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Review Article

# Bacterial Consortia as potential Bioremediation agents for Wastewater Treatment: A Comprehensive Review

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**Abstract**

Bioremediation has become a crucial technology to combat environmental pollution and waste management. This review amalgates the findings from several studies on the use of microorganisms precisely the immobilized bacterial consortia for the bioremediation of pollutants present in wastewater. The review features a variety of techniques such as use of electro spun bacterial nanofibers, microalgae predominant microbial consortia (MPMC) and other novel approaches to improve the efficiency of different bioremediation processes. This review also discusses the key challenges and future directions to present a thorough understanding of the existing condition and possible improvements in this field in the near future.

***Keywords:*** *Bioremediation, Microbial Consortium, Pollutants, Wastewater*

## Introduction

Bioremediation is a process in which biological organisms like bacteria, algae, fungi and plants are used to enzymatically degrade pollutants present in soil and water (Das and Chandran, 2011, Bala *et al.,* 2022). Microorganisms like bacteria, algae and fungi use these pollutants as source of energy for their metabolism and break them down into nutrients and organic matter which are non-toxic or less toxic to the environment and biodiversity (Zeyaullah *et al.,* 2009, Amin *et al.,* 2013). It is regarded as an eco-friendly and less expensive method to combat pollution in comparison to traditional methods like incineration, ocean dumping, landfilling, composting etc. (Bhada-Tata and Hoornweg, 2012; Divya *et al.,* 2015; Cao *et al.*, 2022; Nyika and Dinka, 2022).

Water is earth's most important natural resource. The ever-increasing population, urbanization and rapid industrialization are increasing water pollution (Ojha *et al.,* 2021; Choudhury *et al.*, 2019). Schweitzer and Noblet (2018) described water pollution as "the impairment of given water body with the presence of chemical, physical or biological components". World Health Organization stated that approximately one million people and 3,95,000 children under the age of five years die every year due to the use of polluted water (WHO, 2023). Water pollution has become an issue of global concern due to growing scarcity of sufficient quantity of clean water. Regular monitoring of changes in the quality of water from bodies like rivers and lakes due to anthropogenic activities, press the need of bioremediation.

Since many decades industries like the textile industry, the paper and pulp industry, pharmaceuticals, thermal power stations, food etc. are releasing their wastewater in different water bodies (Sharma and Chaudhary, 2015). 90% of the wastewater discharged from these industries into rivers is untreated and adversely affect the quality of water. According to a report presented by Central Pollution Control Board (CPCB), sewage and textile industry effluents are the major contributors of water pollution. Textile

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industry effluents mainly consist of dyes and heavy metals as pollutants (CPCB, 2023; River Rejuvenation Committee, 2020). Dyes are difficult to degrade and consequently persist in the environment for a long time (Couto, 2009). Presence of dyes in water makes it unacceptable for use due to its color and its carcinogenic, toxic and non-biodegradable nature (Rai *et al.,* 2005; Gupta, 2009; Forgacs *et al.,* 2004). Metal containing chemicals and metal containing complex dyes are used in pre-treatment processes like dyeing, printing and finishing. Generally, textile effluents consist of heavy metals like lead (Pb), arsenic (Ar), chromium (Cr), nickel (Ni), copper (Cu), cadmium (Cd), mercury (Hg) and zinc (Zn). Heavy metals bioaccumulate in tissues and are non-biodegradable due to their complex chemical forms. Sewage consists of water from sinks, washbasins, toilets, soap and detergents, vegetable and fruit peels, flowers, oil, paints and fertilizers (Saxena *et al.,* 2020). Traditional methods for treatment of sewage and wastewater like use of trickling filters, septic systems, waste stabilization ponds and sewage treatment plants are many a times inadequate or unsustainable promoting the application of new biological methods that apply microorganisms for the breakdown of pollutants (Metcalf *et al.,* 1991). This review discusses bioremediation of wastewater, emphasizing mainly on the efficiency and utilization of microbial consortia, the problems that arise while treating specific pollutants and the improvements in the wastewater treatment technologies.

**Bacterial consortium and its role in bioremediation**

Hydrolytic bacteria have the ability to reduce water quality parameters as they secrete hydrolytic enzymes like protease, amylase, lipase and cellulase (Purwaningrum *et al.,* 2021). These enzymes degrade organic pollutants by breaking the chemical bonds of toxic molecules present in water (Ethica *et al.,* 2018; Ethica *et al.,* 2017; Ethica and Sabdono, 2017; Sharma *et al.,* 2018; Karigar and Rao, 2011), thus they are important for bioremediation of sewage and wastewater. Hydrolytic bacteria that are efficient degraders are selected to form a consortium.

A bacterial consortium is a group of two or more bacteria that work synergistically. Unlike individual bacterial isolates, consortia utilize the degradation potential of diverse microorganisms to degrade complex pollutants completely and efficiently (Table 1). Bacterial consortia are effective in bioremediation as they exhibit several of the following attributes

a) Enhanced microbial diversity
   Ali *et al.,* 2009 showed that consortia consisting of several native bacteria were able to degenerate textile effluents, dyes and metals effectively. The microbial diversity in consortia have the capability to breakdown complex contaminants that monoculture systems might not be able to operate on efficiently.
b) Synergistic interactions
   Ethica *et al.,* 2019 evaluated the synergistic and antagonistic interactions between pathogenic and non-pathogenic bacteria before formulating a consortium that is to be used as a bioremediation tool. The study also emphasized on the increased degradation rates and efficiencies produced by interaction of different bacterial species as compared to individual strains.
c) Resilience to variability in environmental factors
   Memon *et al.*, 2020 analysed that immobilization of microbial consortia on natural matrices make them more stable by protecting them from toxic contaminants and pollutants, supplying nutrients for their growth and multiplicity as well as supporting their potential to biodegrade.
d) Complementary function
   Kour *et al.,* 2022 discussed that various bacteria present in a consortium can execute complementary functions. For instance, generating enzymes and biosurfactants which can disintegrate pollutants into simpler compounds that other bacteria can further degenerate.
e) Degradation of complex pollutants
   Dhote *et al.,* 2018 reported the application of specific consortium to degrade petroleum contaminated oil sludge, thus displaying that consortium can effectively handle complex mixtures of pollutants by integrated metabolic processes.

f) Adaptability and growth
Gutierrez *et al.,* 2022 demonstrated that bioaugmentation along with microalgae predominant microbial consortium accelerated the process of bioremediation of a sewage contaminated tropical swamp, emphasizing adaptability and growth advantages of consortia in stressful and harsh environmental conditions.

g) Non pathogenicity
Darmawati *et al.,* 2021 developed a three plate (MacConkey Agar Plate, Blood Agar Plate and Chocolate Agar Plate) pathogenicity scoring system for selecting only non-pathogenic bacteria from the isolates derived from biomedical wastewater to formulate bacterial consortium as bioremediating agent for hospital wastewater.

**Table 1**: Some studies related to bioremediation of wastewater by bacterial consortia and individual bacterial strains

| Bacterial Consortia/Individual Strains | Application/ Action | Reference |
|---|---|---|
| *Bacillus coagulans, Bacillus licheniformis, Bacillus pumilus, Bacillus subtilis, Nitrosomonas* sp., *Pseudomonas putida* | Bioremediate industrial wastewater at Cisirung Waste Water Treatment Plant effectively by reducing BOD by 71.93%, COD by 64.30%, TSS by 94.85% and ammonia by 88.58%. | Safitri *et al.,* 2015 |
| Autochthonous bacteria (indigenous bacteria from the environment) | Degrade organic matter in sewage wastewater | Dhall *et al.,* 2012 |
| Various indigenous hydrolytic bacteria | Bioremediation of biomedical wastewater. | Ethica and Sabdono, 2017 |
| Defined consortium including *Bacillus subtilis, Pseudomonas aeruginosa* (Oil Buster) | Absolute degradation of oil sludge in 20 days. | Dhote *et al.,* 2018. |
| *Bacillus paramycoides, Alcaligenes faecalis* | 100% removal of pharmaceutical compounds in hospital wastewater. | Rashid *et al.,* 2022 |
| *Pseudomonas aeruginosa, Cronobacter sakazakii, bronchispetica Klebsiella oxytoca and Bordetella* | Remove oil from light crude oil when immobilized on corn qgualh, loofah, palm leaf raffia and sponge biocarriers. | Samhan *et al.,* 2017 |
| *Bacillus subtilis* DM-04, *Pseudomonas aeruginosa* M and NM strains | Biodegrade petroleum-oil | Das and Mukherjee, 2007 |
| *Bacillus* sp. AKS2, *Pseudomonas aeruginosa* AKS1 | Degrade crude oil | Chettri *et al.,* 2016 |
| Indigenous bacterial isolate *Nesterenkonia lacusekhoensis* | Remove 11 different types azo dyes namely Methyl red, Tartrazine, Ponceau S, Reactive red 35, Evans blue, Acid red 3R, Acid red, Violet C BL, Reactive violet, Red AG and Methyl orange. | Prabhakar *et al.,* 2022 |
| *Pseudomonas aeruginosa* NY3 | Remove hydrocarbon | Nie *et al.,* 2016 |
| *Streptomyces* sp. | Prevent the multiplication and growth of pathogens | Hossain and Rahman, 2014 |
| *Staphylococcus aureus* and *Bacillus subtilis* | Reduce the levels of pH, BOD and COD in sugar factory wastewater. | Pardamean *et al.,* 2021 |
| Four isolates *Psedomonas otitidis* (K1NA3 and K2NA3), *Acinetobacter haemolyticus* (CNA1) and *Vogesella perlucida* (PRO4NA1) | Remove nitrogenous compounds from aquaculture systems | Ilma *et al.,* 2022 |
| Two isolates CM-S1 and CV-S1 belonged to the genus *Enterobacter* | Possess the ability to degrade malachite green dye in textile effluents | Roy *et al.,* 2020 |
| *Enterobacter* strains namely *E. kobei* (SCUF0000311), *E. cloacae* (SCUF0000312 and *E. hormaechei* (SCUF0000313) used solo and as consortium | Worked to remove heavy metals from industrial wastewater | Kelany *et al.,* 2023 |

