

## REVIEW ARTICLE

## Integrating algal consortia into domestic wastewater biorefineries: Mechanisms, efficiency, and circular economy perspectives

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**Abstract**

Urbanization is occurring on a large scale at an unprecedented pace. In this context, algal consortia represent a sustainable and environmentally friendly solution for domestic wastewater remediation. This review focuses on mixed algal consortia as a treatment approach for domestic wastewater containing organic and inorganic pollutants, including nitrogen, phosphorus, heavy metals, and other chemicals. These consortia demonstrate enhanced pollutant removal efficiencies through synergistic biosorption, bioaccumulation, and biodegradation mediated by multiple algal species. Indeed, algal biomass can be valorized in biorefineries to produce a range of resources, including biofuels, biopolymers, and organic phyco-fertilizers, thereby advancing the circular bioeconomy. Overall, this review positions algal consortia as a potentially low-cost platform that integrates wastewater remediation with bioresource recovery, promoting the transformation of urban ecosystems toward a greener, more resilient future.

**Keywords:** Algal consortia; Phycoremediation; Domestic wastewater; Biorefinery; Circular bioeconomy; Biosorption; Bioaccumulation; Sustainable wastewater treatment

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**1. Introduction**

Algal consortia are complex living communities in which multiple algal species coexist and interact to enhance efficiency across processes, including wastewater treatment, biomass processing, bioenergy production, farming, and medical biotechnology.<sup>1</sup> Algae are adaptable photoautotrophic organisms that grow rapidly, sequester carbon dioxide, take up nutrients, and release valuable bioactive compounds, making them significant ecological resources for sustainability and environmental management.<sup>2,3</sup> Compared to monocultures, algal consortia exhibit improved nutrient removal potential, stability, and environment-responsive characteristics.<sup>4</sup> Phycoremediation uses micro- or macroalgae to remove or transform pollutants, such as toxic chemicals, from wastewater.<sup>5</sup> Heavy organic loads in municipalities generate nutrient-rich wastewater that is discharged into water bodies either untreated or only partially treated. Furthermore, the microalgal consortium used to treat wastewater is advantageous because it sequesters carbon and removes nutrients while generating high biomass.<sup>6</sup> Microalgal consortia can be applied to municipal wastewater and industrial effluents, and to certain waste-derived streams (e.g., leachates), under aerobic or anaerobic process configurations. Numerous studies

have examined the feasibility of using microalgae for wastewater treatment, including their use for nitrogen and phosphorus removal from effluents, commonly recognized as a driver of eutrophication when discharged into aquatic ecosystems.<sup>7</sup> Common wastewater treatment techniques are energy-intensive and not cost-effective in developing countries.<sup>8</sup> This review aims to shed light on the role of algal consortia in domestic wastewater remediation, the mechanisms of pollutant removal, and their potential integration into a circular bioeconomy framework. Furthermore, the paper offers suggestions for future research on the challenges that limit the deployment of algal consortia systems at scale and provides recommendations on their efficacy and sustainability.

## 2. Composition of domestic wastewater and algal systems for wastewater treatment

Domestic wastewater refers to household and residential wastewater (i.e., wastewater generated from toilets, kitchens, bathrooms, and floor drains in houses and similar residential buildings). Because domestic wastewater contains varying concentrations of carbon, nitrogen, and phosphorus, its organic and nutrient loads can be substantial. Several studies have explored the capacity and advantages of microalgal growth for treating wastewater from various sources and have reported on its potential and benefits.<sup>9</sup> Microalgal cultivation on sewage wastewater can enhance the removal efficiencies of nitrogen, carbon, and phosphorus, as well as pollutants, with lower environmental impacts (Figure 1). Globally, microalgal cultivation is being promoted as a sustainable alternative nutrient source, as the long-term application of chemical

fertilizers is increasingly recognized as unsustainable and a contributor to land pollution.<sup>10</sup> Wastewater characterization typically includes measurements of physicochemical and biological parameters, including biochemical oxygen demand, chemical oxygen demand, dissolved oxygen, total solids, total suspended solids, total dissolved solids, total ammonium, total nitrate, soluble phosphorus, total phosphorus, total iron, total chlorine, total magnesium, total calcium, surface-active agents, electrical conductivity, pH, turbidity, total coliform, and heavy metals (Table 1). With regard to chemicals, sewage and domestic wastewater contain inorganic (30%) and organic (70%) substances, as well as various gases.<sup>11</sup> Organic compounds consist mainly of proteins, carbohydrates, and lipids that are indicators of human dietary habits. Inorganic materials include acids, bases, chlorides, trace elements, and toxic compounds. Various biotic and abiotic constituents and pollutants are present in home wastewater, including biodegradable organic materials and other organic matter.<sup>12</sup> Algal coexistence within consortia can generate both cooperative and competitive interactions<sup>13</sup>; metabolite exchange and other cross-feeding processes can increase biomass productivity and pollutant removal efficiency, improving system stability.<sup>14</sup> The effectiveness of algal consortia has been demonstrated across multiple wastewater types, and these systems may be more adaptable to changing environmental conditions (Table 2).

