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## **Integrated Algal–Microbial Consortia for Wastewater Treatment: Mechanisms, Performance and Future Perspectives**

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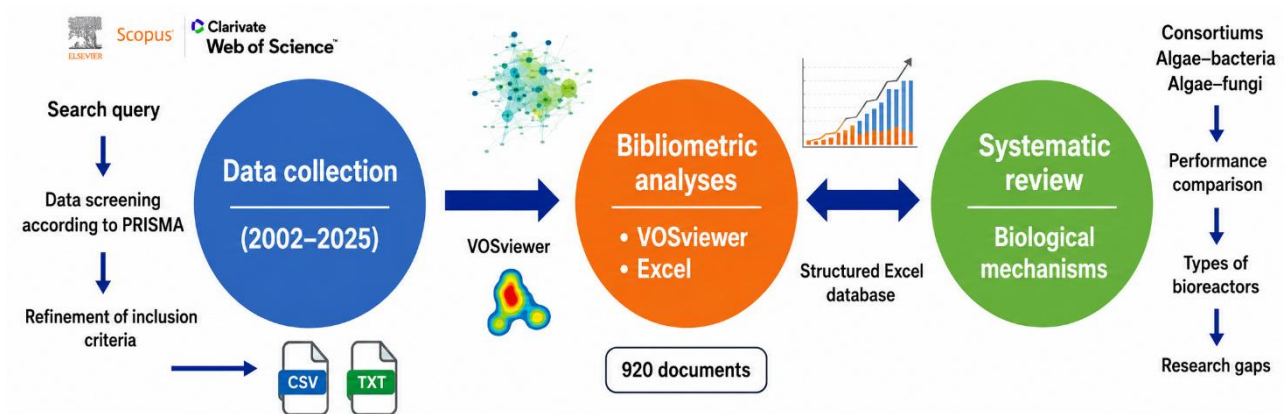
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## Graphical Abstract

This study adopts a systematic PRISMA-based methodology to collect and screen scientific articles from 2002 to 2025 using the main databases Scopus and Web of Science. Bibliometric studies were performed using VOSviewer and Excel to analyze research trends, keyword mapping, and publication patterns from a chosen set of 920 documents. Next, the review integrates the latest understanding of algal-microbial consortia, contrasts their biological mechanisms, efficiencies, identifies the types of reactors used, and pinpointing the gaps in the research field.



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**Abstract:** Algae, especially microalgae and macroalgae, are photosynthetic organisms that have been used for environmental purposes for a long time, which has been covered in depth through research. The major environmental uses of wastewater treatment, including nutrient recovery and reduction of the organic load, are mentioned in the literature. Microalgae are characterized by a very rapid growth, a huge potential to assimilate nitrogen and phosphorus, and an ability to form symbiotic relationships with other microorganisms, whereas macroalgae are mainly recognized for their high biomass production and their capacity to absorb pollutants in the water environment. This review paper has adopted the PRISMA method to strictly select research papers on biological consortia of the following: microalgae, bacteria, microalgae–fungi, macroalgae, bacteria, and macroalgae–fungi. Assessment of the chosen articles indicates that the cohabitation of microalgae and bacteria is the most favored theme in the literature by far, given its well-documented effectiveness and biological stability. In addition, bibliometric analyses show that there has been increasing attention to microalgae–fungi consortia since 2015, indicating new trends towards biofloc formation, which greatly facilitates biomass separation. On the other hand, consortia involving macroalgae in association with microorganisms (either bacteria or fungi) are still in their infancy in research.

**Keywords:** *Agricultural mulching films, Recycling barriers, Circular economy.*

## Introduction

Increasing industrialisation, combined with rapid population growth, has led to large volumes of untreated or inadequately treated wastewater being discharged into the natural environment, particularly in developing regions [1]. Industrial discharges containing nutrients, heavy metals, and toxic organic pollutants contribute significantly to eutrophication, ecosystem degradation, and declining water quality [2]. Beyond environmental concerns, water pollution has a profound impact on human health, leading to waterborne diseases, gastrointestinal infections, and chronic conditions resulting from prolonged exposure to pollutants such as lead, cadmium, and persistent organic pollutants [3]. It is therefore essential that we develop effective, sustainable, and environmentally friendly wastewater treatment solutions, not only to preserve our planet but also to protect our health. It is in this context that algae emerge as a natural and promising solution. Indeed, algae are rich in bioactive compounds such as pigments, proteins, polysaccharides, and lipids. These compounds are particularly valuable as they enhance the economic potential of algae and expand the prospects for biomass utilisation. In particular, their application in wastewater treatment has attracted increasing attention over the last few decades. Both microalgae and macroalgae exhibit a remarkable ability to remove inorganic nutrients such as nitrogen and phosphorus, reduce the organic load, and absorb certain heavy metals and micropollutants present in effluents [4,5]. Moreover, through photosynthesis, algae release oxygen, which in turn enhances biological oxidation processes and thus reduces the energy requirements for mechanical aeration in conventional wastewater treatment systems [6].

Numerous species of microalgae such as *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Tetraselmis suecica* have shown great potential in the treatment of different types of wastewater, such as urban and industrial effluents [7,8]. In parallel, a number of marine macroalgae including *Ulva lactuca*, *Gracilaria* spp., and *Laminaria* spp. have demonstrated a high purification capacity, especially for high salinity effluents and coastal regions [9,10].

Nevertheless, the use of algae in monoculture also has some disadvantages, such as their sensitivity to environmental changes; in some instances, they are not sufficiently efficient for the complete removal of organic matter and total nitrogen [11]. To increase the efficiency of algal systems, new approaches have been developed based on the mixed culture of algae with other microorganisms such as bacteria and fungi. These biological consortia rely on symbiotic interactions and metabolic complementarity, in which photosynthetic organisms produce oxygen and assimilate nutrients, whereas bacteria and fungi degrade complex organic matter, generate carbon dioxide, and release compounds that can be subsequently used by the photosynthetic organisms [12].

Algae–bacteria systems have been widely studied and have progressively demonstrated high effectiveness in achieving the simultaneous removal of organic matter, nitrogen, and phosphorus, as well as reducing the energy demand of wastewater treatment [13]. Recently, algae–fungi consortia have also come into focus, with a growing interest in the form of bioflocs, which facilitate biomass harvesting and increase the stability of treatment processes [14]. These combined strategies represent a promising path towards the development of wastewater treatment technologies that are highly efficient, sustainable, and economically feasible.

