https://doi.org/10.56975/ijcrt.v13i8.292466

IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Integrative Approaches Using Algal-Bacterial Consortia In Wastewater Treatment: A Review Of Progress And Challenges"

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Introduction

The rapid pace of industrialization, urbanization, and agricultural intensification has led to the generation of massive quantities of wastewater containing a complex mixture of organic matter, nutrients (nitrogen and phosphorus), pathogens, heavy metals, and synthetic chemicals. Discharge of untreated or poorly treated wastewater into natural water bodies contributes significantly to environmental pollution, eutrophication, oxygen depletion, and the spread of waterborne diseases. These issues not only threaten aquatic ecosystems but also impact human health and socio-economic development, especially in regions with inadequate wastewater infrastructure.

Traditional wastewater treatment systems, such as activated sludge and chemical coagulation, have been widely used but come with several drawbacks. These include high energy requirements, chemical usage, generation of large volumes of sludge, and limited efficiency in removing emerging contaminants. Moreover, the growing demand for clean water amidst climate change and resource scarcity calls for treatment solutions that are both economically feasible and environmentally sustainable. (Saravanan et al.,2021, Ranjan et al ., 2025).

In this context, algal-bacterial consortia have gained attention as an innovative and eco-friendly approach for wastewater treatment. These systems harness the natural symbiotic relationship between microalgae and heterotrophic bacteria to achieve efficient removal of pollutants.(Xiong et al.,2017, Subhash chandrabose et al 2018). Algae, through photosynthesis, generate oxygen that supports bacterial degradation of organic matter, while bacteria provide carbon dioxide and nutrients that promote algal growth. This mutual interaction not only improves treatment efficiency but also reduces the need for external aeration, minimizes chemical use, and allows for the recovery of valuable biomass.

Given their potential for low-cost operation, high nutrient removal, and biomass valorization, algal-bacterial consortia represent a promising avenue for sustainable wastewater management (El-syed et al 2023). This review explores their mechanisms, benefits, challenges, and potential applications in modern environmental biotechnology.

https://doi.org/10.56975/ijcrt.v13i8.292466

Biology and Ecology of Algal bacterial consortia

Microalgae and bacteria often form mutualistic partnerships in which they coexist and interact closely, frequently developing into organized communities. These consortia are commonly found in natural aquatic environments—such as ponds, lakes, wetlands—and in engineered systems like wastewater treatment plants, where they carry out vital ecological and biological functions The interaction between algae and bacteria is largely synergistic and is based on exchange of nutrients and signaling molecules (Ramanan et al., 2016, Q fi et al., 2021).

In algal-bacterial consortia, microalgae and bacteria engage in mutualistic interactions, exchanging essential metabolites that support each other's growth and functionality. Algae, through photosynthesis, release oxygen utilized by aerobic bacteria, and exude organic carbon compounds such as dissolved organic matter, which serve as substrates for heterotrophic bacteria (Juarez et al., 2022). In return, bacteria supply carbon dioxide through respiration, which algae use for photosynthesis, and also provide vital nutrients like nitrogen (in the form of ammonium or nitrate) and phosphorus via mineralization or nitrogen fixation. Some bacterial species additionally produce vitamin B_{12} and other growth-enhancing factors required by certain algae. These interactions are often stabilized through the formation of biofilms, where extracellular polymeric substances (EPS) secreted by both partners help establish structured, surface-attached communities (Ramanan et al 2016,. Shi et al 2024). Functionally, these consortia play critical roles in both natural and engineered ecosystems by enhancing nutrient cycling (nitrogen, phosphorus, and carbon), supporting bioremediation through the breakdown of pollutants such as dyes and hydrocarbons, and improving wastewater treatment efficiency by removing organic matter, heavy metals, and pathogens (Cai etal.,2013, Iram etal., 2022). They also help maintain oxygen balance in aquatic environments and contribute to the microbial food web, forming the foundation of the microbial loop that supports higher trophic levels.