## 3. Mechanisms of domestic wastewater remediation by algal consortia

Understanding the mechanisms of nutrient removal by microalgae is essential for designing effective wastewater

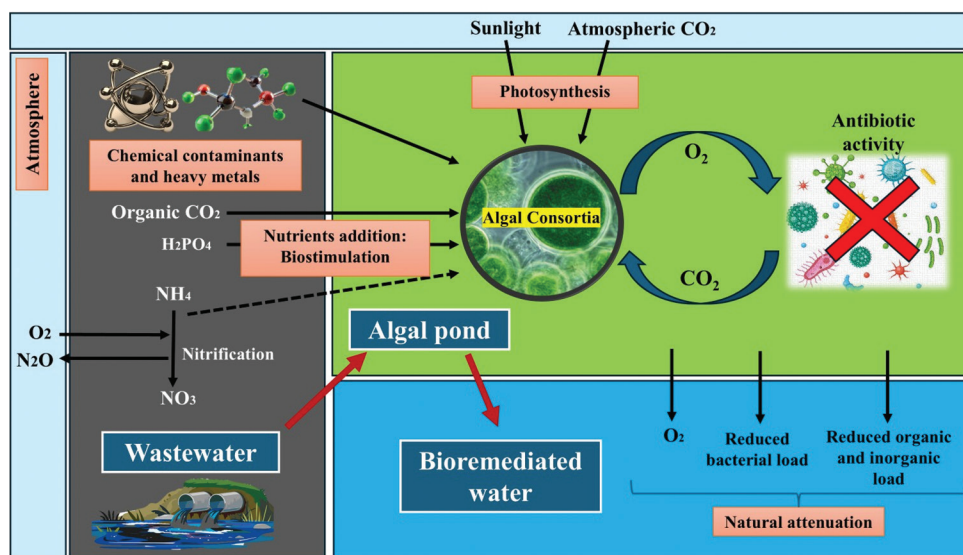


Figure 1. The schematic presentation of algal consortia being used as a bioremediation agent. Image created by the authors.

**Table 1. Physico-chemical characteristics of domestic wastewater and their permissible standard limits**

Physico-chemical and biological analysis parameters	Unit	Permissible standard limits	References
pH	-	6.0–9.0	4,8,15
Nitrate	mg/L	89.0–99.2	
Biochemical oxygen demand	mg/O <sub>2</sub> /L	90.0–99.0	
Chemical oxygen demand	mg/O <sub>2</sub> /L	85.0–99.8	
Total solids	gSS/M <sup>3</sup>	83.0–97.0	
Total Kjeldahl nitrogen	gN/m <sup>3</sup>	85.0–97.0	
Total carbon	gC/m <sup>3</sup>	93.2–99.0	
Total phosphate	gP/m <sup>3</sup>	86.0–98.0	
Phosphate	mg/L	85.0–98.0	

treatment systems. Suspended-cell cultivation-based systems have been predominantly used to treat domestic wastewater.<sup>17</sup> In immobilized-cell systems, microalgal cells are entrapped within a polymeric matrix, and substrates diffuse into and out of the matrix through its pores.<sup>18</sup> Integration of these systems with biopolymers has been reported to improve biomass yield, photosynthetic pigment production, and lipid accumulation. Organic substances present in wastewater during phycoremediation are converted into algal biomass through metabolic pathways that degrade carbohydrates, proteins, lipids, and other bioactive components (Table 3).<sup>10</sup> Microalgae use various remediation pathways, which can be classified into three main types: Biosorption, bioaccumulation, and biodegradation (Figures 2 and 3).<sup>19</sup>

**Table 2. Reports of microalgal consortia and their effective removal efficiencies in organic wastewater**

Sl. No	Algal consortia	Source	Wastewater parameter	Days	Efficiency (%)	References
1.	<i>Chlorella sorokiniana</i> , <i>Chlorella vulgaris</i> , <i>Scenedesmus obliquus</i>	Meat processing wastewater	COD TN TP (PO <sub>4</sub> <sup>3-</sup> )	7 days	91 67 69	4
2.	<i>Chlorella saccharophila</i> , <i>Chlamydomonas pseudococcus</i> , <i>Scenedesmus</i> spp., <i>Neochloris oleoabundans</i>	Dairy wastewater	OD COD TSS TDS TKN Nitrogen (NH <sub>4</sub> <sup>+</sup> ) Nitrogen (NO <sub>3</sub> <sup>-</sup> ) Phosphorus (PO <sub>4</sub> <sup>3-</sup> )	7 days	82.60 88.90 88.25 77.23 98.33 99.61 96.97 93.02	4
3.	<i>Chlorella vulgaris</i> , <i>Chlorella protothecoides</i>	Municipal Wastewater	TN TP TOC COD Orthophosphate	7 days	35.4 74.4 22.2 60.0 87.0	4
4.	<i>Chlorella</i> spp., <i>Scenedesmus</i> spp., <i>Sphaerocystis</i> spp., <i>Arthrospira</i> spp.	Domestic wastewater	Phosphorus (PO <sub>4</sub> <sup>3-</sup> ) Nitrogen (NH <sub>4</sub> <sup>+</sup> )	7 days	53–100 39	4
5.	<i>Phormidium</i> spp., <i>Chlorella pyrenoidosa</i>	Municipal wastewater	COD TAN TP Nitrogen (NO <sub>3</sub> <sup>-</sup> )	7 days	53±2 81±3 75±2 87±5	4
6.	<i>Nostoc muscorum</i> , <i>Anabaena subcylindrica</i>	Sewage wastewater	Phosphorus (PO <sub>4</sub> <sup>3-</sup> ) Nitrogen (NO <sub>3</sub> <sup>-</sup> ) Nitrogen (NH <sub>4</sub> <sup>+</sup> )	8 days	20.8–95 19.6–80 20.9–96	8
7.	<i>Chlorella</i> spp., <i>Merismopedia</i> spp., <i>Closteriopsis</i> spp., <i>Scenedesmus</i> spp.	Municipal wastewater	TP Nitrogen (NH <sub>4</sub> <sup>+</sup> ) Nitrogen (NO <sub>3</sub> <sup>-</sup> ) COD	-	98.28 88.23 86.55 82.45	4
8.	<i>Oscillatoria pseudogeminata</i> , <i>O. proteus</i> , <i>O. trichoides</i> , and <i>Lyngbya ceylanica</i>	Dairy wastewater	pH	-	-	16

(Cont'd...)