Despite the growing body of literature on algal-based wastewater treatment, existing reviews have predominantly focused on microalgae–bacteria systems, with limited attention given to macroalgae-based consortia and tripartite algae–bacteria–fungi interactions. To date, no comprehensive review has comparatively synthesised microalgae–bacteria, microalgae–fungus, macroalgae–bacteria, and macroalgae–fungus systems within a unified analytical framework spanning the past two decades. Addressing this gap, the present review provides a structured comparative analysis of the four principal algal–microorganism consortia, evaluates their pollutant removal performance and operational mechanisms, identifies key technological and biosafety challenges, and proposes strategic directions for large-scale and sustainable implementation. Based on a combined systematic review and bibliometric analysis using the Scopus and Web of Science databases, this study identifies major scientific trends, dominant research themes, knowledge gaps, and future research priorities in this rapidly expanding field.

## **Bibliometric analysis of algae-microorganism consortia for wastewater treatment**

### ***Data Sources***

The bibliographic data used in this study were extracted from two databases, Scopus and Web of Science, to obtain accurate and representative information on research related to wastewater treatment using biological consortia involving microalgae, macroalgae, bacteria, and fungi. Publications were identified using a query combining keywords related to algae, associated microorganisms, and the field of wastewater treatment within the Title–Abstract–Keywords fields: (microalga OR macroalga OR algae\* OR seaweed\*) AND (bacteria\* OR bacterial\* OR fungi\* OR fungal\* ) AND ( wastewater\* OR wastewater treatment\* OR effluent\*). The search was conducted between 2002 and 2025 to document the evolution of the field’s research. Both articles and review papers were selected to provide a thorough understanding of research trends. After that, the bibliographic data were exported and analysed using VOSviewer.

### ***Selection Criteria***

We performed the systematic literature review according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [25]. We conducted the first comprehensive bibliographic review of the literature on the biological treatment of wastewater by microalgae and macroalgae, in consortia with bacteria and fungi, comparing their mechanisms of action, benefits, and drawbacks. Precise inclusion and exclusion criteria were necessary in order to define the research question, reduce selection bias, and ensure scientific homogeneity of the studies. We used peer-reviewed journal articles published between 2002 and 2025. This allowed the examination of both early and recent stages in the development of this research area.

The use of 2002 as the starting date was deliberately selected because the early 2000s marked a period when more organised studies on algal–microbial consortia began to emerge, alongside advances in molecular biology, environmental biotechnology, and wastewater treatment engineering. Before this period, studies were relatively scarce and predominantly focused on monocultures rather than on integrated systems involving macroalgae or microalgae in association with bacteria and fungi. Excluding publications prior to 2002 therefore ensures methodological consistency and focuses the analysis on the phase during which consortium-based approaches became scientifically and technologically relevant. The review was extended to 2025 to include the most recent developments and emerging trends in macroalgae–bacteria–fungi and microalgae–bacteria–fungi systems. The search was mainly restricted to English and French publications, and articles in other languages, conference abstracts without full text, editorial pieces, and non-scientific documents were excluded. In addition, studies that did not explicitly address wastewater treatment or that did not involve algal–microorganism consortia were discarded. The use of these criteria resulted in a final collection of relevant publications for qualitative and bibliometric analyses.

### ***Inclusion and Exclusion Criteria for Articles***

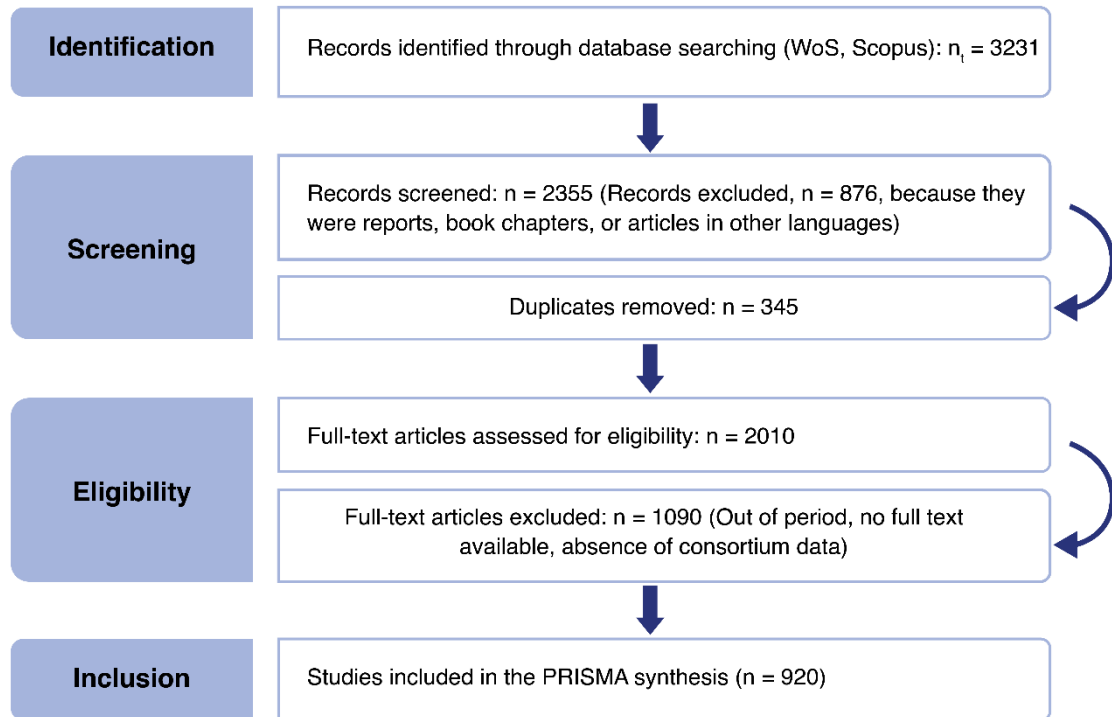
The aim of this research was to investigate patterns of wastewater treatment research using biological consortia of microalgae and macroalgae with bacteria and fungi, through the analysis of studies conducted during the period from 2002 to 2025. The bibliographic search was carried out in the Scopus, ScienceDirect, and Web of Science databases, which are major and reliable sources in the fields of environmental science and biotechnology. Firstly, the total number of articles recorded was 3,231, which were then downloaded in CSV and plain-text file formats for easier

handling and bibliometric analysis. Subsequently, the titles and abstracts of all publications were reviewed to further evaluate their suitability against the inclusion and exclusion criteria that had been set in advance (Table 2). To be included, articles had to explicitly address, either wholly or partially, the use of algae–microorganism consortia in the context of wastewater treatment, bioremediation, or nutrient and pollutant removal.

The screening step led to the rejection of 2,311 papers that did not meet these requirements. In addition, a number of papers examined wastewater treatment using algae or micro-organisms as single components, thus ignoring the interactions within biological consortia, which constituted the basis for their exclusion. After this selection, a final set of 920 articles was chosen for a detailed qualitative and bibliometric study.

