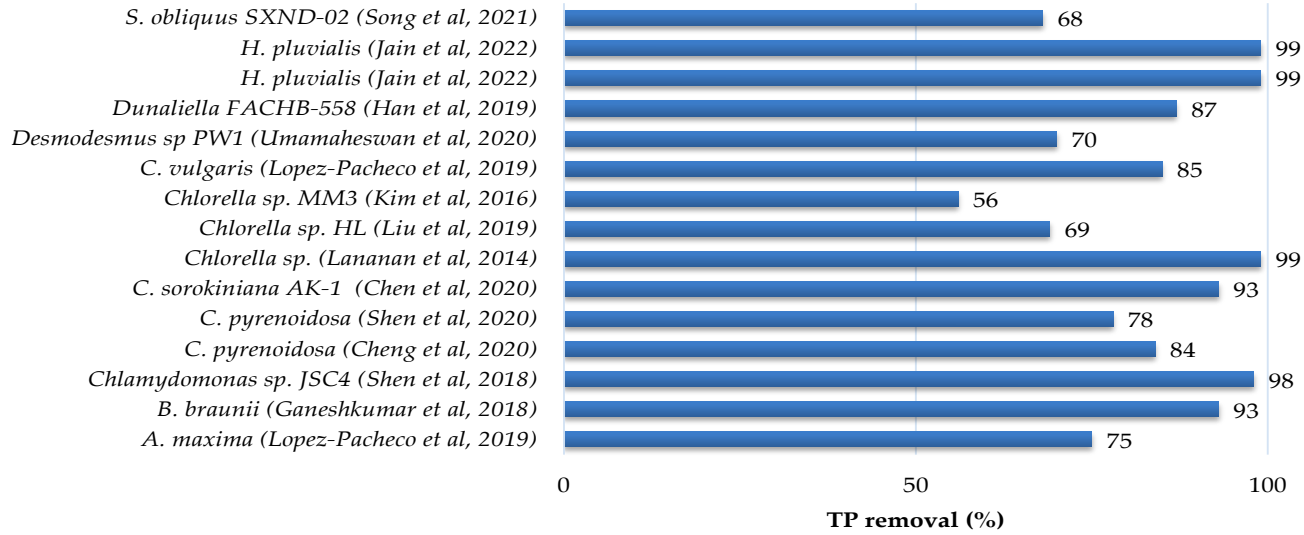
2.2.3. Microalgae Treatment of Agricultural Wastewater

As shown in Table 5, nitrogen, phosphate, and some metal ions are present in agricultural effluent. Wastewaters are dangers to environmental safety if left untreated or cleaned incompetently, resulting in eutrophication of nearby water rivers and greenhouse gas emissions. Lately, considerable research has been conducted on the culture of microalgae in agricultural wastewater for their excellent nutrient removal, energy resource and the other products extracted from microalgal biomass (Tables 7 and 8). The Figure 4 illustrates the removal efficiencies of total nitrate, total phosphate and chemical oxygen demand from agricultural wastewater by different species of microalgae.

Swine wastewater treatment by microalgae was investigated in a recent study [79]. They evaluated the potential of seven strains which are *Chlorella* sp. HQ, *Scenedesmus* sp. LX1, *Chlorella vulgaris* (FACHB-8), *C. pyrenoidosa* (FACHB-5), *S. obliquus* (FACHB-417), *Selenastrum capricomutum* (FACHB-271) and *Chlorella* sp. HL, to remove pollutants from a ten-fold dilution of swine wastewater [79] and they reported that *Chlorella* sp. HL had the highest potential for growth in swine wastewater and nutrient removal among the other species. This strain showed the greatest specific growth rate (μ) and cell density, both of which were 0.51 d^{-1} and 2.43 × 10^7 cells mL^{-1} after nine days of culture, with the TP and COD removal rates of 69.13% and 72.95%, respectively. In addition, [79] suggested that *Chlorella* sp. HL can be a suitable candidate for energy production due to the higher heating value of 18.25 MJ kg^{-1} of *Chlorella* sp. HL biomass. The author of [57] studied the aptitude of *Chlorella vulgaris* MBFJNU-1 strain to reduce the pollutants of swine wastewater using a column photobioreactor in outdoor environments. At the same time, they evaluated the carbon dioxide fixation by this species. Their results suggested that the cultivation of *Chlorella vulgaris* MBFJNU-1 at 3% carbon dioxide, provided the maximum of biomass productivity by about 36 mg L^{-1} d^{-1} and the best removal efficiency rate of TN, TP and COD by about 16.84 mg L^{-1} d^{-1}, 1.40 mg L^{-1} d^{-1} and 8.47 mg L^{-1} d^{-1}, respectively [57]. However, these two studies did not assess the biochemical composition of the studied species grown in swine wastewater, which is a critical parameter to be able to use these microalgae for both wastewater treatment and the generation of high-value products at the same time [57,79].

Other research examined the microalgae immobilization method as an innovative technique to remove contaminants from swine wastewater [58,61]. The author of [58] assessed the ability of three species of *Chlorella sorokiniana* genera to grow and remove pollutants of a 2-fold diluted swine wastewater. They reported that *Chlorella sorokiniana* AK-1 had the highest biomass and protein production rate compared to other species (5.45 g L^{-1} and 0.27 g L^{-1} d^{-1}, respectively) [58]. In the same study, they immobilized *Chlorella sorokiniana* AK-1 cells using sponge, activated carbon, clay and alginate beads as solid carriers in a 2-fold diluted swine wastewater, and found that the sponge immobilization method improved the biomass concentration and protein productivity (8.08 g L^{-1} and 0.272 g L^{-1} d^{-1}, respectively) compared to the control and other solid carriers [58]. In addition, using the sponge as the solid carrier enhanced the removal efficiency of TN, TP and COD from 88.6% to 94.1%, 99.3% to 99.5% and from 84.1% to 91.6%, respectively, compared to the control [58]. A fixed-bed biofilm reactor, as another immobilization technique of algal cells, was used [61] to improve the productivity of the biofilm and the removal efficiencies of total nitrate, total phosphate and metal ion (Cu(II)) from swine wastewater. In this research, they used *Chlamydomonas* sp. JSC4 cells as an attached culture and assessed the effect of different parameters such as the volume of the swine wastewater and the concentration of Cu(II) on the productivity of the biofilm and removal efficiencies [61]. They reported that the swine wastewater had the best productivity levels (49.70 g^{-1} m^{-2} d^{-1}) at an initial composition of 600 mg L^{-1} of total nitrate and 0.23 mg L^{-1} of Cu(II), but when the concentration of Cu(II) was increased to 15 mg L^{-1}, the productivity of the biofilm was decreased to 37.73 g m^{-2} d^{-1} with a TN removal of 85.79%, TP removal of 96.56% and Cu(II) removal of 93.70% [61].





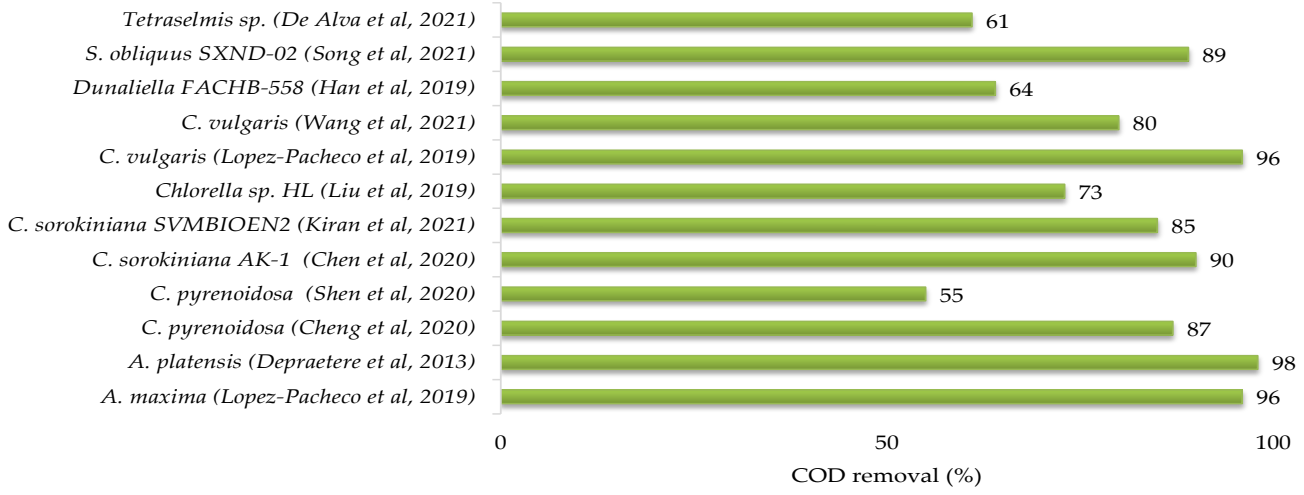


Figure 4. Nutrients and COD removals from agricultural wastewater by microalgae species [56,58,59,61–63,68,70,72,74,75,79,80,82–87].

The microalga *Desmodesmus* sp. PW1 was used to treat piggery wastewater [83]. The results showed that this isolated strain from piggery wastewater had two important potentials, the first was the ability to reduce the pollutants in piggery wastewater, and the second was to self-flocculate in it and overcome the harvesting problem [80]. It can remove about 90% of total nitrogen and about 70% of total phosphorus from piggery wastewater with an initial composition of 296.7 mg L^{-1} of TN and 28.6 mg L^{-1} of TP under 25 °C and 4000 lx [83]. In addition, as this strain can self-flocculate more than 90% in 2.5 h of sedimentation, it could be a promising candidate for biomass and biodiesel production (1.76 g L^{-1} and 7.2%, respectively) [83].

To improve the efficiency of piggery wastewater treatment, [84] used the digestion technique before microalgae treatment, and they used a marine microalgal specie rather than the genus *Chlorella* and *Scenedesmus*, which have been widely used in the literature [84]. In the same investigation, they used the CO_2 produced by the digester to feed the microalgae culture bioreactor during its operation [84]. Under these conditions (CO_2 from digester (94.7%) and pH 7.5), *Tetraselmis suecica* had the highest production of biomass, lipids and carbohydrates, which were 59.8, 25 and 6.5 mg L^{-1} d^{-1}, respectively, with TN and TP removals of 96 and 72%, respectively [84].

Microalgae have also demonstrated their ability to remediate aquaculture effluents [64,78]. Chen et al. [64] reported that *Chlorella sorokiniana* MB-1-M12 was the best candidate to treat shrimp culture wastewater because of its biomass and lutein productivities (1.9 mg L^{-1} d^{-1} and 5.55 mg L^{-1} d^{-1}, respectively) in 75% of shrimp culture effluent. Another recent study used the immobilization method to treat aquaculture wastewater [78]. In this research, they immobilized *Tetraselmis* sp., a marine microalga, using alginate beads in aquaculture wastewater [78]. *Tetraselmis* sp. beads removed about 0.08 mg L^{-1}, 0.10 mg L^{-1} and 0.17 mg L^{-1} from the initial concentration of the total ammonium (7.7 mg L^{-1}), nitrite (3.1 mg L^{-1}) and phosphorus (2 mg L^{-1}) after two days, which corresponds to the following removal efficiencies of 98.9%, 97.7% and 91.1%, respectively [78].

Different wastewaters can also be combined, such as piggery farm wastewater and winery industry wastewater, to be treated by *Chlorella* sp. MM3 strain from the soil [70]. At the ratio 20:80 of piggery and winery wastewaters, *Chlorella* sp. MM3 removed 89.36% for the TN removal efficiency and 56.56% for the TP removal efficiency, and achieved a high lipid yield of about 51% [70]. Recently, 2.5% of cattle wastewater was diluted with domestic wastewater as a substitute for freshwater to be treated by *Chlorella thermophila* (MF179624), isolated from sewage wastewater [71]. They reported that *Chlorella thermophila* grew well (2.17 g L^{-1} of biomass) in 2.5% of cattle wastewater, compared to domestic wastewater (1.22 g L^{-1} of biomass) and bold basal medium (1.24 g L^{-1} of biomass), and gave interesting compounds such as lipids (18.27%), carbohydrates (29.39%) and proteins (44.91%) [71]. *Chlorella thermophila* had the highest removal rates of ammonium (53.74 mg L^{-1} d^{-1}), nitrate (6.96 mg L^{-1} d^{-1}) and more than 99% of phosphorus [71].

Table 7. Treatment of agricultural wastewater by the cultivation of microalgae.

