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Bioremediation of Industrial Wastewater: A Review

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Abstract

Water pollution is on the rise because of increased human population and activities, unsustainable agricultural practices, and rapid industrialization, and it is a major global concern. Therefore, there is a scarcity of clean water, which has been related to diseases like typhoid, diarrhea, cholera, jaundice, and others. Major contaminants include heavy metals, organic, and inorganic pollutants. The use of naturally occurring microorganisms like bacteria, fungi, or plants i.e., Bioremediation to treat polluted wastewater has proven to be effective and efficient. This article briefly discusses the impact of water pollution on the environment, as well as various strategies for removing it.

Keywords: Water pollution; Microorganisms; Bioremediation; Heavy metals; Pollutants; Phytoremediation.

Highlights

There is the development of biological approach i.e., bioremediation which uses living microorganisms for detoxifying toxic substances present in wastewater and is also eco-friendly.

1.0 Introduction

Over the past several decades, the world has experienced problems with a broad range of environmental contamination due to excessive human activities **[1]**. The population explosion in the world has increased the region of polluted water **[2]**. The quantity and quality of waste produced and discharged into natural water sources have therefore been considered and the need for different strategies to resolve water quality problems in the regions has been highlighted **[1].** Water pollution is a major global problem and can be generally categorized into three key categories, namely organic compound contamination, inorganic compounds, and microorganisms **[3]**. The key causes of polluting water quality are modernizing economies, heavy industrial development, urban expansion, and enormous growth in the human population. Recent advancements have been made in bioremediation methods with the aim of successfully restoring contaminated environments **[4].** Several studies have been conducted as an alternative to conventional treatments for the removal of heavy metals present in polluted waters using various microorganisms.

The technique of bioremediation using living microorganisms was invented by M. Robinson **[5]**. It is an innovative and emerging technology due to its improved competence, friendliness to the natural environment, and cost-effectiveness **[6,7].** Bioremediation is a natural alternative process to strategies such as incineration, catalytic degradation, adsorbent use, physical removal, and eventual pollutant destruction **[2].** Since they can be used to remove, concentrate, and extract heavy metals from polluted aquatic habitats, microorganisms are a biological tool for metal removal. The bioremediation strategy is based on the high metal-binding ability of biological agents, which helps to extract heavy metals highly efficiently from polluted areas. Due to the action of microorganisms on pollutants, even when they are present in very dilute solutions, bioremediation by using microorganisms is very helpful and can also adapt to extreme conditions **[3].**

To be successful in the bioremediation process, microorganisms should enzymatically attack contaminants and turn them into harmless product. Only when environmental conditions permit the growth and activity of microbes, bioremediation can be successful **[5,8].** The presence of many indigenous microorganisms in polluted habitats is the secret to addressing most of the problems associated with biodegradation and bioremediation of polluting material.

Bioremediation is a system focused on biological processes for reducing, degrading, modifying, eliminating, immobilizing, detoxifying, mineralizing, or transforming pollutant concentrations to a non-harmful or non-toxic state **[8-10].** The treatment method for water contaminants depends mainly on the type of the pollutant, including agrochemicals, chlorinated compounds, dyes, greenhouse gases, heavy metals, hydrocarbons, radioactive waste, and plastic waste.

This paper reviews a serious concern of water pollution, its causes, and its impacts on the environment and discusses various biological methods for its remediation and converts them into a less toxic form.

2.0 Principle of Bioremediation

The bioremediation hypothesis is based on biodegradation **[8].** Bioremediation is a method in which environmental waste is biologically degraded in a harmless state or to concentrations below the respective concentration limits under controlled conditions set by the governing authorities. **[11].** To degrade harmful chemicals or hazardous waste and turn them into less toxic or non-toxic forms found in wastewater, bioremediation uses naturally occurring living organisms, often microorganisms **[1, 8, 12-15].** It can be used as a green treatment and commercially viable technology, but its efficacy can vary from location to location **[16].** Bacteria, fungi, or plants with the physiological capacity to degrade or detoxify harmful contaminants in water and clean it up are the required microorganisms. **[5, 17].** It is low-cost technology brought on-site **[18].** This technology depends on the creation of microbial consortia or microflora being promoted. They are indigenous to polluted sites and can carry out activities that are needed. Such microbial consortia can be formed by adding nutrition, adding terminal electron acceptor, or regulating temperature and humidity conditions in several ways, such as promoting growth **[19].**