**Table 1.** Inclusion and Exclusion Criteria for the Systematic Review

	<b>Inclusion Criteria</b>	<b>Exclusion Criteria</b>
<b>Publication period</b>	Articles published between 2002 and 2025.	Articles published before 2002, except for a few important theoretical references.
<b>Thematic relevance</b>	Studies explicitly addressing wastewater treatment using biological consortia involving algae–microorganisms, as mentioned in the title, abstract, or keywords.	Articles not directly related to the keywords of interest.
<b>Languages</b>	Publications written in English or French.	Publications in languages other than English or French.
<b>Document types</b>	Peer-reviewed scientific articles, including research articles and literature reviews.	Conference abstracts without full text, reports, or non-peer-reviewed documents.
<b>Duplicates</b>	Only one version retained when the same article is indexed in multiple databases.	Duplicate articles identified across different databases.



**Figure 1.** PRISMA 2020: flow diagram for new systematic review which included searches of databases and registers

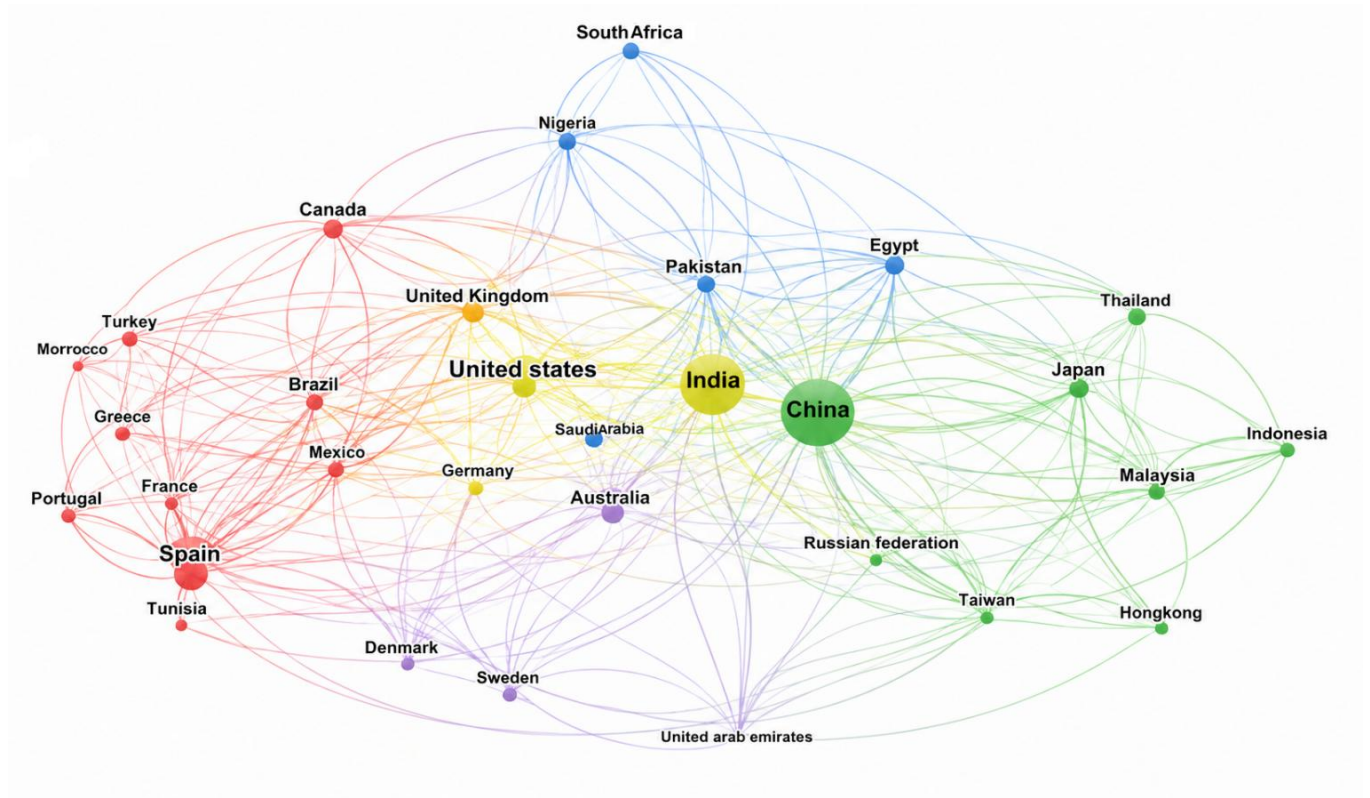
### Interactions between microalgae, macroalgae, fungi, and bacteria

The keyword co-occurrence analysis conducted using VOSviewer highlights the thematic structuring of research on wastewater treatment through biological consortia involving algae and micro-organisms. The network is dominated by the terms “wastewater treatment” and “microalgae”, which occupy a highly connected central position linked to “bacteria”, “biomass”, *Chlorella vulgaris*, “nitrogen”, “nitrate”, “carbon fixation”, and “microalgae–bacteria consortia”. This shows that microalgae–bacteria consortia represent the main axis and the most mature area of the literature, especially in terms of nutrient uptake and improved purification performance.

In contrast, words related to fungi (e.g. fungi, *Aspergillus*, co-cultivation, symbiosis) occur more peripherally and less often, indicating that there is still a significant degree of unexplored potential for the use of algae–fungi consortia as flocculating entities with enzymatic activity and biodegradation capacity. Furthermore, macroalgae (e.g. macroalgae, *Ulva*, seaweed) occupy a marginal position within the network, showing weak connections to the central core. This suggests a major scientific gap regarding macroalgae–bacteria and macroalgae–fungi consortia.



high scientific output. China emerges as the leading scientific driver, with a high and recent publication output, closely connected to India, Japan, and the United States. The latter plays a central role as a collaborative platform linking Asia, Europe, and Latin America. In Europe, Spain is prominent in terms of the extent of collaborations and contributions made to algal bioremediation research.



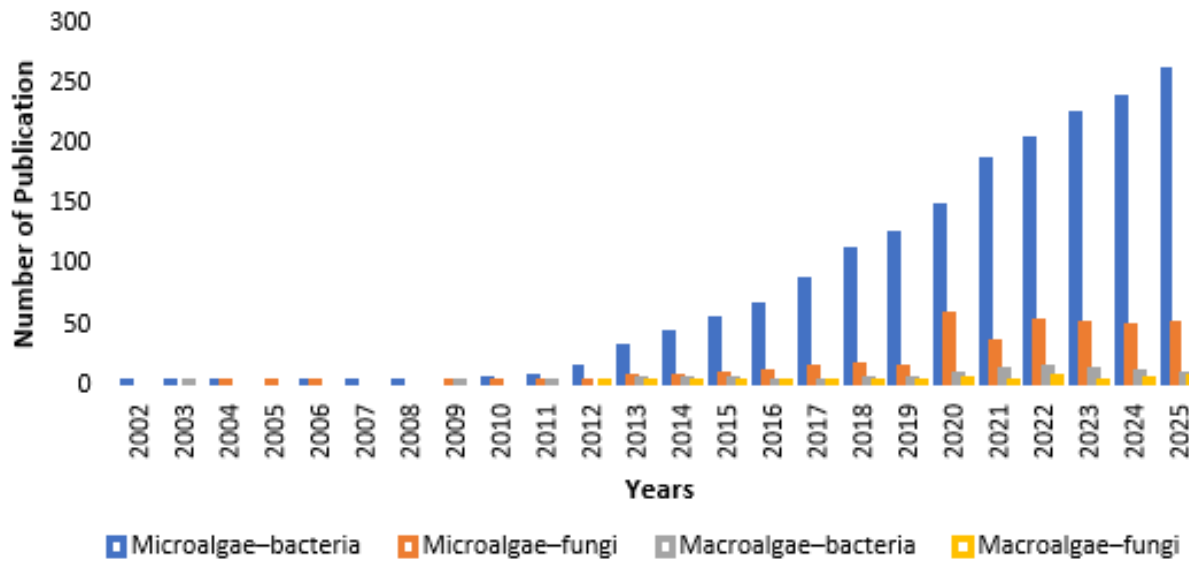
**Figure 3.** Publication distribution of reviewed articles by country