| | | |
|---|---|---|
| A bacterial consortium comprising of 17 isolates (PETBA 01- PETBA 19) belonging to the families *Xanthomonadaceae, Brachybacterium* sp., *Martellela* sp., *Cytophaga* sp., *Sphingomonas* sp., *Sphingopyxis* sp., *Bhargavea* sp., *Mesorhizobium* sp. (3), *Gordonia* (4), *Thalassospire* sp., *Psedomonas* sp. And *Dietzia* sp. entrapped in chitosan beads were used. | Bioremediate oil contaminated mangrove sediments | Angelim *et al.,* 2013 |
| Two isolates namely *Enterobacter cloaceae* 279-56 (R4) and *Pseudomonas otitis* MCC10330 (R19) were used individually. | Eliminate oil content and remove organic load from industrial wastewater | Zabermawi *et al.,* 2022 |
| A strain of purple non-sulphur bacterium *R. capsulatus* was immobilized on iron oxide biochar nanocomposite product. | Remove nutrients like N, P and COD from wastewater. | He *et al*., 2017 |
| Bacterial consortium of *Alcaligenes faecalis, Staphylococcus haemolyticus*, *S. aureus* and *Proteus mirabilis* was immobilized on natural support matrix luffa. | Treatment of pharmaceutical industry wastewater. | Murshid and Dhakshinamoorthy, 2021 |
| MCSt-1 microbial consortium consists of *Enterococcus hirae*, *E. faecium*, *E. xinjiangensis, Klebsiella pneumoniae*, *Stenotrophomonas maltophila* and *Enterobacter mori* immobilized on nylon mesh. | Reduce organic load and nutrient removal from wastewater and improves efficiency of wastewater treatment plants. | Jha *et al.,* 2021 |
| Microbial consortium consisting of 8 bacterial isolates belonging to the genera *Mesophilobacter, Methylococcus, Agrobacterium, Neisseria, Xantobacter, Deinococcus, Sporosarcina* and *Bacillus*. | Clean pollutants in batik water and significant decline in BOD. | Muchtasjar *et al.,* 2019 |
| A bacterial consortium was obtained from commercial BIOWiSH Aqua consists mainly of *Pediococcus acidilactici, P. pentosaceus*, *Lactobacillus plantarum* and *Bacillus subtilis.* | Improve water quality parameters like BOD, COD, TS, TDS, TSS, ammonia, nitrate and TRN of Quhafa wastewater treatment plant influent. | Ibrahim *et al*., 2020 |
| An individual cyanobacterial strain *Leptolyngbya* sp. was used. | Remediate toxic materials like phosphate, nitrate, sulfate, cyanide and phenol present in coke oven effluent. | GuhaThakurta *et al.,* 2018 |
| Two novel strains *Lysinibacillus sphaericus* and *Aeromonas hydrophila* were used. | Highly decolourise four textile azo dyes namely Joyfix Red, Remazol Red, Reactive Red and Reactive Yellow in textile wastewater. | Kumar *et al*., 2016 |
| Bacterial isolates *Acinetobacter* sp. RTE1.4 and *Rhodococcus* sp. CS1 were used. | Remove phenolic compounds from effluents derived from tannery and chemical industry. | Paisio *et al.,* 2014 |
| A single bacterial isolate *Bacillus* sp. was used. | Remove hexavalent chromium from wastewater. | Seragadam *et al.*, 2021 |
| Bacterial consortium of *Bacillus cereus, Exiguobacterium aurantiacum, E. indicum* and *Acinetobacter baumannii* were used. | Degrade azo bonds in dyes to produce non- toxic amines. | Chaurasia *et al.,* 2022 |

Coelho *et al.,* 2015 developed a pie chart (Figure 1.) showing microorganisms like bacteria, yeast, fungi and algae that are commonly used for bioremediation processes. This chart was prepared by them based on papers indexed in ISI Web of Science (2004-2014) reporting the use of microorganisms in bioremediation studies which clearly shows that bacteria hold the largest portion in the chart as compared to the other microbes.

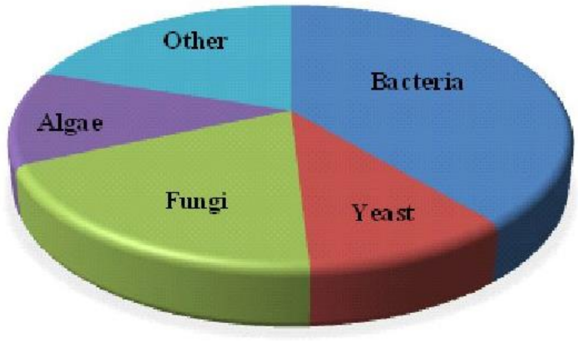


Figure 1: Commonly used microorganisms in bioremediation processes (Coelho *et al.,* 2015)

**Comparative analysis of the efficacy of bacterial consortia with other methods of wastewater treatment has also been reviewed:**

**Conventional Wastewater Treatment Methods**

Conventional wastewater treatment involves physical, chemical and mechanical removal of contaminants from wastewater. These methods need large energy inputs for aeration and chemical processes, rely on chemicals like chlorine and alum for coagulation and disinfection and generate large amount of sludge that is toxic and difficult to dispose. Table 2 depicts a comparative assessment of wastewater treatments. Some of these conventional methods have been discussed below:

**A) Activated Sludge Process**

Activated sludge process is used to remove the nutrients and organic matter, reducing biochemical oxygen demand (BOD) and suspended solids efficiently from wastewater. It can adjust to the different types of wastewaters but quickly responds to the toxic substances and sudden changes in the composition of wastewater (Grady *et al.,* 2011). One of the disadvantages of using this technique is sludge generation that needs proper disposal as it can lead to secondary pollution (Tchobanoglous *et al.,* 2003). Though this process is an effective process but it has high operational complexity requiring continuous monitoring and explicit control over factors like aeration, sludge age and other factors as well as requires enormous energy (Rittmann and McCarty, 2001; Metcalf and Eddy, 2014).

**B) Membrane bioreactors (MBRs)**

Membrane bioreactors are highly competent in eliminating organic matter, nutrients and pathogens producing good quality water. They can work with various types of wastewaters but are highly sensitive to membrane fouling. In comparison to conventional methods, membrane bioreactors produce less sludge. Operation of bioreactors also demands high energy and regular maintenance of membranes. Further, dumping of used membranes can create environmental challenges. This process too has operational complexity and its optimal performance requires systematic maintenance and thorough cleaning processes (Judd, 2010; Meng *et al.,* 2017).

**C) Constructed wetlands**

Removal of nutrients and organic pollutants from wastewater can be done by wetland construction. The effectiveness of wetlands fluctuates with the design and operational conditions. Although performance of such wetlands is limited by the climatic conditions and the accessibility of space still, they can adapt to various types of wastewaters. The operational cost of wetlands is low, but the necessity of high land area can increase its cost capital. The benefit of using this technique is that it is ecofriendly, provides habitats to wildlife and improves native biodiversity. Though wetlands have low operational complexity they require monitoring and periodic maintenance (Ilyas and Masih, 2017; Vymazal, 2011a; Wu *et al.,* 2015).

### D) Advanced oxidation processes (AOPs)

The processes of advanced oxidation are efficient in degrading recalcitrant organic pollutants, pathogens, micropollutants and other emerging contaminants. AOPs frequently require pretreatment to optimize their performance but can work with different types of wastewaters. They demand high power inputs and chemical reagents that escalate their operational cost. If not cautiously restrained, AOPs can generate secondary pollutants which adversely affect the environment. They too have a high operational complexity as it demands strict regulation over reaction conditions and the quantity of oxidants supplied (Rizzo *et al.,* 2013; Wang and Xu, 2012).

Table 2: Comparative analysis of the conventional wastewater treatment methods and bacterial consortia

| Technique | Contaminant Removal | Adaptability | Cost-Effectiveness | Impact on environment | Operational complexity |
|---|---|---|---|---|---|
| **Bacterial Consortia** | High | High | High | Environment friendly | Moderate |
| **Activated sludge** | High | Moderate | Moderate | Potential secondary pollution | High |
| **MBRs** | Very High | High | Low | Sludge production | High |
| **Constructed wetlands** | Moderate to High | Moderate | Low operational | Very eco friendly | Low |
| **AOPs** | Very High | Moderate | Low | Potential secondary pollutants | High |

### Other Bioremediation Methods

Some of the biological bioremediation processes are discussed below and their comparative assessment summarized in table 3.