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Acutodesmus obliquus	Piggery	25 °C for 138 h	COD: 11,100 mg L^{-1}; TN: 981 mg L^{-1}; TP: 81 mg L^{-1}	TN: 175 mg g^{-1} d^{-1}; TP: 1.5 mg g^{-1} d^{-1} COD: 1923 mg g^{-1} d^{-1})	[66]
Arthrospira maxima	10% Nejayote	21 °C; 1.5 L m^{-2} min^{-1} of aeration; 12:12 light: dark	COD: 9153.3 mg L^{-1}; TN: 120.69 mg L^{-1}; TP: 41.16 mg L^{-1}	COD: 96%; TN: 92%; TP: 75%	[62]
Arthrospira platensis	Dairy farm	30 °C; 160 µE m^{-2} s^{-1} (from initial today 6) and 300 µE m^{-2} s^{-1} (from day 7); 12:12 light: dark	COD: 131.691 mg L^{-1}; NO_3-N: 3.452 mg L^{-1}; NH_4-N: 2.998 mg L^{-1}; PO_4-P: 5.672 mg L^{-1}	COD: 98.4%; NO_3-N: 99.6%; NH_4-N: ~100%; PO_4-P: 98.8%	[72]
Botryococcus braunii	Aerated swine	25 °C; 10 µE m^{-2} s^{-1}	TN: 177.9 mg L^{-1}; TP: 19.48 mg L^{-1}	TN: 40.8%; TP: 93.3%	[74]
Chlamydomonas sp. JSC4	Swine	26 °C; 150 µE m^{-2} s^{-1}; 16:8 light: dark; 5% CO_2 at an aeration rate of 0.2 L min^{-1}	TN: 600 mg L^{-1}; TP: 26.2 mg L^{-1}	TN: 92%; TP: 98%	[61]
Chlorella pyrenoidosa	Paddy-soaked	33 °C to 37 °C; 3826–4240 µE m^{-2} s^{-1}	PO_4-P: 211.50 mg L^{-1}; NH_4-N: 265.30 mg L^{-1}	NH_3-N: 75.89%; PO_4-P: 73.71%	[76]
	Five times diluted anaerobically Digested swine	25 °C; 80 µE m^{-2} s^{-1}; 12:12 light: dark	NH_4-N: 134.17 mg L^{-1}; NO_3-N: 14.49 mg L^{-1}; TP: 6.65 mg L^{-1}; COD: 116.10 mg L^{-1}	NH_4-N: 94.1%; NO_3-N: 85.2%; TP: 84.0%; COD: 86.8%	[59]
	Piggery	25 °C to 27 °C; 63 µE m^{-2} s^{-1}	TN: 980 mg L^{-1}; TP: 158 mg L^{-1}; COD: 1000 mg L^{-1}	TN: 74.6%; TP: 77.7%; COD: 55.4%	[68]
Chlorella sorokiniana AK-1	50% Swine	27 °C, 150 µE m^{-2} s^{-1}	TN: 510 mg L^{-1}; TP: 76.1 mg L^{-1}; COD: 506.8 mg L^{-1}	TN: 97.0%; TP: 92.8%; COD: 90.1%	[58]
Chlorella sorokiniana MB-1-M12	Shrimp culture	26 °C; 150 µE m^{-2} s^{-1}	TN: 21.9 ppm; TP < 0.4 ppm; COD: 73.5 ppm	nr	[64]
*Chlorella sorokiniana*SVMBIOEN2	Dairy farm	25 °C; 100 µE m^{-2} s^{-1}; 12:12 light: dark	COD: 2000 mg L^{-1}	COD: 85%;	[85]
Chlorella sp.	Aquaculture	28 °C	NH_4-N: 0.91 mg L^{-1}; PO_4-P: 2.6 mg L^{-1}	NH_4-N: 98.7%; PO_4-P: 92.2%;	[82]
	Aquaculture	25 °C; 3350 Lm	TP: 6.75 mg L^{-1}	TP: 99.15%	[86]
Chlorella sp. GD	Aquaculture	26 °C; 300 µE m^{-2} s^{-1}; aerated with boiler flue gas (approximately 8% CO_2)	pH: 8.5; COD: 112 mg L^{-1}; TN: 60 mg L^{-1}; TP: 6.8 mg L^{-1}	nr	[65]
	Piggery	26 °C; 300 µE m^{-2} s^{-1}; 2% CO_2 aeration rate of 0.2 vvm	pH: 8.5; COD: 430 mg L^{-1};TN: 550 mg L^{-1}; TP: 20 mg L^{-1}	nr	[69]
Chlorella sp. HL	Swine wastewater	25 °C; 60 µE m^{-2} s^{-1}; 16:8 light: dark	TP: 74.61 mg L^{-1}; COD: 12,431.9 mg L^{-1}	TP: 69.13%; COD: 72.95%	[79]

Table 7. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Chlorella sp. MM3	Mixed piggery and winery (20:80 ratio)	23 °C;	TN: 284 mg L^{-1}; TP: 11 mg L^{-1}	TN: 89.36%; TP: 56.56%	[70]
Chlorella thermophila MF179624	2.5% Cattle	25 °C; 100 µE m^{-2} s^{-1}; aeration 0.5 vvm	pH: 6.11, NH_4-N: 22,358 mg L^{-1}; NO_3-N: 3041 mg L^{-1}; PO_4-P: 760 mg L^{-1}	NH_4-N: 53.74 mg L^{-1} d^{-1}; NO_3-N: 6.96 mg L^{-1} d^{-1}; PO_4-P: more than 99%	[71]
Chlorella vulgaris	10% swine	21 °C; 12:12 light: dark; 1.5 L m^{-2} min^{-1} of aeration	COD: 10.933 mg L^{-1}; TN: 163.40 mg L^{-1}; TP: 147.0 mg L^{-1}	COD: 96%; TN: 91%; TP: 85%	[62]
	Poultry slaughterhouse	First stage: acid precipitation of wastewater; Second stage: batch conditions: 25–27 °C; continuous illumination 440 µE m^{-2} s^{-1}; Continuous process: 25 °C; continuous illumination 440 µE m^{-2} s^{-1}	COD: 2185–7313 mg L^{-1}	COD (first step): 80%; COD (second step): more than 83%	[80]
Chlorella vulgaris MBFJNU-1	Swine	Outdoor: (sunlight)	pH: 5.5–6.0; COD: 492.4–500.7 mg L^{-1}; TN: 472.5–547.8 mg L^{-1};TP: 31.8–42.6 mg L^{-1}	COD: 8.47 mg L^{-1} d^{-1}; TN: 16.84 mg L^{-1} d^{-1}; TP: 1.40 mg L^{-1} d^{-1}	[57]
Desmodesmus sp. PW1	Piggery	25 °C; 4000 lx.	TN: 296.7 mg L^{-1}; TP: 28.6 mg L^{-1}	TN:90%; TP:70%	[83]
Dunaliella FACHB-558	Anaerobically digested poultry litter	25 °C; 200 µE m^{-2} s^{-1}; 12:12 light: dark	TN: 100–120 mg L^{-1}; TP: 15–20 mg L^{-1}; TOC: 400–500 mg L^{-1}	TN:63.8%; TP: 87.2%; TOC: 64.1%	[56]
Haematococcus pluvialis	1% Minkery	Green stage: 20 °C; 50 µE m^{-2} s^{-1} continuous light; Red stage: 20 °C; 200 µE m^{-2} s^{-1} continuous light	NH_4-N: 32.5 mg L^{-1}; NO_3-N: 0.1 mg L^{-1}; NO_2-N: 0.1 mg L^{-1}; TP: 14.0 mg L^{-1}	TN: 24.8%, TP: 99.7%	[75]
	1.5% Minkery	Green stage: 20 °C; 50 µE m^{-2} s^{-1} continuous light; Red stage: 20 °C; 200 µE m^{-2} s^{-1} continuous light	NH_4-N: 48.75 mg L^{-1}; NO_3-N: 0.15 mg L^{-1}; NO_2-N: 0.15 mg L^{-1} TP: 21.0 mg L^{-1}	TN: 20.7%, TP: 99.8%	
Scenedesmus obliquus SXND-02	Chicken farm + (7 g L^{-1}) sodium acetate	25 °C; 120 µE m^{-2} s^{-1}; 12:12 light: dark;	nr	TN: 80%; TP: 68%; COD: 89%	[87]
Scenedesmus sp. MUR 272	Anaerobically digested abattoir	Micro-ponds: 20 cm depth; pH 6.5; CO_2 addition on demand; batch mode; 7.3–39.8 °C; 427.6–815.8 W m^{-2}	NH_4-N: 45 mg L^{-1}; PO_4-P: 6.3 mg L^{-1}	NH_4-N: 86%; PO_4-P: 89%	[77]

Table 7. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Tetraselmis sp.	Anaerobically digested piggery	175 ± 25 μE m^{-2} s^{-1}; 12:12 light: dark	nr	TN: up to 99%; TP: up to 73%	[84]
	Synthetic mariculture	23 °C; 1500 μE m^{-2} s^{-1}; 12:12 light: dark	NO_3-N: 45 mg L^{-1}; NO_2-N: 10 mg L^{-1}; Orthophosphates: 17 mg L^{-1}; NH_4-N: 30 mg L^{-1}; COD: 270 mg L^{-1};	TN:95.5%; Orthophosphates: 94.4%; COD: 61.4%	[63]
	Aquaculture	24 °C; 50 μE m^{-2} s^{-1}	NH_4-N: 7.7 mg L^{-1}; NO_2-N: 3.1 mg L^{-1}; PO_4-P: 2 mg L^{-1};	NH_4-N: 0.08 mg L^{-1}; NO_2-N: 0.1 mg L^{-1}; PO_4-P: 0.17 mg L^{-1}	[78]

COD (chemical oxygen demand), NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), PO_4-P (orthophosphate phosphate), TN (total nitrogen), TP (total phosphate) and nr (not reported).

Table 8. Growth parameters and metabolites production of microalgae culture in agricultural wastewater.

Algae Used	Wastewater Type	Growth Rate or Volumetric Productivity	Final Biomass Concentration	Production of Target Metabolites	References
Acutodesmus obliquus	Piggery	1850 mg-cell L^{-1} d^{-1}	nr	nr	[66]
Arthrospira maxima	10% Nejayote	0.27 d^{-1}	32 × 10^4 cell mL^{-1}	nr	[62]
Arthrospira platensis	Dairy farm	0.50 g L^{-1} d^{-1}	4.98 g L^{-1}	Lipids: 30.23%	[72]
Botryococcus Braunii	Aerated swine	nr	0,94 mg L^{-1}	Hydrocarbon: 23.8%	[74]
Chlamydomonas sp. JSC4	Swine	49.70 g m^{-2} d^{-1}	37.73 mg L^{-1}	Carbohydrates: 3920% Lipids: 17.67% Protein: 33.94%	[61]
Chlorella pyrenoidosa	Paddy-soaked	0.42 d^{-1}	1.56 g L^{-1}	Chlorophyll: 15.57 mg L^{-1} Lipids: 27.47% Carbohydrates: 23.77% Proteins: 46.12%	[76]
	Five times diluted anaerobically Digested swine	4.21 g m^{-2} d^{-1}	42.20 g m^{-2}	Proteins: 57.30% Extracellular polysaccharides: 14.87% Crude fibre: 3.08% Crude ash: 5.57%	[59]
	Piggery	nr	nr	Lipids: 6.3 mg L^{-1} d^{-1}	[68]
Chlorella sorokiniana AK-1	50% Swine	nr	5.45 g L^{-1}	Proteins: 0.27 g L^{-1} d^{-1}	[58]
Chlorella sorokiniana MB-1-M12	Shrimp culture	nr	1.9 g L^{-1} d^{-1}	Lutein: 5.19 mg g^{-1}	[64]
Chlorella sorokiniana SVMBIOEN2	Dairy farm	nr	2.33 g L^{-1}	Carbohydrates: 10.2 mg g^{-1} Proteins: 14 mg g^{-1}	[85]
Chlorella sp	Aquaculture	nr	213 cell mL^{-1} d^{-1}	nr	[82]
	Aquaculture	nr	nr	nr	[86]
Chlorella sp. GD	Aquaculture	0.487 d^{-1}	17.4 g L^{-1}	Lipids: 21.3%	[65]
	Piggery	0.839 d^{-1}	0.681 g L^{-1} d^{-1}	Lipids: 21%	[69]
Chlorella sp. HL	Swine	0.51 d^{-1}	2.43 × 10^7 cells mL^{-1}	nr	[79]
Chlorella sp. MM3	Mixed piggery and winery (20:80 ratio)	nr	4.4 × 10^6 cells mL^{-1}	Lipids: 51%	[70]
Chlorella thermophila MF179624	2.5% Cattle	nr	2.17 g L^{-1}	Lipids: 18.27% Carbohydrates: 29.39% Proteins: 44.91%	[71]
Chlorella vulgaris	10% swine	0.57 d^{-1}	128 × 10^6 cells mL^{-1}	nr	[62]
	Poultry slaughterhouse	nr	1.2 g L^{-1}	nr	[80]
Chlorella vulgaris MBFJNU-1	Swine	0.11 d^{-1}	36 mg L^{-1} d^{-1}	nr	[57]
Desmodesmus sp. PW1	Piggery	nr	1.76 g L^{-1}	7.2%	[83]
Dunaliella FACHB-558	Anaerobically digested poultry litter	nr	678 mg L^{-1}	β-carotene: 4.02 mg L^{-1}	[56]
Haematococcus pluvialis	1% Minkery	0.399 mg L^{-1} d^{-1}	681 mg L^{-1}	Astaxanthin: 39.72 mg L^{-1}	[75]
	1.5% Minkery	0.451 mg L^{-1} d^{-1}	906.33 mg L^{-1}	Astaxanthin: 16.64 mg L^{-1}	
Scenedesmus obliquus SXND-02	Chicken farm + (7 g L^{-1}) sodium acetate	nr	2.18 g L^{-1}	Lipids: 50.22%	[87]
Scenedesmus sp. (MUR 272)	Anaerobically digested abattoir	nr	19.24 g m^{-2} d^{-1}	nr	[77]
	Anaerobically digested piggery	nr	59.8 mg L^{-1} d^{-1}	Lipids: 25 mg L^{-1} d^{-1} Carbohydrates: 6.5 mg L^{-1} d^{-1}	[84]
Tetraselmis sp.	Synthetic mariculture	0.067 d^{-1}	1.19 g L^{-1}	Lipids: 62.16 mg g^{-1}	[63]

nr (not reported).

2.3. Industrial Wastewater

2.3.1. Physicochemical Properties

Industrial wastewater could come from a wide range of industries (Figure 5), such as the textile and food processing industries (sugar, starch, vegetable oil, shortening, potato, dairy, fruit juice and beverage, brewery and distillery industries) [88,89] and is one of the most significant pollution sources in the environment and has different properties.

Different techniques have been used to treat this type of wastewater, among them is the treatment by microalgae [90]. Table 9 summarizes the properties of different industrial wastewaters which have been treated using microalgae, food-processing wastewater being the most investigated wastewater in the literature. This type of wastewater often has a high chemical oxygen demand and high total nitrate and total phosphate concentrations levels [5], for example, an olive oil mill wastewater contains 56,740–124,600 mg L^{-1} of COD, 130–190 mg L^{-1} of TN and 350 mg L^{-1} of TP, as well as soybean wastewater which has 5320–22,700 mg L^{-1} of COD, 267.1–950 mg L^{-1} of TN and 23.28–56.3 mg L^{-1} of TP [89,91–96]. Winery wastewater has a high COD content (119,300 mg L^{-1}) and a lower TN (12.14 mg L^{-1}) and TP content (3.46 mg L^{-1}) [70]. On the other hand, textile wastewater is characterized by a high concentration of the total suspended and dissolved solids, chemical oxygen demand and a strong color [5,97]. As reported in Table 9, it contains 1050 mg L^{-1} of TSS, 1378.2–4458 mg L^{-1} of COD and 43.57 NTU, which is lower than a palm oil mill effluent (244 NTU) [98,99].