**Table 2. (Continued)**

Sl. No	Algal consortia	Source	Wastewater parameter	Days	Efficiency (%)	References
			Color			
			Odor			
			TDS			
			COD			
			BOD			
9.	Mixed algae culture of <i>Microspora</i> spp., <i>Navicula</i> spp., <i>Lyngbya</i> spp., <i>Cladophora</i> spp., <i>Spirogyra</i> spp., and <i>Rhizoclonium</i> spp.	Sewage wastewater	COD	8 days	683.6 mg/O <sub>2</sub> /L	8
			BOD		389.8 mg/O <sub>2</sub> /L	
			TSS		891.9 gSS/m <sup>3</sup>	
			TDS		4,546.2 g/m <sup>3</sup>	
			TP		20.9 mg/L	
			Nitrogen (NO <sub>3</sub> <sup>-</sup> )		11.7 mg/L	
			Phosphorus (PO <sub>4</sub> <sup>3-</sup> )		9.4 mg/L	
			Sulfate ion		53.5 mg/L	
			Chloride ion		51.5 mg/L	
10.	<i>Ulothrix zonata</i> , <i>Ulothrix aequalis</i> , <i>Rhizoclonium hieroglyphicum</i> , and <i>Oedogonium</i> spp.	Dairy manure wastewater	TN	7 days	62	10
			TP		70	

Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; NH<sub>4</sub><sup>+</sup>: Ammonium ion; NO<sub>3</sub><sup>-</sup>: Nitrate ion; OD: Dissolved oxygen; PO<sub>4</sub><sup>3-</sup>: Phosphate ion; TDS: Total dissolved solids; TKN: Total Kjeldahl nitrogen; TN: Total nitrogen; TOC: Total organic carbon; TP: Total phosphorus; TSS: Total suspended solids.

**Table 3. Mechanisms of nutrient uptake into the algal biomass**

Nutrients	Mechanisms of uptake into the algal biomass	References
Dissolved carbon dioxide	Integration into the Calvin cycle	20
Organic carbon	Integration into the respiratory metabolism pathways	21
Nitrogen	Fixation into ammonia, followed by conversion into amino acids	22
Nitrates and nitrites	Reduction into ammonium, followed by conversion into amino acids	23
Ammonium	Direct conversion into amino acids	24
Phosphorus	Phosphorylation and chemical precipitation	25

### 3.1. Biosorption

Biosorption is one of the earliest and most rapid mechanisms by which algal consortia remove contaminants from domestic wastewater. This process is largely physicochemical and occurs at the cell surface, without requiring metabolic energy. The outer wall of microalgae is rich in functional groups, such as hydroxyl, carboxyl, amino, phosphate, and sulfate moieties, that provide multiple binding sites for dissolved pollutants.<sup>26</sup> Through electrostatic attraction, ion exchange, complexation, and van der Waals forces, contaminants, including nutrients, heavy metals, dyes, and organic molecules, can be passively immobilized onto the algal surface.<sup>27</sup> A key characteristic

of biosorption is its speed, as pollutant binding occurs almost immediately upon contact with the algal biomass. This makes biosorption particularly effective during the initial stages of wastewater treatment, especially under fluctuating or high pollutant loads.<sup>28</sup> In algal consortia, the diversity of cell wall compositions among species further enhances biosorption capacity by providing a broader range of binding sites than monocultures. The other major advantage of biosorption is that it does not rely on active metabolism, allowing both living and non-living algal biomass to participate in pollutant removal. This feature is especially beneficial in unfavorable environmental conditions, where algal growth may be limited. However, biosorption also has inherent limitations. The process is reversible, and changes in pH, ionic strength, or competing ions may lead to desorption of bound pollutants. Moreover, biosorption alone does not transform contaminants, but merely transfers them from the aqueous phase to the biomass, necessitating careful handling or downstream processing of the spent algal material.<sup>29</sup>

### 3.2. Bioaccumulation

Bioaccumulation is the active uptake and internalization of pollutants into algal cells and is therefore metabolically driven. Unlike biosorption, this mechanism requires living cells and energy-dependent transport systems. Pollutants first cross the cell membrane via diffusion, facilitated transport, or active transport, and are subsequently compartmentalized within cellular