### E) Phytoremediation

Phytoremediation has a slower degradation rate than bacterial consortia because plants generally need time for assimilation and degradation of pollutants. The acclimatization of phytoremediation is restricted to defined pollutants like heavy metals and particular environmental conditions. Plants are economical in improving soil structure and fertility. Therefore, this method is considered as eco-friendly and sustainable. The biggest disadvantage of using phytoremediation is the demand for larger land areas and longer time frames to achieve the desired result (Vymazal, 2011b; Rai *et al.,* 2019). According to Rai *et al.,* 2019 the method of phytoremediation could be used to remove heavy metals from soil and water. This method is effective but really slow and easily affected by plant growth cycles. Plants like *Brassica juncea, Helianthus annuus*, willow, *Vetiveria zizaniodes* and water hyacinth have been used.

### F) Mycoremediation

Fungi have slower degradation rate as compared to bacterial consortia but they are highly effective in breaking down pesticides, petroleum hydrocarbons and other complex organic compounds. Fungi are tolerant to hostile environmental conditions and possess the potential to degrade a vast range of pollutants due to their high adaptability. Fungi promote ecological balance thus creating a positive impact on the environment. Mycoremediation is a low maintenance process when indigenous fungal species are used (Muliyadi *et al.,* 2022; Khan *et al.,* 2013). Mulyadi *et al.* (2022) have exhibited the use of fungus like *Pleurotus pulmonarius* for treatment of dye containing textile wastewater although the process is time consuming. *Aspergillus niger, Aspergillus fumigatus* and *Aspergillus niveus* are a few fungi that have the potential for bioremediation (Saeed *et al.,* 2022).

### G) Phycoremediation

Phycoremediation has emerged out as an effective method to remove nutrients from wastewater and degrade organic pollutants. Environmental factors like light and temperature significantly affect its degradation rate. Although algae are adaptable to many different water bodies, their efficiency changes with change in environmental conditions. It is advantageous to use algae for treatment of wastewater because algae liberate oxygen during the process which improves the quality of water and supports aquatic life. Low operational cost makes phycoremediation cost effective but it is challenging to use algae on a large scale as its uncontrolled growth can lead to algal blooms and massive deaths of marine life. Algae like *Spirulina platensis, Chlorella* sp*., Scenedesmus obliquus, Anabaena sphaerica, Nannochoropsis oculata* and others have been used so far for treatment of wastewater (Olguin *et al.,* 2003; Li *et al.,* 2011; Xin *et al.,* 2010; Abdel-Raouf *et al.,* 2012; Deniz and kepekci, 2015). The microalgae *Chlorella minutissima,* can be grown in nutrient rich sewage wastewater reducing its pollutant load. The water then has nutrients and contaminants within the safe limit and can be used to irrigate agricultural fields (Sharma *et al*., 2020).

### H) Bacterial Consortia

Bacterial consortia have shown remarkable performance in bioremediation of wastewater because of several important factors such as the increased rate of degradation attained by bacterial consortia in contrast to monoculture systems. This rise in efficiency is accounted to the cooperative interactions between various species within the consortia, which collectively boost the bioremediation process and result in fast and absolute degradation of pollutants. Bacterial consortia can survive under a wide range of environmental conditions and target broad spectrum of pollutants because they manifest the trait of high adaptability. The attribute of versatility makes them precious for treating different types of wastewaters. Use of bacterial consortia decreases the dependence on chemical treatments and diminishes secondary pollution. Furthermore, the use of native bacterial consortium cuts down the requisite external input and costly chemicals, thereby decreasing the overall treatment costs and making the application of bacterial consortia cost effective. These microbes are preferred bioremediating agents due to their ability to be easily manipulated and they have rapid growth (Ayilara and Babalola, 2023). All these traits make bacterial consortia a powerful and sustainable tool for bioremediation of wastewater. For instance, many studies have demonstrated that bacterial consortia had surpassed individual strains in destruction of petroleum hydrocarbons due to their high degradation rates when applied to the field (Gogoi *et al.,* 2003). Nayak *et al.,* 2024 used microbial fuel cells comprising bacterial consortia to treat industrial wastewater which resulted in efficient degradation of pollutants along with power generation.

**Table 3:** Comparative analysis of different biological bioremediation processes

| Method | Degradation Rate | Adaptability | Environmental Impact | Cost-Effectiveness |
|---|---|---|---|---|
| **Bacterial Consortia** | High | High | Environmentally friendly | High |
| **Phytoremediation** | Moderate | Moderate | Environmentally friendly | Low |
| **Mycoremediation** | Moderate | High | Positive | Moderate |
| **Phycoremediation** | Moderate | Moderate | Positive (oxygen production) | Moderate |

### Case Studies and application of bacterial consortia in bioremediation of contaminated water

In 1989, Exxon Valdez oil spill took place in Alaska when a tanker collided with a reef releasing approximately 11 million gallons of crude oil into the sea (Jain *et al.,* 2011). Consequently, the sea and seashore became contaminated with oil adversely affecting the regional ecological communities (Atlas, 1995). This spill caused the death of 250 thousand sea birds (Mapelli *et al*., 2017). A bacterial consortium consisting of bacteria mainly belonging to genera *Pseudomonas*, *Alcanivorax* and *Rhodococcus* was applied to the site to degrade the hydrocarbons in the oil. The consortium worked efficiently by breaking down the oil and notably decreasing the impact of spill on the environment. Gradually, the native microbial populations were able to grow and multiply, thereby supporting the bacterial consortium in reviving the affected area (Baniasadi and Mousavi, 2018; Brooijmans *et al.,* 2009; Boufadel *et al.,* 2016).

The operations conducted by the military have led to chemical contamination of the soil and associated groundwater in Area 6 of Dover Air Force Base, Delaware. Chlorinated solvents that pollute the soil and water, mainly consist of trichloroethylene (TCE) and perchloroethylene (PCE) (Davis *et al.,* 2002). It was decided to achieve site specific cleanup by following "monitored natural attenuation" (Clement *et al.,* 2000). A consortium of bacteria including *Dehalococcoides* spp. was inoculated to the contaminated site because it can utilize sodium lactate provided as substrate to multiply and convert toxic chlorinated solvents to non-toxic ethene by reductive dichlorination. There was drastic decrease in the level of contaminants and improvement in quality of groundwater after the utilization of the consortium (Bloom, 2015).

More than 300 oil lakes were created in Kuwait after the Gulf War in 1990 (Al-Awadhi *et al.,* 1996, Islam *et al.,* 2018). About 20-25 barrels of oil seeped out at that time causing massive soil contamination (Al-Gharabally and Aisha-Al-Barood, 2015). Bioremediation was considered as one of the techniques that can be used to remediate the contaminated soil and was widely studied (Balba *et al*., 1998; Cho *et al.,* 1997). These studies have detected several potential hydrocarbon degrading microorganisms such as *Hyphomicrobiaceae, Porphyromonadaceae* and *Eurotiomycetes* (Bruckberger *et al.,* 2019). Overtime, these microbes have successfully degraded petroleum and recovered the soils health and fertility.

**Technological advancements in the field of bacterial bioremediation of wastewater**

Combination of innovative techniques and new materials can open avenues for application of bacterial consortia for bioremediation in various industrial and environmental sectors.

**a) Improved Immobilization and Encapsulation Techniques**

- Biofilm based Reactors- Usually bioreactors like moving bed biofilm reactors (MBBR) and fixed film bioreactors are used to treat contaminated wastewaters. Their capabilities are enhanced by employing natural matrixes like coconut coir, walnut shell and others for better adhesion and multiplicity of bacterial consortia cells on membranes, resulting in efficient bioremediation with cost effective and non-toxic immobilization materials (Memon *et al.,* 2020; An *et al.,* 2024).
- Microencapsulation- Modern microencapsulation techniques provide protection to bacteria and their steady supply in wastewater (Aeron and Morya, 2017). Techniques like freeze drying and electrospinning are used to encapsulate bacterial strains into microcapsules and nanofibers respectively (Ethica *et al.,* 2020; Ethica *et al.,* 2021, Valdivia-Rivera *et al.,* 2021). *Pseudomonas aeruginosa* has been encapsulated within polyethylene oxide (PEO) and polyvinyl alcohol (PVA) for electro spun nanofibrous membrane. This membrane was employed to remove methylene blue dye (Sarioglu *et al*., 2017). Zamel and Khan (2021) devised bacterial immobilized cellulose acetate nanofibers for dye removal from industrial wastewater.
- Immobilization using cryogel- Cryogels have certain desirable features like high mechanical strength which make them an ideal biocarrier to protect their inherent macroporous structure, non-toxic nature, low cryogelation temperatures and defrosting at room temperatures (Okay and Lozinsky, 2014). Additionally, cryogels have wide interconnected pores for immobilization of bacteria, high biological stability and efficient mass transfer systems for enhancing biodegradation (Ai-Jwaid *et al.,* 2018). Cryogels are actually a type of hydrogel which is formed by polymerization at some zero temperatures. Gradually, hydrogels are becoming popular in the field on bioremediation due to their high efficiency, high degradation rates and adversity resisting properties. Among other hydrogels, BI hydrogel has qualified as a smart material to be used for bioremediation (Mehrotra *et al*., 2021).