Mechanism of Biotreatment in Algal-Bacterial Consortia

The biotreatment mechanism in algal-bacterial consortia is rooted in the dynamic and synergistic interactions between microalgae and bacteria, enabling efficient removal of contaminants from wastewater. A core process in the consortium is the exchange of respiratory gases—microalgae, through photosynthesis, generate oxygen during daylight hours, which is utilized by aerobic bacteria for the oxidation of organic pollutants. In return, bacterial respiration provides carbon dioxide, which supports continuous algal photosynthetic activity. This reciprocal relationship creates a stable internal oxygen-carbon dioxide balance, reducing the need for external aeration and energy input (Mosa et al., 2021). The consortia are also highly effective in nutrient removal. Bacteria oxidize ammonia to nitrite and nitrate via nitrification, while algae assimilate various nitrogen species (NH_4^+, NO_2^-, NO_3^-) and phosphate ions (PO_4^{3-}) for biomass production. Additionally, under low-oxygen conditions, some bacteria perform denitrification, converting nitrate into nitrogen gas, thus aiding in nitrogen removal (Wang et al., 2016).

The consortia facilitate the degradation of organic matter, significantly lowering biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Bacteria carry out the primary decomposition, while the oxygen released by algae enhances aerobic degradation pathways. Both algae and bacteria play important roles in the removal of heavy metals and toxic compounds. Their cell surfaces contain functional groups capable of adsorbing metals such as lead, cadmium, and chromium, while some bacteria enzymatically reduce toxic metal ions into less harmful forms, contributing to detoxification (Yadav et al., 2022). Elevated pH levels caused by algal photosynthesis inhibit pathogenic microorganisms, and the consortium further enhances pathogen removal through the production of reactive oxygen species (ROS) and bactericidal compounds from certain bacterial strains.

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https://doi.org/10.56975/ijcrt.v13i8.292466

Another critical mechanism is **bioflocculation**, driven by the secretion of extracellular polymeric substances (EPS) by bacteria and exopolysaccharides by algae. These biopolymers help aggregate suspended solids and microbial cells, promoting sedimentation and improving effluent clarity (Gao et al., 2022). EPS also create protective microenvironments that enhance stress tolerance and allow the consortia to adapt to fluctuations in temperature, light intensity, and pollutant concentrations. Furthermore, the algal-bacterial system is capable of degrading or adsorbing emerging micropollutants, such as pharmaceuticals, personal care products, endocrine-disrupting compounds, and synthetic dyes, either through enzymatic breakdown or surface binding (Ali et al., 2024).

Importantly, the efficiency of these mechanisms is influenced by factors such as light availability, nutrient concentration, hydraulic retention time, and microbial species composition. The flexibility of the system allows for adaptation to both high-load and variable-quality wastewaters. In summary, the algal-bacterial consortium functions as a robust, self-sustaining, and ecologically balanced system capable of simultaneously achieving oxygenation, nutrient recycling, organic matter degradation, metal detoxification, and pathogen suppression in wastewater treatment processes.

Algae ⇄ Bacteria

↑ ↑

|—O_2 |—CO_2

| |—$NH_4^+ \rightarrow NO_3^- \rightarrow N_2$

↓ ↓

Photosynthesis Organic Matter Degradation

Nutrient Uptake Heavy Metal Reduction

Pathogen Inhibition Bioflocculation

Designs and Systems Used for Algal-Bacterial Consortia in Wastewater Treatment

A variety of engineered systems have been developed to harness the potential of algal–bacterial consortia for effective wastewater treatment. These systems are broadly categorized into open systems and closed systems, each offering distinct operational advantages. Among open systems, high-rate algal ponds (HRAPs) are the most widely used due to their low cost and simplicity (Picot et al.,1991). HRAPs are shallow raceway ponds designed to promote photosynthetic oxygenation, algal growth, and bacterial activity simultaneously (Craggs et al., 2014). They typically operate under natural light and are aerated through paddle wheels, enabling continuous mixing and enhanced gas exchange. Another open system is the waste stabilization pond (WSP), which relies on natural algal-bacterial interactions and is particularly suited for rural or decentralized wastewater management (Park et al., 2011).