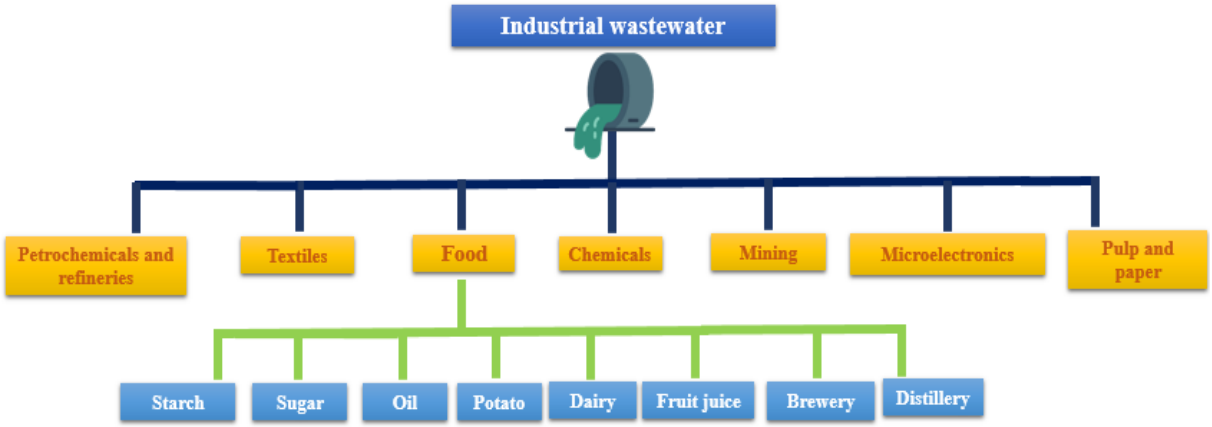


Figure 5. Industrial wastewater types.

Chemical industry wastewater, such as that from pesticides and pharmaceutical processing industries, used in the literature as culture mediums for microalgae, contains high total organic carbon (TOC) and low total nitrate (TN) and total phosphate (TP) concentrations, with 7185.93 and 480.93 mg L^{-1} of TOC, 0.02 and 0.23 mg L^{-1} of TN and 1.01 and 0.52 mg L^{-1} of TP, for pharmaceutical and pesticide processing wastewaters, respectively [32].

Table 9. Industrial wastewater composition.

Type	pH	TSS (mg L^{-1})	TOC (mg L^{-1})	COD (mg L^{-1})	NO_3-N (mg L^{-1})	NO_2-N (mg L^{-1})	NH_4-N (mg L^{-1})	NH_3-N (mg L^{-1})	PO_4-P (mg L^{-1})	TN (mg L^{-1})	TP (mg L^{-1})	References
Olive Oil Mill	4–5.37	41,220–83,160	-	56,740–124,600	99.13		-	2.3	360	130–190	350	[91,92]
Textile	10.5–10.9	1050	-	1378.2–4458	16.12	-	28.35	-	2.1–22.3	40	-	[99,100]
Olive Oil Washing	6.29	-	191.5	1362	-	-	<4	-	-	7.49	1.63	[17]
Starch	2.13–7.3	1000–92,000	8770	792.28–7426	606	108	2.7–503	-	1.2–336	265.10–379.5	28.34–67.9	[101–105]
Digested Starch	7.3–7.5	-	-	702.4–102.5	-	-	217.6–334.7	-	19.3–32.9	240.3–382.7	22.7–40.2	[106]
Alcohol	3.2–4.5	-	-	45,638.06–65,000	-	-	214.56–279.72	-	19.71	618.68–725.34	47.16–64.38	[104,105]
Reeling	7.39	-	-	11	-	-	-	-	-	2.43	1.07	[107]
Cooking Cocoon	7.52	-	-	2925	-	-	-	-	-	267.5	23.1	[107]
Frigon	>12	-	-	14,820	-	-	-	-	-	910.9	92.8	[107]
Seafood	7.92	-	-	1220.8	6.99	0.73	117.22	-	-	121.07	57.32	[108]
Brewery	5.5–6	300–320	1400–1500	2000–3000	-	-	-	-	-	30–45	12–16	[109]
Rose Oil	6.05–6.14	-	-	1200–2087	13.5	-	12.36	-	<0.05	-	-	[110]
Rolling Mill Industry	6.05	-	-	-	11.5	-	-	-	-	-	-	[111]
Vinegar	5.6	-	-	740	-	-	-	17.7	-	20.5	7.4	[112]
Dairy Industrial	3.69–9.11	111–1510	143.3–722	342–7110	64	5.03	18.45–46.5	31.4–90.4	5.58–31.0	65.06–103.6	8–105.1	[113–118]
Winery	3.51–4.2	9780	-	119,300	-	-	-	-	-	12.14	3.46	[70,119]
Soy Sauce	6.548	-	992	3263.33	-	-	168.44	-	-	173.53	10.21	[120]
Palm Oil Mill	7–8	880–3900	1400	2898.72–4395.6	-	-	254	-	273	5.06–376	39.4–58	[98,121–123]
Lactic Acid	5.3	-	-	12,571	-	-	-	169	-	651	28.2	[124]
Instant Coffee	4.54	1000	7600	4940	-	-	-	-	-	75.63	7.81	[125]
Dairy Products	10.26	60	7420	190	-	-	-	-	-	18.04	2.63	[125]
Pesticides Industry	9.2	-	480.93	-	-	-	-	-	-	0.23	0.52	[32]
Pharmaceutical Industry	11.88	-	7185.93	-	-	-	-	-	-	0.02	1.01	[32]
Petroleum Industry	7.97	-	288.60	-	-	-	-	-	-	0.5	0.58	[32]
Soybean	4.2–6	-	-	5320–22,700	-	-	3–52.1	15.25	100	267.1–950	23.28–56.3	[93–96]

Type	Chloride (mg L^{-1})	Na (mg L^{-1})	F (mg L^{-1})	Fe (mg L^{-1})	Cu (mg L^{-1})	Zn (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Pb (mg L^{-1})	Turbidity NTU	References
Textile	1019.46	-	-	-	-	-	-	-	-	-	43.57	[99]
Olive Oil Washing	172	-	-	-	1.6	-	62.4	-	-	-	-	[17]
Starch	-	315.21–719.40	-	0.94–32.86	-	0.86–1.24	3.711–181.16	98.40–126.36	112.34–174.47	-	-	[102,104,105]
Digested Starch	-	417.6–790.1	-	0.9–3.6	0.09–0.21	-	97.6–166.9	72.8–102.3	-	-	-	[106]
Alcohol	-	226.17–787.74	-	1.47–2.3	-	0.06–0.1	49.12–152.20	16.95–96.14	127.63–157.75	-	-	[104,105]

Table 9. *Cont.*

Type	Chloride (mg L^{-1})	Na (mg L^{-1})	F (mg L^{-1})	Fe (mg L^{-1})	Cu (mg L^{-1})	Zn (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Pb (mg L^{-1})	Turbidity NTU	References
Rolling Mill Industry	172.3	60	-	3.51	8.5	0.75	-	-	-	2.48	-	[111]
Vinegar Production	-	-	-	-	-	-	13.9	39.5	69.9	-	-	[112]
Dairy Industrial	199–385	42	6	-	-	-	9.85	564	-	-	-	[113,118]
Winery	-	84.54	-	2.037	0.0059	0.6087	15.14	39.5	235.7	0.0004	-	[70,119]
Palm Oil Mill	-	2.99	-	1.67	<0.01	<0.01	3.8–672.22	0.8	3072.03–4393.89	-	244	[98,121]
Instant Coffee	-	0.059	-	9.762	-	0.032	28.10	-	-	-	-	[125]
Dairy Products	-	0.067	-	-	-	0.017	2.72	-	-	-	-	[125]
Cassava Flour/Starch	-	0.003	-	-	0.021	0.358	45.83	-	-	-	-	[125]
Soybean Curd	961	1387	-	5.16–41	0.55	6.91	35–173.5	51.47–366	1280	-	-	[93–95]

TSS (total suspended solids), TOC (total organic carbon), COD (chemical oxygen demand), NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), NH_3-N (ammonia-nitrogen), PO_4-P (orthophosphate phosphate), TN (total nitrogen), TP (total phosphate), Na (sodium), F (fluorine), Fe (iron), Cu (copper), Zn (zinc), Mg (magnesium), Ca (calcium), K (potassium), Pb (lead), NTU (nephelometric turbidity units) and nr (not reported).

2.3.2. Pretreatment

The industrial wastewater must be pretreated after characterization and before treatment with microalgae. Similarly to domestic and agricultural wastewaters, the procedures employed in the literature include sedimentation, filtration, acidification and centrifugation for the removal of suspended materials, as well as an autoclave or UV radiation sterilization for the removal of bacteria and other microorganisms found in industrial wastewater (Table 10). Filtration has also been used to remove germs depending on the pore size of the filter employed, for example, Hao et al. utilized the membrane filtration with a pore size of 0.22 µm to filter and sterilize industrial wastewater [8]. They reported that soy sauce wastewater composition had changed after sterilization by an autoclave at 121 °C for 30 min, with a change in the chemical oxygen demand from 3263.33 to 3463.33 mg L^{-1}, total organic carbon from 992.00 to 1042.80 mg L^{-1}, total nitrogen from 173.53 to 176.49 mg L^{-1}, ammonium nitrogen from 168.44 to 158.85 mg L^{-1} and the total phosphorus from 10.21 to 5.57 mg L^{-1}, and there was no change in the soy sauce wastewater color [120].

Table 10. Pretreatment methods of industrial wastewater before microalgae cultivation.

Wastewater	Pretreatment Method	Microalgae	References
Tobacco	Filter-sterilized by a 0.22 µm membrane filter (Millipore, USA)	*Chlorella pyrenoidosa* (No.FACHB-863)	[8]
Palm oil mill (POME)	Filtered through a microfiber mesh and sterilized in an autoclave	*Chlorella zofingiensis*	[98]
Cassava processing	Autoclaved at 121 °C for 15 min, then filtered on filter paper	*Arthrospira platensis*	[101]
Palm oil mill (POME)	Filtered with filter cloth and re-filtered through glass microfibers filter (Whatman, Grade GF/C 1.2 mm) and autoclaved at 121 °C and at a pressure of 15 psi for 20–30 min	*Nannochloropsis* sp.	[121]
Soy sauce	Centrifuged (1644× *g* 5 min), then autoclaved at 121 °C for 30 min	*Spirulina* NCU-Sm	[120]
Potato	Acidified with sulfuric acid to pH 5, then autoclaved at 121 °C for 30 min	*Scenedesmus* sp. HXY5	[126]
Olive oil washing	Centrifuged and filtered–sterilized through a glass wool pre-filter and cellulose nitrate membrane (0.45 µm)	*Chlorella pyrenoidosa*	[17]
Soybean processing	Centrifuged (5000 rpm), and filtered by a microporous filter membrane (0.45 µm), then sterilized by high-pressure steam at 121 °C	*Chlorella* sp. L166	[96]
Vinegar production	Centrifuged for 10 min at 5000 rpm, and sterilized at 121 °C and 120 kPa for 20 min	*Chlorella* sp.	[112]
Soybean processing	Filtrated then autoclaved at 120 °C for 30 min	*Chlorella* L166	[94]
Anaerobic palm oil mill	Centrifuged at 8000 rpm for 10 min	*Scenedesmus* sp. and *Chlorella* sp.	[122]
Starch processing plant	Filtered through 0.45 mm polyester filters and sterilized through UV-B radiation (UV doses 810 mJ cm^{-2} at a distance of 10 cm)	*Chlorella pyrenoidosa* (FACHB-9)	[102]
Cassava	Sterilized at 121 °C for 10 min	*Desmodesmus aramatus*	[103]
Anaerobically digested starch	Allowed to settle for 5–7 h in several tanks and filtered using polyester filters (1 µm)	*Chlorella pyrenoidosa* (FACHB-9)	[104]
Raw dairy	Filtered through a non-woven geotextile membrane (100 GSM grade)	*Ascochloris* sp. ADW007	[113]
Seafood processing	Filtered using 0.45 µm pore size GF/C glass microfiber filters	*Chlorella* sp.	[108]
pesticides industry, pharmaceutical industry, petroleum industry	Filtered and sterilized using vacuum filtration unit and autoclaved at 121 °C for 15 min	*Nannochloropsis oceanica*	[32]

Table 10. *Cont.*

Wastewater	Pretreatment Method	Microalgae	References
Anaerobic digested starch	Allowed to settle for several hours and filtered using a 0.45 µm polyester filter then sterilized	*Chlorella pyrenoidosa* (FACHB-9)	[105]
Anaerobic digested starch processing	Allowed to settle for 5–7 h in a settling tank and filtered with 270 mesh (53 lm) polyester filter bags	*Chlorella pyrenoidosa* (FACHB-9)	[127]
Raw dairy	Settled by gravity overnight and filtered through gauze	*Chlorella* sp.	[73]
Meat processing plant	Centrifuged at 8000 rpm for 10 min and sterilized at 121 °C for 30 min	*Chlorella* sp.	[128]
Pulp and paper industry	Addition of 1 mL of SuperFloc C-581 flocculant per 50 mL of effluent. Setteled for 20 min then filtred through a mesh filter with pore size of 5 µm and sterilized with a 500 mL bottle top polystyrene filter with pore size of 0.22 µm.	*Nannochloropsis oculata*	[129]
Raw dairy	Centrifuged (5000 rpm, 10 min) then autoclaved	*Chlorella zofingiensis*	[114]

2.3.3. Microalgae Treatment of Industrial Wastewater

Despite the great variety of industrial effluent, (Tables 11 and 12 and Figures 6 and 7), microalgae have mostly been utilized to remediate wastewaters from the food industry, because they contain a lot of organic materials and are nontoxic for microalgae cultivation. For instance, in pilot scale conditions (open troughs with a semi-cylindrical barrel form, 29–42 °C, 28.944–196.015 W m^{-2} light intensity), *Ascochloris* sp. ADW007 demonstrated its capacity to reduce the pollutants found in raw industrial dairy wastewater (pH: 3.69, COD: 7110 mg L^{-1}, TN: 137 mg L^{-1}, TP: 105.1 mg L^{-1}) as well as its ability to produce lipids for the generation of biodiesel [113]. In comparison to laboratory scale conditions, the strain produced the most biomass (0.207 g L^{-1} d^{-1}) and lipids (34.98%) while also having the greatest wastewater treatment efficiency with hollow fiber filtration and activated carbon treatment as post-harvesting techniques (COD: 95.1%, TN: 79.7%, TP: 98.1%) [113]. Lactic acid wastewater was also used to cultivate *Scenedesmus dimorphus* for 10 days, allowing total nitrogen and total phosphate elimination rates of 96.31% and 90.78%, respectively, as well as a high lipid production of 1.54 g L^{-1} compared to a BG11 culture medium (1.04 g L^{-1} of lipids) [124]. Authors found that this treated wastewater might be used four times to produce lactic acid, potentially offsetting the expenses of lactic acid wastewater disposal [124]. Recently, a piece of research examined the potential of microalgae in producing electricity and industrial dairy wastewater treatment [115]. They isolated several marine microalgae and evaluated their electrogenic and redox peak activities. Of 18 microalgae isolates, *Coelastrella* sp. showed a better electrogenicity and redox peak and capability to remove nutrients from dairy wastewater, with the best removal efficiencies of NH_4-N (90.38%), NO_3-N (90.24%), P (66.75%), COD (69.44%) and TOC (83.51%) in a lab-scale raceway pond [115]. In addition, soy processing wastewaters treatment was also investigated using microalgae treatment [89,91,96]. Three different dilutions were used to cultivate two *Chlorella* species L166 and L38 in soybean effluent (0, 10 and 100 times) [94]. The results showed that *Chlorella* sp. L38, grown in a 10-times-diluted soybean effluent, had the highest removal efficiencies for TN (84.7%), TP (97.3%), and COD (70.5%), but that *Chlorella* L166 strain produced the highest levels of lipids by about 7.22 mg L^{-1} d^{-1} and polysaccharides by about 2.86 mg L^{-1} d^{-1} under the same conditions of culture [94].

