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Integrated Bacterial-Microalgal Consortium for the Efficient Removal of Organic Pollutants from Water Bodies - A review

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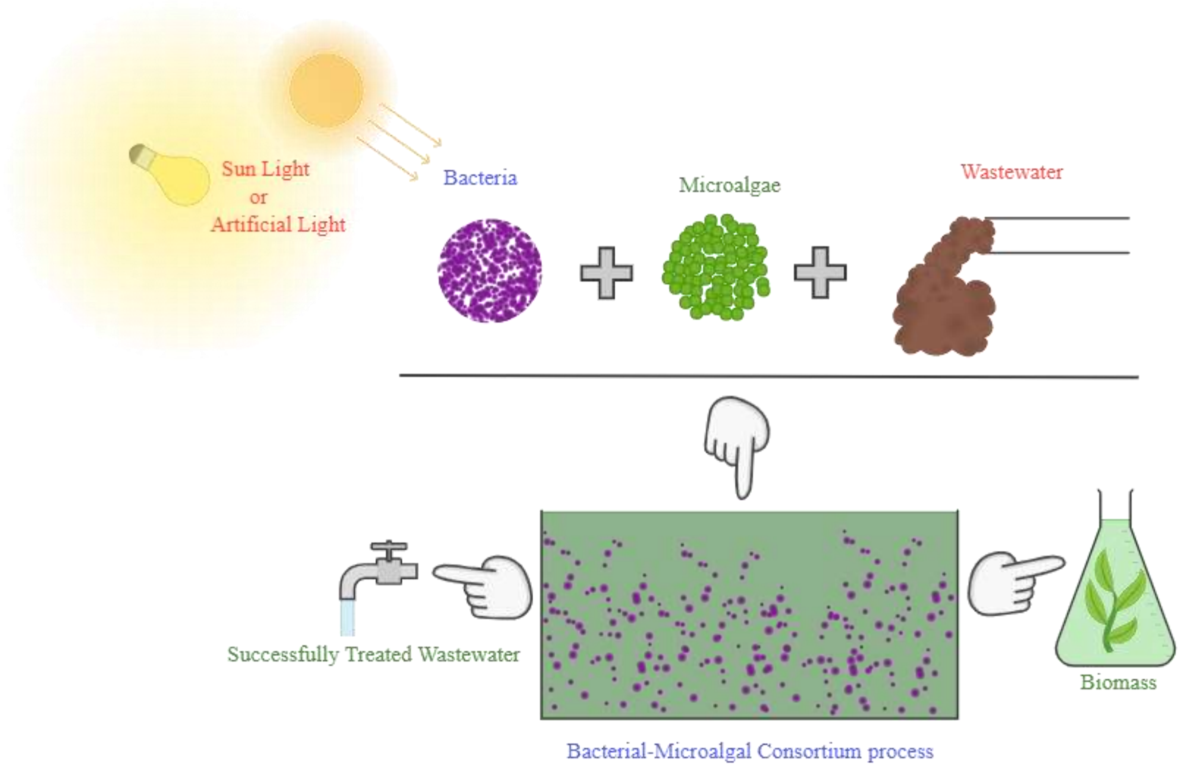
ABSTRACT

Research and the development of innovative techniques to lessen the emission and effects of organic pollutants must continue to protect the ecosystem and human wellness. Adopting a holistic and sustainable approach can ensure a cleaner and healthier ecosystem for current and future generations. Industrial wastewater, with its myriad organic pollutants, has caused an enduring impact on both the ecosystem and human wellness. The customary methods of eliminating these pollutants are expensive and can potentially cause (SP) secondary pollution, leading to untold harm. However, in an attempt to address this problem, sustainable techniques such as biodegradation, biosorption, and bioaccumulation have taken centre stage, experiencing a surge in popularity. One such approach, which shows great promise, is the bacterial-microalgal consortium, which aims to treat wastewater. The marvellous synergy between the two organisms, bacteria and microalgae, allows for the efficient extraction of organic contaminants from wastewater. because of ingenious mechanisms at work, the microalgae utilise the power of photosynthesis to create organic carbon and oxygen, providing their bacterial counterparts with the necessary energy and carbon sources for growth. In exchange, the bacteria help the microalgae by removing organic pollutants, phosphorus and nitrogen, from the wastewater. The unmatched benefits of the bacterial-microalgal consortium have transformed the treatment of the wastewater sector. The combined strength of the two organisms results in enhanced efficiency, cost-effectiveness, and sustainability. Furthermore, the ecosystem impact of this technique is comparatively smaller than traditional methods, making it a wise choice for mitigating adverse impacts of industrial effluent and boosting ecosystem sustainability. Hence, the adoption of green technologies is imperative to create a cleaner and healthier ecosystem, and the bacteria-microalgae consortium is the ideal solution. With its ability to revolutionise wastewater treatment, this eco-friendly approach is poised to transform the landscape of sustainable development.

Keywords: Bacterial-Microalgal Consortium, Treatment of wastewater, Organic pollutants, Biological treatment



1 Introduction

Water is the fundamental component of all living things, survival has been severely impacted by pollution and contamination, causing significant impediments to accessing safe and clean water. The worldwide problem of water pollution is amplified by the staggering It is estimated that around 80% of untreated water is dumped into the ecosystem (Lin, 2022). The buildup of organic matter, such as animal and plant waste, in water bodies, causes the accumulation of nutrients, leading to eutrophication and other harmful effects. Organic pollutants, a group of chemical compounds containing carbon, are omnipresent in ecosystem matrices, including water, soil, and air, causing harm to living organisms (Jayaraj, 2016). The ingress of these compounds into the ecosystem from numerous sources, including industrial processes, transportation, waste disposal, and agricultural activities. The production of chemicals, plastics, and synthetic materials is the primary source of organic pollutants in the ecosystem, resulting from industrial processes. Agriculture activities such as the application of fertilizers and pesticides further contribute to organic pollutants in the soil and water (Alengebawy, 2021). The existence of organic contaminants in the ecosystem poses significant risks to human wellness and the ecosystem, causing several adverse effects such as cancer, developmental disorders, reproductive problems, and immune system dysfunction (Manisalidis, 2020). Organic pollutants also lead to ecosystems' degradation, resulting in biodiversity loss, and impairing natural processes such as nutrient cycling and water purification. Several measures are taken to prevent and manage the disposal of organic pollutants into the ecosystem, including enacting regulations and policies like the Stockholm Convention on Persistent Organic Pollutants (Landrigan, 2020). Implementing best management practices in agriculture and industry is vital to reducing the number of organic pollutants released into the ecosystem. Bioremediation, a promising technique involving the use of microorganisms to break down or modify organic pollutants, can help reduce the impact of organic pollutants on the ecosystem. Sustainable technologies, such as renewable energy sources, green chemistry, and natural products, have also been devised to tackle the problem of organic pollutants (Bala, 2022). By adopting such measures, we can help ensure the availability of safe and clean water for all living beings.