- 3D Printing of Immobilization Carriers- 3D printing is a pioneering technology that presents high control over the shape, size and surface area of the printed objects. One of the critical advantages of using this technology in bioremediation is to be able to design carriers with intricate features that can improve microbial colonization and efficient degradation of toxic pollutants (Duty *et al.,* 2017). Schaffner *et al.* (2017) developed a living and functional material by encapsulating bacteria *Pseudomonas putida*. This material was biocompatible, consisting of sodium hyaluronate and glycidyl methacrylate, and was capable of degrading a common contaminant phenol after 40h into non-poisonous biomass. The University of Rochester have developed a method for 3D printing of genetically modified *E. coli* biofilms for detoxification and bioremediation purposes (Meyer, 2020; Finny, 2024).
- Immobilization by magnetic nano particles (MNPs) - The growing use of magnetic nanoparticles for immobilization of bacteria is due to the ease in the separation and recovery of these particles by application of magnetic field and enhancement in efficiency and reusability of particles. Gram positive bacteria *Bacillus subtilis* were immobilized on iron oxide nanoparticles by Nadi *et al.* (2018). These $Fe_3O_4$ nanoparticles degraded azo dyes present in water and increased the degradation rate to 80%. These nanoparticles could be reused up to 7 batch cycles.

**b) Enhanced bacterial Strains**

- Rapid progress in the field of synthetic biology have led to genetic modification of bacterial strains to amplify their potential to degrade recalcitrant pollutants, withstand toxic conditions and metabolize a large range of contaminants (Xue *et al.,* 2022a). French *et al.,* 2020 genetically modified *E. coli* to overexpress three enzymes namely almA, XylE, p450cam increasing degradation of target hydrocarbon substrates to 60-99%. Upon death these *E. coli* cells pass the vector containing the genes to local microbial communities to continue degradation of substrates. Xue *et al.* (2020b) designed genetically engineered *E. coli* cells that are programmed to express $Hg^{2+}$ adsorption proteins only when $Hg^{2+}$ concentration in water crosses the threshold limit. These cells absorb $Hg^{2+}$ from the surrounding contaminated water. These are programmed to die when $Hg^{2+}$ concentration drops below the threshold. These cells could be reused for 5 cycles with adsorption efficiency more than 95%.

**c) Use of sustainable and biodegradable materials**

- Plant based materials- Environment friendly alternatives to synthetic polymers like lignin, cellulose based materials are explored to obtain sustainable and biodegradable carriers for bacterial immobilization (Armanu and Volf, 2022; Safitri *et al*., 2015; Samhan *et al*., 2017; Dzionek *et al.,* 2016).
- Eco-friendly biopolymers- Development of biodegradable polymers like polyhydroxyalkanoates (PHA) for encapsulation of bacteria. These polymers have less environmental impact after use (Sharma *et al.,* 2024).

**d) Nanotechnology in bioremediation**

- Nanoparticle based carriers- Nano remediation is an effective method as compared to other methods of pollutant removal because of low cleanup cost and minimal amount of production of toxin (Mandeep and Shukla, 2020). Nano particles are used to eliminate fatal contaminants like xenobiotics, synthetic dyes and heavy metals (Chaudhary *et al.,* 2023).

## Discussion

This review article emphasizes the considerable potential of bacterial consortia as a revolutionary approach to wastewater treatment. The ability of these microbial assemblages to degrade a broad array of pollutants cooperatively, to improve treatment stability, and to expedite resource recovery, offers potent benefits over traditional methods. Many documented cases have been discussed in this article where various consortia have removed complex and recalcitrant pollutants successfully highlighting the power of microbial cooperation, superior performance compared to monocultures, and resilience against environmental fluctuations. Growing emphasis on sustainable wastewater management lead us to discuss certain consortia with the ability to facilitate nutrient recovery and bioenergy production as these systems can contribute to a circular economy by transforming waste into valuable resources and reduce the impact of treatment processes on environment.

**Challenges in field applications**

1. Fluctuating environmental factors like temperature, oxygen, nutrient availability etc. which affect the efficiency of microbial consortiums when used in field
2. The increasing complexity of pollutant mixtures namely polycyclic aromatic hydrocarbons (PAHs) (Vidali, 2001; Mckew *et al*., 2007), polychlorinated biphenyls (PCBs) (Wantanabe, 2001; Hesnawi *et al.* 2014), dioxins and furans (Gupta *et al.,* 2013; Singh *et al.,* 2016), synthetic dyes (Dos Santos *et al.,* 2007; Katheresan *et al.,* 2018), pharmaceutical compounds (Sharma and Chaudhary, 2015; Ghosh, 2006), plasticizers and microplastics (Malik *et al.*, 2014; Velusamy *et al.,* 2021) which are a challenge to enzymatic degradation by microbial consortia and have a high possibility of forming toxic intermediates due to incomplete breakdown.
3. The demand for cheap and expandable solutions that can be applied to developing countries and countries with large populations like India.

There is a compelling need for:

- Developing optimized nonpathogenic microbial consortiums that can be applied to the field directly.
- Enhancing the degradation potential of microbes with the help of genetic engineering.
- Developing integrated bioremediation systems that combine physical, chemical and biological methods.
- Developing microbial bioremediation technologies to extract heavy metals present in wastewater so that these heavy metals can be reused.
- Developing bioremediation technologies that produce byproducts such as biodiesel that can be used as an alternative source of energy.
- Developing techniques to produce microbial enzymes, purifying them, stabilizing them and using them directly for bioremediation.
- Developing better, cheaper, biodegradable and eco-friendly matrices for immobilization of microbial consortiums.
- Devising new techniques for immobilization, encapsulation and adherence of microbial consortiums.
- Developing self-healing and adaptive polymers that possess the capability to repair themselves after physical or chemical damage, continuing to protect bacteria and do not interrupt their bioremediation activity.

**Conclusion**

Currently, the utilization of microorganisms in bioremediation presents a sustainable and effective approach for managing waste and environmental pollutants. This review converges the remarkable progress made in the field of bioremediation of wastewater and stresses on the urgent need for profound researches and innovations to meet the increasing challenges of environmental pollution. Figure 2 outlines the key points of this review article.


Figure 2: Summary of edge of bacterial consortia over other wastewater treatment methods

## Conflict of Interest

The authors declare no conflict of interest.

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## References

Abdel-Rouf, N., Al-Homaidan, A. A., & Ibraheem, I. B. M. (2012). Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences*, *19*(3), 257-275. https://doi.org/10.1016/j.sjbs.2012.04.005

Aeron, G., & Morya, S. (2017). Immobilization and microencapsulation. J Adv Res Biotech, 2(3), 1-4. http://dx.doi.org/10.15226/2475-4714/2/3/00129.

Al-Awadhi, N., Al-Daher, R., ElNawawy, A., & Salba, M. T. (1996). Bioremediation of oil-contaminated soil in Kuwait. I. landfarming to remediate oil-contaminated soil. *Soil and Sediment Contamination*, *5*(3), 243-260. https://doi.org/10.1080/15320389609383528

Al-Gharabally, D., & Al-Barood, A. (2015). Kuwait environmental remediation program (KERP): remediation demonstration strategy. *Biological and Chemical Research*, *2015*, 289-296. http://www.ss-pub.org/wp-content/uploads/2015/09/BCR2015051501.pdf

Ali, N., Hameed, A., & Ahmed, S. (2009). Physicochemical characterization and bioremediation perspective of textile effluent, dyes and metals by indigenous bacteria. *Journal of Hazardous Materials*, *164*(1), 322-328. https://doi.org/10.1016/j.jhazmat.2008.08.006

Al-Jwaid, A. K., Berillo, D., Savina, I. N., Cundy, A. B., & Caplin, J. L. (2018). One-step formation of three-dimensional macroporous bacterial sponges as a novel approach for the preparation of bioreactors for bioremediation and green treatment of water. *RSC Advances*, *8*(54), 30813-30824. https://doi.org/10.1039/C8RA04219E

Amin, A., Naik, A. R., Azhar, M., & Nayak, H. (2013). Bioremediation of different waste waters-a review. *Continental Journal of Fisheries and Aquatic Science*, *7*(2), 7. https://doi.org/10.5707/cjfas.2013.7.1.7.17

An, X., Wang, Y., Yu, C., & Hu, X. (2024). Biochar-bacteria coupling system enhanced the bioremediation of phenol wastewater-based on life cycle assessment and environmental safety analysis. *Journal of Hazardous Materials*, *480*, 136414. https://doi.org/10.1016/j.jhazmat.2024.136414

Angelim, A. L., Costa, S. P., Farias, B. C. S., Aquino, L. F., & Melo, V. M. M. (2013). An innovative bioremediation strategy using a bacterial consortium entrapped in chitosan beads. *Journal of Environmental Management*, *127*, 10-17. https://doi.org/10.1016/j.jenvman.2013.04.014

Armanu, E. G., & Volf, I. R. I. N. A. (2022). Natural Carriers for Bacterial Immobilization Used in Bioremediation. *Universitatea Tehnică "Gheorghe Asachi" din Iaşi. Iasi*, 109-122. DOI: 10.5281/zenodo.7545779

Atlas, R. M. (1995). Petroleum biodegradation and oil spill bioremediation. *Marine Pollution Bulletin*, *31*(4-12), 178-182. https://doi.org/10.1016/0025-326X(95)00113-2