In contrast, African countries and some parts of the Global South are severely underrepresented, reflecting a geographical imbalance and an under exploitation of scientific potential. This discrepancy highlights the importance of strengthening international collaborations and supporting applied studies in local contexts under high environmental pressure.

### Annual distribution of documents

Figure 4 depicts a steady and significant growth in publications over the 2002–2025 period covering algae–microorganism consortia. The quantity of studies was very low during the 2002–2012 timeframe, and scientists were considered to be in an exploratory phase of research. From 2013 onwards, and more significantly after 2015, the number of publications increased rapidly; microalgae–bacteria consortia have dominated the field, accounting for over 1,100 publications,

and represent the primary research focus, especially in wastewater treatment and biomass valorisation.



**Figure 4.** Evolution of the Numbers of publications on algae × microorganisms consortia (2002–2025).

On the other hand, macroalgae consortia remain a niche research area that is still underexplored, and are therefore becoming an emerging field. Similarly, for microalgae–fungi consortia, a recent rise in the number of papers has been observed, reflecting an increasing interest in microbial combinations and the production of metabolites for biotechnological applications.

## General Overview

### Definition

The term algae has been used since ancient times and was first introduced by Carl Linnaeus in 1753. Subsequently, in 1789, Antoine Laurent de Jussieu established a classification of plants and defined algae in relation to the entire plant kingdom, thereby establishing their current taxonomic status in botany [15]. The scientific discipline dedicated to the study of algae is known as phycology [16].

Algae are a group of photosynthetic organisms, meaning they convert light energy into chemical energy through the process of photosynthesis. They are found in aquatic environments and may be microscopic, referred to as “microalgae”, or macroscopic, known as “macroalgae”. The latter are attached to substrates in coastal areas, are visible to the naked eye, and can reach several meters in length. The term “seaweed” is generally used to refer to benthic marine algae (macroalgae). These

macroalgae are defined as multicellular eukaryotic organisms exhibiting considerable morphological diversity.

To identify a marine macroalga, phycologists primarily examine its appearance and its environment. For identification at a more specific level, the most relevant attributes are mainly colour, shape, thallus configuration, and the possible presence of calcification. In certain cases, information relating to reproduction and the structure of reproductive organs is also required. In order to correctly identify biological material, detailed microscopic examination of vegetative and reproductive characteristics is necessary [17].

Microalgae, on the other hand, live suspended in water (from the surface down to the seabed). Often called phytoplankton, microalgae are unicellular or undifferentiated multicellular organisms. Under this designation, they belong either to the Eukaryotes or the Prokaryotes, the latter being represented mainly by cyanobacteria, also known as blue-green algae. Their size ranges from a few micrometres to around one hundred micrometres. Observation therefore requires the use of an optical or electron microscope [18]. Despite this morphological diversity, they share common biological characteristics. To date, more than 156,000 species and subspecies of algae have been described worldwide [19].

## **General Characteristics**

### ***Cytological and Biochemical Features***

Algal cells are surrounded by a rigid cell wall [16,20]. In many cases, this wall is composed of a network of cellulose fibres. Other polysaccharides such as pectin, xylans, mannans, alginates, and fucoidans may also be present [21]. All algae contain chlorophyll a. Some species also contain other types of chlorophyll, which differ slightly from chlorophyll a [21]. These chlorophylls are associated with numerous additional accessory pigments, such as carotenoids and, more rarely, phycobiliproteins, which give the different algal groups their distinctive colours [22].

### ***Mode of nutrition***

Algae, like the majority of plants, absorb light energy through pigments (chlorophyll and others) located in plastids in eukaryotes or dispersed in the hyaloplasm in prokaryotes (cyanobacteria). Through chlorophyll a, this energy is converted into chemical energy; this process is known as photosynthesis. It is used in the production of carbon-based organic compounds from mineral

elements (CO<sub>2</sub>, H<sub>2</sub>O) extracted from the environment, which makes algae autotrophic organisms. This series of reactions leads to the release of oxygen.

The gaseous exchanges carried out by chlorophyll (absorption of CO<sub>2</sub> and release of O<sub>2</sub>) occur in parallel with respiratory gaseous exchanges (absorption of O<sub>2</sub> and release of CO<sub>2</sub>). The release of CO<sub>2</sub> during the night is linked to respiration; during the day, this respiratory activity is masked by photosynthetic activity, which is quantitatively greater and characterized by the release of O<sub>2</sub> [23,24].

### ***Characteristics of wastewater***

Water is one of the most important resources for the life of human beings, animals, and plants on planet Earth. It covers about 71% of the Earth's surface [26]. Over the last couple of decades, the shortage of freshwater has become a major issue worldwide as natural water resources are being overexploited. The Technical Report on Water and Climate Change by the United Nations and United Nations Environment Programme reveals that the world population will reach approximately 8.5 billion in 2030, 9.7 billion in 2050, and nearly 11 billion in 2100 [27].

Besides population increase, alterations in socio-economic settings and lifestyle changes leading to different consumption patterns will result in major changes in the quantity and quality of wastewater, and therefore will place new burdens on existing wastewater treatment systems, which may not be able to handle these new challenges. It is a fact that only 20% of the wastewater produced worldwide is treated adequately before it is discharged, and of that treated wastewater (TW), only 2–15% is reused for irrigation depending on the region [28]. Around 80% of the total wastewater generated worldwide is discharged without proper treatment, according to the 2017 United Nations World Water Development Report 2017 [29].