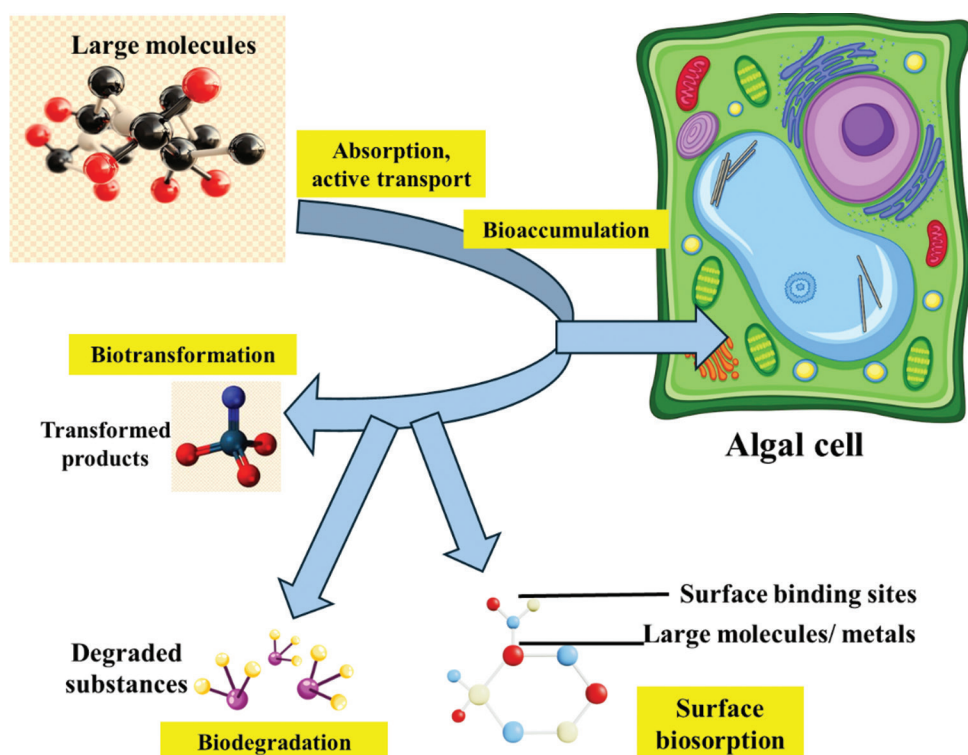


Figure 2. Mechanistic events during algal remediation. Image created by the authors.

organelles, such as vacuoles, chloroplasts, or the cytoplasm.<sup>30</sup> One defining feature of bioaccumulation is its selectivity, and algal cells regulate nutrient and certain contaminant uptake based on physiological demand and environmental stress. In domestic wastewater systems, bioaccumulation plays a critical role in the assimilation of nitrogen, phosphorus, and trace metals, which are incorporated into cellular components, including proteins, nucleic acids, and pigments. Exposure to toxic elements often induces oxidative stress, leading to the activation of antioxidant enzymes and metal-chelating molecules, thereby enabling detoxification while maintaining cellular function.<sup>31</sup>

The principal advantage of bioaccumulation lies in its ability to permanently remove pollutants from wastewater through intracellular sequestration and metabolic assimilation. In algal consortia, species-specific uptake capacities complement each other, resulting in enhanced overall remediation efficiency. This mechanism is constrained by algal growth rates and physiological tolerance thresholds. Excessive pollutant concentrations may inhibit cellular metabolism, reduce photosynthetic efficiency, or lead to cell death. In addition, bioaccumulation is inherently slower than biosorption, as it depends on active growth and cellular adaptation.<sup>32</sup>

### 3.3. Biodegradation

Biodegradation is the most complex and transformative mechanism of wastewater remediation by algal consortia. In this process, organic pollutants are enzymatically broken down into simpler, less toxic molecules that can be further metabolized or released as end products, such as carbon dioxide, water, or inorganic ions. Microalgae secrete a range of enzymes, including oxidoreductases, hydrolases, and oxygenases, that play a central role in degrading complex organic compounds, such as hydrocarbons, pharmaceuticals, and dyes.<sup>33</sup> A distinguishing characteristic of biodegradation is its integrative nature, as it often occurs alongside biosorption and bioaccumulation. Pollutants initially adsorbed to the cell surface or internalized into the cell may subsequently undergo enzymatic transformation. In algal consortia, interspecies interactions further enhance biodegradation, as different species contribute complementary enzymatic capabilities, creating a more robust and versatile degradation network.<sup>9</sup>

The major advantage of biodegradation is its capacity to detoxify pollutants rather than merely immobilizing them. This makes it particularly valuable for long-term wastewater treatment and environmental safety. Biodegradation is sensitive to environmental conditions such as light availability, oxygen concentration, pH, and temperature. The process is also slower compared to

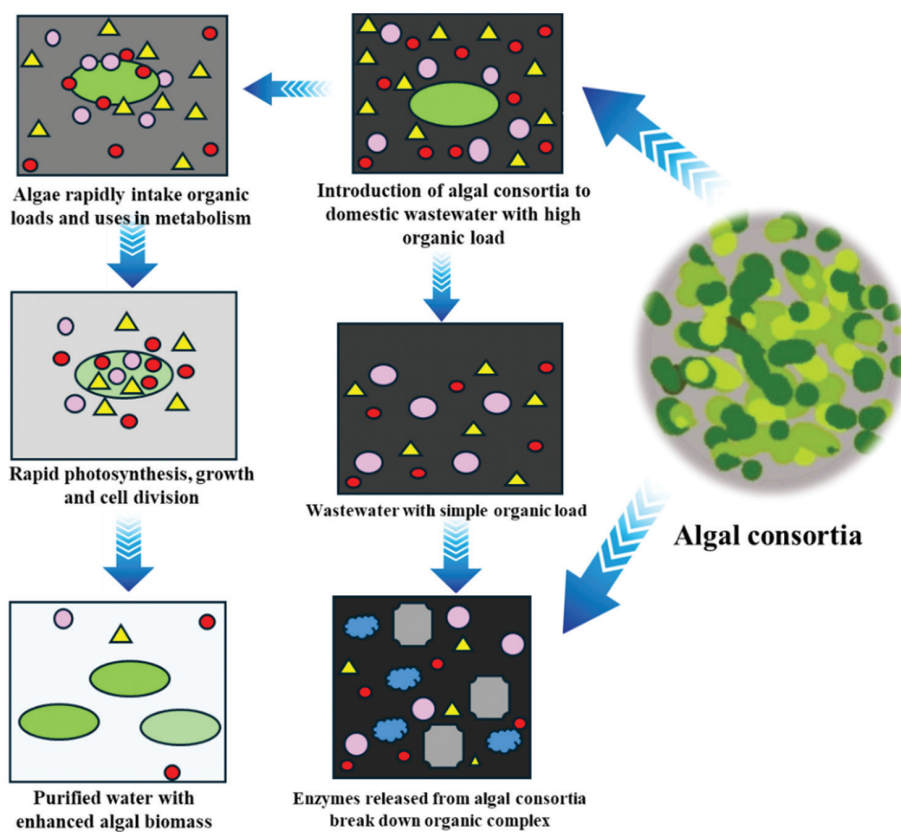


Figure 3. Holistic mechanism of using algal consortia in domestic wastewater treatment. Image created by the authors.