Microorganisms make use of these pollutants as nutrients or energy sources in bioremediation processes **[2].** In certain cases, indigenous microorganisms may already be present on-site, while others may be extracted from elsewhere and then added to the treated material through the bioreactor **[5].** It is important to note that while bioremediation relies on the growth and activity of microbes, its effectiveness is highly dependent on the environmental factors that influence microbe growth and degradation rates. **[17].**

So, overall, the technique of bioremediation depends on finding the right microorganisms in the right place for the effective degradation process under the required environmental conditions. It is possible to improve the biological processes involved in bioremediation technologies and focus on the removal from the water of hazardous contaminants. This leads to the mineralization of waste material into water, carbon dioxide, biomass, or other non-hazardous materials, thus reducing the need for further treatment. Bioremediation refers to the treatment of a large range of compounds **[17].**

Microorganisms may even be used to degrade pesticides, agricultural chemicals, fuel oil components, and even non-biodegradable substances such as chlorinated solvents, chlorofluorocarbons, and other synthetic organic compounds, in addition to urban waste and process water. The microorganisms may be native to a polluted area or they may be isolated and carried to the contaminated site from elsewhere. Contaminant compounds are transformed by living organisms via responses that take place as part of their metabolic processes. Biodegradation of a substance is also caused by the behavior of many species **[17].**

3.0 Causes of water pollution.

3.1 Inorganic chemicals

This includes a range of pollutants like hydrocarbons, heavy metals, inorganic anions, radioactive material, insecticides, pharmaceuticals, cosmetics, etc. In higher concentrations, their presence can degrade water potability for living organisms. Hg, Cd, Cr-containing industrial waste, nitrogen-containing domestic and agricultural waste, and naturally occurring substances like F, As, and B may all be sources. Heavy metals are introduced through human activities such as inadequate sanitation systems, unsafe agricultural practices, industrial discharges, etc. **[20, 21].**

3.2 Major inorganic water pollutants

This can include heavy metals halides, radioactive materials, trace elements, inorganic salts, sulfates, cyanides, oxyanions, cations. These inorganic pollutants are not readily degraded and remain in aqueous environments for a longer time, which may cause further degradation **[20, 22, 23].**

3.3 Water contamination by heavy metals

Industrial wastewater can contain enormous concentrations of toxic heavy metals as well as other contaminants, which can harm any ecosystem and an environmental living entity like As, Cd, Cr, Cu, Co, Hg, Ni, Pb, Sn, and Zn. Wastewater from mines, hospital waste, electroplating, smelters, sewage, battery plants, dyes, alloys, and electronic factories are some sources of toxic heavy metals. These heavy metals are polluted by natural or anthropogenic sources of water. Volcanoes, soil erosion, and rock disintegration are examples of natural causes, while human activities that cause water contamination include petroleum combustion, mineral extraction, landfilling, urban water discharge, mining operations, industrial discharge, irrigation, metal processing, printed circuit board manufacturing, coloring dyes, and so on. This renders the water unfit for human use. **[20, 24, 25].**

3.4 Water pollution by organic compounds

PCBs, pesticides, fertilizers, herbicides, phenols, polycyclic aromatic hydrocarbons (PAHs), aliphatic, heterocyclic compounds, bacteria, sewage, agricultural runoffs, and food processing are only a few of the chemical pollutants contained in wastewater. Industrial and agricultural activity may be the source of organic wastewater. It may include wastewater from farmland containing a high concentration of pesticides or herbicides, coke plant which contains different PAHs, a chemical industry which contain various heterogeneity compounds such as PCB, PBDE, food industry, municipal. Such organic pollutants found in water can pose human health hazards and can also affect the environment **[22, 26, 27].**

TABLE 1. Common heavy metals, standard, and health problems (*Source: Srivastav et.al, 2020*)

S.No.	Heavy Metals	Heavy Metal Source	Maximum Contaminant Level (MCL)(mg/L) by USEPA	Health Problems
1.	Arsenic	Natural: Geogenic Anthropogenic: Industrial discharge	0.05	Skin diseases, carcinogenicity
2.	Cadmium	Natural: Geogenic	0.005	Kidney diseases
3.	Chromium	Natural: Geogenic Anthropogenic: Steel factories, paper, and pulp mills	0.1	Allergy and skin inflammation
4.	Copper	Natural: Geogenic Anthropogenic: Chemicals used for preservation of woods, corrosion of pipes	1.3	Problems to the stomach, liver, kidney
5.	Lead	Natural: Geogenic Anthropogenic: corrosion of pipes	0.015	Retards physical and mental growth, kidney disorders, and high blood pressure
6.	Mercury	Natural: Geogenic Anthropogenic: refineries discharge	0.002	Kidney and spinal card disorders