Ayilara, M. S., & Babalola, O. O. (2023). Bioremediation of environmental wastes: the role of microorganisms. *Frontiers in Agronomy*, *5*, 1183691. https://doi.org/10.3389/fagro.2023.1183691

Bala, S., Garg, D., Thirumalesh, B. V., Sharma, M., Sridhar, K., Inbaraj, B. S., & Tripathi, M. (2022). Recent Strategies for Bioremediation of Emerging Pollutants: A Review for a Green and Sustainable Environment. *Toxics*, *10*(8), 484. https://doi.org/10.3390/toxics10080484

Balba, M. T., Al-Awadhi, N., & Al-Daher, R. (1998). Bioremediation of oil-contaminated soil: microbiological methods for feasibility assessment and field evaluation. *Journal of Microbiological Methods*, *32*(2), 155-164. https://doi.org/10.1016/S0167-7012(98)00020-7

Baniasadi, M., & Mousavi, S.M. (2018). A comprehensive review on the bioremediation of oil spills. *Microbial Action on Hydrocarbons*, 223-254. https://doi.org/10.1007/978-981-13-1840-5_10

Bhada-Tata, Perinaz, & Hoornweg, D. A. *What a waste: a global review of solid waste management (English).* Urban development series knowledge papers, no. 15 Washington, D.C.: World Bank Group. Available at: < http://documents.worldbank.org/curated/en/302341468126264791/What-a-waste-a-global-review-of-solid-waste-management >

Bloom, A. C. (2015). *Bioremediation of a Large Chlorinated Solvent Plume, Dover AFB, DE.*. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States). Available at:< https://www.ornl.gov/publication/bioremediation-large-chlorinated-solvent-plume-dover-afb-de >

Boufadel, M. C., Geng, X., & Short, J. (2016). Bioremediation of the Exxon Valdez oil in Prince William sound beaches. *Marine Pollution Bulletin*, *113*(1-2), 156-164. https://doi.org/10.1016/j.marpolbul.2016.08.086

Brooijmans, R. J., Pastink, M. I., & Siezen, R. J. (2009). Hydrocarbon-degrading bacteria: the oil-spill clean-up crew. *Microbial Biotechnology*, *2*(6), 587. https://doi.org/10.1111/j.1751-7915.2009.00151.x

Bruckberger, M. C., Morgan, M. J., Bastow, T. P., Walsh, T., Prommer, H., Mukhopadhyay, A., Kaksonen, A. H., Davis, G. B., & Puzon, G.J. (2020). Investigation into the microbial communities and associated crude oil-contamination along a Gulf War impacted groundwater system in Kuwait. *Water Research*, *170*, 115314. https://doi.org/10.1016/j.watres.2019.115314

Cao, Z., Yan, W., Ding, M., & Yuan, Y. (2022). Construction of microbial consortia for microbial degradation of complex compounds. *Frontiers in Bioengineering and Biotechnology*, *10*, 1051233. https://doi.org/10.3389/fbioe.2022.1051233

Central Pollution Control Board (CPCB). (2023). Directions Under Section 18. Available at: < https://cpcb.nic.in/openpdffile-direction.php>.

Chaudhary, P., Ahamad, L., Chaudhary, A., Kumar, G., Chen, W. J., & Chen, S. (2023). Nanoparticle-mediated bioremediation as a powerful weapon in the removal of environmental pollutants. *Journal of Environmental Chemical Engineering*, *11*(2), 109591. https://doi.org/10.1016/j.jece.2023.109591

Chaurasia, P., Jasuja, N. D., & Kumar, S. (2022). A sustainable approach in bioremediation of textile dye effluent by microbial consortia. *International Journal for Research in Applied Science and Engineering Technology*, *10*(1), 868-876. https://doi.org/10.22214/ijraset.2022.39950

Chettri, B., Mukherjee, A., Langpoklakpam, J. S., Chattopadhyay, D., & Singh, A.K. (2016). Kinetics of nutrient enhanced crude oil degradation by *Pseudomonas aeruginosa* AKS1 and *Bacillus* sp. AKS2 isolated from Guwahati refinery, India. *Environmental Pollution*, *216*, 548-558. https://doi.org/10.1016/j.envpol.2016.06.008

Cho, B. H., Chino, H., Tsuji, H., Kunito, T., Nagaoka, K., Otsuka, S., Yamashita, K., Matsumoto, S., & Oyaizu, H. (1997). Laboratory-scale bioremediation of oil-contaminated soil of Kuwait with soil amendment materials. *Chemosphere*, *35*(7), 1599-1611. https://doi.org/10.1016/S0045-6535(97)00220-8

Choudhury, R., Singh, K., Sharma, U., Newar, P., Newar, A., & Nath, D. (2019). Basic Physiochemical Analysis of water samples collected from East Sikkim. *World Journal of Pharmaceutical and Life Sciences, 5(*1), 79-89. Available at: <https://www.researchgate.net/publication/332802215_Basic_Physicochemical_Analysis_of_Water_Samples_Collected_from_East_Sikkim>. [Accessed: 21/12/24].

Clement, T. P., Johnson, C. D., Sun, Y., Klecka, G. M., & Bartlett, C. 2000. Natural attenuation of chlorinated ethene compounds: model development and field-scale application at the Dover site. *Journal of Contaminant Hydrology*, *42*(2-4), 13-140. https://doi.org/10.1016/S0169-7722(99)00098-4

Coelho, L. M., Rezende, H. C., Coelho, L. M., de Sousa, P. A. R., Melo, D. F. O., & Coelho, N. M. M. (2015). Bioremediation of Polluted Waters Using Microorganisms. InTech. http://dx.doi.org/10.5772/60770

Couto, S.R. (2009). Dye removal by immobilised fungi. *Biotechnology advances*, *27*(3), 227-235. https://doi.org/10.1016/j.biotechadv.2008.12.001

Darmawati, S., Muchlissin, S. I., Ernanto, A. R., Sulistyaningtyas, A. R., Fuad, H., Rahman, K. M. Z., Sabdono, A., & Ethica, S. N. (2021, March). Pathogenicity scoring system for selection of bacterial consortium formulated as bioremediation agent of Hospital Wastewater in central Java. In *IOP Conference Series: Earth and Environmental Science*, 707(1), 012003. *IOP Publishing*. https://doi.org/10.1088/1755-1315/707/1/012003

Das, K., & Mukherjee, A. K. (2007). Crude petroleum-oil biodegradation efficiency of *Bacillus subtilis* and *Pseudomonas aeruginosa* strains isolated from a petroleum-oil contaminated soil from North-East India. *Bioresource Technology*, *98*(7), 1339-1345. https://doi.org/10.1016/j.biortech.2006.05.032

Das, N., & Chandran, P. (2011). Microbial degradation of petroleum hydrocarbon contaminants: an overview. *Biotechnology Research International*, *2011*(1), 941810. https://doi.org/10.4061/2011/941810

Davis, John W., J. Martin Odom, Kim A. DeWeerd, David A. Stahl, Susan S. Fishbain, Robert J. West, Gary M. Klecka, and John G. DeCarolis. "Natural attenuation of chlorinated solvents at Area 6, Dover Air Force Base: characterization of microbial community structure." *Journal of Contaminant Hydrology* 57, no. 1-2 (2002): 41-59. https://doi.org/10.1016/S0169-7722(01)00217-0

Deniz, F. & Kepekçi, R. (2015). Bioremediation of contaminated water with unnatural dye using blue-green alga *Spirulina platensis*. *Environmental Progress & Sustainable Energy*. 34. https://doi.org/10.1002/ep.12137

Dhall, P., Kumar, R., & Kumar, A. (2012). Biodegradation of sewage wastewater using autochthonous bacteria. *The Scientific World Journal*, *2012.* https://doi.org/10.1100/2012/861903

Dhote, M., Kumar, A., & Juwarkar, A. (2018). Petroleum contaminated oil sludge degradation by defined consortium: Influence of biosurfactant production. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, *88*, 517-523. https://doi.org/10.1007/s40011-016-0778-z

Divya, M., Aanand, S., Srinivasan, A., & Ahilan, B. (2015). Bioremediation–an eco-friendly tool for effluent treatment: a review. *International Journal of Applied Research*, *1*(12), 530-537. Available at: <https://www.researchgate.net/publication/315802463_Bioremediation_-_An_eco-friendly_tool_for_effluent_treatment_A_Review>.