biosorption and may be inhibited by highly recalcitrant or toxic compounds. In addition, incomplete degradation can sometimes lead to the formation of intermediate byproducts, which may pose environmental risks if not fully mineralized.<sup>34</sup>

#### 4. Efficiency comparison: Algal consortia versus monocultures

Microalgae are used to remove nutrients and contaminants from various types of domestic wastewaters. Because of environmental and nutrient-level variations, as well as contamination, it is challenging to maintain a continuous, stable monoculture throughout the entire operational cycle. Controlling pollutant concentrations, biomass production, and process stability in wastewater during treatment is difficult to achieve with monocultures. In contrast, the contributions of microalgal consortia surpass those of single-species systems in pollutant removal, biomass production, and process stability.<sup>13</sup> The biggest advantage of consortia is their metabolic diversity and functional complementarity (Figure 4). Different algal species have different nutrient uptake rates, growth rates, and pollutant tolerance. Together, these species have synergistic

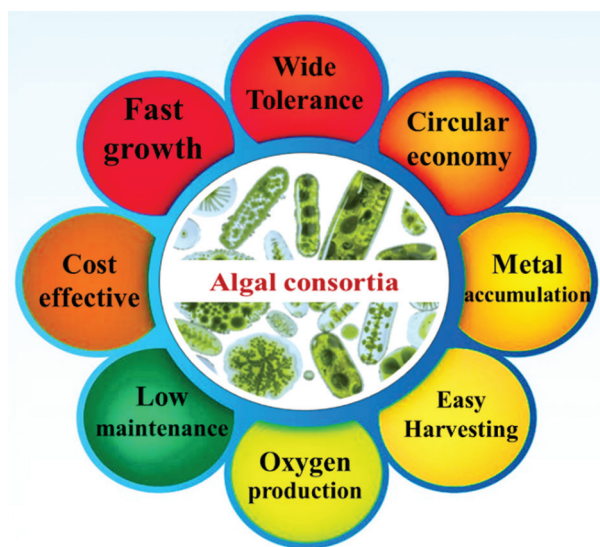


Figure 4. Advantages of using algal consortia. Image created by the authors.

interactions while simultaneously removing various contaminants, nitrogen, phosphorus, carbon compounds, and heavy metals. Mixed-algal systems are therefore capable of performing complex degradation processes that are

commonly inefficient in monocultures. Algal consortia are often more resilient to fluctuations in light, temperature, and pH, reducing the risk of invasion or culture collapse. This ecological stability can translate into more reliable biomass yield and temperature performance.<sup>9</sup> On the other hand, monocultures are susceptible to rapid collapse, for example, due to environmental stressors or biological activity. The heterogeneous physiological requirements and photosynthetic efficiencies of algal species enable consortia to use resources more effectively than individual species.<sup>35</sup> These collaborative exchanges can involve metabolites, signaling compounds, and growth-promoting substances, enabling greater nutrient removal and biomass accumulation. The most frequently used systems are naturally occurring prokaryotic and eukaryotic in aquatic settings or engineered for purpose-optimized performance.<sup>10</sup>

It is important to note that reported removal efficiencies across studies are strongly influenced by experimental design and operating conditions. Variations in wastewater composition, reactor configuration, light availability, hydraulic retention time, and cultivation scale make direct comparison of efficiency values challenging. Numerous high removal rates reported under laboratory conditions are achieved using synthetic or well-controlled wastewater, which may not fully reflect the complexity of real domestic effluents. Consequently, efficiency metrics should be interpreted within their experimental context rather than as universally comparable benchmarks. Recognizing these limitations is essential when assessing the scalability and reproducibility of algal consortia-based systems for practical wastewater treatment applications.

When comparing algal consortia with monocultures, the most meaningful difference lies not in, but how in quickly nutrients are removed under ideal conditions, but how reliably the system performs over time. Monocultures can show high removal efficiencies in controlled environments; however, their performance often becomes unstable when wastewater composition, light intensity, or temperature varies. In contrast, the algal consortia tend to buffer these variations because different species contribute complementary metabolic and physiological functions. When one species is stressed or temporarily underperforms, others can continue to sustain nutrient uptake and biomass production. This ecological balance reduces the risk of culture collapse and helps maintain the consistent removal of organic components. Consequently, for domestic wastewater treatment where influent quality is inherently variable, long-term stability, adaptability, and operational reliability become more relevant performance indicators than short-term peak efficiencies, making algal consortia a more practical choice than monocultures.



**Figure 5.** Different applications of biomass from algal consortia. Image created by the authors.

## 5. Valorization of biomass from algal consortia: The algal biorefinery approach

A biorefinery is a facility that uses algal biomass to produce bioenergy and value-added products. Waste-to-worth is the idea of using microalgae not only to capture nutrients from water bodies, but also to convert nutrient-rich algal biomass into useful products, thereby stimulating a circular bioeconomy.<sup>36</sup> On the other hand, there is a platform that develops sustainable technologies and could go one step beyond the “trash-to-cash” idea by producing industrially important renewable chemicals or minerals. In this section, details of several microalgae-derived biomass for valorization are discussed (Figure 5).