4.0 Effects of water pollution on organisms

Irreparable damage to marine environments can be caused by water pollution from heavy metals coming from anthropogenic and industrial activities. They can have a detrimental impact on fauna and flora and are not biodegradable (i.e., they can pose a significant threat to both life and the environment) **[3].** Depending on their types and sources, the impact of pollutants can vary. Any of the waste is known as carcinogens, such as heavy metals, dyes, and some organic pollutants. Some hormones, pharmaceuticals, cosmetics, and waste materials for personal care are chemicals that can cause endocrine destruction that can influence the reproduction and growth of humans and non-human animals in the endocrine system **[28].** Hormonal imbalances can be caused by most inorganic chemicals. The biosphere of plants and animals living in water bodies or species exposed to water is adversely affected by water contamination. Infectious diseases such as cholera, typhoid, gastroenteritis, dengue, diarrhea, vomiting, jaundice, malaria, chikungunya, skin, and kidney disorders are caused by this contaminated water **[29].**

Heavy metals are lethal and can be carcinogenic often. They may have adverse health effects on all living species. If the heavy metal concentration is increased above the amount recommended by the WHO, then toxic effects on aquatic systems can be produced. There may be a variety of skin conditions, such as melanosis, keratosis, cancer, gangrene, etc. **[20].**

Heavy metals have adverse toxic effects on humans such as moderate eye, nose, and skin irritation, extreme headache, stomachache, diarrhea, hematemesis, vomiting, and dizziness, organ failures such as necrosis, cirrhosis, hypertension, low blood pressure, and gastrointestinal discomfort. Arsenic can cause lung, liver, and bladder cancer. As well as damage to the kidneys and lungs, cadmium can cause bone fragility. Kidney and brain damage may be caused by exposure to lead. Low lead concentration exposure in children can impair learning, affect the functions of attention and reaction, cause memory loss, and can make children aggressive. Miscarriage can be caused by elevated levels of lead exposure in pregnant women. In men, the organ responsible for the development of sperm is damaged. Because of its ability to exist in urine for about 2 months, Mercury causes renal dysfunction. Exposure to metals in crustaceans may lead to loss of food appetite and consequently body weight loss. In adults, continuous exposure can decrease reproduction and impede larval development. It can also trigger nerve, kidney, and muscle dysfunction **[30, 31].**

Toxic chemicals present in water, such as dyes, can have a direct effect on marine animals, plants, and humans. They cause sunlight to penetrate water bodies, lowering dissolved oxygen levels and killing photosynthetic organisms and other marine life. Dye is mutagenic and carcinogenic. Pharmaceutical water can be harmful to marine animals in both acute and chronic forms. EDCs can cause endocrine irregularities and increase the risk of human cancer. They can cause endocrine system disruption in aquatic life by reducing egg and sperm cell development **[31].**

5.0 Mechanisms associated with bioremediation by microorganisms.

Bacteria, microalgae, fungi, and yeast are essential classes of microorganisms that are widely used for bioremediation.

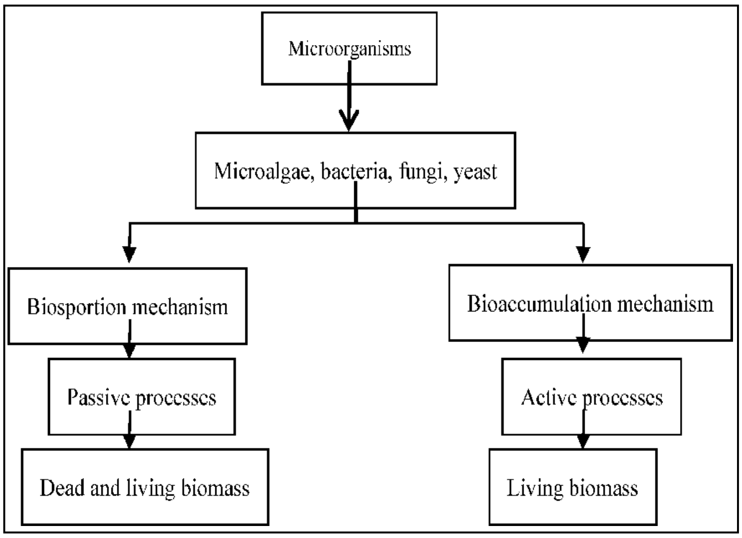

Figure 1: Microorganisms employed in the bioremediation and processes/mechanisms involved in the case of dead and living biomass (*Source: Coelho et.al, 2015*)