1.1 There are two types of organic pollutants: persistent and non-persistent.

1.1.1 Persistent organic pollutants (POPs)

Persistent organic pollutants (POPs) are substances that resist decomposition and can stay in the environment for decades to millennia. Since they are frequently lipophilic and have low water solubility, these contaminants can resist environmental degradation and remain in the food web. POPs are a class of chemicals that also includes dioxins, PCBs, and dichlorodiphenyltrichloroethane (DDT). POPs are still present and pose major risks to both people and ecosystems (Guo, 2019). By contaminating watery species, these pollutants have the potential to infiltrate the entire food web, where they can have negative side effects like cancer, reproductive issues, and brain impairment. Due to their ability to move long distances via water as well as air currents, POPs may also spread widely and have an influence on ecosystems far from their original location (Campanale, 2020).

1.1.2 Non-persistent organic pollutants (NPOPs)

Non-persistent organic pollutants (NPOPs) are a diverse array of chemicals that are comparatively easier to degrade in the ecosystem and have a shorter lifespan. These pollutants encompass a wide spectrum of chemicals, Pesticides, medications, and personal care items are examples of such substances. Owing to their hydrophilic nature and heightened water solubility, NPOPs are more vulnerable to degradation through biological and chemical processes (Boulkhessaim, 2022). Although NPOPs are generally deemed less dangerous than persistent organic pollutants (POPs), they still present a notable risk to human wellness and the ecosystem. These pollutants can accumulate in aquatic ecosystems, inducing toxic effects on aquatic organisms and triggering disruptions in their hormone systems and developmental abnormalities. Furthermore, the wide-ranging application of NPOPs in agriculture and industry has led to their detection in drinking water sources, sparking concerns about their potential effects on human wellness. It is essential to take note that the ecosystem effect on a pollutant is not exclusively decided by its persistence. Other factors, including the chemical composition of the pollutant and its potential to bioaccumulate, can contribute to its toxicity and potential harm (Tchounwou, 2012).

1.2 Bacterial-Microalgal Consortium

A Bacterial-Microalgal Consortium, an assemblage of cooperative bacteria and microalgae, possess a myriad of functional capabilities. Thorough investigations have been carried out

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on their potential use in the bioremediation of contaminated water bodies and the treatment of wastewater. Microalgae, being minute, photosynthetic organisms, have the ability to transmute carbon dioxide and nutrients into biomass with light energy (Khan, 2018). They have the propensity to flourish in diverse bodies of water such as freshwater and saltwater. On the other hand, bacteria are heterotrophic microbes, that can extract carbon and energy from organic substances. They play a significant role in the decomposition of organic materials in bodies of water. By amalgamating Bacterial-Microalgal Consortium, ecosystem remediation can reap copious benefits. Microalgae are exceptionally proficient in removing nutrients such as phosphorus and nitrogen from water bodies, which in turn, lowers the peril of eutrophication. Furthermore, microalgae absorb carbon dioxide (CO_2) and other greenhouse gases, consequently contributing to the combat against climate change. During photosynthesis, they also generate oxygen, improving the water quality and promoting aerobic microbial activity (Sarwer, 2022). On the other hand, bacteria can also contribute to ecosystem remediation by breaking down organic pollutants in water bodies such as pesticides, hydrocarbons, and pharmaceuticals. They employ an array of metabolic pathways to degrade these substances into less harmful compounds. Additionally, certain bacteria have the potential to form biofilms on surfaces, which serve as physical barriers against contaminants and avert their spread. In a consortium of bacteria and microalgae, both species work in collaboration to purify the water and remove contaminants (Miglani, 2022). Microalgae provide bacteria with oxygen and organic materials, promoting their activity and growth. Furthermore, bacteria supply microalgae with nutrients such as phosphorus and nitrogen, facilitating their growth and development (Singh, 2014). Some bacteria secrete compounds that aid in the growth of microalgae, such as phytohormones, thereby enhancing their efficiency and proliferation (Sun, 2018). In general, the Bacterial-Microalgal consortium is a promising method for cleaning up the ecosystem, particularly in relation to water body treatment and bioremediation of contaminated water sources. This technology provides numerous benefits, including minimal energy consumption, high efficiency, and the capability to treat multiple contaminants simultaneously, surpassing conventional treatment techniques. Nonetheless, additional research is necessary to improve the setup and functioning of bacteria-microalgae consortia and explore their potential uses in various ecosystem conditions (Al-Jabri H, 2021). The intricate relationship between bacteria and microalgae in the treatment of wastewater facilities highlights the multifaceted nature of microbial ecology. While negative impacts on microalgae growth can arise from the prevalence of bacteria, a collaborative effort between these organisms can lead to efficient nutrient removal. Such findings emphasise the importance of further exploring and understanding the intricacies of microbial interactions for the continued advancement of the treatment of wastewater technologies.

2 Various Methods and Paths Way for Eliminating Organic Pollutants from Water Bodies

A variety of procedures is used to remove organic contaminants from bodies of water, such as physical, chemical, and biological ones. Physical techniques like filtration and sedimentation work well to remove bigger particles, but they are less successful in removing dissolved organic materials (Sathya, 2022). Organic contaminants can be chemically eliminated chemically using techniques like coagulation and oxidation; however, these processes frequently call for the inclusion of chemicals and can lead to dangerous byproducts. Since they rely on biological processes to degrade organic matter, such as biodegradation and biofiltration, these techniques have shown promise in the elimination of organic pollutants (Pachaiappan, 2022). For these techniques to work at their best, however, environmental factors and microbial ecosystems must be carefully optimised. For the removal of organic pollutants, physical techniques including adsorption, ion exchange, and ultrafiltration have also been applied. For the removal of certain chemical molecules or compounds with specific functional groups, adsorption and ion exchange are particularly efficient (Qasem, 2021). Contrarily, ultrafiltration employs a membrane to filter out organic pollutants and other particles according to size. However, it can be expensive to maintain, and the water might need to be pretreated. (AOPs) Advanced oxidation processes, for example, demonstrated the possibility of detoxifying organic contaminants. AOPs convert organic pollutants into smaller, less dangerous molecules by using powerful oxidants like ozone or hydrogen peroxide. AOPs, however, may call for the inclusion of chemicals and can also result in the production of hazardous byproducts like bromate. organic pollutants removal is accomplished using biological techniques, including membrane bioreactors (MBRs) and activated sludge (Deng, 2015). To degrade organic pollutants and transform them into CO_2 and water, these techniques rely on populations of microbial organisms. MBRs may generate high-quality effluent and are particularly effective at eliminating dissolved organic materials. However, installing and maintaining them may be costly. Treatment of wastewater is necessary to safeguard the ecosystem and public health .However, wastewater often contains organic pollutants, which can be challenging to remove (Amenorfenyo, 2019). Organic pollutants can cause problems such as taste and odor issues, disinfection byproduct formation, and membrane fouling. Fortunately, there are different routes for effective organic pollutants from wastewater elimination.