In contrast, closed systems such as photobioreactors (PBRs) provide greater control over environmental parameters like light intensity, CO_2 concentration, temperature, and mixing. PBRs are especially effective in maximizing biomass productivity and ensuring year-round treatment efficiency (Acién et al., 2016). They include tubular, flat-panel, and airlift designs, often integrated with LED lighting or CO_2 injection systems to optimize algal photosynthesis. Membrane photobioreactors (MPBRs) are a hybrid design that combines a photobioreactor with membrane filtration units, allowing for solid-liquid separation, higher effluent quality, and biomass recovery (Gao et al., 2022). Another advanced system is the algal-bacterial granular

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sludge reactor (ABGS), which enhances sedimentation and harvesting due to compact, self-aggregated bio-granules (Liu et al., 2023).

To increase treatment efficiency, many systems employ two-stage configurations, where the first stage focuses on nutrient and organic matter removal (often via HRAPs), and the second stage uses PBRs or MPBRs for polishing and biomass harvesting (Kumar et al., 2023). Recent innovations include attached growth systems, such as algal biofilms or rotating algal biofilm reactors (RABRs), which allow for easy biomass harvesting and stable performance under fluctuating load conditions (Farooq et al., 2023). The choice of system depends on factors such as wastewater characteristics, land availability, operational costs, and climate. Proper reactor design, combined with optimized hydraulic retention time (HRT), light regimes, and microbe selection, is crucial for achieving maximum pollutant removal and biomass productivity (Acién et al., 2016; Cai et al., 2013).

Performance in Different Wastewater Types

Algal-bacterial consortia exhibit remarkable adaptability and efficiency across diverse wastewater types due to their metabolic complementarity and ecological resilience. Their performance varies depending on the wastewater characteristics, such as nutrient concentration, organic load, presence of toxic compounds, and light availability.

In municipal wastewater, these consortia have demonstrated high removal efficiencies for biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium, nitrate, and phosphate. Studies using *Chlorella vulgaris* and *Bacillus subtilis* in high-rate algal ponds (HRAPs) showed over 90% removal of total nitrogen and significant COD reduction with simultaneous biomass generation (Woertz et al., 2009; Craggs et al., 2014). The oxygen produced by algae supports aerobic bacterial metabolism, reducing the need for mechanical aeration and lowering operational costs.

In agricultural wastewater, such as livestock effluents and piggery slurry, algal-bacterial systems are effective in treating high ammonia loads, often exceeding 300 mg/L. However, these wastewaters may require pre-treatment or dilution to reduce turbidity and prevent light limitation (You et al., 2021). Certain ammonia-tolerant algae, such as *Scenedesmus obliquus*, and nitrifying/denitrifying bacteria, have been used successfully in two-stage systems to remove nitrogen and phosphorus while recovering biomass for biofertilizer or feed applications.

Industrial wastewaters present more complexity due to the presence of recalcitrant compounds. In textile effluents, algal-bacterial consortia have shown potential for decolorization and degradation of azo dyes, using algal photosynthesis to support aerobic bacterial breakdown of dye intermediates (Xiong et al., 2017). Likewise, in food and beverage industry wastewater, which is rich in sugars and fats, consortia involving *Chlorella* and *Lactobacillus* species have been applied for COD reduction and simultaneous lipid accumulation.

In metal-contaminated wastewater—such as from mining or tanneries—the EPS produced by bacteria and algae can bind heavy metals (e.g., Cr, Cu, Zn), and some bacteria can enzymatically reduce toxic metal ions (e.g., Cr^{6+} to Cr^{3+}). However, performance may be affected by extreme pH or metal toxicity, requiring buffer systems or adapted strains for effective treatment (Patel et al., 2023).