Two mechanisms, such as biosorption and bioaccumulation, are involved in bioremediation. Biosorption is a reversible and quick passive adsorption process. There may be both living and dead biomass for biosorption. This approach requires low costs since it is possible to regenerate and reuse the biomass collected from industrial waste multiple times **[3].**

Bioaccumulation is a mechanism in which the concentration or accumulation of toxins in marine species is increased by absorption from the surrounding environment **[32].** Both intra- and extracellular processes are included. Only living biomass may occur for bioaccumulation. This approach involves costly costs since it takes place in the presence of living cells where reuse is limited **[3].**

6.0 Methods of bioremediation for wastewater

6.1 Bacteria

Bacteria possess a large range of potential for bioremediation. From both an economic and environmental point of view, they profit from **[33].** A significant environmental issue emerges from heavy metal emissions from industrial applications. E.g., Cd, Cr, Cu, Hg, and Zn, respectively. Chromium is a poisonous heavy metal commonly used in the manufacturing sectors of electroplating, leather tanning, garment dyeing, and metal processing. Several microorganisms, such as Desulfovibrio vulgaris, Arthrobacter, Pseudomonas sp., Serratia marcescens, Ochrobactrum sp., Bacillus sp., Cellulomonas spp., Acinetobacter, and Ochrobactrum, have been known to reduce highly soluble and toxic Cr (VI) to less soluble and less toxic Cr (III). The protein concentration of wastewater was decreased by *Arthrobacter psychrolactophilus Sp 313* **[34, 35].** They are used for the disposal of industrial sewage. Several distinct bacteria such as *endophytes, pseudomonas, and B. subtilis* were used in the treatment process **[36].** *Klebsiella pneumonia* strain CF-S9 was also used **[37].**

Application of Oxygenic Photosynthetic Bacteria (Cyanobacteria) in Bioremediation

Cyanobacteria are commonly used in the treatment of wastewater, the removal of heavy metals, crude oil, pesticides, and oxidation of color. Since cyanobacteria need nitrogen for metabolism, nitrate removal by these organisms is generally very successful. For the removal of the nitrate *Synechococcusspstrain PCC7942, PCC6803*, and *Synechocystis minima CCAP148014*, three distinct cyanobacterial species were used. Nitrogen and phosphorus were effectively extracted by the *Phormodium tenue* strain and *Phormodium bohneri*. Anabaena variabilis, Anabaena oryzae, and Tolypothrix ceytonica besides cyanobacteria strains were also treated with a mixture of industrial and domestic wastewater. Organic matter has been deleted by *A. variabilis* and *A. oryzae* respectively. *T. ceytonica* and *A. variabilis* were used for solid removal. *Anabaena subcylindrica* and *Nostoc muscorum* have extracted heavy metals such as copper, cobalt manganese, Zn and Cu and lead from sewage wastewater. Copper was extracted using Nostoc PCC 7936 and Cyanospira capsulate (II). For the elimination of both Zn and Cu, T. certonic is used. The degradation of crude oil was achieved by *Oscillatoria salina, Aphanocapsu sp. Terenbans* and *Plectonema.*Lindane pesticides were degraded by *Anabaena sp. PCC 7120* and *Nostoc ellipsosporum strain B1453-7*. Oscillatoria formosa NTDM 02 was found to be very effective at extracting dye from the textile industry. **[38].**

Application of Anoxygenic Photosynthetic Bacteria in Bioremediation

During pharmaceutical wastewater treatment, the *PPB, Rhodobacter sphaeroides Z08 was* added. Phosphorus was also removed by *R. sphaeroides IL106*. The strain of *Rubrivivasgelatinous*designated as *SS51* and *SY40* degraded the organic contaminants from the wastewater manufacturing latex. To extract heavy metals, *R. sphaeroids KMS24* and *Rhodobium marium NW16* have been found. For pesticide degradation, *R. palustris WS17* was used. *PNSB, R. Palustris ASI.2353* used in the degradation of coloring **[38].**