Dos Santos, A. B., Cervantes, F. J., & Van Lier, J. B. (2007). Review paper on current technologies for decolourisation of textile wastewaters: perspectives for anaerobic biotechnology. *Bioresource technology*, *98*(12), 2369-2385. https://doi.org/10.1016/j.biortech.2006.11.013

Duty, C. E., Kunc, V., Compton, B., Post, B., Erdman, D., Smith, R., Lind, R., Lloyd, P., & Love, L. (2017). Structure and mechanical behavior of Big Area Additive Manufacturing (BAAM) materials. *Rapid Prototyping Journal*, *23*(1), 181-189. https://doi.org/10.1108/RPJ-12-2015-0183

Dzionek, A., Wojcieszyńska, D., & Guzik, U. (2016). Natural carriers in bioremediation: A review. *Electronic Journal of Biotechnology*, *23*, 28-36. https://doi.org/10.1016/j.ejbt.2016.07.003

Ethica, S. N., & Sabdono, A. (2017, June). Bio-remediation potential of hydrolytic bacteria isolated from hospital liquid biomedical waste in Central Java. In *Proceedings of the 3rd world congress on New Technologies*. https://doi.org/10.11159/icbb17.111

Ethica, S. N., Firmansyah, A., Purwaningrum, E., Hidayati, N., Muchlissin, S. I., Sukeksi, A., ... & Sabdono, A. (2021, May). Degradation performance and microencapsulation of hydrolytic bacterial consortium formulated as bioremediation agent of liquid biomedical waste. In *IOP Conference Series: Earth and Environmental Science* (Vol. 743, No. 1, p. 012009). IOP Publishing. https://doi.org/10.1088/1755-1315/743/1/012009

Ethica, S. N., Muchlissin, S. I., Saptaningtyas, R. A. G. I. L., & Sabdono, A. G. U. S. 2018. Protease producers predominate cultivable hydrolytic bacteria isolated from liquid biomedical waste. *Asian Journal of Chemistry*, *30*(9), 2035-2038. https://doi.org/10.14233/ajchem.2018.21400

Ethica, S. N., Muchlissin, S. I., Saptaningtyas, R., & Sabdono, A. (2017, October). Sampling mikrobiologi limbah biomedis rumah sakit di kota Semarang Jawa Tengah. In *Prosiding Seminar Nasional & Internasional* (Vol. 1, No. 1). Available at:< https://www.researchgate.net/publication/320146318_Sampling_Mikrobiologi_Limbah_Biomedis_Rumah_Sakit_di_Kota_Semarang_Jawa_Tengah >.

Ethica, S. N., Muslim, R., Widyawardhana, R. B. I., Firmansyah, A., & Imam, S. (2019). Synergism and antagonism among indigenous hydrolytic bacteria from biomedical wastes for the generation of bacterial consortium used as bioremediation agent. *Int J Environ Sci Dev*, *10*(12). https://doi.org/10.18178/ijesd.2019.10.12.1213

Finny, A. S. (2024). 3D bioprinting in bioremediation: a comprehensive review of principles, applications, and future directions. *PeerJ*, *12*. https://doi.org/10.7717/peerj.16897

Forgacs, E., Cserháti, T., & Oros, G. (2004). Removal of synthetic dyes from wastewaters: a review. *Environment international*, *30*(7), 953-971. https://doi.org/10.1016/j.envint.2004.02.001

French, K. E., Zhou, Z., & Terry, N. (2020). Horizontal 'gene drives' harness indigenous bacteria for bioremediation. *Scientific Reports*, *10*(1), 15091. https://doi.org/10.1038/s41598-020-72138-9

Ghosh, S. K. (2006). Functional coatings and microencapsulation: a general perspective. *Functional Coatings: by polymer microencapsulation*, 1-28. https://doi.org/10.1002/3527608478

Gogoi, B. K., Dutta, N. N., Goswami, P., & Mohan, T. K. (2003). A case study of bioremediation of petroleum-hydrocarbon contaminated soil at a crude oil spill site. *Advances in Environmental Research*, *7*(4), 767-782. https://doi.org/10.1016/S1093-0191(02)00029-1

Grady Jr, C. L., Daigger, G. T., Love, N. G., & Filipe, C. D. (2011). *Biological wastewater treatment*. CRC press. https://doi.org/10.1201/b13775

Guha Thakurta, S., Aakula, M., Chakrabarty, J., & Dutta, S. (2018). Bioremediation of phenol from synthetic and real wastewater using *Leptolyngbya* sp.: a comparison and assessment of lipid production. *3 Biotech*, *8*, 1-10. https://doi.org/10.1007/s13205-018-1229-8

Gupta, N., Yadav, K. K., Kumar, V., & Singh, D. (2013). Assessment of physicochemical properties of Yamuna River in Agra City. *International Journal of ChemTech Research*, *5*(1), 528-531. Available at: < https://www.researchgate.net/publication/236215738_Assessment_of_Physicochemical_Properties_of_Yamuna_River_in_Agra_City >. [Accessed: 21/12/24].

Gupta, V. K. (2009). Application of low-cost adsorbents for dye removal–a review. *Journal of Environmental Management*, *90*(8), 2313-2342. Https://Doi.Org/10.1016/J.Jenvman.2008.11.017

Gutiérrez, J. E., Gutiérrez-Hoyos, N., Gutiérrez, J. S., Vives, M. J., & Sivasubramanian, V. (2022). Bioremediation of a sewage-contaminated tropical swamp through bioaugmentation with a microalgae-predominant microbial consortium. *Indian Journal of Microbiology*, *62*(2), 307-311. https://doi.org/10.1007/s12088-021-00990-y

He, S., Zhong, L., Duan, J., Feng, Y., Yang, B., & Yang, L. (2017). Bioremediation of wastewater by iron oxide-biochar nanocomposites loaded with photosynthetic bacteria. *Frontiers in Microbiology*, *8*, 823. https://doi.org/10.3389/fmicb.2017.00823

Hesnawi, R., Dahmani, K., Al-Swayah, A., Mohamed, S., & Mohammed, S. A. (2014). Biodegradation of municipal wastewater with local and commercial bacteria. *Procedia Engineering*, *70*, 810-814. https://doi.org/10.1016/j.proeng.2014.02.088

Hossain, N., & Rahman, M. (2014). Antagonistic activity of antibiotic producing *Streptomyces* sp. against fish and human pathogenic bacteria. *Brazilian Archives of Biology and Technology*, *57*, 233-237. https://doi.org/10.1590/S1516-89132014000200011

Ibrahim, S., El-Liethy, M. A., Elwakeel, K. Z., Hasan, M. A. E. G., Al Zanaty, A. M., & Kamel, M. M. (2020). Role of identified bacterial consortium in treatment of Quhafa Wastewater Treatment Plant influent in Fayuom, Egypt. *Environmental Monitoring and Assessment*, *192*, 1-10. https://doi.org/10.1007/s10661-020-8105-9

Ilma, Q., Dinoto, A., Setianingrum, N., Mulyadi, M., Agustyani, D., Radiastuti, N., & Julistiono, H. (2022). Isolation and identification of bacteria removing nitrite, nitrate, and ammonium from bioballs filter. *Indonesian Aquaculture Journal*, *17*(1), 13-22. https://doi.org/10.15578/iaj.17.1.2022.13-22

Ilyas, H., & Masih, I. (2017). The performance of the intensified constructed wetlands for organic matter and nitrogen removal: A review. *Journal of Environmental Management*, *198*, 372-383. https://doi.org/10.1016/j.jenvman.2017.04.098

Islam, M. N., Taki, G., Jung, Y. J., Jung, S. K., & Park, J. H. (2018). Remediation of gulf war oil spill contaminated soil by a subcritical water extraction process: oil removal, recovery, and degradation. *Soil and Sediment Contamination: An International Journal*, *27*(2), 120-130. https://doi.org/10.1080/15320383.2018.1432563

Jain, P. K., Gupta, V. K., Gaur, R. K., Lowry, M., Jaroli, D. P., & Chauhan, U. K. (2011). Bioremediation of petroleum oil contaminated soil and water. *Research Journal of Environmental Toxicology*, *5*(1), 1-26. https://doi.org/10.3923/rjet.2011.1.26

Jha, V., Dafale, N. A., Hathi, Z., & Purohit, H. (2021). Genomic and functional potential of the immobilized microbial consortium MCSt-1 for wastewater treatment. *Science of the Total Environment*, *777*, 146110. https://doi.org/10.1016/j.scitotenv.2021.146110

Judd, S. (2010). *The MBR book: principles and applications of membrane bioreactors for water and wastewater treatment*. Elsevier.

Karigar, C. S., & Rao, S. S. (2011). Role of microbial enzymes in the bioremediation of pollutants: a review. *Enzyme Research*, *2011*(1), 805187. https://doi.org/10.4061/2011/805187

Katheresan, V., Kansedo, J., & Lau, S. Y. (2018). Efficiency of various recent wastewater dye removal methods: A review. *Journal of Environmental Chemical Engineering*, *6*(4), 4676-4697. https://doi.org/10.1016/j.jece.2018.06.060

Kelany, M. S., El-Sawy, M. A., El-Gendy, A. R., & Beltagy, E. A. (2023). Bioremediation of industrial wastewater heavy metals using solo and consortium Enterobacter spp. *Environmental Monitoring and Assessment*, *195*(11), 1357. https://doi.org/10.1007/s10661-023-11951-x

Khan, S., Afzal, M., Iqbal, S., & Khan, Q. M. (2013). Plant–bacteria partnerships for the remediation of hydrocarbon contaminated soils. *Chemosphere*, *90*(4), 1317-1332. https://doi.org/10.1016/j.chemosphere.2012.09.045

Kour, D., Khan, S. S., Kour, H., Kaur, T., Devi, R., Rai, P. K., Judy, C., McQuestion, C., Bianchi, A., Spells, S., & Mohan, R. (2022). Microbe-mediated bioremediation: Current research and future challenges. *Journal of Applied Biology and Biotechnology*, *10*(2), 6-24. https://doi.org/10.7324/JABB.2022.10s202

Kumar, S. S., Shantkriti, S., Muruganandham, T., Murugesh, E., Rane, N., & Govindwar, S. P. (2016). Bioinformatics aided microbial approach for bioremediation of wastewater containing textile dyes. *Ecological Informatics*, *31*, 112-121. https://doi.org/10.1016/j.ecoinf.2015.12.001