### 5.1. Feedstock potential of algal biomass

Algal biomass is referred to as a 3G feedstock because it has higher biomass productivity than plant-based lignocellulosic biomass. Previous studies focused on biodiesel production, but reported limitations, including low yield and high production cost.<sup>37</sup> Recently, research has focused on using algal biomass as a feedstock for multiple biobased products due to its high carbohydrate and protein content. A study reported that microalgal biomass mostly contains ash (5–17%), crude protein (18–46%), carbohydrates (18–46%), and crude lipid (12–48%) along with the embedded energy content of 19–27 MJ kg<sup>-1</sup>.<sup>38</sup> Algae are a rich source of metabolically active compounds, including amino acids, carotenoids, lipids, fatty acids of dietary value, polysaccharides, and proteins.

Recent studies have identified antibacterial, antioxidant, anti-inflammatory, antitumor, and antiviral properties, in addition to the well-established finding that algal biomass itself serves as a dietary and nutrient source for food and feed standards.<sup>39</sup> Although algal carotenoids are secondary pigments, they possess therapeutic properties. The nutritional value of algal metabolites is notable, as they can replace animal protein and lipid sources in the aquaculture industry. *Arthrospira* and *Chlorella* are well known for their very high protein content, ranging from 50% to 70% of their dry weight, along with essential fatty acids, antioxidants, and micronutrients crucial for the health of livestock and fish.<sup>27</sup> Algal species have evolved carbon-concentrating mechanisms and can thrive in complex waste streams and polluted environments, making them promising bio-factories for biorefinery approaches. Algal fuels, including both liquid fuels (biodiesel and bioethanol) and gaseous fuels (biomethane, biogas), are renowned in global energy markets as a promising alternative to conventional fossil fuels.<sup>40</sup> The remarkable activities of algal biomass have upsurged its value in the global market, which has demanded intensive research on cultivation and valorization methods to attain a sustainable supply chain.

## 5.2. Biodiesel

Algal oleochemicals are a sustainable environmental solution for producing green energy (biodiesel) that integrates carbon dioxide sequestration and waste minimization through a biorefinery approach. Lipids, being low-value compounds, are used to produce a byproduct or for bioremediation, although biodiesel recovery is the primary target.<sup>41</sup> It is a liquid fuel derived from algal lipids and valorized through various conversion technologies such as transesterification and thermochemical conversion.<sup>42,43</sup> *Chlorella* spp. is among the most commercially used algae for biodiesel production and has been genetically modified in a few cases for enhanced lipid yield and carbon capture.<sup>44</sup> As a carbon-neutral fuel, algal biodiesel can effectively replace conventional fuels, thereby reducing harmful greenhouse gases in the atmosphere. Bioenergy supply chains could be improved by new and emerging technological platforms that process feedstock biomass into one or more forms of energy in a closed-loop system. In this way, algal biomass could be used to produce algal fuels and serve as a potential candidate in the green energy sector with biorefining value.<sup>38</sup>

## 5.3. Biohydrogen

Biohydrogen is a promising renewable energy carrier because it produces no direct carbon dioxide emissions at the point of use. After lipid recovery, delipidified

microalgae residue (DMR) remains a rich source of carbohydrates and proteins, serving as an organic substrate for various hydrogen-producing microbes. DMRs undergo a harsh oil-extraction process and are therefore expected to be directly converted to hydrogen or other fuels after standard pre-treatment procedures.<sup>41</sup> Wieczorek *et al.*<sup>45</sup> investigated the potential of *Chlorella vulgaris* for the production of biohydrogen, wherein enzymatic pre-treatment of dry biomass (10 g volatile solids [VS] L<sup>-1</sup>) resulted in sevenfold higher biohydrogen production (135 ± 3.11 mL hydrogen g<sup>-1</sup> VS) than corresponding untreated biomass (19 ± 2.94 mL hydrogen g<sup>-1</sup> VS). On the other hand, microalgal species such as *Chlamydomonas reinhardtii* can produce hydrogen in the presence of light due to the enzymatic activity of chloroplast [Fe]-hydrogenase.<sup>46</sup> Due to its high energy content (120 kJ g<sup>-1</sup>) and sustainability, biohydrogen can be used as a “classic fuel” to support our energy infrastructure and to replace the current fossil-based fuels.

## 5.4. Biomethane

Biomethane, one of the major constituents of biogas, is produced by anaerobic digestion of organic wastes. Biogas generation from organic waste depends on the feedstock's carbon-to-nitrogen ratio. DMR has a high carbon-to-nitrogen ratio and is well-suited to methanogenic microbes for producing methane-rich biogas. Various algal species, such as *Nannochloropsis salina* and *C. variabilis*, have been applied.<sup>47</sup> Biomethane has a high calorific value and can enhance the biorefinery process. Biogas contains 70% methane, which can be used for cooking, heating, and lighting. It is a promising value-added product of microalgae biorefinery.<sup>41,48</sup>

## 5.5. Bioethanol

Bioethanol is considered a sustainable fuel because it is non-toxic and produced efficiently from renewable feedstocks. Delipidified biomass is a byproduct of algal industries. It acts as a potential source for bioethanol production. Enzymatic hydrolysis of raw or pre-treated DMR has yielded sugar at 37–43% (w/w). Bioethanol yield from DMR after saccharification and fermentation has been reported by various researchers, ranging from 0.14 to 0.26 g/g DMR.<sup>45,49–52</sup>