6.2 Algae

Algae play an important role in the natural water purification process. They can be used for poisonous and radioactive metal ion sorption and precious metal ion recoveries, such as gold and silver. They grow rapidly and assimilate nutrients present in wastewater (C, N, and P), and are helpful in the remediation of nutrients. It is an alternative technology for the economic and environmental treatment of sewage wastewater **[39].**

Microalgae- Several authors have identified the use of microalgae to extract nutrients from various wastes to avoid further degradation of the water quality of wastewater **[1].** Textile wastewater (TWW) contains the nutrients required for algae cultivation (phosphate, nitrates, micronutrients, etc.) as well as organic dyes (a potential source of carbon). Microalgae such as dyes and nutrients can be used effectively in the bioremediation of clothing wastewater (TWW) **[40].** For its growth, microalgae utilize dyes and nutrients present in wastewater. Using the culture of *C. vulgaris, S, quadricauda*the bioremediation of wastewater can be achieved. *C. vulgaris* is used to handle the production of diluted ethanol and citric acid from the wastewater industry. It increases the decrease in effluent values of both BOD and COD. Nitrate removal was conducted using *C. vulgaris* and *S. quadricauda*. The phosphate was extracted efficiently by *S. quadricauda*. *C. vulgaris* remove phosphate by using phosphorus for growth during the remediation. *(Kshirsagar, 2013; Salgueiro et.al, 2016)*. *Chlorella vulgaris strain UMACC 001* is used to bioremediate clothing wastewater (TW). For color removal from dyes and wastewater, living and non-viable algae have been used. There are two methods of bioremediation of TWW using microalgae, i.e., bioconversion and bioaccumulation, or biosorption operation **[41].** Microalgae ingest these dyes as a source of carbon during the bioconversion process and transform them into metabolites. Microalgae, however, can also function as a biosorbent in which these dyes can be adsorbed to their surface. For TWW bioremediation, both phenomena can take place simultaneously. Enzyme degradation, adsorption or both may be the mechanism involved in the aggregation of microalgae. Microalgae have a high sorption potential due to their properties such as high surface area and good binding affinity for azo dyes. Cells of non-living algae absorb the biosorption of metal ions on the surface of the cell membrane. Algae-based biosorption of heavy metal ions in wastewater can provide an environmentally safe, cheaper, and more effective method of extracting metal ions from wastewater **[42].** A valuable biosorbent for the removal of reactive dye (Synazol) from textile wastewater has been shown to be the non-viable biomass of *Spirogyra*. Living biomass of macroalgae like Caulerpalentillifera and Caulerpa scalpelliformis can remove basic dyes through biosorption. Some algae, such as *Phormidium,* can break down the dyes to simpler compounds by bioconversion. Immobilized algae are used to extract color from the surface of textile dyes. *Chlorella* and *Spirulina* are effective in handling the removal of wastewater **[41].** Chlorella vulagris, Chlorella pyrenoidosa, Scenedesmus bijugatus, and Oscillatoria tenuisin are among the microalgae that can degrade azo dyes into simple aromatic amines. **[43, 44].** *Chlorella sp*. and *Scenedesmus sp*. Usually, *Microalgae G23, Spirulina platensis, Cosmarium sp*. were used against various forms of wastewater, because they are more potent **[44, 45].**

6.3 Fungi

Heavy metals such as Zn, Cd, Pb, Fe, Ni, Ag, Th, Ra & U are consumed by filamentous fungi. Biosorbents may use the ability of fungal biomass to extract heavy metals and radionuclides from contaminated waters. White rot fungi such as *Pycnoporus sanguineus laccase* and *Phanaerochaete chrysosporium* can destroy harmful contaminants such as straw, sawdust, or maize cobs **[5, 46].** Metal ions are absorbed by *Penicillium, Aspergillus, Rizopus, Mucor, Saccharomyces, and Fusarium. Penicillium* is used to biobsorb heavy metals (Cr, Ni, Zn, Pb & As). The radionuclides (U, Th & Sr) can be biosorbed by *Penicillium, Rizopus* and *Saccharomyces* **[47].** For the bioremediation of distillery wastewater, *Trametes pubescens MB 89, Ceriporiopsis subvermispora, Pycnoporus cinnabarinus* and *UD4* were used. White rot fungi can degrade phenolic waste of high intensity **[48].** Industrial wastewater is being degraded by white-rot fungi. To decolorize and reduce the chemical oxygen demand (COD) of molasses wastewater, *Coriolus versicolor, Funalia trogii, Phanerochaete chrysosporium* and *Pleurotus pulmonarius* may be used **[49].**