2.1 Treatment of Organic Contaminants in Water Bodies

Water pollution, including organic pollutants like pesticides, herbicides, plastics, solvents, fuels, and other compounds containing carbon, is a consequence of many industrial and domestic activities (Pizzini, 2022). Organic pollution can poison animals and aquatic creatures, among other issues. accumulation in the food web, posing dangers to both human and animal health, decreased purity and quality of the water hazardous disinfection byproducts developing excessive proliferation of aquatic plants and algae, or eutrophication increased risk of infections and illnesses (Bashir, 2020). Traditional treatment techniques remove organic contaminants from water bodies using chemical, physical, and biological approaches, either alone or in combination.

2.1.1 Biological treatment

Biological treatment for organic pollutants removal is a procedure that employs microorganisms to degrade and remove organic materials from bodies of water. The first step is carried out in a bioreactor, which is a tank or vessel that provides an ecosystem for bacteria to flourish and thrive. Microorganisms feed on organic molecules in wastewater and convert them into CO2, H2O, and microbial biomass. Biological methods approaches have been shown to be effective in eliminating organic materials from bodies of water. The most often utilised biological therapy (Narayanan, 2019).

Activated Sludge (AS) Process:

The activated sludge (AS) process is an extensively used biological technique for the elimination of organic matter from wastewater. This intricate procedure involves combining the wastewater with a battalion of microorganisms like fungi and bacteria in a specially designed aeration tank. These tiny creatures are entrusted with the critical responsibility of gobbling up all the organic material present in the water, thereby converting it into CO_2, H_2O, and last but not least, creating new microbial cells. Subsequently, the solution is left to settle, allowing for the excess microorganisms and organic matter to be separated and extracted through the process of sedimentation. This elaborate process requires the utmost precision and careful attention to detail to ensure that the result is a clean and safe ecosystem for all (Samer, 2015).

Aerated Lagoons:

Aerated lagoons are shallow, man-made ponds used to clean wastewater. The lagoons are intended to create an excellent ecosystem for microorganisms to naturally breakdown organic materials. The water is constantly aerated, supplying oxygen to the bacteria, and the organic stuff degrades over time. The finished effluent is then either released into the ecosystem or utilised for irrigation (Abdel-Raouf, 2012).

Constructed Wetlands(CW):

CW is either artificially created or naturally occurring ecosystems that employ plants, microorganisms, and other aquatic organisms to eliminate contaminants from the water. The flowing water is directed through a sequence of constructed wetlands, where contaminants are absorbed by and broken down by plants and microbes, including organic substances. Constructed wetlands are highly efficient at removing nutrients, such as phosphate (P) and nitrogen (N), which might end in eutrophication (Wang, 2022).

Trickling Filters:

Trickling filters are beds of rocks, gravel, or other media that offer a surface for microorganisms to grow on. The wastewater is allowed to flow through the media, where the microorganisms devour the organic material, transforming it into CO_2, H_20, and new microbial cells. The effluent is then collected and treated further before being discharged into the environment (Pal, 2016).

Membrane Bioreactors:

Membrane bioreactors are an innovative solution for the treatment of wastewater that combines biological treatment and membrane filtration techniques. Microorganisms are employed in the biological aspect to degrade the organic matter in wastewater. The wastewater mixture then traverses through a membrane, which acts as a filter, to separate microorganisms and suspended solids from the effluent. To ensure that the effluent meets the ecosystem standards, it is disinfected before release. Membrane bioreactors have transformed the treatment of wastewater and are playing a vital role in preserving the ecosystem (Asante-Sackey, 2022).

Advantages and Limitations:

Biological treatment methods offer several advantages over chemical and physical treatment methods. They are cost-effective, environmentally friendly, and produce fewer harmful byproducts. However, the effectiveness of biological treatment methods is influenced by numerous elements, like the type and concentration of organic material, temperature, pH, and types of microorganisms present. Additionally, biological treatment procedures take longer to achieve the desired standard of treatment compared to chemical and physical treatment methods (Ceretta, 2021).

2.1.2 Physical treatment methods

Physical treatment procedures are frequently employed to purify organic pollutants. To remove or degrade organic contaminants, these approaches employ physical processes such as filtration, adsorption, and oxidation (Shahidi, 2015).

Filtration: Water flows over a filter media as part of filtration, a popular physical treatment technique, to get rid of organic pollutants. Sand, gravel, or activated carbon are just a few examples of material resources that can be filter media. While activated carbon filters are used to eliminate herbicides and pesticides, among other dissolved organic contaminants, sand filters are frequently used to eliminate suspended solids and organic matter (Cescon, 2020).

Adsorption: Adsorption is another physical treatment approach that removes organic pollutants from water by using adsorbent materials. Adsorbent materials with large surface areas, such as activated carbon, zeolites, and clays, can absorb organic pollutants by a variety of mechanisms, Van der Waals forces and electrostatic attraction are examples of such forces.. Because of its versatility and effectiveness in adsorption, activated carbon is one of the most flexible and useful compounds. Adsorbent materials were frequently used to remove organic pollutants from water (Almeida-Naranjo, 2023).

Oxidation: Chemical oxidants are the quintessential agents employed in the physical treatment process of oxidation to enable the conversion of insidious organic contaminants into less deleterious and toxic ones. The chemical oxidants that reign supreme in the realm of water treatment are chlorine, ozone, and hydrogen peroxide. Among them, ozone and hydrogen peroxide occupies a paramount position for their capability to induce sophistica ted oxidation procedures that can comprehensively break down a plethora of intricate organic pollutants. In contrast, chlorine finds its application mainly as a disinfectant and oxidant, rather than being exploited for intricate oxidation processes (Chhaya V. Rekhate, 2020).

Ultraviolet (UV): UV (ultraviolet) light is a physical treatment method that employs UV to destroy organic pollutants. UV radiation may dissolve organic pollutants by interacting with them to produce free radicals, which can then be broken down into smaller molecules. This process is known as photolysis (Yousif, 2013).