**Table 2.** Algal growth factors

	Category	Factor	Effect on Algal Growth	Examples / Conditions
Macroalgae	Climatic factors	Light intensity	Determines spatial distribution, biomass and thallus morphology	Photophilous algae in exposed areas; sciaphilous species in shaded areas; polymorphism in charophytes
		Temperature / seasonality	Influences seasonal dynamics, species succession and phenology	Summer thermophilic species; winter species (e.g. <i>Hydrurus foetidus</i> ) disappearing above 13 °C
	Habitates Conditions	Substrate	Determines anchorage, stability and growth mode	Rhizoids (charophytes), basal discs ( <i>Rhizoclonium</i> ), colonisation of sediments ( <i>Phormidium</i> , <i>Lyngbya</i> )
		Current velocity	Influences thallus morphology, compactness and attachment	Rheophilic species ( <i>Lemanea</i> ); species carried by the current ( <i>Spirogyra</i> )
		Water depth	Controls light penetration and biomass stability	Optimal biomasses below 1 m; some charophytes up to 10 m
		Light	Energy source for photosynthesis; influences productivity	Light intensity, spectral quality and photoperiod are determining factors; risk of photoinhibition
	Microalgae	Abiotic factors	Temperature	Controls metabolic activity and growth
pH			Influences carbon assimilation and cellular stability	Optimum generally between 8.2 and 8.7; controlled by aeration or CO <sub>2</sub> injection
Salinity			Affects osmotic and ionic balance	Osmotic stress in case of sudden variation; adjustment by dilution or salt addition
Carbon			Key element for photosynthesis	Supplied in the form of CO <sub>2</sub> or bicarbonates
Nutritional factors		Nitrogen	Essential for protein and nucleic acid synthesis	NO <sub>3</sub> <sup>-</sup> , NH <sub>4</sub> <sup>+</sup> , urea
		Phosphorus	Essential for nucleic acids and ATP	Soluble phosphates required
		Trace elements & vitamins	Support enzymatic functions	Mg, Ca, Mn, Zn, Cu, Mo; vitamins sometimes beneficial
		Associated micro-organisms	Competition or synergy	Presence of bacteria, fungi, viruses
Biotic & operational factors		Hydrodynamic conditions	Affect light exposure and gas transfer	Residence time, mixing, shear stress
		Gas transfer	Controls availability of CO <sub>2</sub> and O <sub>2</sub>	Essential in dense cultures

**Table 3.** Comparison of different characteristics of wastewater from different sources

Wastewater source	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	Nitrogène (mg/L)	Phosphorus (mg/L)	Reference
Municipal wastewater	7.4	—	816 ± 129 (COD)	—	110 ± 16 (TN)	15.3 ± 1.3 (PO <sub>4</sub> -P)	[32]
	7.2 ± 0.5	—	245.6 ± 16 (TOC)	—	101.3 ± 2.8 (TN)	5.2 ± 1.3 (PO <sub>4</sub> -P)	[33]
Domestic wastewater	7.6 ± 0.3	—	411 ± 156 (COD)	—	37.0 ± 9.3 (TKN)	9.2 ± 2.6 (TP)	[34]
	7.4 ± 0.15	—	430 ± 198 (COD)	—	60 ± 11 (TKN)	8.7 ± 1.6 (TP)	[35]
Cheese industry	3.82–5.98	15,500–18,000	44,774–66,739	320.5–436.5	-	PO <sub>4</sub> -P: 291–350	[36]
Dairy	4.53 ± 0.67	170 ± 121.24	1007.3 ± 224.19	299.67 ± 89.97	NH <sub>4</sub> <sup>+</sup> : 5.23 ± 5.26; NO <sub>2</sub> <sup>-</sup> : 0.35 ± 0.13; NO <sub>3</sub> <sup>-</sup> : 25.67 ± 13.68; TKN: 16.31 ± 0.58	PO <sub>4</sub> <sup>3-</sup> : 46.97 ± 33.59	[37]
	6.58 ± 0.1	11,000 ± 50	13,054 ± 5	9622 ± 2.51	NO <sub>3</sub> <sup>-</sup> -N: 6.62 ± 0.43; TKN: 69.32 ± 1.01	PO <sub>4</sub> <sup>3-</sup> -P: 13.12 ± 0.7	[38]
Sugar refinery	4.77–4.94	1164–14,491	11,333–357,725	300–2533	NH <sub>4</sub> <sup>+</sup> : 104.98–177.3; NO <sub>2</sub> <sup>-</sup> : 0.45–2.79; NO <sub>3</sub> <sup>-</sup> : 127–1477; TKN: 0.66–27.07	PO <sub>4</sub> <sup>3-</sup> : 46.97–1426	[36]
Sugar	7.51	1070	1526.9	1413	TKN : 4.93	4.24	[39]
Cassava starch processing	4.5–4.92	6300	10,496	827	TN: 542.5	TP: 94	[40]
Cassava biogas effluent	7.5 ± 1.0	205 ± 12.3	47.67 ± 2.36	—	—	PO <sub>4</sub> <sup>3-</sup> : 23.53 ± 1.70	[41]
Fish processing	—	1128 ± 16.0	—	360 ± 15.46	NH <sub>3</sub> -N: 2.0; NH <sub>4</sub> <sup>+</sup> -N: ≈320; NO <sub>2</sub> <sup>-</sup> -N: ≈0.56; NO <sub>3</sub> <sup>-</sup> -N: ≈22.6	—	[42]
Tuna wash processing	7.38	139.15 g/L	—	23.48 ± 0.7	TKN: 18.2 ± 0.2	PO <sub>4</sub> <sup>3-</sup> : 1.62 ± 0.1	[43]
Dyeing industry	—	52.4	111	—	—	—	[44]
Pharmaceutical industry	—	120	490	370	—	—	[45]
	5–9.5	—	2580–6840	89	NH <sub>4</sub> -N: 64.2 NO <sub>3</sub> -N : 0.24 TN :228	—	[46,47]
Fish processing industries Maroc	—	4877	10557	3537	TN : 631	84	[48]

New chemical formulations, regularly introduced into communities for use in industries, agriculture, and homes, have caused wastewater quality to deteriorate, leading to the generation of water pollutants that are hard to eliminate and often contain nutrients and pesticides. Approximately 0.1% of wastewater comprises suspended and dissolved solids, mainly made up of inorganic and non-biodegradable substances [30]. The organic matter in wastewater mainly comprises proteins, carbohydrates, and lipids derived from the wastes of agricultural and food processing industries [31].