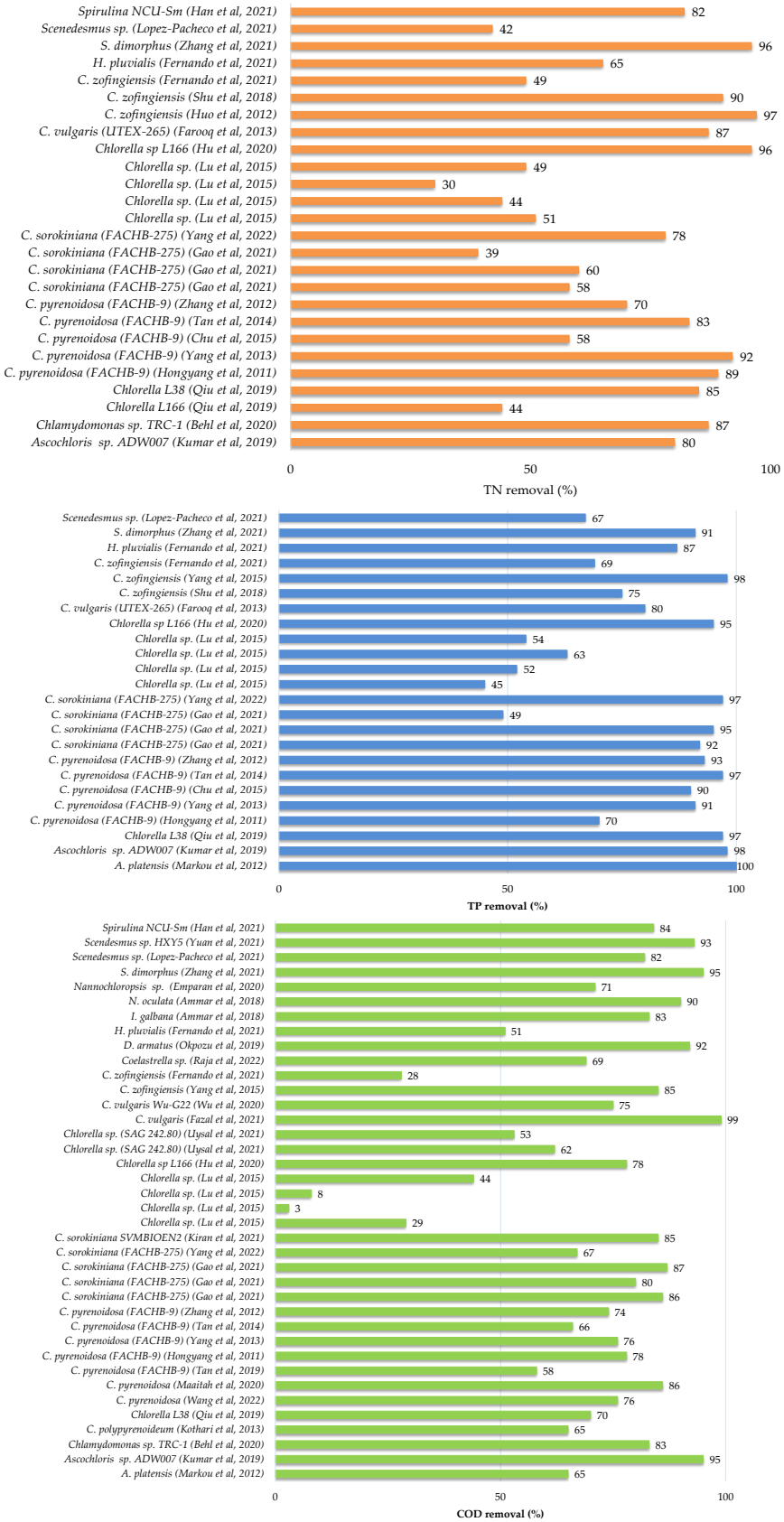


Figure 6. Nutrients and COD removals from industrial wastewater by microalgae species [17,85,91,94–96,98–100,103,105–107,109,110,113,115,117,118,120,123,124,126–137].

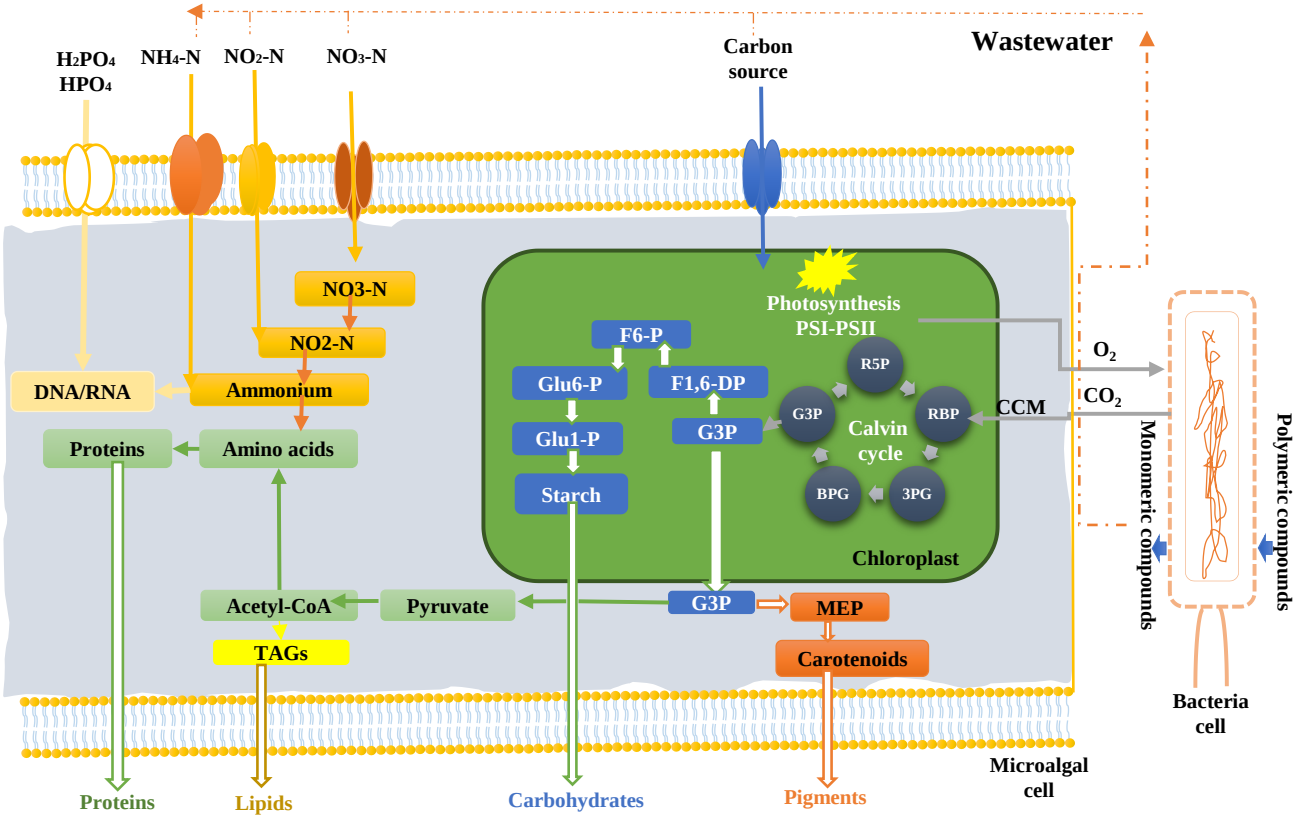


Figure 7. Wastewater pollutants mechanisms of bioremediation by microalgae. NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), H_2PO_4 (dihydrogen phosphate), HPO_4 (hydrogen phosphate), HMs (Heavy metals), CCM (carbon concentrating mechanism), RBP (ribulose biphosphate), R5P (ribulose 5 phosphate), G3P (glyceraldehyde 3 phosphate), BPG (bis-phosphoglycerate), 3PG (3 phosphoglycerate), F1,6-DP (fructose 1,6-bisphosphate), F6-P (fructose 6 phosphate), Glu6-P (glucose 6 phosphate), Glu1-P (glucose 1 phosphate), MEP (methylerythritol phosphate) and TAGs (triacyl glycerols).

In another study, *Chlorella* sp. L166 was co-cultured with soybean effluent (COD: 5320 mg L^{-1}, TN: 106.99 mg L^{-1}, TP: 23.28 mg L^{-1}) and CO_2 from flue gas [96]. The concentration of chlorophyll a was 48.08 mg L^{-1}, when the N/P ratio was 5:1 in the 20% soybean effluent and 5% CO_2 (0.1 vvm) [96]. Furthermore, *Chlorella* sp. L166 obtained the maximum removal efficiencies of TN of 96.07, TP of 95.55%, COD of 78.20% and a CO_2 fixation of 28.60% [96]. Therefore, it was discovered that *Chlorella* sp. L166 had the capacity to remove CO_2 in flue gas while also treating a soybean processing effluent [96]. In a recent piece of work, Han et al. [120] employed a soy sauce processing effluent (NH_4-N: 168.44 mg L^{-1},TN: 173.53 mg L^{-1}, COD: 3263.33 mg L^{-1}) as a culture medium to feed *Spirulina* and remove pollutants. The findings showed that *Spirulina* NCU-Sm grew well in raw soy sauce wastewater and produced a maximum biomass of 1.984 g L^{-1} with a removal efficiency 93.86% for NH_4-N, 81.76% for TN and 84.08% for COD [120].

Researchers have also evaluated the wastewater from oil-producing industries such as olive oil and palm oil to determine the potential of microalgae to treat this type of wastewater and produce a microalgal biomass as well as compounds with high added values such as lipids and carbohydrates [92,121,130]. During the 14 days of culture, Resdi et al. employed different ratios of palm oil effluent diluted with marine water (0, 20, 40, 60 and 80% dilutions) to cultivate *Nannochloropsis* sp. compared to palm oil effluent diluted with Walne's medium [121]. They discovered that *Nannochloropsis* sp. thrived well in 60% palm oil mill effluent diluted with marine water, had the best specific growth rate of 0.39/d, the maximum cell density of 7.93 107 cell/mL, 61.60% lipids, and could remove 11.31 mg/mg/d of the

chemical oxygen demand [121]. In contrast, Emparan et al. immobilized *Nannochloropsis* sp. in the form of beads using sodium alginate to assess the treatment of palm oil mill wastewater diluted 10 times in comparison with free cell culture [130]. Other authors immobilized *Nannochloropsis* sp. and found that it achieved the best biomass of 1.27 g L^{-1} and could remove 71% of the chemical oxygen demand (COD) from palm oil mill effluent, compared to culture with free-cells of *Nannochloropsis* sp. which showed 0.37 g L^{-1} for biomass production and 48% of the COD removal efficiency [130]. This sodium alginate immobilization technique did not interrupt the development of *Nannochloropsis* sp., but rather optimized it by facilitating the passage of nutrients from palm oil mill effluent through the membrane pores of beads, allowing the authors to conclude that this technique is viable for palm oil mill wastewater treatment [130]. Recently, [92] used raw and diluted olive mill wastewater after treatment by anaerobic digestion followed by ultrafiltration to cultivate *Scenedesmus* sp., which had the highest biomass productivity (0.15 g L^{-1} d^{-1}) in 25% of the ultra-filtrated anaerobic liquid digestate of the olive mill with a nitrate removal efficiency of 98%. Additionally, *Arthrospira platensis* has been utilized to remediate cassava processing effluent [101]. The authors cultivated *Arthrospira platensis* for eight days in an SKM culture medium with modest changes (NaCl: 8 g L^{-1}, $NaHCO_3$: 5 g L^{-1}, $Ca(H_2PO_4)_2{\cdot}H_2O$: 0.01 g L^{-1}, urea: 0.1 g L^{-1}) and with a daily addition of a volume of cassava processing effluent as a source of nutrients (0–2 mL L^{-1} of culture) [101]. The findings demonstrated that when 1.5 mL d^{-1} L^{-1} of cassava wastewater was added to the culture, *Arthrospira platensis* could successfully remove nitrogen (88.4%) and phosphate (43.4%) [101]. Over 99% of ammonium, nitrites and nitrates may be reduced by adding up to 2.0 mL d^{-1} L^{-1} of cassava processing effluent [101]. The authors of [103] examined the reduction of the chemical oxygen demand of cassava wastewater (COD: 1570.00 mg L^{-1}) and the biosynthesis of lipids by the microalga *Desmodesmus armatus* in both heterotrophic and mixotrophic growing modes. After 14 days of culture, they discovered that *Desmodesmus armatus* can biosynthesize 21.91% of lipids and remove 92% of the COD in the mixotrophic mode, as opposed to 74% of the COD and 20.86% of lipids in the heterotrophic mode [103]. Other food-processing wastewaters such as winery, potato and instant coffee wastewaters, have also shown their ability to be treated by microalgae [119,125,126]. The authors of [119] used a continuous flow photobioreactor with a membrane column to co-culture *Chlorella vulgaris* and *Arthrospira platensis* for 15 days, using winery wastewater (119.3 g L^{-1} COD) as the culture medium. This co-culture technique allowed the removal of 75% of the chemical demand from the industrial winery wastewater for a retention time of 2 days, producing a lipid yield of 278 mg g^{-1} and a biomass of 3.61 g L^{-1} [119]. In a lab test, five species of *Scenedesmus* and three species of *Desmodesmus* were examined to find the potential of microalgae for potato wastewater remediation with a high pigment content [126]. They found that *Scenedesmus* sp. HXY5 grew the fastest in potato wastewater, yielding the highest biomass of 2.64 g L^{-1} and a total pigment yield of 18.45 mg L^{-1}, with a lutein yield of 11.46 mg L^{-1}. It displayed an outstanding wastewater purification capability, with removal efficiencies of 59% for the total dissolved nitrogen (TDN), 32% for the total dissolved phosphate (TDP), and 93% for the COD [126]. *Chlorella sorokiniana* (IPRChs7104) was cultivated using wastewater from the instant coffee and cassava wastewater during 52 days of culture, under 28 °C, 130 µmol m^{-2} s^{-1} and a 12:12 h photoperiod [125]. The results showed a significant decrease in the chemical oxygen demand from 7200 mg L^{-1} to 435 mg L^{-1}, and 4940 mg L^{-1} to 1240 mg L^{-1} for cassava and instant coffee wastewater, respectively [125].