Physical treatment techniques have significant drawbacks while they occasionally useful for eliminating organic contaminants from water. Some organic contaminants, like herbicides and pesticides, may be difficult to remove using adsorption and filtering techniques because they need sophisticated oxidation procedures, which are not always effective. Physical treatment techniques may also be unsuitable for large-scale water treatment given their expensive running costs and high energy needs (Cevallos-Mendoza, 2022).

2.1.3 Chemical treatment method

toxic organic substances in water bodies are frequently removed using chemical treatment techniques. These procedures involve the breakdown utilising to eliminate organic pollutants from water by chemicals like oxidants, coagulants, and flocculants (Sharma, 2017).

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Chlorination: Chlorination is one of the most often used applied chemical treatment processes. To oxidise and disinfect organic contaminants, water is chlorinated by adding chlorine gas or sodium hypochlorite. Chlorination effectively reduces the quantity of organic pollutants in the water while also eradicating bacteria, viruses, and algae (Al-Abri, 2019).

***Ozonation*:** Ozonation is another chemical treatment technique. Utilising ozone gas to oxidise and degrade toxic organic substances in water is known as ozonation. Pesticides, herbicides, and medicines are just a few of the many organic contaminants that ozone may effectively oxidise and degrade (Hua, 2006).

***coagulation and flocculation*:** chemical treatment techniques like flocculation and coagulation use substances like alum, ferric chloride, and polyaluminum chloride to remove organic contaminants from water. To generate bigger particles that are readily removed by or filtration sedimentation, coagulation includes chemical augmentation that neutralises the charge on suspended particles. To encourage the creation of flocs, which are bigger particles created by the building up of smaller particles, floculation is the gentle mixing of water (Kurniawan, 2020).

***Advanced oxidation processes (AOPs*):** Advanced oxidation processes (AOPs) use powerful oxidants such as hydrogen peroxide, ozone, and UV light to destroy organic pollutants in water. AOPs can degrade a wide range of organic pollutants, including those that are resistant to current treatment techniques (Cardoso, 2021).
One of the primary advantages of chemical treatment processes is their ability to efficiently remove a variety of organic pollutants from water. Large volumes of water may be treated further using chemical methods, which are also rather easy to utilise. They can be expensive, create hazardous byproducts, and require constant monitoring to ensure that the water is safe for consumption (Saleh, 2020).

2.2 Recent breakthroughs in biological treatment of organic matter elimination from wastewater. The studies evaluated reveal that different biological approaches are successful at extracting natural organic materials from wastewater. The results highlight the significance of the use of advanced

The biological treatment used to remove natural organic matter	**Removal**	**Advantages**	**Disadvantages**	**Reference**
biochar as a potential adsorbent	90% micropol lutants (MP)	Highly porous and adsorptive, Renewable and sustainable, Low cost compared to other adsorbents,	Can be expensive to produce on a large scale, Requires careful monitoring to prevent fouling, Can be affected by high solids	Kearns, J et al., 2021 (Kearns, 2021)

		Can be produced from a variety of feedstock's, Can remove a wide range of organic compounds, Can be regenerated for repeated use	concentrations, and May require pre-treatment to improve adsorption.	
Moving Bed Biofilm Reactor (MBBR)	78.4% Organic matter	really effective elimination, Versatility, minimal energy use, Small footprint, can be applied to several types of effluent, Produces high-quality effluent	Requires periodic replacement of GAC media, Can be affected by high solids concentrations, Requires specialized expertise for operation, Requires careful monitoring to prevent fouling	Lopez-Lopez et al., 2012 (Lopez-Lopez, 2012)
microbial fuel cell (MFC)	91.2% Total phospho rus	minimal energy use, Can be used to generate electricity, can handle many forms of wastewater treatment, No moving parts or chemicals required	Limited by low power output, Can be affected by high solids concentrations, Limited by low organic loading rates, Requires careful maintenance to prevent fouling	Erazo et al., 2023 (Erazo, 2023)
membrane bioreactor (MBR)	95% Nitrogen , 96%Am monium, 99% COD,	Excellent level of treatment efficiency, Compact design allows for small footprint, Produces high-quality effluent, Can handle high hydraulic and organic loads, Can remove a variety of contaminants, Long membrane lifespan	Can be expensive to install and operate, Requires careful maintenance to prevent fouling, and affected by fluctuations in pH and temperature , Membrane replacement can be costly	Ali Izadia et al., 2020 (Izadia, 2020)

photocatalytic oxidation process	80% (HA and FA)	Can effectively degrade a wide range of organic contaminants, requires no chemicals or additives, Can operate at ambient temperature and pressure, Can produce high-quality effluent, minimal energy use, and Long-term cost savings	Relatively slow process, Requires UV light source which can be expensive and energy-intensive, Limited lifespan of photocatalytic materials, Performance can be affected by water quality parameters	Gowland et al., 2021 (Gowland, 2021)
electrocoagulation process	96.2% true color (TC)	Effective at removing a variety of contaminants, involving NOM, Can operate at a diverse pH and salinity range, does not require the use chemicals or additional materials, Relatively fast treatment process, Can improve the settling properties of sludge	Requires a power source, which can be expensive, Can produce sludge that requires disposal, Electrodes can corrode and require replacement, Water quality characteristics might have an impact on performance.	de Oliveira et al., 2020 (de Oliveira, 2020)
a constructed wetland	80.8% NOM	A natural treatment process that doesn't require energy input, has Low maintenance requirements and operational costs, Creates a habitat for wildlife and enhances biodiversity, Can be aesthetically pleasing and integrated into the landscape	Can be affected by temperature and weather conditions, Requires a relatively large land area, May not be suitable for sites with high groundwater tables, Performing well can affected by hydraulic loading rates, Long start-up period before treatment efficiency is achieved	X. Lv et al., 2011 (Ruan, 2011)

anaerobic-aerobic bioreactor	95% Nitrogen	Can handle a broad range of organic loading rates, Can produce biogas, which can be used as an energy source Low sludge production compared to conventional treatment methods, Suitable for both municipal and industrial wastewater treatment	Requires a relatively large land area, Requires careful monitoring and management to maintain anaerobic-aerobic balance, Can be affected by changes in temperature and pH Can produce odors and require odor control measures, Initial capital costs can be high	Del Pozo et al., 2003 (Del Pozo, 2003)
hybrid ozone-biological process	COD 72%	A significant oxidising agent is ozone, which helps to break down organic matter and pathogens, customized to treat an extensive variety of wastewater kinds and flows, improve overall water quality and reduce the potential for waterborne diseases	Expensive to implement and maintain, Requires a significant quantity of energy to generate ozone, which can increase operating costs, Ozone is harmful to aquatic life if not properly managed and can create disinfection byproducts, run and maintain with an elevated level of technical expertise	Jagadevan et al., 2013 (Jagadevan, 2013)
combined process of ozone and hydrogen peroxide	89% anthracite and geosmins 90%	Highly effective at removing natural organic matter, Oxidizes a wide range of organic toxic material, Does not produce sludge or require disposal of spent media, and is easily integrated with other treatment processes	Higher cost of ozone and hydrogen peroxide, Ozone and hydrogen peroxide can be hazardous to handle Requires careful control of process parameters, and produce potentially harmful by-products	Beniwal et al., 2018 (Beniwal, 2018)