For pharmaceutical and hospital wastewater, algal-bacterial consortia can partially degrade antibiotics, hormones, and personal care products through a combination of photodegradation,

https://doi.org/10.56975/ijcrt.v13i8.292466

biosorption, and enzymatic transformation. Advanced systems like membrane photobioreactors (MPBRs) have been developed to enhance the removal of emerging contaminants, although removal efficiency can vary with compound structure and operational conditions (Cai et al., 2013).

Additionally, in greywater and sewage sludge filtrates, these consortia offer an eco-friendly alternative for nutrient polishing and biomass recovery. The treatment performance in these systems is influenced by factors such as light-dark cycles, CO_2 supplementation, hydraulic retention time (HRT), algal-bacterial species compatibility, and reactor design. In general, consortia-based systems show better adaptability to wastewater variations compared to monocultures, making them suitable for decentralized and integrated wastewater treatment.

Advantages over Traditional Systems

Algal–bacterial consortia offer several advantages over conventional wastewater treatment systems, particularly in terms of sustainability, energy efficiency, and resource recovery. One of the most notable benefits is the self-sustaining oxygen supply through algal photosynthesis, which significantly reduces the need for mechanical aeration—a major energy-consuming step in activated sludge systems (Craggs et al., 2014). This makes algal-bacterial systems more energy-efficient and environmentally friendly. Moreover, these consortia facilitate simultaneous removal of multiple pollutants, including organic matter, nutrients (nitrogen and phosphorus), heavy metals, and even emerging contaminants like pharmaceuticals and dyes, which are often inadequately removed by conventional systems (Xiong et al., 2017; Cai et al., 2013).

Another key advantage is the reduction of chemical usage; while traditional systems often require chemical coagulants or disinfectants, algal–bacterial systems can achieve pathogen removal through increased pH, oxygen levels, and antimicrobial compound production. The consortia also support resource recovery by converting nutrients and CO_2 into biomass, which can be harvested and valorized as biofertilizer, animal feed, or biofuel feedstock (Woertz et al., 2009; Acién et al., 2016). In terms of operational flexibility, these systems can be deployed in various configurations—from open high-rate algal ponds (HRAPs) to closed photobioreactors—and adapted to different wastewater types, including municipal, industrial, agricultural, and pharmaceutical effluents (Bhatt et al., 2022, Banerjee et al 2023).

Additionally, algal-bacterial systems promote carbon neutrality by capturing CO_2 during algal photosynthesis, contributing to climate change mitigation goals. Their modular and decentralized nature makes them ideal for use in rural or off-grid areas, where traditional infrastructure may be lacking. Lastly, the formation of bioflocs through EPS production enhances biomass separation and reduces sludge handling requirements. Collectively, these features position algal–bacterial consortia as a next-generation alternative to conventional treatment systems, particularly in the context of circular bioeconomy and sustainable development.

Limitations and Challenges

Despite their numerous advantages, algal-bacterial consortia face several limitations and operational challenges that hinder large-scale implementation. One of the major constraints is the dependency on light for algal photosynthesis, which restricts efficiency during night-time or in low-light environments and makes system design more complex in temperate or high-latitude regions (Acién et al., 2016). Moreover, maintaining the balance between algal and bacterial populations is critical but challenging, as fluctuations in temperature, pH, or nutrient concentrations can lead to dominance by one group, resulting in reduced treatment efficiency or biomass productivity. Harvesting microalgae is another technical bottleneck due to their small size and low settling rates, often requiring energy-intensive processes like centrifugation or membrane filtration, which increase operational costs (Cai et al., 2013).

The sensitivity to environmental fluctuations, such as high ammonia levels, toxic industrial compounds, or heavy metal concentrations, can inhibit both algae and bacteria if not properly managed. Wastewaters with high turbidity or low transparency further limit light penetration, affecting algal growth and overall system performance. Additionally, scalability and land requirements remain concerns—especially for open systems like HRAPs—making them less suitable for dense urban areas. In closed systems like photobioreactors, although more controlled, the capital and operational costs are significantly higher compared to conventional activated sludge processes (Craggs et al., 2014).