## 5.6. Biopolymers

DMR is an excellent source of biopolymers, such as polyhydroxybutyrate (PHB) and polyhydroxyalkanoates, which are important for their biodegradability, chemical diversity, biocompatibility, and production from renewable carbon resources.<sup>53</sup> Numerous strains, particularly cyanobacteria such as *Anabaena* spp., *Synechocystis* spp.,

and *Synechococcus* spp., can accumulate PHBs when cultivated in wastewater with PHB content ranging from 2.4% to 7.4% dry cell weight.<sup>19</sup> Furthermore, the biomass itself can serve as a source for developing starch-based bioplastics or as a reinforcing agent to enhance the properties of existing bioplastics through blending.

## 5.7. Algal metabolites

According to the Food and Agriculture Organization, algal proteins have high nutritional value and are competitive as food and feed ingredients.<sup>54</sup> Research has shown that marine algal polysaccharides have immense potential as a source of industrially viable and novel products. Polysaccharides are used worldwide as nutraceuticals, cosmeceuticals, pharmaceuticals, drug-delivery vehicles, fertilizers, and aquafeed.<sup>55</sup> Microalgae are sustainable sources of essential oils with large amounts of long-chain n-3 polyunsaturated fatty acids, omega-3 fatty acids, docosahexaenoic acid, and eicosapentaenoic acid, and moderate percentages of monounsaturated fatty acids and lesser amounts of saturated fatty acids. Vegan diets are low in vitamins, so algal foods are a source of folate, Vitamin B12, and niacin. *Chlorella pyrenoidosa* and *Arthrospira platensis* are largely cultured for the purpose of commercial Vitamin B.<sup>56</sup> Algae are rich in carotenoids; for example, *Dunaliella salina* and *A. platensis* have high carotenoid levels. Algal carotenoids act synergistically to prevent cellular damage in cancer patients, reduce cardiovascular disease risk, and lower blood cholesterol, and are used as antioxidants.<sup>57</sup>

## 5.8. Organic phyco-fertilizers

Algal biomass acts as an effective source of biofertilizer for food crops. Besides increasing the micronutrient availability in the soil, mainly iron, copper, zinc, and manganese, algal consortia can also enhance their organic-carbon content. This increase in soil quality is accompanied by higher grain yields and product quality, as the grains are more nutritious. For instance, Ferreira *et al.*<sup>58</sup> achieved significant improvement in root length and GI of some seed types (tomato, watercress, cucumber, soybean, wheat, and barley seeds) after application of the biomass of a microalgal consortium composed of *Tetrademus obliquus*, *Chlorella protothecoides*, *C. vulgaris*, and *Synechocystis* spp. at 0.5 g/L. Microalgae utilization in sustainable agriculture is likely to be one of the most important applications of microalgal biomass in the short term, particularly for biomass cultivated from domestic wastewater in wastewater treatment and agriculture, and will also improve the economic feasibility of microalgal production and downstream processing.<sup>59,60</sup>

While algal consortia offer the dual benefits of wastewater remediation and biomass valorization, they also entail inherent trade-offs. High pollutant removal efficiency can sometimes lead to changes in biomass composition, such as altered lipid, carbohydrate, or protein content, which may affect the quality and yield of downstream products, such as biofuels, biopolymers, and fertilizers. Conversely, optimizing biomass for specific biorefinery applications may slightly compromise nutrient uptake or treatment performance. Understanding and balancing these interactions is crucial to designing consortia that effectively support circular bioeconomy frameworks without significantly sacrificing either remediation efficiency or product suitability.

## 6. Environmental and socioeconomic implications

Beyond nutrient removal, such systems contribute to environmental sustainability by reducing organic load, lowering greenhouse gas emissions through carbon sequestration, and enabling the recovery of water, nutrients, and biomass within a circular economy framework. From a socioeconomic perspective, algal consortia offer opportunities for decentralized, low-energy wastewater treatment, particularly in resource-limited regions, while simultaneously generating numerous value-added products. By linking wastewater remediation with resource recovery and local economic benefits, this approach aligns environmental protection with social and economic sustainability, making it a viable strategy for long-term urban and peri-urban water management.

Sustainability, based on the effective integration of product recovery and waste management, is a key element of the future bioeconomy, which relies on sustainable biological feedstocks and biotechnology methods for valorization, looped through biorefineries.<sup>61</sup> Microalgal biomass incorporation into bioprocesses increases carbon utilization and supports a sustainability-integrated, low-carbon economy. Growing algae in carbon dioxide-rich habitats reduces greenhouse gas emissions and produces renewable feedstocks for various purposes.<sup>13</sup> The fermentative valorization of algal biomass yields biorenewable resources that produce biofuels, such as hydrogen and methane, as well as renewable short-chain fatty acids. These may be used as biopolymer molecules to produce stable solids, such as biopolymers and carbon fixation, or as eco-compliant plastics for waste materials without the consumption of chemical substances. Algae possess the metabolic versatility to transform a single biomass into several value-added products.<sup>62</sup> Algal biomass is a valuable raw material for food, feed, and

fuel production, where renewability is a key requirement in sustainable sectors. Integrated algal processing can enable zero-waste, carbon-neutral technologies and lower reliance on synthetic metabolites and land-based crops.<sup>5,13</sup> In addition, algae are contributing to environmental remediation in their generation of renewable fuels with no sulfur, their removal of complex waste products, and storage of atmospheric and industrial carbon dioxide. Most fundamentally, algae may provide promising solutions to environmental challenges by generating clean, zero-sulfur, carbon-neutral renewable fuels and, eventually, by degrading complex waste streams and reducing the effects of a changing world by sequestering atmospheric carbon dioxide and industrial carbon dioxide emissions.<sup>63</sup> Algal biotechnologies integrated into wastewater treatment and bioresource recovery systems form the backbone of such a comprehensive solution—a model which combines environmental restoration, climate intervention, and socioeconomic progress, characteristics of a truly sustainable circular bioeconomy.