The bioremediation of textile effluents was also assessed [99,100,131]. *Chlorella vulgaris* was cultivated in a raw and diluted (50%) textile wastewater and was compared to BG11 medium as the control during the 14 days of culture [131]. A maximum growth of 1.62 OD_{680} with a higher COD removal of 99.7% was obtained in the 50% textile wastewater, followed by 1.56 OD_{680} and 94.4% of the COD removal in the BG11 medium, and 0.89 OD_{680} with 76.3% of the COD removal in the raw textile wastewater [131]. They also demonstrated that *C. vulgaris* had the maximum of the fatty acid methyl esters (FAMEs)

yield in the BG11 medium, followed by a diluted (50%) and raw textile wastewater of 31.26 mg g^{-1}, 11.07 mg g^{-1} and 9.12 mg g^{-1}, respectively [131]. In contrast, for *Chlorella vulgaris* Wu-G22 immobilized with sodium alginate (3%) and cultivated for 10 days in textile wastewater, 75% of chemical oxygen demand removal efficiency and maximum FAMEs accumulation were achieved compared to diluted effluent [100]. After the cultivation of *Chlamydomonas* sp. TRC-1 in textile wastewater for 7 days of culture, removal efficiencies of the COD, total nitrogen, nitrates and phosphates of 83.08%, 87.15%, 91.75% and 92.36%, respectively, were observed [99]. In addition, they demonstrated that the harvested biomass had a capacity for lipid accumulation (79.1%) and bioelectricity generation (current density of 3.6 A m^{-2}, power of 4.13 $\times$ 10^{-4} W and power density of 1.83 W m^{-2}) [99].

Table 11. Treatment of industrial wastewater by the cultivation of microalgae.

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Arthrospira platensis	Cassava	24 °C; 30 µE m^{-2} s^{-1}	pH: 3.9; PO_4-P: 0.336 g L^{-1}; NO_3-N: 0.606 g L^{-1}; NO_2-N: 0.108 g L^{-1}; NH_4-N: 0.503 g L^{-1}	PO_4-P: 43.4%; NO_3-N: 88.4%; NO_2-N: 100%; NH_4-N: 99.9%	[101]
Arthrospira (Spirulina) platensis SAG 21.99	10% olive oil mill + 1 g L^{-1} $NaNO_3$ + 5 g L^{-1} $NaHCO_3$	30 °C; 10,000 lx; 20:4 light: dark	pH: 5.42; COD: 43.87 g L^{-1}; TP: 0.23 g L^{-1}; TN: 1.67 g L^{-1}; Carbohydrates: 13.40 g L^{-1}; Phenols: 3.12 g L^{-1}	COD: 65.53%; TP: 100%; Carbohydrates: 88.41%; Phénols: 100%	[91]
Ascochloris sp. ADW007	Raw dairy	29–42 °C; 28,944–196,015 W m^{-2};	pH: 3.69; COD: 7110 g L^{-1};TN: 137 mg L^{-1}; TP: 105.1 mg L^{-1}	COD: 95.1%; TN: 79.7%; TP: 98.1%	[113]
Chlamydomonas sp. TRC-1	Textile	27 °C; 100 µE m^{-2} s^{-1}; 16:8 light: dark;	COD: 1378.2 mg L^{-1};TDS: 8195 mg L^{-1}; TSS:1050 mg L^{-1}; TS: 9245 mg L^{-1}; TN: 40 mg L^{-1}; NO_3-N: 16.129 mg L^{-1}; PO_4-P: 2.1 mg L^{-1}; Hardness: 168.38 mg L^{-1}; Cl: 1019.46 mg L^{-1}; Turbidity: 43.57 NTU; Alkalinity: 1162.66 mg L^{-1}	COD: 83.08%; TDS: 82.11%; TSS: 87.40%; TS: 82.64%; TN: 87.15%; NO_3-N: 91.75%; PO_4-P: 92.36%; Cl: 41.43%; Turbidity: 72.45%; Alkalinity: 45.64%	[99]
Chlamydomonaspolypyrenoideum	Dairy industry	28 ± 2 °C; 10 W m^{-2}; 12:12 light: dark	NO_3-N: 48.7 mg L^{-1}; NO_2-N: 3.05 mg L^{-1}; PO_4-P: 3.9 mg L^{-1}; COD: 6000 mg L^{-1}	NO_3-N: 90%; NO_2-N: 74%; PO_4-P: 70%; COD: 64.8%	[118]
Chlamydomonas reinhardtii CC124	Olive mill	28 °C; 70 µE m^{-2} s^{-1} (Acclimated for 3 weeks)	COD: 5065.35 mg L^{-1}; TN: 7.01 mg L^{-1}; TP: 42.94 mg L^{-1}	TN: 65 mg L^{-1}	[132]
Chlorella L166	10 times diluted Soybean	22 °C; 6000 lx	TN: 0.95 g L^{-1}; TP: 0.12 g L^{-1}; COD: 22.70 g L^{-1}	TN: 43.9%; TP: 72.8–90.4%; COD: 37.1–61.1%	[94]
Chlorella L38	10 times diluted Soybean	22 °C; 6000 lx	TN: 0.95 g L^{-1}; TP: 0.12 g L^{-1}; COD: 22.70 g L^{-1};	TN: 84.7%; TP: 97.3%; COD: 70.5%;	
Chlorella pyrenoidosa	Dairy	27 °C; 120 µE m^{-2} s^{-1}; 150 rpm	nr	COD: 76.17%; NH_4-N: 98.10%;	[133]
	90% Olive oil washing + 10% urban	25 °C; 126.2 µE m^{-2} s^{-1}, 12:12 light: dark; pH 8	PO_4-P: 6.97 mg L^{-1}; NO_3-N: 40.8 mg L^{-1}; COD: 1251 mg L^{-1}	PO_4-P: 56.4%; NO_3-N: 49%; COD: 86.3%	[17]
Chlorella pyrenoidosa (FACHB-9)	A mixed acidified and secondary treated starch (1:1)	32 °C, 127 µE m^{-2} s^{-1}; 12:12 light: dark	pH: 2.7/7.2; TN: 362.6–302.4 mg L^{-1}; NH_4-N: 79.5–273.6 mg L^{-1}; TP: 61.3–55.2 mg L^{-1} COD: 6196/892 mg L^{-1}	COD: 57.9%	[102]
	Soybean	27 °C; 40.5 µE m^{-2} s^{-1}; 14:10 light: dark;	NH_4-N: 52.1 mg L^{-1}; TP: 56.3 mg L^{-1}; TN: 267.1 mg L^{-1}; COD: 13,215 mg L^{-1}	NH_4-N:89.1%; TP:70.3%; TN:88.8%; COD: 77.8%	[95]
	Alcohol and anaerobically digested starch (1:15)	30–32 °C; 12:12 light: dark	TN: 725.34–307.64 mg L^{-1}; TP: 64.38–37.57 mg L^{-1}; COD: 45,683.06–792.28 mg L^{-1}	COD: 405.18 mg L^{-1} d^{-1}; TN: 49.15 mg L^{-1} d^{-1}; TP: 6.72 mg L^{-1} d^{-1}	[104]

Table 11. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
	Alcohol and anaerobically digested starch (AW/ADSW = 0.053:1, *v*/*v*)	25 °C; 127 μE m^{-2} s^{-1}; 12:12 light: dark	TN: 618.68–265.10 mg L^{-1};TP: 47.16–28.34 mg L^{-1}; COD: 65,000–926.3 mg L^{-1};	COD: 75.78%; TN: 91.64%; TP: 90.74%;	[105]
	Anaerobic digested starch	19.6–36.5 °C; 79,500 lx; 8.6:15.4 light: dark;	TN: 289.6 mg L^{-1}; TP: 38.8 mg L^{-1}	TN: 57.9%; TP: 89.9%	[127]
	Anaerobic digested starch	35–39 °C; 220 μE m^{-2} s^{-1}	TN: 240.3–382.7 mg L^{-1}; TP: 22.7–40.2 mg L^{-1}; COD: 702.4–1026.2 mg L^{-1}	TN: 83.06%; TP: 96.97%; COD: 65.99%	[106]
	Soybean	28 °C in the dark	TN: 189.9 mg L^{-1}; TP: 45.6 mg L^{-1}; COD: 8087 mg L^{-1};	TN: 70%; TP: 92.7%; COD: 73.6%	[134]
Chlorella pyrenoidosa (No. FACHB-863)	Tobacco	25 °C, 80 μE m^{-2} s^{-1}; 12:12 light: dark	pH: 5; TN: 151.91 mg L^{-1}; NH_4-N: 3.58 mg L^{-1}; TP: 6.38 mg L^{-1}; COD: 574.16 mg L^{-1}	TN: 94.58 mg L^{-1}; NH_4-N: 3.44 mg L^{-1}; TP: 3.12 mg L^{-1}; COD: 157.5 mg L^{-1}	[8]
Chlorella sorokiniana (FACHB-275)	Frigon + reeling	25 °C; 50 μE m^{-2} s^{-1}; 12:12 light: dark	COD: 5400.0 mg L^{-1}; TN: 308.0 mg L^{-1}; TP: 23.2 mg L^{-1}	COD: 86.1%; TN: 58.4%; TP: 91.9%	[107]
	Frigon + distilled water	25 °C; 50 μE m^{-2} s^{-1}; 12:12 light: dark	COD: 5050.0 mg L^{-1}; TN: 306.8 mg L^{-1}; TP: 26.2 mg L^{-1}	COD: 80.0%; TN: 60.4%; TP: 94.9%	
	Cooking cocoon	25 °C; 50 μE m^{-2} s^{-1}; 12:12 light: dark	COD: 2925.0 mg L^{-1}; TN: 267.5 mg L^{-1}; TP: 23.1 mg L^{-1}	COD: 86.6%; TN: 38.9%; TP: 49.4%	
	Cooking cocoon	25 °C; 150 μE m^{-2} s^{-1}; 16:8 light: dark	nr	NH_4-N: 92.61%; COD: 66.88%; TN: 78.50%; TP: 97.31%	[135]
Chlorella sorokiniana (IPRChs7104)	Wastewater from the instant coffee	28 °C; 130 μE m^{-2} s^{-1}; 12:12 light: dark (2nd cycle, 52 d)	pH: 4.54; COD: 4940 mg L^{-1}	COD_{fin}: 1240 mg L^{-1}	[124]
	Dairy products	28 °C; 130 μE m^{-2} s^{-1}; 12:12 light: dark (2nd cycle, 52 d)	pH: 10.26; COD: 190 mg L^{-1}	COD_{fin}: 158 mg L^{-1}	
	Cassava flour/starch	28 °C; 130 μE m^{-2} s^{-1}; 12:12 light: dark (2nd cycle, 52 d)	pH: 3.62; COD: 7200 mg L^{-1}	COD_{fin}: 435 mg L^{-1}	
Chlorella sorokiniana SVMBIOEN2	Dairy	25 °C; 100 μE m^{-2} s^{-1}; 12:12 light: dark	COD: 2000 mg L^{-1}	COD: 85%	[85]
Chlorella sp.	Aerated Seafood processing	25 °C; 135 μE m^{-2} s^{-1}	pH: 7.14; COD: 295.1 mg L^{-1}; TN: 94.80 mg L^{-1}; TP: 45.89 mg L^{-1}	TN: 4.98 mg L^{-1} d^{-1}; TP: 1.91 mg L^{-1} d^{-1}	[108]
	Meat processing (CUT + KILL)	25 °C; 120 μE m^{-2} s^{-1}	COD: 2100 mg L^{-1}; TN: 212.0 mg L^{-1}; TP: 53.6 mg L^{-1}	COD: 29.52%; TN: 50.94%; TP: 44.95%	[128]
	Meat processing (DS + KILL)	25 °C; 120 μE m^{-2} s^{-1}	COD: 2100 mg L^{-1}; TN: 204.9 mg L^{-1}; TP: 24.1 mg L^{-1}	COD: 3.21%; TN: 44.46%; TP: 52.11%	