biological activated carbon (BAC) process	90% TOC	Effective at removing a variety of organic hazardous contaminants, the biodegradability of organic toxic contaminants, not producing harmful by-products, is used for pre-treatment or post-treatment, and is easily integrated with other treatment processes	Requires an additional carbon source for biological activity, is susceptible to fouling and clogging, May require periodic replacement of carbon media, Requires maintenance and monitoring, High capital and operational costs	Angelika Hess et al., 2021 (Hess, 2021)
membrane distillation process	98–99.8% DOC	The high rejection rate for natural organic matter Can operate at low temperatures and pressures, Can handle high levels of dissolved solids, is utilised for treating a variety of conditions of wastewater, Compatible with renewable energy sources	Limited flux and throughput, Membrane fouling and scaling Require regular cleaning and maintenance, Membrane replacement can be costly, Capital and operational costs can be high, Limited commercial availability and scalability	Muhammad Bilal Asif et al., 2021 (Asif, 2021)

3 Interaction between microalgae and bacteria

The interaction between bacteria and microalgae is an important biological process that serves an important role. Role in eliminating natural organic compounds from aquatic ecosystems, including wastewater. This symbiotic relationship entails the exchange of nutrients and metabolites between bacteria and microalgae, which leads to the efficient degradation of organic matter in aquatic ecosystems. Microalgae use sunlight and CO_2 for photosynthesis, which produces organic matter that serves as a substrate for bacteria. In turn, bacteria release nutrients that are utilised by microalgae (Leong, 2019). One promising approach to harness this symbiotic relationship is through the use of an integrated Bacterial-Microalgal Consortium, wherein bacteria and microalgae are co-cultivated in a photobioreactor. This technique has demonstrated remarkable potential in removing organic matter, phosphorus (P) and nitrogen (N) from wastewater while simultaneously producing biomass that is used as a valuable important asset in biofuel manufacture or as a fertilizer. The bacteria-microalgae interaction is a crucial process for efficiently removing organic material from aquatic ecosystems, and it holds promising applications in the treatment of wastewater and resource recovery (Tang, 2020). Figure 1 depicts a visual of the interactions and mechanisms of the Bacterial-Microalgal Consortium for organic pollutants elimination from organic wastewater.