### **Risks of wastewater to the environment and human health**

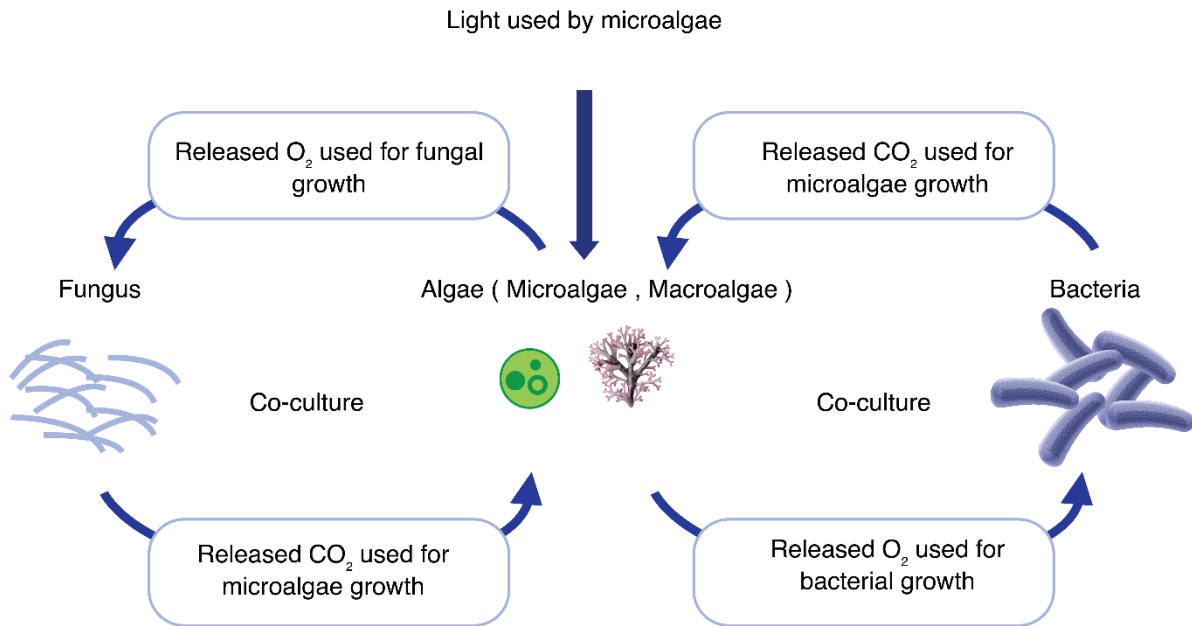
One of the major sources of environmental pollution and health hazards is untreated wastewater, which is usually rich in organic materials, nitrogen, phosphorus, and other chemical and biological pollutants [49]. When these wastewater effluents are released directly into water bodies, they may trigger eutrophication, a phenomenon that causes rapid growth of algae and a decrease in oxygen levels, ultimately leading to serious alterations in aquatic ecosystems [50].

In addition, wastewater has the potential to harbour a variety of pathogenic microorganisms including bacteria, viruses, and parasites, which cause waterborne diseases such as diarrhoea, cholera, and hepatitis [29]. Hence, contact with such contaminated waters is a major health threat, especially in areas with limited wastewater treatment facilities, where it contributes to the perpetuation of a cycle of parasitic and chemical transmission between the environment and humans [51].

### ***Consortia of microalgae and macroalgae with bacteria and fungi for wastewater treatment***

The high efficiency of microalgae–fungi and microalgae–bacteria co-cultivation systems in wastewater treatment is primarily based on synergistic metabolic interactions among the different microorganisms. In these consortia, microalgae assimilate inorganic carbon and nutrients through photosynthesis, producing oxygen that supports the aerobic metabolism of heterotrophic microorganisms, which are responsible for the oxidation of organic matter and the release of carbon dioxide and mineralised nutrients, which promote algal growth [26].

Fungal extracellular enzymes in microalgae–fungi systems are the principal agents that break down complex organic materials and suspended solids into low-molecular-weight substrates, thus increasing nutrient bioavailability, biomass production, and biofloc formation, which facilitates harvesting [52]. The efficiency of these systems relies heavily on the initial inoculation ratio, which determines the growth balance and the degree of pollutant removal [52].



**Figure 5.** Schematic representation of the algal-fungal co- cultivation and Mechanism of algal-bacterial symbiotic relationship for industrial wastewater treatment.

## Removal of contaminants by Consortia of microalgae and macroalgae with bacteria and fungi for wastewater treatment

### Nitrogen Removal

The performance of the nitrogen removal process in biological wastewater treatment systems depends on a balance between the nitrification–denitrification stages, ion fluxes within the system, and the uptake of nutrients by microbial and algal biomass. These functional differences account for the variability in performance among different treatment systems. Microalgae–bacteria consortia are usually those that achieve the highest and most stable nitrogen removal efficiencies, as they combine autotrophic oxygen production with bacterial nitrogen transformation metabolisms.

In an inverted fluidised bed biofilm reactor (IFBBR) inoculated not only with *Chlorella* but also with different microalgae from the order *Trebouxiophyceae*, and with bacteria included in the genera *Nitrosomonas*, *Gordonia*, *Ignavibacterium*, and *Limnobacter*, total nitrogen removal exceeded 95% and was maintained for 240 days, without any need for aeration or the addition of an external carbon source. The efficiency of nitrogen removal largely depends on how the consortium manages to carry out complete nitrification and denitrification processes. Mechanistically, this reflects the long-term stability of the system [53].

The same trend was observed with a consortium composed of *Chlorella protothecoides*, *Bacillus licheniformis*, and *Pseudomonas putida*; a system that was operated under blue light conditions ( $1.8 \text{ L min}^{-1}$ , 20% inoculum) and was able to remove 93.7% of the total nitrogen and 98.4% of the ammonium in 48 hours [54]. The rapid removal of ammonium shows that microalgal assimilation and bacterial nitrification operate effectively in tandem. Moreover, the presence of heterotrophic bacteria may have helped to mineralise more organic nitrogen in a short time, which would provide more ammonium than the system would have contained if it consisted only of microalgae and nitrifying bacteria.

In contrast, microalgae–fungi consortia achieved lower nitrogen removal efficiencies, ranging from 74% to 87% [55,13]. Such a difference is consistent with mechanistic expectations. Fungi lack the nitrification pathway, and nitrogen removal in these systems depends primarily on assimilation. Although granule formation improves biomass retention and sedimentation, it does not by itself provide the biochemical pathways needed for complete denitrification. As a result, nitrogen transformation remains, to a large extent, incomplete, especially in wastewater that is high in inorganic nitrogen. This is one reason why the study of the treatment of oil-industry produced water showed that nitrate removal efficiencies were 63.4% for  $25 \text{ mg L}^{-1}$ , 44.4% for  $50 \text{ mg L}^{-1}$ , and as low as 31.7% for  $100 \text{ mg L}^{-1}$ , strongly suggesting a decrease in removal efficiency with increasing initial nitrate concentration [56].

Although macroalgae–bacteria consortia operated in tank-type reactors (20 L tanks) have shown removal efficiencies for total nitrogen (TN),  $\text{NO}_3^-$ -N, and  $\text{NO}_2^-$ -N exceeding 99%, which is extremely high, the treatment, which lasted 16 days, revealed that the addition of *Bacillus subtilis* and *Bacillus licheniformis* significantly altered the structure of the bacterial community in both the water and on the algal surface. As a result, functional bacteria responsible for the nitrogen cycle, such as *Algoriphagus* and *Marivita*, were enriched. This interaction between algae and bacteria resulted in a significant enhancement of nitrogenous nutrient removal [57].