Table 11. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
	Meat processing (MPGP + KILL)	25 °C; 120 μE m^{-2} s^{-1}	COD: 3020 mg L^{-1}; TN: 197.6 mg L^{-1}; TP: 44.7 mg L^{-1}	COD: 7.95%; TN: 30.06%; TP: 63.51%	
	Meat processing (REFINERY + KILL)	25 °C; 120 μE m^{-2} s^{-1}	COD: 2340 mg L^{-1}; TN: 251.0 mg L^{-1}; TP: 31.3 mg L^{-1}	COD: 43.91%; TN: 49.48%; TP: 54.45%	
Chlorella sp. L166	Soybean processing	25 °C; 6000 lx; 24:0 light: dark	pH: 6; COD: 5320 mg L^{-1}; TN: 106.99 mg L^{-1}; TP: 23.28 mg L^{-1}	COD: 78.20%; TN: 96.07%; TP: 95.55%	[96]
Chlorella sp. (SAG 242.80)	Rose oil processing effluent (Race way)	17–19.5 °C; 256–329 μE m^{-2} s^{-1}	COD: 2343 mg L^{-1}; NH_4-N: 10.67 mg L^{-1}; NO_3-N: 2.40 mg L^{-1}	COD: 61.76%; NH_4-N: 66.99%; NO_3-N: 17.22%	[110]
	Rose oil processing effluent (Tubular photobioreactor)	28.5–31.5 °C; 256–329 μE m^{-2} s^{-1}	COD: 2342 mg L^{-1}; NH_4-N: 13.25 mg L^{-1}; NO_3-N: 1.85 mg L^{-1}	COD: 53.03%; NH_4-N: 34.95%; NO_3-N: 8.63%	
Chlorella vulgaris	Industrial	25 °C; 2500 lx; 12:12 light: dark	TN: 11.5 mg L^{-1}; Cu: 8.50 mg L^{-1}; Cd: 1.31 mg L^{-1}; Ni: 0.16 mg L^{-1}; Fe: 3.51 mg L^{-1}; Pb: 2.48 mg L^{-1};	TN: 0.19 mg L^{-1}; Cu: 7.63 mg L^{-1}; Cd: 0.60 mg L^{-1}; Ni: 0.14 mg L^{-1}; Fe: 2.80 mg L^{-1}; Pb: 1.72 mg L^{-1}	[111]
	50% Textile	4000–5000 lx;	COD: 500–1200 mg L^{-1}	COD: 99.7%; NO_3-N: 95.7%; PO_4-P: 96.3%	[131]
Chlorella vulgaris (UTEX-265)	Brewery	25 °C; 100 μE m^{-2} s^{-1}; 150 rpm; airflow rate of 100.0 cc/min;	pH: 5.5–6.0; COD: 2000–3000 mg L^{-1}; TN: 30–45 mg L^{-1}; TP: 12–16 mg L^{-1}	TN: 87%; TP: 80%	[109]
	Brewery	25 °C; 100 μE m^{-2} s^{-1}	pH: 5.5–6.0; COD: 2000–3000 mg L^{-1}; TN: 30–45 mg L^{-1}; TP: 12–16 mg L^{-1}	More than 70% of the nutrients	
Chlorella vulgaris Wu-G22	Textile	30 °C; 4300 lx; pH 8.0	pH: 10.5; COD: 4458 mg L^{-1}; NH_4-N: 8.35 mg L^{-1}; TP: 22.3 mg L^{-1}	COD: 75%; NH_4-N: 90%	[100]
Chlorella zofingiensis	10% Dairy (pH regulation by CO_2)	6.2–20.8 °C; 310–1035 klx; 5–6% CO_2	TN: 11.8 mg L^{-1}; PO_4-P: 14.9 mg L^{-1};COD: 119.5 mg L^{-1}	TN: 79.6%; PO_4-P: 42.0%	[136]
	10% Dairy (pH regulation by acetic acid)	6.2–20.8 °C; 310–1035 klx; 5–6% CO_2	TN: 11.8 mg L^{-1}; PO_4-P: 14.9 mg L^{-1};COD: 119.5 mg L^{-1}	TN: 97.5%; PO_4-P: 51.7%	
	Dairy	25 °C; 200 μE m^{-2} s^{-1}; 5–6% CO_2	TN: 75.5 mg L^{-1}; TP: 48.0 mg L^{-1}; COD: 1428 mg L^{-1}	TN: 90.3%; TP: ~75%	[117]
	Dairy	25 °C; 200 μE m^{-2} s^{-1}; 5% CO_2	TN: 136.5 mg L^{-1}; TP: 85.0 mg L^{-1}; COD: 1858 mg L^{-1}	TN: 93.64%; TP: 98.45%; COD: 85.05%	[114]
	2.5% Palm oil mill effluent	Green stage: 28 °C; 3000 lx; 12:12 light: dark Red stage: 28 °C, 6000 lx continuous light	TN: 9.4 mg L^{-1}; TP: 1.45 mg L^{-1}; COD: 72.46 mg L^{-1}	TN: 49.3%, TP: 69.4%; COD: 28%	[98]

Table 11. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Coelastrella sp.	Dairy	Under sunlight	pH: 8.65; P: 8.0 mg L^{-1}; NH_4-N: 39.3 mg L^{-1}; NO_3-N: 64.1 mg L^{-1}; COD: 1970 mg L^{-1}; TOC: 722 mg L^{-1}	P: 66.75%; NH_4-N: 90.38%; NO_3-N: 90.24%; COD: 69.44%; TOC: 83.51%	[115]
Desmodesmus armatus	Cassava	Heterotrophic: in the dark for 14 days	pH: 5.70; COD: 1570.00 mg L^{-1}	COD: 74%	[103]
	Cassava	Mixotrophic: 4:20 light: dark for 14 days	pH: 5.70; COD: 1570.00 mg L^{-1}	COD: 92%	
Haematococcus pluvialis	7.5% Palm oil mill effluent	Green stage: 28 °C; 3000 lx; 12:12 light: dark Red stage: 28 °C; 6000 lx; 24:0 light: dark	TN: 28.2 mg L^{-1}; TP: 4.4 mg L^{-1}; COD: 217.40 mg L^{-1}	TN: 64.9%; TP: 86.7%; COD: 50.9%	[98]
Isochrysis galbana	Al-Ahdab oilfield produced water	2000 lx; 25 °C; 18:6 light: dark	COD: 1300 mg L^{-1}; NH_4-N: 31 mg L^{-1}	COD: 83%	[137]
Nannochloropsis oculata	Al-Ahdab oilfield produced water	25 °C; 2000 lx; 18:6 light: dark	COD: 1300 mg L^{-1}; NH_4-N: 31 mg L^{-1}	COD: 90%	[137]
Nannochloropsis sp.	Palm oil mill effluent	23 ± 10.5 °C; 100 µE m^{-2} s^{-1}	COD: 4196.67 mg L^{-1}	COD: 11.31 mg mg^{-1} d^{-1}	[121]
	10% Palm oil mill effluent	Immobilized microalgae on sodium alginate beads	COD: 3250 mg L^{-1}	COD: 71%	[130]
Nostoc commune	Industrial	25 °C; 2500 lx; 12:12 light: dark	TN: 11.5 mg L^{-1}; Cu: 8.50 mg L^{-1}; Cd: 1.31 mg L^{-1}; Ni: 0.16 mg L^{-1}; Fe: 3.51 mg L^{-1}; Pb: 2.48 mg L^{-1}	TN: 0.27 mg L^{-1}; Cu: 7.77 mg L^{-1}; Cd: 0.67 mg L^{-1}; Ni: 0.14 mg L^{-1}; Fe: 2.80 mg L^{-1}; Pb: 1.66 mg L^{-1}	[111]
Oscillatoria limosa	Industrial	25 °C; 2500 lx; 12:12 light: dark	TN: 11.5 mg L^{-1}; Cu: 8.50 mg L^{-1}; Cd: 1.31 mg L^{-1}; Ni: 0.16 mg L^{-1}; Fe: 3.51 mg L^{-1}; Pb: 2.48 mg L^{-1}	TN: 0.15 mg L^{-1}; Cu: 7.70 mg L^{-1}; Cd: 0.61 mg L^{-1}; Ni: 0.14 mg L^{-1}; Fe: 2.7 mg L^{-1}; TP: 1.68 mg L^{-1}	[111]
Scenedesmus dimorphus	Lactic acid	25 °C; 2500 lx; 14:10 light: dark	COD: 12 571 mg L^{-1}; TN: 651 mg L^{-1}; NH_3-N: 169 mg L^{-1}; TP: 28.2 mg L^{-1}	COD: 95.06%; TN: 96.31%; NH_3-N: 98.22; TP: 90.78%	[124]
Scenedesmus sp.	25% of ultra-filtrated anaerobic liquid digestate of olive mill	25 °C; 80.2 µE m^{-2} s^{-1}; 24:0 light: dark	TN: 96 mg L^{-1}	TN: 98%	[92]
	Industrial	nr	TN: 5.06 mg L^{-1}; TP: 39.4 mg L^{-1}; COD: 4395.6 mg L^{-1};	TN: 42%; TP: 67%; COD: 82%	[123]
Scenedesmus sp. and *chlorella* sp.	Palm oil mill effluent	25 °C; 14,000 lx; 24:0 light: dark	TN: 330 mg L^{-1}; PO_4-P: 273 mg L^{-1}; COD: 2900 mg L^{-1}; TOC: 1400 mg L^{-1}	TN: 86%; PO_4-P: 85%; COD: 48%; TOC: 77%	[122]

Table 11. *Cont.*

Algae Used	Wastewater Type	Conditions of Culture	Nutrient Concentration	Average Nutrient Removal Rate	References
Scendesmus sp. HXY5	Potato	25 °C; 60 μE m^{-2} s^{-1}; 12:12 light: dark;	TDN: 127.98 mg L^{-1}; TDP: 11.11 mg L^{-1}; COD: 1504 mg L^{-1};	TN: 59%; TP: 32%; COD: 93%	[126]
Spirulina NCU-Sm	Soy sauce	30 °C; 50 μE m^{-2} s^{-1}	NH_4-N: 168.44 mg L^{-1}; TN: 173.53 mg L^{-1}; COD: 3263.33 mg L^{-1}	NH_4-N: 93.86%; TN: 81.76%; COD: 84.08%	[120]

TOC (total organic carbon), COD (chemical oxygen demand), TDS (total dissolved solid), TSS (total suspended solid), TS (total solid), NO_3-N (nitrate-nitrogen), NO_2-N (nitrite-nitrogen), NH_4-N (ammonium-nitrogen), PO_4-P (orthophosphate phosphate), TN (total nitrogen), TP (total phosphate), Cl (chloride), Cu (copper), Fe (iron), Cd (cadmium), Ni (nickel), Pb (lead).

Table 12. Growth parameters and metabolites production of microalgae culture in industrial wastewater.

Algae Used	Wastewater Type	Growth Rate or Volumetric Productivity	Final Biomass Concentration	Production of Target Metabolites	References
Arthrospira platensis	Cassava	1.16 d^{-1}	14,410 cells mL^{-1}	Exopolysaccharides: 0.41 g L^{-1}	[101]
Arthrospira (Spirulina) platensis SAG 21.99	10% olive oil mill + 1 g L^{-1} $NaNO_3$ + 5 g L^{-1} $NaHCO_3$	4.4 g L^{-1} h^{-1}	1696 mg L^{-1}	Carbohydrates: 33.64%; Lipids: 16.91%; Proteins: 31.52%; Chlorophyll: 1.02%	[91]
Ascochloris sp. ADW007	Raw dairy	0.131 g L^{-1} d^{-1}	2.23 g L^{-1}	Lipids: 34.67%	[113]
	Raw dairy	0.102 g L^{-1} d^{-1}	1.73 g L^{-1}	Lipids: 24.99%	
	Raw dairy	0.207 g L^{-1} d^{-1}	1.44 g L^{-1}	Lipids: 34.98%	
Chlamydomonas sp. TRC-1	Textile	0.28 g L^{-1} d^{-1}	2.49 g L^{-1}	Lipids: 79.1%; Saturated fatty acid (SFA): 46.51%; Monounsaturated fatty acids (MUFAs): 20.7%; Polyunsaturated fatty acids (PUFAs): 11.3%;	[99]
Chlamydomonas polypyrenoideum	Dairy industry	nr	3.8 g	Lipids: 1.6 g L^{-1}	[118]
Chlamydomonas reinhardtii CC124	Olive mill	22.2 mg L^{-1} h^{-1}	nr	Carbohydrates: 32.6%; Proteins: 53.87%	[132]
Chlorella L166	10 times diluted Soybean	nr	nr	Lipids: 7.22 mg L^{-1} d^{-1}; Polysaccharides: 2.86 mg L^{-1} d^{-1}	[94]
Chlorella L38	10 times diluted Soybean	nr	nr	Lipids: 3.89 mg L^{-1} d^{-1}; Polysaccharides: 1.38 mg L^{-1} d^{-1}	
Chlorella pyrenoidosa	Dairy	nr	nr	nr	[133]
	90% Olive oil washing +10% urban	0.0203 h^{-1}	1.73 × 10^{-3} g L^{-1} h^{-1}	Lipids: 51.5%; Proteins: 43.7%	[17]
Chlorella pyrenoidosa (FACHB-9)	A mixed acidified and Secondary treated starch (1:1)	1.27 d^{-1}	3.3 g L^{-1}	Carbohydrates: 24.4%; Lipids: 18.7%; Proteins: 49.7%; Chlorophyll: 2.8%	[102]

Table 12. *Cont.*

Algae Used	Wastewater Type	Growth Rate or Volumetric Productivity	Final Biomass Concentration	Production of Target Metabolites	References
	Soybean processing	nr	0.64 g L^{-1} d^{-1}	Lipids: 37%	[95]
	Alcohol and anaerobically digested starch (1:15)	0.98 d^{-1}	2.76 g L^{-1}	Lipids: 19.68%	[104]
	Alcohol and anaerobically digested starch (0.053:1, v/v)	0.56 d^{-1}	3.01 g L^{-1}	Lipids: 127.71 mg L^{-1} d^{-1}	[105]
	Anaerobic digested starch	0.82 d^{-1}	1.29 g L^{-1}	Lipids: 43.37 mg L^{-1} d^{-1};	[127]
	Anaerobic digested starch	1.02 d^{-1}	0.37 g L^{-1} d^{-1}	Lipids: 7.32%;	[106]
	Soybean	0.058 d^{-1}	6.2 g L^{-1}	Lipids: 0.53 mg L^{-1} d^{-1}	[134]
Chlorella pyrenoidosa (No. FACHB-863)	Tobacco	nr	540.24 mg L^{-1}	Lipids: 268.60 mg L^{-1}	[8]
Chlorella sorokiniana (FACHB-275)	Frigon + reeling	0.36 d^{-1}	19.3 mg L^{-1}	Lipids: 26.2%; Proteins: 49.5%; Carbohydrates: 21.2%	[107]
	Frigon + distilled water	0.35 d^{-1}	17.7 mg L^{-1}	Lipids: 22.4%; Proteins: 47.3%; Carbohydrates: 20.2%	
	Cooking cocoon	0.33 d^{-1}	15.4 mg L^{-1}	Lipids: 22.1%; Proteins: 45.7%; Carbohydrates: 20.8%	
	Cooking cocoon	0.496 d^{-1}	3.43 mg L^{-1}	Lipids: 27.95%; Proteins: 53.25%; Carbohydrates: 14.25% Pigments: 2.66%	[135]
Chlorella sorokiniana (IPRChs7104)	Wastewater from the instant coffee	nr	0.88 g L^{-1}	nr	[125]
	Dairy products	nr	0.35 g L^{-1}	nr	
	Cassava flour/starch	nr	1.23 g L^{-1}	nr	
Chlorella sp.	Aerated Seafood	0.156 d^{-1}	77.7 mg L^{-1} d^{-1}	Lipids: 20.4 mg L^{-1} d^{-1}	[108]
	Meat processing	nr	1.538 g L^{-1}	Lipids: 17.54%; Proteins: 68.65%	[128]
	Meat processing	nr	0.675 v	Lipids: 14.50%; Proteins: 60.87%	
	Meat processing	nr	1.388 g L^{-1}	Lipids: 18.89%; Proteins: 61.20%	
	Meat processing	nr	1.400 g L^{-1}	Lipids: 20.57%; Proteins: 64.76%	
	Brewery	nr	1.22 g L^{-1}	Lipids:10%	[109]
	Brewery	nr	2.74 g L^{-1}	Lipids: 50.23 mg L^{-1} d^{-1}	
	Dairy	0.193 d^{-1}	1.37 g L^{-1}	FAMEs: 87.09 mg L^{-1}	[138]
Chlorella vulgaris	Dairy	0.261 d^{-1}	0.26 g L^{-1}	FAMEs: 27.18 mg L^{-1}	[138]
	50% Textile	nr	1.62 OD_{680}	FAMEs: 11.07 mg g^{-1}	[131]
Chlorella vulgaris (UTEX-265)	Brewery	nr	1.5 g L^{-1}	Lipids: 18%	[109]