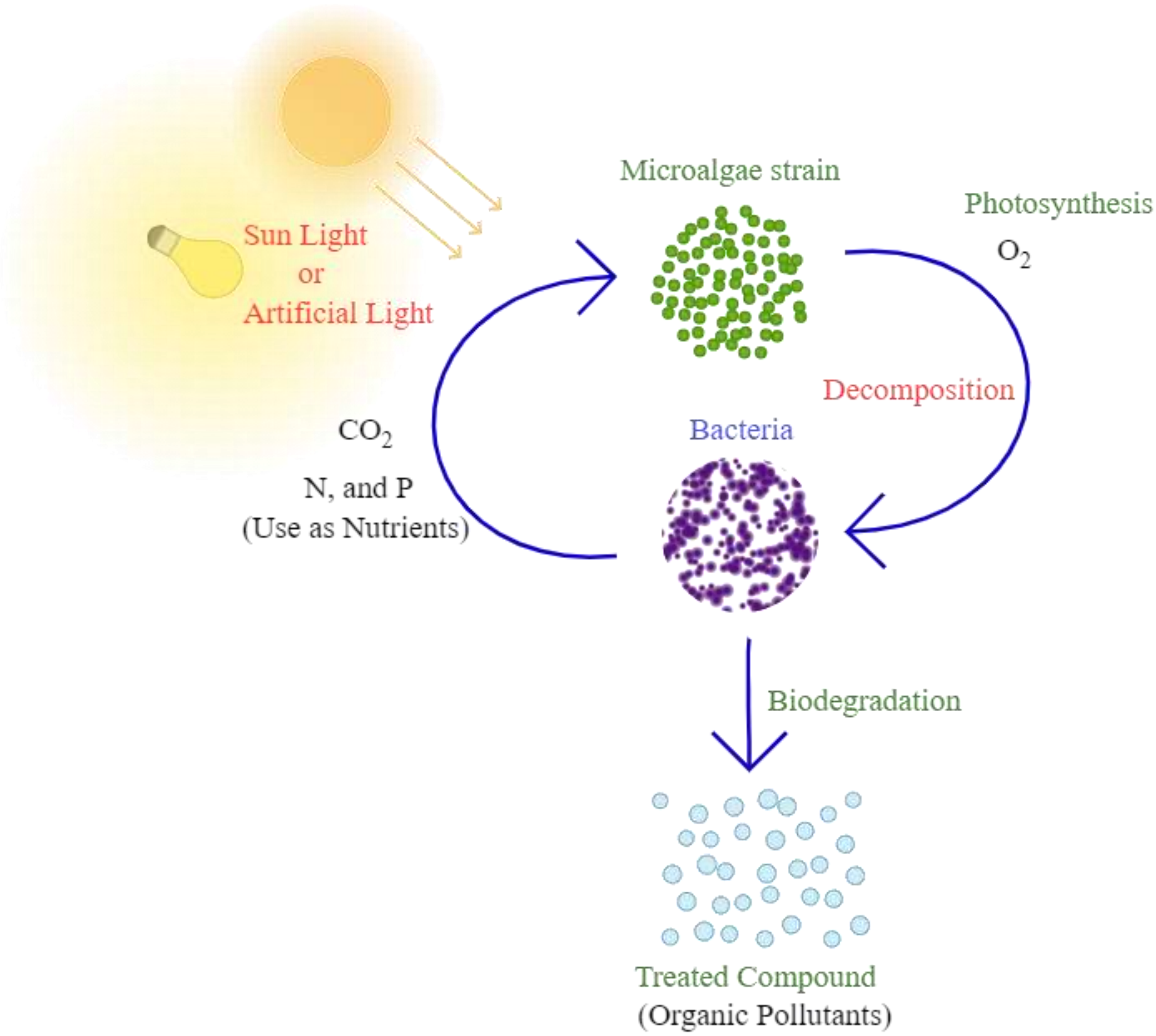

Fig.1 Mechanisms and interactions of Bacterial-Microalgal Consortium

3.1 Mutualism

The profound and intricate relationship between bacteria and microalgae is a type of symbiosis that embodies mutualism, a state in which both microorganisms benefit from each other's presence in a highly interdependent manner. In aquatic ecosystems, microalgae utilise the power of photosynthesis to produce organic matter, which bacteria then utilise as a substrate for their growth and metabolism. In turn, bacteria liberate vital nutrients such as phosphorus (P) and nitrogen (N) that are required for microalgae growth, thereby forging a harmonious and mutually beneficial relationship (Yong, 2021). This intriguing mutualistic interaction between bacteria and microalgae plays a pivotal role in removing organic matter and nutrients from aquatic ecosystems, including wastewater, thereby contributing to the maintenance of ecological balance. Notably, recent studies have shown that an integrated bacteria-microalgae system can efficiently remove pollutants from wastewater, paving the way for a sustainable and cost-effective approach to water treatment (Mathew, 2022). The mutualism between bacteria and microalgae is an indispensable process that holds immense potential for the development of sustainable treatment of wastewater technologies. The bacteria-microalgae mutualistic interaction can elicit synergistic effects that augment their abilities, such as bacteria providing microalgae with nutrients and growth-promoting factors, and microalgae reciprocating by supplying bacteria with oxygen and organic matter. This mutualistic relationship can result in increased biomass production, nutrient removal efficiency, and pollutant removal efficiency. In addition, the mutualistic interaction between bacteria and microalgae can augment the removal of pollutants from wastewater. Microalgae have the ability to remove pollutants through biosorption and biodegradation, while bacteria can biodegrade complex organic compounds. When combined, the integrated bacteria-microalgae system can efficiently remove pollutants from wastewater (Mustafa, 2021). Moreover, microalgae have an innate ability to absorb decomposed matter, which contributes to their nourishment and growth. Researchers conducted a groundbreaking experiment employing four distinct consortia, namely Phototrophic algae, heterotrophic zooflagellates, mixotrophs, and heterotrophic bacteria to study the coexistence of microorganisms. The study found that mixotrophs exhibit a range of mixotrophic strategies, includes virtual heterotrophy and virtual autotrophy, particularly when the system lacked carbon sources and had low phosphorus levels (0.0001 mol/m3). The researchers also proposed that for growth, heterotrophic bacteria could ingest DOC generated by other microorganisms, but heterotrophic zooflagellates relied solely on bacterial feed and light sources (Crane, 2010).

3.2 Interspecific Antagonism

In some situations, bacteria and microalgae can have competitive relationships. Factors like as nutrition availability, light intensity, and pH can all impact Antagonism amongst these microbes.

3.2.1 Nutrient Antagonism:

The fascinating realm of microbial ecology presents a complex dynamic of nutrient Antagonism between bacteria and microalgae, particularly in the treatment of wastewater facilities. The process of outcompeting, which refers to the ability of one organism to surpass another in nutrient consumption, is a common occurrence in these ecosystems. Nitrogen and phosphorus are two of the primary nutrients sought after by bacteria, and their affinity for these compounds can lead to microalgae being restricted in their growth. Conversely, microalgae can emerge triumphant in their Antagonism with bacteria for trace elements and micronutrients. Recent research delved into the nature of this nutrient rivalry between bacteria and microalgae in the treatment of wastewater systems. The study revealed that the introduction of bacteria to a microalgae-dominated system sparked heightened Antagonism for resources, thereby reducing the growth and productivity of microalgae. These findings underscore the potential for negative impacts on microalgae growth stemming from the prevalence of bacteria in the treatment of wastewater ecosystems (Han, 2022). Yet, not all is doom and gloom in this ecosystem. Some instances of mutualistic interactions have been observed, where bacteria and microalgae work together to remove nutrients from wastewater effectively. Microalgae can provide oxygen to the system through photosynthesis, thereby creating a supportive ecosystem for the growth of bacteria, which in turn consume nutrients. This collaborative effort results in the removal of nutrients from wastewater, which improves overall efficiency (Chen, 2011).

Light Antagonism:

Both bacteria and microalgae require light for their growth and metabolism. In environments with limited light, microalgae can shade out bacteria and limit their growth. Conversely, the high light intensity can favor bacteria over microalgae due to their ability to use organic carbon sources in the dark (Jiang, 2022) .the study found that the growth and photosynthesis of microalga Chlorella vulgaris were inhibited by the existence of the bacterium Pseudomonas aeruginosa, which competed for light and nutrients (Xiao, 2015). In contrast, another research the bacterium Bacillus amyloliquefaciens improved the growth and photosynthesis of microalgae Dunaliella tertiolecta by producing indole-3-acetic acid, a growth-promoting substance (Delgadillo-Mirquez, 2016).

3.2.2 pH Antagonism:

The optimal pH levels for bacteria and microalgae can diverge, generating Antagonism in ecosystems where pH levels vary. For instance, specific microalgae species tend to favour a slightly alkaline ecosystem, while certain bacterial strains prefer a slightly acidic one. This Antagonism ultimately affects the overall performance of bacteria-microalgae systems (Fuentes, 2016), and the pH of the aquatic ecosystem acts as a pivotal factor in shaping the dynamic between these microorganisms. In a recent researchers discovered that bacteria and microalgae had divergent pH preferences, granting a competitive edge to either group based on the pH levels present in the ecosystem. Concretely, at a pH of 8.5, microalgae displayed greater dominance, whereas at a pH of 7.5, bacteria were more formidable in nutrient consumption (Qi, 2021). Another investigation indicated that the dominance of either microalgae or bacteria in nutrient Antagonism was heavily influenced by pH, with microalgae exhibiting heightened competitiveness at higher pH levels. These findings highlight the criticality of regulating pH levels during the cultivation of bacteria and microalgae, as it can potentially exert momentous impacts on their growth and productivity (Mu, 2021).