A 20 L Moving Bed Biofilm Reactor (MBBR) was used in another experiment to treat wastewater from a marine aquaculture system using the macroalga *Chaetomorpha maxima* directly integrated into the reactor (MBBR–MA). Bacterial biofilm formed on the mobile carriers (K1), whereas the algal filaments existed freely in the medium, taking advantage of continuous aeration and a 12 h light / 12 h dark photoperiod. On average, this co-system achieved a TN reduction of  $42.8 \pm 5.5\%$  [5].

Macroalgae–fungi systems are still very much a poorly understood area when it comes to their effectiveness in removing nitrogen. We simply lack sufficiently detailed data on nitrogen speciation

to fully understand the processes occurring in these systems, which represents a major knowledge gap. On the whole, bacteria have to be part of the picture if nitrogen is to undergo a full cycle of transformations. Consortia of microalgae and bacteria are the best solution, as they not only remove nitrogen very quickly but also efficiently, whereas macroalgae–bacteria systems rank next, mainly being able to remove nitrogen by assimilation. On the other hand, metabolic pathways are the limiting factors for microalgae–fungi consortia.

### Phosphorus Removal

Phosphorus elimination by algae–microorganism consortia is mainly achieved through assimilation, although it can be further enhanced by interactions that trigger precipitation processes and polyphosphate accumulation. Recent research has developed a vertical rotating biofilm reactor in which a microalgae–bacteria consortium grows as a biofilm on vertically oriented discs that are only partly immersed, so they are alternately in contact with wastewater and air. The system was employed in sequential batch and semi-continuous modes using a mixed effluent composed of municipal wastewater and soybean soaking water. In batch mode, the system was able to remove phosphorus with an efficiency of 97.6% [58].

The high efficiency of this system can be explained by the fact that algal growth is facilitated through the bacterial mineralisation of organic phosphorus compounds. Bacterial activity increases phosphorus availability, whereas the dense biofilm structure helps increase retention time and enhance nutrient capture. In addition, microalgae can store phosphorus in their cells as polyphosphates, which is one of the ways to temporarily store excess nutrients under conditions of high nutrient availability. In a highly specialised agro-industrial setting, the treatment of swine farming wastewater using a combination of microalgae and bacteria has been highly efficient, achieving an approximate 70% reduction in orthophosphate [13].

Regarding microalgae–fungi consortia, two separate studies examined the co-culture of *Tetrademus obliquus* and *Cunninghamella echinulata*, but reported very different phosphorus removal rates. In research on the treatment of oil-produced water, the microalgae–fungi consortium achieved an average phosphorus removal of about 36% at an initial concentration of approximately 30 mg L<sup>-1</sup> [56]. By contrast, in research dealing with the tertiary treatment of cheese whey, the same consortium achieved a much higher removal efficiency of between 66% and 70% for lower initial phosphorus concentrations (4.5–18 mg L<sup>-1</sup>) [55].

This contrast is therefore unlikely to be related to the species employed, but rather to the type of effluent and operational conditions. In addition, oil-produced water has high salinity, a high hydrocarbon load, and a toxic environment that can limit biological phosphorus assimilation and microalgal growth. In contrast, cheese whey contains a simple organic substrate, facilitating biomass development, and thus phosphorus is more readily incorporated into cells. Hence, although the same microorganisms are studied, differences in phosphorus bioavailability, chemical complexity of the medium, and operational parameters explain the variation in removal efficiencies.

Although there are very few studies that explicitly investigate macroalgae–fungi consortia, research on macroalgae consortia with bacteria already shows great potential for phosphorus removal in wastewater. For instance, one experiment demonstrated up to 83.7% phosphorus removal in a Moving Bed Biofilm Reactor (MBBR) via the direct addition of the macroalga *Chaetomorpha maxima* to the reactor (MBBR–MA). In such a system, the bacterial biofilm formed on the mobile carriers (K1), whereas the algal filaments floated freely. This research clearly shows that macroalgae can take up and use soluble nutrients even under real wastewater conditions [5].

Although this level of efficiency is inferior to that seen in some microalgae–bacteria systems, it nevertheless opens the door to considering fungal integration as a means to enhance biosorption and enzymatic phosphorus degradation in future macroalgae–fungi consortia. Microalgae–bacteria and microalgae–fungi consortia offer rapid and efficient phosphorus removal, whereas macroalgae–bacteria combinations are limited by their lower cell division rate and available surface area, although they still have the potential for biomass conversion.

### **COD Removal**

COD removal efficiency is largely dependent on oxygen levels and the ability of heterotrophic organisms to degrade organic matter. Systems that combine microalgae and bacteria have shown COD removal results of between 77% [13] and 95.6% [58], the main reason being that microalgae perform photosynthesis and release oxygen, which helps bacteria carry out aerobic oxidation of organic matter. Such oxygen supply through photosynthesis drastically limits the need for external aeration, resulting in much lower energy consumption. In addition, a stable biofilm provides better microbial retention and prevents biomass loss in semi-continuous setups.

Microalgae–fungi consortia have also been shown to perform effectively, achieving COD removal rates of 75–77% [55]. In microalgae–bacteria systems for dairy wastewater, similar levels of COD

removal were observed [13]; nevertheless, it is not appropriate to interpret these results as indicating equal system effectiveness when applied to swine effluents. Not only the composition but also the organic complexity of the two wastewater types varies considerably: dairy effluents normally contain substrates that are more easily biodegradable, whereas swine wastewater is usually characterised by high levels of organic matter, nitrogen, and more diverse organic fractions. Furthermore, the fungal system reached the COD removal target within three days, whereas the bacterial consortium required approximately six weeks to achieve the same objective. This marked difference in treatment duration highlights fundamentally distinct degradation kinetics.

Macroalgae–fungi systems have achieved up to 80% COD removal using mixed biomass of *Ulva* and *Aspergillus niger*, and 100% with consortia composed of *Laminaria* and *Aspergillus niger* in fish processing wastewater [12]. This is because biosorption by macroalgae complements fungal enzymatic degradation. Nevertheless, oxygen transfer limitations in dense macroalgal biomass may reduce degradation rates compared to those in microalgae.

In macroalgae–bacteria systems used in aquaculture wastewater, COD removal is usually less efficient than in microalgae–bacteria or microalgae–fungi consortia. For example, a recent paper has shown that COD reductions ranged between 50.88% and 68.61% in shrimp farming effluents using *Caulerpa* sp. associated with immobilised bacteria [59].

To sum up, microalgae–bacteria and microalgae–fungi consortia provide faster and more extensive degradation of organic matter, whereas macroalgae–bacteria systems are still mainly based on assimilation processes.