Table 12. *Cont.*

Algae Used	Wastewater Type	Growth Rate or Volumetric Productivity	Final Biomass Concentration	Production of Target Metabolites	References
	Brewery	nr	3.2 g L^{-1}	Lipids: 108.0 g L^{-1} d	
Chlorella zofingiensis	10% Dairy (pH regulation by CO_2)	nr	10.9 × 10^6 cells mL^{-1}	Lipids: 17.9%	[136]
	10% Dairy (pH regulation by acetic acid)	nr	9.05 × 10^6 cells mL^{-1}	Lipids: 31.8%	
	Dairy	nr	3.8 g L^{-1}	Lipids: 27.7%	[117]
	Dairy	nr	1.58–1.69 g L^{-1}	Lipids: 11.5–15.8%	[114]
	2.5% Palm oil mill effluent	0.2 d^{-1}	0.48 g L^{-1}	Astaxanthin: 2.71 mg L^{-1}	[98]
Coelastrella sp.	Dairy	nr	4.61 g L^{-1} d^{-1}	nr	[115]
Desmodesmus armatus	Cassava	0.14 d^{-1}	52.14 mg L^{-1} d^{-1}	Lipids: 20.86%	[103]
	Cassava	0.15 d^{-1}	70.83 mg L^{-1} d^{-1}	Lipids: 21.91%	
Haematococcus pluvialis	7.5% Palm oil mill effluent	0.21 d^{-1}	0.52 g L^{-1}	Astaxanthin: 22.43 mg L^{-1}	[98]
Isochrysis galbana	Al-Ahdab oilfield produced water	0.169 d^{-1}	0.899 g L^{-1}	Oil content: 82%	[137]
Nannochloropsis oceanica	Pesticides industry	27.78 mg/L d^{-1}	nr	Lipids: 24.49%	[32]
	Pharmaceutical industry	5.59 mg L^{-1} d^{-1}	nr	Lipids: 25.22%	[32]
	Petroleum industry	24.78 mg L^{-1} d^{-1}	nr	Lipids: 27.40%	[32]
Nannochloropsis oculata	Al-Ahdab oilfield produced water	0.179 d^{-1}	1.0166 g L^{-1}	Oil content: 89%	[137]
Nannochloropsis sp.	Palm oil mill effluent	0.39 d^{-1}	7.93 × 10^7 cells/mL	Lipids: 61.60%, PUFAs: 59.13%	[121]
	10% Palm oil mill effluent	nr	1.27 g L^{-1}	nr	[130]
Scenedesmus dimorphus	Lactic acid	nr	5.32 g L^{-1}	Lipids: 28.61%	[124]
Scenedesmus sp.	25% of ultra-filtrated anaerobic liquid digestate of olive mill	0.5 d^{-1}	0.15 g L^{-1} d^{-1}	nr	[92]
	Industrial	0.15 d^{-1}	0.69 g L^{-1}	nr	[123]
Scenedesmus sp. and *chlorella* sp.	Palm oil mill effluent	stage 1: 0.1273 d^{-1} stage 2: 0.5858 d^{-1}	stage 1: 0.0204 g L^{-1} d^{-1} stage 2: 0.4403 g L^{-1} d^{-1}	Stage 1: Lipids: 17.19%; Carbohydrates: 2.06%; Proteins: 48.6% Stage 2: Lipids: 19.29%; Carbohydrates: 10.58%; Proteins: 57.36%	[122]
Scendesmus sp.HXY5	Potato	1.64 mg L^{-1} d^{-1}	2.64 g L^{-1}	Total pigment yield: 18.45 mg L^{-1}; Lutein yield: 11.46 mg L^{-1}	[126]
Spirulina NCU-Sm	Soy sauce	nr	1.984 g L^{-1}	nr	[120]

nr (not reported).

3. Microalgal Mechanisms for Wastewater Bioremediation

As shown in Tables 1, 5 and 10, which summarize the wastewater composition utilized in the literature in the field of microalgae wastewater treatment, domestic, agricultural and industrial wastewaters contain carbon and various nitrogen sources such as nitrate, nitrite and ammonium, as well as phosphate from both inorganic and organic sources and heavy metals [139]. Microalgae can biodegrade these contaminants through a variety of methods, including absorption, fixation, bioabsorption and precipitation [5]. Microalgal–bacterial consortia have also been shown to improve the efficiency of wastewater treatment procedures [140,141]. Figure 7 illustrates the numerous microalgal techniques for biodegrading pollutants present in wastewater with the support of bacteria.

3.1. CO_2 Fixation

The carbon concentrating mechanism (CCM) and photosynthetic carbon metabolic pathways are the mechanisms that microalgae utilize for CO_2 fixation when they are grown in wastewater [142]. Microalgae may absorb photons from the sun and use CO_2 or HCO_3^- dissolved in wastewater as a carbon source for photosynthesis, CO_2 can enter the cell through diffusion, and HCO_3^- enters the cell through active transport [5,142]. Furthermore, they use heterotrophic or mixotrophic modes to absorb inorganic and organic carbon from wastewater for metabolic control and the production of biomolecules such as carbohydrates and lipids [5,143,144]. The biological reaction of carbon fixation and biomolecule production is shown in Equations (1) and (2) [5].

$$HCO_3^- + H^+ \leftarrow (Carbonic\ anhydrase\ 1) \rightarrow CO_2 + H_2O - (Light\ energy) \rightarrow Rubisco \rightarrow Glyceraldehyde\ 3\ phosphate \rightarrow Carbohydrates \quad (1)$$

$$Glucose - (Glycolysis) \rightarrow Pyruvate \rightarrow Acetyl\ CoA \rightarrow Malonyl\ CoA \rightarrow FFAs\ (free\ fatty\ acids) \rightarrow TAGs \quad (2)$$

where Equation (1): CO_2 fixation and carbohydrate generation; Equation (2): glucose utilization to pyruvate, acetyl-CoA, and fatty acid synthesis.

3.2. Nitrogen Sources Assimilation

Ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and nitrite nitrogen (NO_2-N) enter microalgal cells via active transport [142]. Ammonium nitrogen (NH_4-N) is a key component in microalgae growth [145]. For this reason, before being assimilated, nitrate and nitrite are converted to ammonium by enzymes nitrate reductase and nitrite reductase [142] as demonstrated by the equations below (3)–(5):

$$NO_3^- - (Nitrate\ reductase) \rightarrow NO_2^- - (Nitrite\ reductase) \rightarrow NH_4^+ \quad (3)$$

$$NH_4^+ + Glutamate - (Glutamine\ synthase) \rightarrow L - Glutamine \quad (4)$$

$$L - Glutamine \rightarrow Amino\ acids \rightarrow Proteins \quad (5)$$

Here, Equation (3): ammonium-based nitrate and nitrite reduction; Equation (4): reaction of glutamine synthesis; Equation (5): proteins formation.

3.3. Phosphate Source Assimilation

Phosphorus restriction in a culture medium is an efficient technique to enhance microalgal metabolism since phosphorus is required for metabolic activities [144,146,147]. It is essential for energy transmission and nucleic acid synthesis [142]. Depending on the source of wastewater, phosphorus is present in the form of polyphosphate and orthophosphate [5]. These forms penetrate microalgal cells by active transport [142] and are consumed as $H_2PO_4^-$ and HPO_4^{2-} [139] PO_4^{3-} are removed directly by incorporating them into organic substances (e.g., phospholipids) via the phosphorylation process [142].

$$Polyphosphate \rightarrow \frac{H_2PO_4^-}{HPO_4^{2-}} - (Phosphorylation) \rightarrow ATP + Nucleic\ acid + phospholipids \quad (6)$$

Here, Equation (6): *ATP*, nucleic acid and phospholipids formation.

Furthermore, environmental conditions including the pH level, temperature and dissolved oxygen may influence P nutrient removal [142]. Phosphorus precipitation, for example, can be observed at a pH of 8.5 in the presence of carbonate and magnesium ions in wastewater as calcium or magnesium phosphates [5].

3.4. Heavy Metals Biodegradation

Heavy metals present in wastewater have a number of harmful consequences on the environment and people's health, some of which can cause cancer [148]. Microalgae have demonstrated their capabilities despite the fact that heavy metals are more difficult to remove by physicochemical procedures than other wastewater elements [149]. This is due to the strong affinity interaction that exists between the microalgal cell wall and heavy metals [150]. There are five primary methods through which microalgae eliminate heavy metals from wastewater: intracellular bioaccumulation, ionic and covalent bond formation, exchange of cation and the complexes and chelates formation [139,148,149,151]. In addition, once inside the microalgae, heavy metals are biotransformed and compartmentalized in cell organelles [139,148,149,151]. These different mechanisms are illustrated in Figure 8.

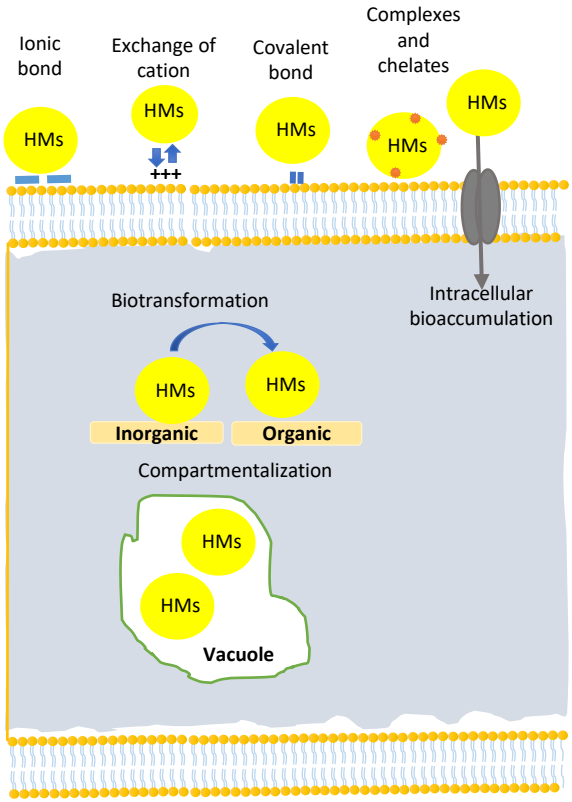


Figure 8. Heavy metals (HMs) mechanisms of bioremediation by microalgae.

4. Economic Analysis of Microalgae Wastewater Treatment Technologies

4.1. Microalgae-Based Wastewater Treatment Technologies

Conventional wastewater treatment procedures consist of four main steps: preliminary, primary, secondary and tertiary treatments when physical, chemical and biological processes are used as the traditional methods [152]. Ion exchange, membrane filtration, coagulation or flocculation, bacteria-based remediation techniques and adsorption are only a few of the widely utilized techniques in traditional wastewater treatment (Figure 9).

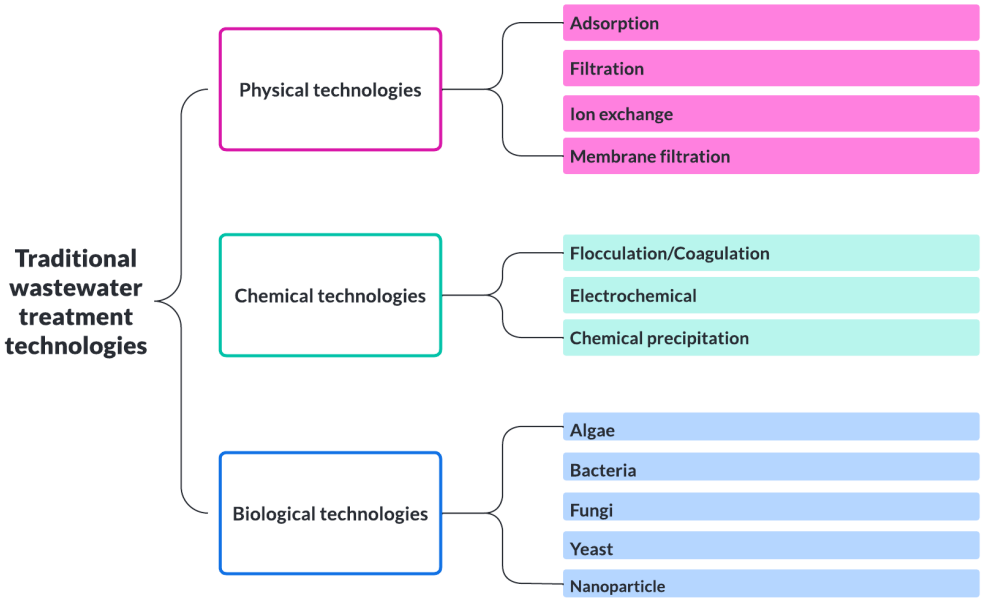


Figure 9. Traditional wastewater treatment technologies.

Our literature review demonstrates that microalgae monoculture systems have shown to be beneficial as an innovative wastewater treatment technology. Recently, microalgae have been co-cultured with other microorganisms such as bacteria, fungi and yeast to enhance pollutant removal efficiencies and reduce the cost of the treatment process [153–158].