There is also a lack of standardized protocols and regulatory frameworks for algal-bacterial-based treatment systems, which limits their commercial deployment and public acceptance. Furthermore, the variability in wastewater composition across industries necessitates tailored consortia and reactor designs, increasing the complexity of application (You et al.,2021). Finally, long-term ecological stability of mixed cultures remains an area of concern, as contamination, competition, or mutation can disrupt the microbial balance. Addressing these challenges requires interdisciplinary research focusing on genetic engineering, system automation, cost-effective harvesting, and integrated process optimization to realize the full potential of algal-bacterial consortia in sustainable wastewater treatment.

Future Prospects and Research Gaps

Algal-bacterial consortia have demonstrated significant promise in advancing sustainable wastewater treatment, but several challenges remain that limit their full-scale implementation. Future research should focus on improving the stability and resilience of the consortia under varying environmental and wastewater conditions. There is a pressing need to understand interspecies interactions at the molecular level, particularly signaling pathways such as quorum sensing and metabolite exchange, to better control and optimize consortia performance. Enhancing biomass harvesting techniques—especially from suspended cultures—remains another bottleneck, requiring innovation in cost-effective, energy-efficient methods like magnetic separation, membrane technologies, or biofilm-based harvesting. Furthermore, scale-up studies that evaluate performance in real-world, high-load wastewater environments are limited and must be expanded. The integration of consortia systems with other treatment modules, such as anaerobic digestion or electrochemical units, presents a valuable avenue for achieving energy-neutral or even energy-positive operations. Finally, regulatory frameworks and public acceptance, especially regarding the reuse of treated water and algal biomass, must be addressed. Bridging these research and policy gaps will be critical to realizing the full potential of algal-bacterial systems in circular and climate-resilient wastewater management strategies

Conclusion

The application of algal-bacterial consortia in wastewater treatment offers a sustainable, energy-efficient, and multifunctional alternative to traditional treatment systems. These consortia exploit the natural synergy between microalgae and bacteria, where algae contribute oxygen through photosynthesis, supporting bacterial aerobic degradation of organic matter, while bacteria provide carbon dioxide and essential nutrients that enhance algal growth. This mutualistic interaction enables simultaneous removal of organic pollutants, nitrogen, and phosphorus, significantly reducing the reliance on external aeration and chemical inputs.

Compared to conventional activated sludge processes, algal-bacterial systems show improved performance in terms of operational cost, environmental impact, and biomass valorization. Recent innovations—such as photogranules, oxygenic granular sludge, biofilm reactors, and quorum-sensing-mediated optimization—

have enhanced treatment efficiency, biomass stability, and the recovery of value-added products including bioenergy, biofertilizers, and bioplastics. Furthermore, the integration of these systems with carbon capture and biohydrogen production technologies represents a step forward in achieving climate-resilient, energy-positive wastewater treatment solutions.

However, several challenges and research gaps hinder the wide-scale adoption of these systems. These include limited understanding of microbial interactions at the molecular level, inefficiencies in large-scale biomass harvesting, and the need for optimization under fluctuating wastewater characteristics. Additionally, the scalability, economic feasibility, and regulatory approval of these systems remain key concerns. Real-world demonstrations using high-load and diverse wastewater types are limited and must be expanded to validate laboratory-scale successes.

Future research should focus on improving the ecological and operational robustness of algal-bacterial consortia through advanced omics, systems biology, and bioengineering approaches. Policy frameworks and public engagement will also play crucial roles in mainstreaming these technologies. Overall, algal-bacterial consortia hold significant promise to transform wastewater treatment from a linear, resource-intensive process into a closed-loop, sustainable, and environmentally friendly approach aligned with circular economy and carbon-neutrality goals.

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