### **Heavy Metals and Emerging Contaminants**

Heavy metals refer to elements with atomic densities of at least  $4000 \text{ kg m}^{-3}$  [60]. They are a global environmental concern because of their non-biodegradability, toxic effects, and capacity to strongly bioaccumulate. In addition, heavy metals, even at trace levels, may lead to serious human and animal health hazards. Three main categories of heavy metals are commonly recognised: radionuclides (U, Ra, Am, and Th), precious metals (Au, Pd, Pt, and Ru), and toxic metals (Cu, Cr, As, Zn, Ni, Ag, Sn, Co, and Pb) [61,62].

Heavy metals in water are not only the result of natural geological activities but also of human-induced factors such as industrial waste discharges and agricultural runoff. Accordingly, a large number of techniques have been proposed to eliminate heavy metals from polluted waters, but their effectiveness differs. Among these approaches, biological treatments have come to be seen as a promising option. For instance, a combination of microalgae and bacteria can remove up to 84% of Fe, 44% of Cu, and 48% of Mn from pig farm wastewater [13].

It is believed that metal binding occurs through functional groups on the cell walls of algae and bacteria, which carry negative charges, such as carboxyl, hydroxyl, and phosphate groups. Nevertheless, copper and manganese were only partially removed, indicating differences in metal-specific affinity. These systems may also respond more effectively under simultaneous stress conditions, a feature observed in microalgae–fungi co-culture systems. A co-culture of *Chlorella sorokiniana* and *Aspergillus oryzae* resulted in the removal of 86% of  $\text{Zn}^{2+}$  and the degradation of 84.6% of estrone [58].

Moreover, metabolite profiling showed an upregulation of the tricarboxylic acid cycle and an increased release of organic acids, which may be responsible for metal chelation and oxidative degradation of endocrine disruptors, respectively. Thus, this reflects a metabolic acclimation during stress exposure rather than mere passive adsorption.

Recent studies indicate that integrated macroalgae–fungi systems represent an effective and eco-friendly approach to wastewater treatment, as they rely on the synergistic effects of nutrient biosorption and fungal enzymatic activity. For example, a combination of the macroalga *Spirogyra maxima* and the fungi *Trichoderma asperellum* or *Mucor racemosus* was employed to treat Wadi al Kharazi wastewater in Iraq: the co-culture reduced bicarbonate concentrations from  $204.9$  to  $162.8 \text{ mg L}^{-1}$  and decreased sulphate levels by up to 48%, thus demonstrating that the combined effect of the two organisms is superior to that of either one used individually [63].

In addition, macroalgae–fungi assemblies are useful for the remediation of pharmaceutical residues, achieving biosorption levels above 70% and enzymatic breakdown of persistent organic compounds through enzymes such as laccases and peroxidases [64,65]. Microalgae–fungi consortia are the most effective for complex contaminants and metals, followed by microalgae–bacteria systems. Macroalgae–bacteria systems still require optimisation and long-term studies. Nevertheless, issues such as metal desorption, biomass recovery strategies, and the long-term stability of these systems remain insufficiently explored.

### **Challenges**

Despite the promising potential of algal–microorganism consortia for wastewater treatment, several scientific, technical, and operational barriers still limit their large-scale implementation. One of the main challenges lies in selecting compatible species and controlling interspecies interactions. The performance of these systems strongly depends on the metabolic cooperation between microalgae, macroalgae, bacteria, and fungi. These interactions are highly sensitive to environmental and operational parameters, including light intensity, pH, temperature, mixing conditions, and nutrient availability. Inadequate control of these parameters can disrupt consortium stability, reduce biomass productivity, and ultimately decrease pollutant removal efficiency. Another important limitation concerns the use of filamentous fungi in algal–fungal systems. Although many fungal species exhibit excellent bioflocculation capacity, some are opportunistic or potentially pathogenic microorganisms, raising biosafety concerns and limiting their application in large-scale wastewater treatment processes. Consequently, ensuring the safe use of fungal strains remains a critical issue for the development of these systems.

In addition, most studies investigating algal–microorganism consortia have been conducted under controlled laboratory conditions, often using sterilised or synthetic wastewater. In contrast, real wastewater environments contain complex indigenous microbial communities, variable pollutant loads, and fluctuating environmental conditions. These factors may significantly influence consortium stability, microbial competition, and overall treatment efficiency, making the transition from laboratory studies to real wastewater systems particularly challenging.

From a technical standpoint, reactor design and operational control also pose significant challenges. It remains technically difficult to achieve adequate light penetration in these systems, efficient biomass distribution, and stable mixing conditions in large-scale systems remain challenging.

Furthermore, the need for optimised lighting, mixing, and process control may increase operational costs, thereby limiting the economic feasibility of large-scale applications.

Finally, beyond these technical challenges, there are also issues related to regulation and public acceptance. The use of bio-based treatment technologies involving diverse microbial biomass may require specific biosafety regulations and public support, particularly when applied to domestic or industrial wastewater treatment systems.

### **Future Perspectives and Conclusion**

Algae–microorganism consortia such as microalgae–bacteria, microalgae–fungi, macroalgae–bacteria, and macroalgae–fungi represent some of the most promising biotechnological approaches for sustainable wastewater treatment. Various studies have demonstrated the ability of these consortia to efficiently remove nitrogen, phosphorus, organic matter (COD), certain heavy metals, and emerging contaminants, together with reduced energy consumption associated with aeration and the potential for biomass valorisation. The combined metabolic activities of these organisms not only result in superior treatment efficiency compared to single-species cultures but also pave the way for developing less energy-demanding processes.

In addition to providing an overview of the salient features of the different types of algae–microorganism consortia used in wastewater treatment, this paper also outlines the major biochemical processes through which metabolic synergies lead to higher pollutant removal efficiencies than in single-species systems. A further contribution of this paper is the identification of principal research gaps, including the scarcity of work on macroalgae-based systems and on algae–fungi interactions. Among the technical and scientific issues still to be addressed are the stability of consortia over long periods, microbial community dynamics, biosafety considerations (especially concerning fungal strains), pilot-scale validation, and the application of advances in reactor design. Moreover, economic evaluations and life cycle analyses are still underrepresented in the literature.

Future research directions could include the identification of robust and non-pathogenic algal and fungal species capable of thriving under natural environmental conditions and withstanding environmental stress, including strains with favourable growth characteristics and high productivity. Further work should focus on improving co-culture systems so that they operate effectively under practical conditions, including natural light and minimal external nutrient supply. The development of integrated systems that promote biomass retention and enhance operational

stability is also required, alongside pilot-scale experiments to assess long-term performance and economic viability.

In sum, although algae–microorganism-based wastewater treatment technologies show considerable promise, their progression to industrial-scale applications will require systematic comparative studies, advances in reactor engineering, and rigorous techno-economic evaluation.

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