4 Bacteria-Microalgae Consortia's Mechanisms for Removing Organic Pollutants from Waterbodies

Bacteria-microalgae consortia are being recognised as an effective and economically viable method for eliminating natural organic pollutants from water bodies. These consortia utilise various techniques to remove pollutants, such as adsorption, biodegradation, and biosorption. Furthermore, bacteria-microalgae consortia can recover valuable resources like biomass and lipids, which are employed in the development of biofuels along with high-value products. These methods present significant potential for reducing the ecosystem and economic costs of the treatment of wastewater while providing a source of renewable energy and other economically valuable products (Nagarajan, 2022).bacteria-microalgaeconsortia have emerged as a promising approach for eliminating organic pollutants from water bodies. The mechanisms underlying this process are still being investigated, but several studies have illuminated the potential strategies used by these consortia (Mojiri, 2022). One of the primary mechanisms for removing organic pollutants is utilising organic matter as a source of carbon for bacteria and microalgae. Microalgae are autotrophic organisms that can use inorganic carbon for photosynthesis, while bacteria are organic carbon and heterotrophic require. Consequently, the combination of bacteria and microalgae in a consortium enables the use of both inorganic and organic carbon sources, resulting in more effective organic pollutant removal. Along with carbon utilisation, bacteria-microalgae consortia can also eliminate organic pollutants through physical adsorption and biodegradation (Ronan, 2021). Physical adsorption occurs when organic pollutant molecules adhere to the surface of microalgae or bacteria, while biodegradation entails the breakdown of organic pollutants by enzymes secreted by microorganisms. Both of these techniques can help to eliminate organic contaminants from water bodies. Ecosystems factors like light intensity, pH, and nutrient availability can affect the efficiency of organic pollutant removal bybacteria-microalgaeconsortia. For instance, high light intensity can stimulate photosynthesis in microalgae, leading to increased carbon utilisation and organic pollutant removal (Oruganti, 2022). Similarly, optimal pH conditions for both bacteria and microalgae can boost their metabolic activities and enhance organic pollutant removal efficiency. Nutrient availability, particularly nitrogen and phosphorus, is also essential for microalgae growth and can influence the overall performance of the consortium (Yaakob, 2021).

4.1 Biosorption

Biosorption is the process by which microorganisms accumulate and bind pollutants onto their surfaces. This process is particularly effective for the elimination of heavy metals and organic pollutants in water. The electrostatic mechanism is involved in the biosorption mechanism attraction between the surface of the microorganisms and the charged pollutant molecules. The microorganisms can also secrete extracellular polymers, which act as binding agents for the pollutants, further enhancing the biosorption process. Biodegradation is another mechanism used by bacteria-microalgae consortia to remove organic pollutants. Biodegradation involves microorganisms that break down organic contaminants into simpler and less toxic compounds (Michalak, 2013). Microorganisms use the pollutants as a source of energy and nutrients for their metabolism. The biodegradation process is particularly effective for the elimination of organic pollutants like pesticides, herbicides, and hydrocarbons. Bioaccumulation is a process by which microorganisms absorb and accumulate pollutants within their cells. This process is particularly effective for the removal of persistent organic pollutants, which are resistant to biodegradation. The microorganisms can accumulate pollutants within their cells, and the concentration of pollutants can be reduced through subsequent harvesting of the microorganisms (Miglani, 2022). The waste biomass of Nostoc linckia was efficient in eliminating reactive dye from aqueous systems. The biosorption process was pH-dependent, with at pH 2, the clearance effectiveness of dangerous reactive red 198 dye (94%) was found. A pseudo-second-order model, showing that the biosorption process was chemically regulated, governed the adsorption kinetics. The greatest biosorption efficiency was 116.28 mg/g, showing the significant potential of *Nostoc linckia* biomass for the removal of reactive dye from wastewater. The study concluded that *Nostoc linckia* biomass can be a promising biosorbent for the treatment of textile effluents containing reactive dyes (Mona, 2011). The potential of cyanobacteria for decolorizing textile dyes were investigated. The cyanobacteria used in the study was Anabaena sp. and it was found to be capable of decolorizing the azo dye Reactive Red 198 within 48 hours of incubation. The best temperature and pH for decolorization were discovered to be 7.0 and 30°C, accordingly. The decolorization

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efficiency of the strain was found to be 96% and 98% for 50 and 100 mg/L concentrations of the dye, respectively. The study also showed that the presence of other chemicals such as salts and detergents did not significantly affect the decolorization efficiency of *Anabaena sp* (Parikh, 2005).

4.2 Biodegradation

Bacteria-microalgae biodegradation process involves the use of a consortium of microalgae and bacteria to eliminate organic pollutants from water bodies. Process relies on the ability of microalgae and bacteria to metabolize and degrade organic pollutants through various mechanisms such as biosorption, biodegradation, and biotransformation. microalgae play a crucial role in removing organic pollutants by adsorbing them onto their cell walls or intracellularly, while bacteria break down the pollutants into basic compounds that are able to utilised as a carbon and energy source. The metabolic products of microalgae and bacteria can further aid in the breakdown of organic contaminants through various chemical reactions. According to the study, the exposure of two strains, populi VP2, M. and A. sydowii VP4, to contaminated dirt extracts resulted in a notable reduction of most organic pollutants. The ability of these strains to degrade pollutants decreased as the concentration of AEC, or aqueous extract of contaminated soil, increased in the selective liquid medium. However, at 30% AEC concentration, M. populi VP2 displayed a remarkable ability to remove pollutants and generate novel products via enzymatic degradation and oxidation. Similarly, A. sydowii VP4 also removed pollutants and their byproducts at the same AEC concentration. These data imply that the strains recovered from severely polluted soil are pathogenic and utilised in aqueous soil extracts, Organic pollutants act in the same way as metabolic carbon does. A. sydowii VP4 outperformed M. populi VP2 in terms of biodegradation efficiency. This is due to changes in the cell's surface, which may have increased the cell permeability to hydrophobic compounds. This enhancement in cell permeability may have facilitated the degradation of pollutants largely (Sannino, 2016). The study by Ishchi and Sibi (2020) aimed to examine Chlorella vulgarises potential, a freshwater microalga, and the degradation of azo dyes. The researchers began by experimenting with characteristics such as starting dye concentration, biomass pH, temperatures, and content to determine the best conditions for dye breakdown. They discovered that a starting dye concentration of 50 mg/L, a pH of 7.0, a temperature of 30 °C, and a biomass content of 0.6 g/L resulted in the best dye breakdown. Using several models, the researchers also investigated the kinetics of dye degradation by C. vulgaris. They found that the process followed pseudo-first-order kinetics, indicating that the pace of dye degradation was proportionate to the dye's residual concentration. The rate constant for dye degradation was found to be 0.014 min^-1. C. vulgaris has been shown to be capable of eliminating azo dyes from wastewater, and the results could be useful for the optimization of large-scale treatment processes. The potential of microalgae for the decolorization and degradation of monoazo and diazo dyes was investigated. The microalgal strains used in the study were Chlamydomonas reinhardtii, Chlorella vulgaris, and Scenedesmus obliquus the findings revealed that all three microalgae strains decolorize and degrade the dyes. The highest decolorization rate was observed for Chlamydomonas reinhardtii with 97.3% decolorization of monoazo dye and 92.3% decolorization of diazo dye within 72 hours of incubation. Scenedesmus obliquus showed the highest degradation rate with 92.6% degradation of monoazo dye and 84.5% degradation of diazo dye within 168 hours of incubation. Chlorella vulgaris showed the lowest decolorization and degradation rates compared to the other two strains. The study concluded that microalgae have the potential as an inexpensive and effective method for eliminating textile dyes from untreated water (Ishchi, 2020).