## 7. Challenges and limitations

While algal consortia have shown great potential for wastewater remediation and bioenergy production, they still pose numerous concerns surrounding their application. Growth optimization, biomass harvesting, and process scalability are major bottlenecks that prevent the implementation of cost-effective, energy-efficient approaches. Stable algal growth under variable wastewater conditions requires a balance among various physical, chemical, and biological parameters, including nutrient composition, light intensity, and hydraulic retention time.<sup>64,65</sup> Challenges remain in tuning these parameters for large-scale cultivation. Engineering synthetic or semi-synthetic algal consortia is an emerging approach to improve pollutant degradation efficiency.<sup>66</sup> Communities with at least one genetically altered strain would enable targeted changes in specific metabolic pathways that are required for nitrogen, phosphorus, or heavy metal removal. Yet, bioengineered systems require robust regulation and long-term ecological monitoring to ensure environmental safety and stability. A significant limitation also resides in the heterogeneity and complexity of wastewater composition. There is very little metabolic flexibility for one type of algal species to degrade or assimilate all types of contaminants. Therefore, selecting strains for consortium formation is important. Certain pollutants may block photosynthesis or inhibit enzyme activity, reducing remediation efficiency.<sup>67</sup> Furthermore, most efforts have taken place in laboratory environments; therefore, applying laboratory parameters to field-scale systems is limited by environmental variability,

microbial contamination, and variable lighting or nutrient availability. Economic and technological limitations also exist for commercial algal cultivation. High operational costs, energy-intensive harvesting systems, and the use of costly chemical solvents for recovery pose the primary challenges. Efficient extraction of value-added metabolites from algal biomass requires cost-effective, environmentally friendly, and productive solvents.<sup>68</sup>

Despite promising laboratory- and pilot-scale outcomes, comprehensive life-cycle assessment and techno-economic analysis of algal consortia-based wastewater treatment systems remain limited. Most available studies focus on short-term performance metrics, while long-term operational stability, energy balance, and cost efficiency under real wastewater conditions are rarely evaluated. The scarcity of full-scale case studies further restricts direct assessment of economic feasibility and environmental trade-offs. Addressing these gaps through integrated life-cycle assessment-techno-economic analysis frameworks and extended field-scale investigations will be essential for translating algal consortia from experimental systems to reliable wastewater treatment technologies. Accordingly, the sustainability and cost-effectiveness of algal consortia should be viewed as potential outcomes rather than established attributes. While existing studies suggest promising environmental benefits and resource recovery opportunities, these advantages are strongly dependent on system design, operational scale, and local conditions. A cautious interpretation is therefore necessary until economic and systems-level assessments become widely available.

## 8. Future prospects and conclusion

Growing algal consortia in nutrient-rich domestic wastewater provides an environmentally sustainable solution for pollutant removal and waste disposal, generating usable biomass. Not only are environmental problems addressed, but valuable goods such as biofuels, biofertilizers, and organic soil boosters are also harvested. As algal consortia grow, their synergistic metabolic functions enable them to increase nutrient uptake and remove contaminants more efficiently compared to a single species. These cooperative communities convert wastewater into a living resource and provide environmental resilience. In the future, promising prospects include creating algal consortia that integrate species with complementary traits, such as metal-binding properties and nitrogen- or carbon-assimilation capabilities. This is important for understanding how these microorganisms interact with one another, how they conduct metabolic exchanges, and how they can also balance in common environments. Globally, the use of algal products is on the rise, as they

are widely used in nutrition, pharmaceuticals, energy, and agriculture. Algae are a highly suited biological solution for a waste-to-value-oriented next generation, equipped with the rapid expansion, carbon dioxide fixing, and valuable metabolite formation needed for exploitation. Advances in genetics, metabolic engineering, and process design enable us to more effectively extract pollutants, maximize biomass production, and recover energy and materials from waste streams. Microalgae also show promise as a pre-treatment step in wastewater treatment; they reduce the organic load and suspended solids before traditional treatment is required. Such systems can be embedded in existing infrastructure, making them environmentally friendly and cost-effective for water management. From a broader perspective, success in algal consortia will require sustained participation of researchers, engineers, and policymakers. Innovatively developed together and brought into the open with sufficient awareness, these living systems may pave the way for sustainable resource use.

This review demonstrates that algal consortia provide a stable and adaptable option for domestic wastewater treatment, largely because the coexistence of multiple algal species allows key remediation functions to be shared and sustained under variable conditions. Through the combined action of surface interactions, intracellular uptake, and enzymatic transformation, algal consortia can remove major nutrient loads and associated contaminants more consistently than single-species systems. At the same time, the biomass produced during treatment is a usable resource rather than residual waste, with demonstrated potential to be converted into bioenergy, biofertilizers, and other value-added products. Taken together, these features position algal consortia not simply as a treatment technology, but as a practical link between wastewater management and resource recovery, where environmental remediation and material reuse can be addressed within the same operational framework.

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## Conflict of interest

The authors declare that they have no competing interests.

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## Ethics approval and consent to participate

Not applicable.

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