Microalgae-bacteria co-culture system was used by Liu et al. [155] to optimize ammonia nitrogen removal from actual rare earth element tailings (REEs) wastewater, using *Chlorococcum robustum* as microalga species. Liu et al. [155] found that this strategy of treatment achieved a 97.46% removal of ammonia nitrogen at a ratio of 1:3 of microalgae-bacteria consoritium. Walls et al. [158] used *Scenedesmus* sp. with a native wastewater yeast to treat municipal wastewater and achieved a 96% removal of nitrate and a 100% removal of total ammonia with a 93% removal of orthophosphate [158]. A filamentous fungi (*Aspergillus oryzae*) was cultured with *Chlorella pyrenoidosa* to valorize starch wastewater into high-value biomass [157]. Wang et al. [157] reported that this technology increased the removal efficiencies of major pollutants, with the chemical oxygen demand, total nitrogen, and total phosphate removal efficiencies reaching 92.08, 83.56 and 96.58%, respectively. Ray et al. [159] summarized these technologies and reported that microalgae such as *Chlorella vulgaris*, *Chlorella variabilis*, *Scenedesmus obliquus* and *Scenedesmus capricornutum* were co-cultured with Fungi species, among them *Mucor circinelloides* UMN-B34, *Ganoderma lucidum*, *Aspergillus* sp., *Aspergillus niger*, *Pleurotus geesteranus* and *Pleurotus ostreatu* to remove nutrients and cadmium by forming biopellets as well as harvesting a microalgal biomass. Furthermore, they indicated that *Chlorella sorokiniana*, *Chlorella vulgaris*, *Scenedesmus obliquus*, *Selenastrum capricornutum* and *Spirulina platensis* were used in microalgae-bacteria consortium with *Proteobacteria*, *Pseudomonas* sp., *Acinetobacter* sp., *Rhodococcus* sp., *Mycobacterium* sp., *Burkholderia cepacia*, *Alcaligenes* sp. and *Azospirillum brasiliense* for organic chemical pollutants and heavy metal removals from wastewater and greenhouse gas mitigation [159]. *Chlorella vulgaris* was cocultured with *Yarrowia lipolytica* for ammonia nitrogen and sulfate removals, but with *Saccharomyces cerevisiae for* in situ CO_2 mitigation along with a reduction in the aeration costs of microalgae-yeast technology [159].

In addition to bacteria, fungi and yeast, nanoparticles such as iron oxide and ZnO were also used as a consortium with microalgae to remove pollutants from wastewater [160,161]. Vasistha et al. [160] used an integrated approach microalgae-ZnO nanoparticle association to improve the nutrient removal from sewage wastewater and biodiesel production, and demonstrated that the microalga *Chlorosarcinopsis* sp. MAS04-ZnO consortium achieved

the maximum biomass of 3.43 g L^{-1} in primary treated wastewater with a 1.9-fold increase in cellular lipid compared to the BG11 medium.

4.2. Economic Assessment of Microalgae-Based Wastewater Treatment

The feasibility of wastewater treatment by microalgae toward a biorefinery system is influenced by a number of variables, including upstream and downstream processing, environmental effects and commercial analysis [5]. Assessment of the economic analysis can be examined by LCA and TEA, which are life cycle assessments and techno economic assessments, respectively [162]. Generally, LCA uses "cradle-to-grave" system boundaries that take into account every step of the treatment process to quantify the mass and energy exchanges between the treatment system and the overall environment. However, the TEA is often fixed to the treatment stage using "cradle-to-gate" system limitations, eliminating the waste treatment [163]. The five phases of TEA are generally the process design, mass and energy balance, cost projections, profitability and sensitivity analysis [163]. Therefore, a complete schematic design of the entire treatment process is essential to properly estimate the cost of the microalgae-based wastewater treatment process in a biorefinery system. The design process is the mean problem that limit both LCA and TEA analysis, thus, it is clear that there is huge research gap from lab-scale to pilot or large-scale, which limits the implementation of microalgae-based wastewater treatments in a biorefinery system.

According to earlier research, regular open ponds or even sophisticated high-rate algal ponds (HRAP) are the most effective approach for growing microalgae in wastewater [164]. The environmental effect of HRAP systems for wastewater treatment has been evaluated through research using the life cycle assessment approach. They showed that, when compared to traditional systems (such as activated sludge systems), HRAPs might potentially aid to minimize environmental impacts and costs linked with wastewater treatment [165–168]. Kohlheb et al. [168] evaluated the sustainability of HRAP systems for municipal wastewater treatments by microalgae compared to sewage sludge systems. According to their findings, modern HRAP technology is more energy-efficient than an activated sludge-based sequencing batch reactor, requiring just 22% of their electricity demand [168]. Furthermore, HRAP is more cost-effective (0.18 € m^{-3}) compared to activated sludge (0.26 € m^{-3}) and more ecologically friendly, with reduced global warming ($146.27.10^3$ kg CO_2 equivalent m^{-3}) and eutrophication potentials (126.14 vs. $158.01.10^6$ kg PO_4 equivalent m^{-3}), but the net environmental benefit of an activated sludge-based sequencing batch reactor was slightly larger than HRAPs because of the removal rate of nutrients [168].

Recently, Nasir et al. [169] compared co-pyrolyzing sewage sludge and wastewater-grown microalgae for biofuel production using LCA, global warming, energy recovery, and economic analysis in five scenarios while varying the mixture of sewage sludge and microalgae. They found that the 1:1 mixture produced the largest net profit (9% higher than sewage sludge). However, the environmental effect of the 1:1, 1:2 and 2:1 scenarios was lower than that of sewage sludge alone. For energy consumption, due to the high moisture content of the feedstock, they revealed that drying was the most energy-intensive operation, accounting for 69–88% of total used energy [169]. In another study, Arashiro [170] investigated the possible ecological effects of microalgae systems for wastewater treatment and bioproduct extraction. In this regard, a life cycle evaluation of two systems treating urban wastewater and food-processing wastewater with the recovery of bioproducts and bioenergy was performed. Furthermore, both solutions were compared to an existing method employing a typical growth medium for microalgae cultivation, in order to demonstrate the potential benefits of using wastewater against traditional cultivation methodologies [170]. They proved that the organization that treated food-processing wastewater with unialgal culture had lesser environmental consequences than the system that treated urban wastewater with mixed cultures [170]. When compared to a traditional system employing a standard growing medium, bioproduct recovery from

microalgae wastewater treatment systems can minimize environmental impacts by up to five times [170].

Life cycle and technoeconomic analysis are being explored and provide a significant challenge for researchers, particularly for economic evaluation, with the goal of establishing an industrial-scale system for wastewater treatment by microalgae.

5. Challenges and Prospects

Domestic, agricultural and industrial wastewaters have recently received increased attention from microalgae researchers in order to assess the capability of microalgae to reduce contaminants found in these various forms of wastewater, and furthermore, project a microalgal biorefinery system. Microalgae have demonstrated their ability to remove these pollutants, but this ability can be increased if the difficulties encountered during culture are resolved. Figure 10 depicts a number of challenges (economic and biological) associated with the microalgae-based wastewater treatment process as well as ideas in order to deal with these issues.

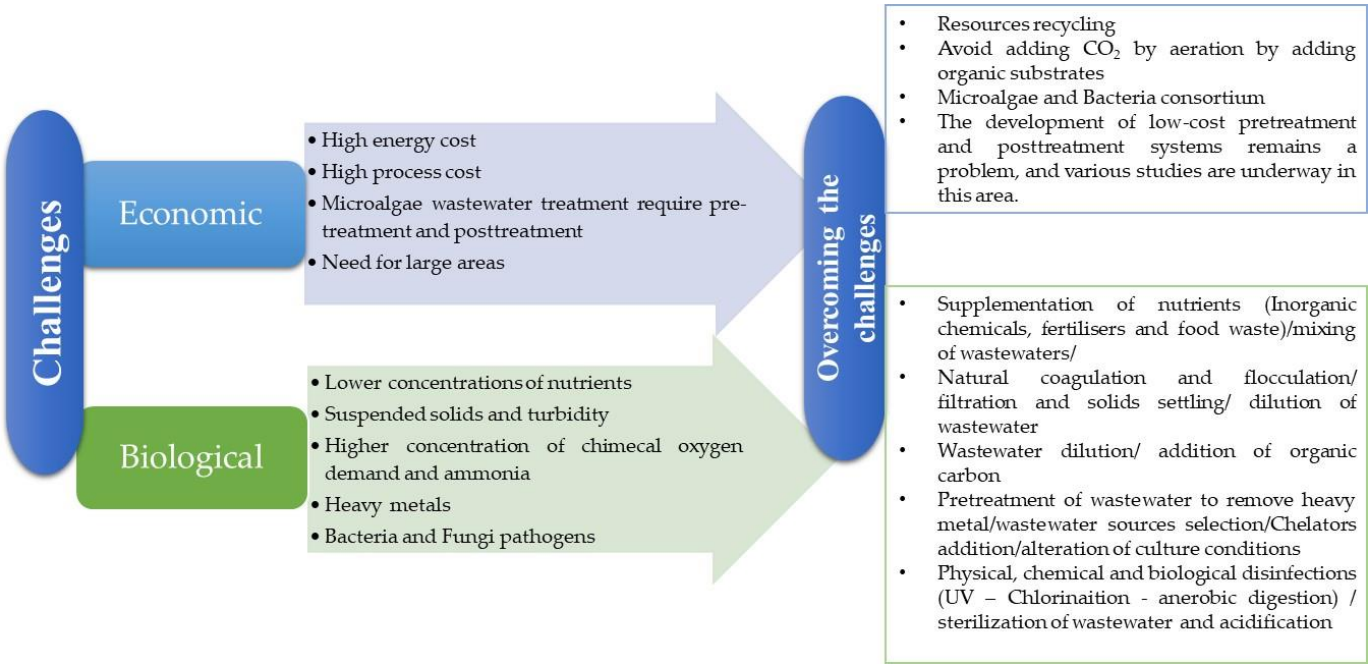


Figure 10. Limitations in growing microalgae in wastewater and possible solutions.

Microalgae cell growth can be limited by low nutrient in wastewater, however this is one of the biological obstacles that can be solved by combining different wastewaters, adding inorganic compounds, fertilizers, and food waste [41,74,91,105]. Using agricultural waste (poultry litter) mixed with municipal wastewater to cultivate *Acutodesmus obliquus* result in a biomass 74.67% higher than using agricultural waste as culture medium [41]. The effect of alcohol wastewater as an anaerobic digested starch wastewater supplement on the removal of pollutant load by the microalgae *Chlorella pyrenoidosa* has been evaluated [105]. The strain was grown in various concentrations of anaerobic digested starch wastewater (ADS) and alcohol wastewater (A), but the proportion 1/0.053 of ADS/A wastewaters generated the highest results in terms of biomass (3.01 g/L), lipid production (127.70 mg/L/d), and pollutants removals (75.78%, 91.64 % and 90.74% of COD, TN and TP respectively) [105]. In contrast, researchers employed the dilutions approach to maximize the development of the microalgae in wastewater that had a high concentration of chemical oxygen demand and organic carbon addition to alleviate ammonia toxicity [162,171,172]. As reported, large amounts of ammonia can be toxic to cells by inhibiting development, photosynthesis and chlorophyll production, also destroying pH and C/N balances [145,171,173]. Temperature and pH both affect the presence of NH_3-N, which predominates when pH is greater than

9.25 [145]. Two processes through which ammonia is toxic to the growth of microalgae can be observed: free NH_3 diffusion in addition to NH_4^+ production in thylakoid under acidic conditions (reduces ATP to ADP conversion) and the promotion of NH_3 ligation (harms the oxygen-evolution complex subunit) [145]. Additionally, in microalgae culture system with a temperature between 20 and 25 °C and a pH of 9.5, the photosynthesis is reduced up to 90% only because of 2 to 3 µM of NH_3, hence the need to minimize ammonia toxicity [174]. Several different strategies exist to reduce toxicity of ammonia, including dilution, chemical stripping and addition of organic carbon [171]. Indeed, using glucose as carbon source for three species of microalgae (*Chlorella sorokiniana*, *Coelastrum* sp., and *Desmodesmus communis*) was found to minimize toxicity in all species at ammonia concentrations ranging from 50 to 1000 mg/L [171].

Others biological obstacles, such as high content of suspended solids, turbidity, heavy metals and bacteria can be overcome using appropriate pre-treatment methods for each obstacle. The previous Tables 2, 6 and 9 describe a few pretreatment techniques that were employed in the literature prior to the cultivation of microalgae but most of them are not possible at large scale. One of the challenges could thus be to develop industrializable pre-treatments processes.

In the field of microalgae growth in wastewater for biomass generation and nutrient removal, the development and design of low-cost microalgae culturing systems is now a critical topic [175]. Closed photobioreactors often cost a lot of money and have a difficult design. The capital costs of a flat-panel photobioreactor, a tubular photobioreactor, and a bubble-column photobioreactor were reported to be 42.2, 26.2, and 15.5 \$ m^{-2}, respectively [175]. Ahmed et al. reported that the culture stage used the majority of the operational resources and photobioreactors (PBR) and require around ten times as much energy when utilizing pumping and/or aeration [150]. The conventional method for growing photoautotrophic microalgae uses CO_2 as carbon source. However, procedures for purifying, storing, and distributing CO_2 raise the cost of producing microalgae. Cultivation using carbon dioxide in dissolved form or using bacteria to produce CO_2 were proposed as promising solution to overcome this challenge [7,175]. Bicarbonate could be used in the culture medium, that could result in productivity up to 50% greater than that of CO_2 while decreasing the cost of culture by 55% [175]. The resources recycling approach is also a strategy to reduce the cost of cultivation system [176].

In addition, another barrier to large-scale wastewater microalgae-based treatment is the downstream processing of microalgae. Numerous studies are now being conducted to develop highly effective inexpensive harvesting approaches [4,157,177,178]. Ref. [4] harvested *Chlorella* sp. biomass using *Aspergillus* sp., a filamentous fungal in molasses wastewater, to simplify the harvesting technique and minimize the process's production cost [4]. Coagulation (aluminum sulphate, ferricchloride, Tanfloc SG and Zetag 8185 coagulants) followed by dissolved air flotation (DAF) have shown high efficiency but the significant residual content of iron and aluminum in the final effluent necessitates prudence when using metal salts [177].

Although wastewater-grown microalgae have a significant potential, there have only been a few investigations of the value of biomass. Therefore, future studies should concentrate on finding the best wastewater sources, optimizing growing conditions, accumulation of product, and concomitantly extracting product and converting biomass. In order to provide suitable circumstances for microalgae development, it is also necessary to develop effective and affordable pretreatment techniques as well as integrated reactor systems.

6. Conclusions

In this review, it has been demonstrated in Section 2 that several species of microalgae, including *Chlorella pyrenoidosa*, *Chlorella sorokiniana*, *Chlorella vulgaris*, *Chlorella zofingiensis*, *Nannochloropsis* and *Scenedesmus*, can be used to remove pollutants from wastewater in a microalgal biorefinery system because of their capacity to accumulate high added value substances like lipids, carbohydrates, and carotenoids (astaxanthin and lutein). However,

the cultivation of microalgae in wastewater requires efficient and less expensive pretreatment and downstream processes to be able to use the biomass produced as well as the treated wastewater (Sections 2.1.2, 2.2.2 and 2.3.2). Indeed, this problem constitutes a major challenge on which scientists are working, in addition to the search for adequate sources of wastewater as well as technical and economic studies (Section 4).

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