4.3 Adsorption

Bacteria-microalgae adsorption is a process that involves the use of bacteria and microalgae to eliminate organic pollutants from bodies of water. The process relies on the ability of bacteria and microalgae to adsorb organic pollutants onto their cell surfaces, where they can be broken down and degraded (Touliabah, 2022). The selection of bacteria and microalgae is based on their ability to adsorb specific pollutants, which is due to the abundance of functional groups such as carboxyl, hydroxyl, and amine on their cell surfaces. In order to optimise the adsorption process, varied circumstances such as pH, salinity, and temperature are adjusted to alter the surface charge and hydrophobicity of the microorganisms (Abdelfattah, 2022).To ensure that the functional groups on cell surfaces are ionised and capable of adsorbing the pollutants, the pH of the solution is adjusted accordingly. Similarly, the temperature and salinity are altered to optimise the growth and metabolic activity of the microorganisms, which directly affects their ability to adsorb and degrade the pollutants. Once the pollutants have been adsorbed onto the cell surfaces, the microorganisms are separated from the water, and the pollutants can be desorbed using solvents or other desorption agents (Jeong, 2020). In a recent study conducted by Khader et al. (2022), to eliminate organic contaminants from generated water, a batch adsorption treatment was applied. The results indicated that the adsorption efficiency increased with increasing contact time and adsorbent dose, With a contact period of 120 minutes and an adsorbent dosage of 2 g/L, the best extraction efficiency of 99.97% was achieved. The best match for the experimental data was determined to be Langmuir isotherm model., demonstrating that monolayer adsorption occurred. Furthermore, the study found demonstrated the adsorption process followed pseudo-second-order kinetics, indicating that chemical adsorption was the rate-limiting phase. In summary, the study demonstrated that batch adsorption treatment using The adsorbent of choice was an efficient approach for eliminating organic contaminants from generated water (Khader, 2022).

5 Prospects for the Future and Limitations

The utilisation of integrated bacteria-microalgae consortia for the effective removal of organic compounds from water bodies has shown promising results and has the potential to become a viable solution for water pollution control in the future. One of the primary advantages of this approach is a natural and sustainable process that relies on the synergistic relationship between microalgae and bacteria. Microalgae are capable of fixing CO2 and using sunlight to produce organic compounds, while bacteria can degrade organic pollutants through various mechanisms, such as enzymatic degradation, adsorption, and biofilm formation. A study was conducted to assess the process of creating biofuel from microalgae developed anaerobically in digest wastewater. According to the findings, microalgae can minimise 57.4% of eutrophication issues, 2.7% of global warming, and 22.6% of O3, indicating that biofuel generation from microalgae combined with wastewater treatment is a potential technique. Microalgal biomass can also be utilised as a material for use for the production of proteins, carbohydrates, lipids, and vitamins. Therefore, the cultivation of microalgae holds great potential for sustainable and versatile applications in various industries (Abdelfattah, 2022). The combination of these two organisms in a consortium can

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result in the removal of organic pollutants from water bodies through a variety of mechanisms, including biosorption, biodegradation, and photodegradation. bacteria-microalgae consortia can effectively remove an extensive number of organic pollutants from water bodies, like pharmaceuticals, industrial chemicals and pesticides.In addition to their effectiveness in removing organic pollutants, bacteria-microalgae consortia have several other advantages over traditional wastewater treatment methods. For example, they require less energy and are more cost effective than traditional methods such as activated sludge treatment (Cuellar-Bermudez, 2017).They also produce valuable byproducts such as biofuels, bioplastics, and animal feed, which can help to offset the costs of the treatment process. Looking forward, there are several areas where further research and development are needed to fully realize the potential of bacteria-microalgae consortia for water pollution control. One area of research is the optimization of the consortium composition and cultivation conditions to maximize pollutant removal efficiency. This includes determining the optimal microalgae and bacterial species, as well as the optimal growth conditions such as nutrient concentrations, light intensity, and temperature. Scalable and inexpensive culture techniques for Bacterial-Microalgal Consortium. Current cultivation systems, such as photobioreactors, are often expensive and require large amounts of energy to operate. Developing more efficient and cost-effective cultivation systems will be key to making bacteria-microalgae consortia a viable solution for water pollution control on a larger scale. there is a need for further research on the long-term environmental effects of using bacteria-microalgae consortia for water pollution control. While these consortia are natural and sustainable, there is still a need to assess their impact on the wider ecosystem and ensure that their use does not cause unintended environmental consequences (Alazaiza, 2022).
Despite the potential benefits of using an integrated bacteria-microalgae consortium for the elimination of organic pollutants from water bodies, some limitations need to be addressed. the efficiency of the process is affected Temperature, the amount of light, and nutrition availability are all environmental influences. These factors can influence both bacteria-microalgae metabolism and development, which can affect the pace and amount of organic elimination of pollutants (Rahimi, 2020). The specificity of the bacteria-microalgae consortia for particular organic compounds may vary, and the consortium mightn't be effective for the elimination of all forms of pollutants. the maintenance of a stable consortium requires careful management, as changes in the composition of the consortium or the introduction of new microorganisms can have unpredictable effects on the process. The scale-up of the process from laboratory to industrial scale can be challenging, and the economic feasibility of the process needs to be carefully evaluated (Gururani, 2022).

6 Conclusion

The effective elimination of organic contaminants from water bodies is made possible by the incorporation of integrated bacterial-microalgal consortia. Findings of various studies suggest that these consortia can effectively remove contaminants like phenols industrial effluents, and other polluted water sources that come with polycyclic hydrocarbons (PAHs) and cyanotoxins. The synergistic interactions in bacteria and microalgae allow for the elimination of several contaminants, and the procedure is highly efficient and inexpensive. Research has also shown that utilising immobilized bacterial-microalgal consortia enhance the decontamination of pollutants as it allows for better retention and utilization of bacteria and microalgae within the system. Moreover, utilizing immobilized systems can help overcome several of the challenges connected to the maintenance of free-living bacterial-microalgal consortia, such as nutrient limitations and contamination. The success of integrated bacterial-microalgal consortia for pollutant elimination is largely depending on a number of parameters, such as the kind and quantity of pollutant concentration and formation of the consortium, and operating conditions. Optimization of these elements can result in higher removal efficiencies and better system performance.

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