Li, Y., Chen, Y. F., Chen, P., Min, M., Zhou, W., Martinez, B., Zhu, J., & Ruan, R. (2011). Characterization of a microalga Chlorella sp. well adapted to highly concentrated municipal wastewater for nutrient removal and biodiesel production. *Bioresource Technology*, *102*(8), 5138–5144. https://doi.org/10.1016/j.biortech.2011.01.091

Lozinsky, V. I., & Okay, O. (2014). Basic principles of cryotropic gelation. *Polymeric cryogels: Macroporous gels with remarkable properties*, 49-101. https://doi.org/10.1007/978-3-319-05846-7_2

Malik, D., Singh, S., Thakur, J., Singh, R. K., Kaur, A., & Nijhawan, S. (2014). Heavy metal pollution of the Yamuna River: An introspection. *Int. J. Curr. Microbiol. Appl. Sci*, *3*(10), 856-863. http://www.ijcmas.com/vol-3-10/Darshan%20Malik,%20et%20al.pdf

Mandeep, & Shukla, P. (2020). Microbial nanotechnology for bioremediation of industrial wastewater. *Frontiers in Microbiology*, *11*, 590631. https://doi.org/10.3389/fmicb.2020.590631

Mapelli, F., Scoma, A., Michoud, G., Aulenta, F., Boon, N., Borin, S., Kalogerakis, N., & Daffonchio, D. (2017). Biotechnologies for marine oil spill cleanup: indissoluble ties with microorganisms. *Trends in biotechnology*, *35*(9), 860-870. DOI: 10.1016/j.tibtech.2017.04.003

McKew, B. A., Coulon, F., Yakimov, M. M., Denaro, R., Genovese, M., Smith, C. J., Osborn, A. M., Timmis, K. N., & McGenity, T. J. (2007). Efficacy of intervention strategies for bioremediation of crude oil in marine systems and effects on indigenous hydrocarbonoclastic bacteria. *Environmental Microbiology*, *9*(6), 1562-1571. https://doi.org/10.1111/j.1462-2920.2007.01277.x

Mehrotra, T., Dev, S., Banerjee, A., Chatterjee, A., Singh, R., & Aggarwal, S. (2021). Use of immobilized bacteria for environmental bioremediation: A review. *Journal of Environmental Chemical Engineering*, *9*(5), 105920. https://doi.org/10.1016/j.jece.2021.105920

Memon, H., Lanjewar, K., Dafale, N., & Kapley, A. (2020). Immobilization of microbial consortia on natural matrix for bioremediation of wastewaters. *International Journal of Environmental Research*, *14*, 403-413. https://doi.org/10.1007/s41742-020-00267-0

Meng, F., Zhang, S., Oh, Y., Zhou, Z., Shin, H. S., & Chae, S. R. (2017). Fouling in membrane bioreactors: An updated review. *Water research*, *114*, 151-180. https://doi.org/10.1016/j.watres.2017.02.006

Metcalf & Eddy, Abu-Orf, M., Bowden, G., Burton, F. L., Pfrang, W., Stensel, H. D., Tchobanoglous, G., Tsuchihashi, R., & AECOM (Firm). (2014). *Wastewater engineering: treatment and resource recovery*. McGraw Hill Education. https://ptabdata.blob.core.windows.net/files/2017/IPR2017-01468/v22_FWS1016%20-%20Metcalf.pdf

Metcalf, L., Eddy, H.P., & Tchobanoglous, G. (1991). *Wastewater engineering: treatment, disposal, and reuse*, Vol. 4, New York: McGraw-Hill.

Meyer A.S. (2020). 3d printing of biofilms. Available at: https://patents.google.com/patent/US20220243190A1 US20220243190A1>

Muchtasjar, B., Hadiyanto, H., & Izzati, M. (2019, August). Microbial degradation of batik waste water treatment in Indonesia. In *IOP Conference Series: Earth and Environmental Science* (Vol. 314, No. 1, p. 012020). IOP Publishing. https://doi.org/10.1088/1755-1315/314/1/012020

MULIYADI, S.A., MULOK, T. E. T. Z., HUSSAIN, N. H., & Nor, R. M. (2022). Bioremediation of textile wastewater using *Pleurotus pulmonarius*. *Journal of Sustainability Science and Management*, *17*(2), 67-76. http://doi.org/10.46754/jssm.2022.02.007

Murshid, S., & Dhakshinamoorthy, G. P. (2021). Application of an immobilized microbial consortium for the treatment of pharmaceutical wastewater: Batch-wise and continuous studies. *Chinese Journal of Chemical Engineering*, *29*, 391-400. https://doi.org/10.1016/j.cjche.2020.04.008

Nadi, A., Boyer, D., Charbonnel, N., Boukhriss, A., Forestier, C., & Gmouh, S. (2019). Immobilisation of bacteria onto magnetic nanoparticles for the decolorisation and degradation of azo dyes. *IET nanobiotechnology*, *13*(2), 144-149. https://doi.org/10.1049/iet-nbt.2018.5026

Nayak, J. K., Gautam, R., & Ghosh, U. K. (2024). Bioremediation potential of bacterial consortium on different wastewaters for electricity and biomass feedstock generation. *Biomass Conversion and Biorefinery*, *14*(10), 11295-11308. https://doi.org/10.1007/s13399-022-02992-2

Nie, M., Nie, H., He, M., Lin, Y., Wang, L., Jin, P., & Zhang, S. (2016). Immobilization of biofilms of *Pseudomonas aeruginosa* NY3 and their application in the removal of hydrocarbons from highly concentrated oil-containing wastewater on the laboratory scale. *Journal of Environmental Management*, *173*, 34-40. https://doi.org/10.1016/j.jenvman.2016.02.045

Nyika, J., & Dinka, M. O. (2022). A mini-review on wastewater treatment through bioremediation towards enhanced field applications of the technology. *AIMS Environmental Science*, *9*(4), 403-431. DOI: 10.3934/environsci.2022025

Ojha, N., Karn, R., Abbas, S., & Bhugra, S. (2021, June). Bioremediation of industrial wastewater: a review. In *IOP Conference Series: Earth and Environmental Science* (Vol. 796, No. 1, p. 012012). IOP Publishing. https://doi.org/10.1088/1755-1315/796/1/012012

Olguín, E. J., Galicia, S., Mercado, G., & Pérez, T. (2003). Annual productivity of *Spirulina (Arthrospira*) and nutrient removal in a pig wastewater recycling process under tropical conditions. *Journal of Applied Phycology*, *15*, 249-257. https://doi.org/10.1023/A:1023856702544

Paisio, C. E., Quevedo, M. R., Talano, M. A., González, P. S., & Agostini, E. (2014). Application of two bacterial strains for wastewater bioremediation and assessment of phenolics biodegradation. *Environmental Technology*, *35*(14), 1802–1810. https://doi.org/10.1080/09593330.2014.882994

Pardamean, M. A., Islamy, R., Hasan, V. E. R. Y. L., Herawati, E. Y., & Mutmainnah, N. (2021). Identification and physiological characteristics of potential indigenous bacteria as bioremediation agent in the wastewater of sugar factory. *Sains Malaysiana*, *50*(2), 279-286. http://dx.doi.org/10.17576/jsm-2021-5002-01

Prabhakar, Y., Gupta, A., & Kaushik, A. (2022). Using indigenous bacterial isolate *Nesterenkonia lacusekhoensis* for removal of azo dyes: A low-cost ecofriendly approach for bioremediation of textile wastewaters. *Environment, Development and Sustainability*, *24*(4), 5344-5367. https://doi.org/10.1007/s10668-021-01661-0

Purwaningrum, E., Zulaikhah, S. T., & Ethica, S. N. (2021). Characterization Of Bacteria from Liquid Clinical Laboratory Waste with Potential as Bioremediation Agent. *World Journal of Pharmaceutical & Lifa Sciences*, *7*(9), 1626. Available at:<

https://www.researchgate.net/publication/353945056_Characterization_of_Bacteria_from_Liquid_Clinical_Laboratory_Waste_with_Potential_as_Bioremediation_Agent>.

RAI, H. S., BHATTACHARYYA, M. S., SINGH, J., BANSAL, T. K., VATS, P., & BANERJEE, U. C. (2005). Removal of Dyes from the Effluent of Textile and Dyestuff Manufacturing Industry: A Review of Emerging Techniques With Reference to Biological Treatment. *Critical Reviews in Environmental Science and Technology*, *35*(3), 219–238. https://doi.org/10.1080/10643380590917932.

Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F., & Kim, K.H. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, *125*, 365-385. https://doi.org/10.1016/j.envint.2019.01.067

Rashid, A., Mirza, S. A., Keating, C., Ali, S., & Campos, L. C. (2022). Indigenous *Bacillus paramycoides* spp. and *Alcaligenes faecalis*: sustainable solution for bioremediation of hospital wastewater. *Environmental Technology*, *43*(12), 1903-1916. https://doi.org/10.1080/09593330.2020.1858180

Rittmann, B. E. (2001). Environmental Biotechnology: Principles and Applications.

River Rejuvenation Committee (RRC) Govt. of NCT of Delhi. 2020. Action Plan for Rejuvenation of River Yamuna. Available at:<https://environment.delhi.gov.in/sites/default/files/inline-files/rrc_delhi.pdf>.

Rizzo, L., Manaia, C., Merlin, C., Schwartz, T., Dagot, C., Ploy, M. C., Michael, I., & Fatta-Kassinos, D. (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. *Science of the total environment*, *447*, 345-360. https://doi.org/10.1016/j.scitotenv.2013.01.032

Roy, D. C., Sheam, M. M., Hasan, M. R., Saha, A. K., Roy, A. K., Haque, M. E., ... & Biswas, S. K. (2020). Isolation and characterization of two bacterial strains from textile effluents having Malachite Green dye degradation ability. *bioRxiv*, 2020-03. https://doi.org/10.1101/2020.03.29.014274

Saeed, M. U., Hussain, N., Sumrin, A., Shahbaz, A., Noor, S., Bilal, M., ... & Iqbal, H. M. (2022). Microbial bioremediation strategies with wastewater treatment potentialities–A review. *Science of the total environment*, *818*, 151754. https://doi.org/10.1016/j.scitotenv.2021.151754

Safitri, R., Priadie, B., & Permatasari, D. I. (2015). The performance of bacterial consortium in various carriers on the bioremediation of river water polluted by domestic sewage. *Earth Observation & Surveying, Environ. Engin*, *4*, 120-126. http://repository.unpad.ac.id/id/eprint/23627

Safitri, R., Priadie, B., Miranti, M., & Astuti, A. W. (2015). Ability of bacterial consortium: *Bacillus coagulans, Bacilus licheniformis, Bacillus pumilus, Bacillus subtilis, Nitrosomonas* sp. and *Pseudomonas putida* in bioremediation of waste water in Cisirung waste water treatment plant. *AgroLife Scientific Journal*, *4*(1), 146-152. https://agrolifejournal.usamv.ro/index.php/agrolife/article/view/402

Samhan, F., Elliethy, M., Hemdan, B., Youssef, M., & El-Taweel, G. (2017). Bioremediation of oil-contaminated water by bacterial consortium immobilized on environment-friendly biocarriers. *Journal of Egyptian Public Health Association*, *92*(1), 44-51. https://doi.org/10.21608/EPX.2018.6649

Sarioglu, O. F., Keskin, N. O. S., Celebioglu, A., Tekinay, T., & Uyar, T. (2017). Bacteria encapsulated electrospun nanofibrous webs for remediation of methylene blue dye in water. *Colloids and surfaces. B, Biointerfaces*, *152*, 245–251. https://doi.org/10.1016/j.colsurfb.2017.01.034.

SAXENA, A., GUPTA, V., & SAXENA, S. (2020). BIOREMEDIATION: A GREEN APPROACH TOWARDS THE TREATMENT OF SEWAGE WASTE. *Journal of Phytological Research*, *33*(2). Available at:< https://www.researchgate.net/publication/351702301_BIOREMEDIATION_A_GREEN_APPROACH_TOWARDS_THE_TREATMENT_OF_SEWAGE_WASTE >.

Schaffner, M., Rühs, P. A., Coulter, F., Kilcher, S., & Studart, A. R. (2017). 3D printing of bacteria into functional complex materials. *Science advances*, *3*(12), eaao6804. https://doi.org/10.1126/sciadv.aao6804

Schweitzer, L., & Noblet, J. (2018). Water contamination and pollution. In *Green chemistry*,261-290. *Elsevier*. https://doi.org/10.1016/B978-0-12-809270-5.00011-X

Seragadam, P., Rai, A., Ghanta, K. C., Srinivas, B., Lahiri, S. K., & Dutta, S. (2021). Bioremediation of hexavalent chromium from wastewater using bacteria-a green technology. *Biodegradation*, *32*(4), 449-466. https://doi.org/10.1007/s10532-021-09947-w

Sharma, B., Dangi, A. K., & Shukla, P. (2018). Contemporary enzyme-based technologies for bioremediation: a review. *Journal of Environmental Management*, *210*, 10-22. https://doi.org/10.1016/j.jenvman.2017.12.075

Sharma, G. K., Khan, S. A., Shrivastava, M., Gupta, N., Kumar, S., Malav, L. C., Nogiya, M., & Dubey, S. K. (2020). Bioremediation of sewage wastewater through microalgae (*Chlorella minutissima*). *Indian Journal of Agricultural Sciences*, *90*(10), 2024-8. https://doi.org/10.56093/ijas.v90i10.107985

Sharma, M., & Chaudhry, S. (2015). Impact of Industrial Pollution on Yamuna River: A Review. *Kurukshetra, India: ResearchGate Publication*. https://doi.org/10.13140/RG.2.1.3632.8401

Sharma, M., Tellili, N., Kacem, I., & Rouissi, T. (2024). Microbial Biopolymers: From Production to Environmental Applications—A Review. *Applied Sciences*, *14*(12), 5081. https://doi.org/10.3390/app14125081

Singh, R., Kumar, M., Mittal, A., & Mehta, P. K. (2016). Microbial enzymes: industrial progress in 21st century. *3 Biotech*, *6*, 1-15. https://doi.org/10.1007/s13205-016-0485-8

Tchobanoglus, G., Burton, F., & Stensel, H. D. (2003). Wastewater engineering: treatment and reuse. *American Water Works Association. Journal*, *95*(5), 201.

Valdivia-Rivera, S., Ayora-Talavera, T., Lizardi-Jiménez, M. A., García-Cruz, U., Cuevas-Bernardino, J. C., & Pacheco, N. (2021). Encapsulation of microorganisms for bioremediation: Techniques and carriers. *Reviews in Environmental Science and Bio/Technology*, *20*(3), 815-838. https://doi.org/10.1007/s11157-021-09577-x

Velusamy, S., Roy, A., Sundaram, S., & Kumar Mallick, T. (2021). A review on heavy metal ions and containing dyes removal through graphene oxide‐based adsorption strategies for textile wastewater treatment. *The Chemical Record*, *21*(7), 1570-1610. https://doi.org/10.1002/tcr.202000153

Vidali, M. (2001). Bioremediation. an overview. *Pure and Applied Chemistry*, *73*(7), 1163-1172. https://doi.org/10.1351/pac200173071163

Vymazal, J. (2011a). Constructed wetlands for wastewater treatment: five decades of experience. *Environmental Science & Technology*, *45*(1), 61-69. DOI: 10.1021/es101403q. https://doi.org/10.1021/es101403q

Vymazal, J. (2011b). Plants used in constructed wetlands with horizontal subsurface flow: a review. *Hydrobiologia*, *674*(1), 133-156. https://doi.org/10.1007/s10750-011-0738-9

Wang, J. L., & Xu, L. J. (2012). Advanced oxidation processes for wastewater treatment: formation of hydroxyl radical and application. *Critical Reviews in Environmental Science and Technology*, *42*(3), 251-325. https://doi.org/10.1080/10643389.2010.507698

Watanabe, K. (2001). Microorganisms relevant to bioremediation. *Current opinion in biotechnology*, *12*(3), 237-241. https://doi.org/10.1016/S0958-1669(00)00205-6

World Health Organization (WHO). (2023). Drinking-water. Available at:< https://www.who.int/news-room/fact-sheets/detail/drinking-water>. [Accessed: 3/3/24].

Wu, H., Fan, J., Zhang, J., Ngo, H. H., Guo, W., Liang, S., Hu, Z., & Liu, H. (2015). Strategies and techniques to enhance constructed wetland performance for sustainable wastewater treatment. *Environmental Science and Pollution Research*, *22*, 14637-14650. https://doi.org/10.1007/s11356-015-5151-x

Xin, L., Hong-Ying, H., Ke, G., & Ying-Xue, S. (2010). Effects of different nitrogen and phosphorus concentrations on the growth, nutrient uptake, and lipid accumulation of a freshwater microalga Scenedesmus sp. *Bioresource Technology*, *101*(14), 5494-5500. https://doi.org/10.1016/j.biortech.2010.02.016

Xue, Y., Du, P., Shendi, A. A. I., & Yu, B. (2022b). Mercury bioremediation in aquatic environment by genetically modified bacteria with self-controlled biosecurity circuit. *Journal of Cleaner Production*, *337*, 130524. https://doi.org/10.1016/j.jclepro.2022.130524

Xue, Y., Qiu, T., Sun, Z., Liu, F., & Yu, B. (2022a). Mercury bioremediation by engineered *Pseudomonas putida* KT2440 with adaptationally optimized biosecurity circuit. *Environmental Microbiology*, *24*(7), 3022-3036. https://doi.org/10.1111/1462-2920.16038

Zabermawi, N. M. O., Alyhaiby, A. H., & El-Bestawy, E. A. (2022). Microbiological analysis and bioremediation bioassay for characterization of industrial effluent. *Scientific Reports*, *12*(1), 18889. https://doi.org/10.1038/s41598-022-23480-7

Zamel, D., & Khan, A. U. (2021). Bacterial immobilization on cellulose acetate-based nanofibers for methylene blue removal from wastewater: Mini-review. *Inorganic Chemistry Communications*, *131*, 108766. https://doi.org/10.1016/j.inoche.2021.108766

Zeyaullah, M. D., Atif, M., Islam, B., Abdelkafe, A. S., Sultan, P., ElSaady, M. A., & Ali, A. (2009). Bioremediation: A tool for environmental cleaning. *African Journal of Microbiology Research*, *3*(6), 310-314. https://doi.org/10.5897/AJMR.9000136