Three kinds of species may be used to remediate OMWW: white rot fungi (including Lentinula and Pleurotus edible mushrooms), *Aspergillus sp.,* and many different types of yeast. They mitigate COD, phenolics, and OMWW color. For the remediation of OMWW, white rot fungi, including Coriolus versicolor and *Funalia trogii, Geotrichum candidum, Lentinula (Lentinus) edodes, and Phanerochaete sp*, were used **[50].**

Most potential candidates are fungi and play an important role in bioremediation **[6].** Among them, white-rot fungi have a variety of environmental contaminant degradation advantages. *Aspergillus terreus, Cladosporium oxysporum, Mucor thermohyalospora, Fusarium ventricosum, Phanerochaete chrysosporium, and Trichoderma harzianum* are used to degrade endosulfan fungi like *Aspergillus niger.*To degrade and detoxify textile wastewater and crude oil, fungi of the class *zygomycetes* and *Aspergillus, mucor, penicillium* were used.*Penicillium chrysogenum, Scedosporium apiospermum, Penicillium digitatum, and Fusarium solani* are used for the degradation of polychlorinated biphenyls (PCB). *Suillus bovines* and *Rhizopogon roseolus* are used in combination with Pinus to extract cadium. Some plant-related fungi, such as *A. nidulans, Bjerkandera adusta, Trameteshirsuta, T. viride, Funalia trogii, Irpex lacteus, P. ostreatus,* are used to decolorize waste from the textile industry **[6, 10].**

6.4 Yeast

Heavy metals like Zn, Cd, Pb, Fe, Ni, Ag, Th, Ra & U are absorbed by yeast **[5].** *Trichosporon cutaneum, Candida tropicalis, and Saccharomyces sp.* are yeasts that are used in OMWW bioremediation. Yeasts are also efficient in lowering COD levels and removing mono- and polyphenols **[50].** They are used in the treatment of textile wastewater because it is capable of absorbing, accumulating and degrading toxic chromophores into simpler compounds. They can be used as biosorbents for dye biosorption and have enzymes for the degradation of dyes. Yeast like *Candida krusei, Trichosporon beigelii, Galactomyces geotrichum, S. Cerevisiae,* etc., used to biodegrade dyes, etc. **[43].**

6.5 Aerobic biodegradation

The theory of aerobic biodegradation requires the necessity of oxygen for the degradation of contaminants by degradable species. Oxygenase and peroxidase can be produced by bacteria and fungi. The triggered sludge reactor and the membrane bioreactor have aerobic biodegradation reactors **[26, 36].**

6.5.1 Activated sludge reactor.

Activated sludge is a procedure used with the use of air and a biological floc consisting of protozoans and bacteria to treat commercial, domestic, and sewage wastewater. Ardern and Lockett invented this method. The organic matter, nitrogenous matter, and phosphate in the wastewater are eliminated **[7, 26, 51].** This system is used most widely for the treatment of secondary wastewater **[52].** In this step, contaminants are removed using activated sludge, which is a bacterial biomass suspension. **[53].**

It requires two different phases: aeration and settlement of sludge. The first step is to apply primary treated wastewater to the aeration tank, where air or oxygen-containing mixed microbial population is added to grow biological flocks made up of microorganisms including saprotrophic, nitrobacteria, and denitrifying bacteria that reduce the organic content of wastewater. The suspension of bacterial biomass (activated sludge) is responsible for organic pollutant degradation. Biological flocks settle out of suspension and form sludge in the settling tank, separating biological sludge from clarified effluent, which is free of solids and discharged as the final effluent. The process helps to replace organic matter, nitrogenic matter, phosphate in wastewater **[54].**

Figure 2: The scheme of activated sludge reactor (*Source: Zheng et.al, 2013*)

6.5.2 Membrane bioreactor

A newly developed technology is the Membrane Bioreactor (MBR). This groundbreaking technology combines the membrane method with biologically activated sludge, such as microfiltration or ultrafiltration, or with biological reactions used for urban and industrial wastewater treatment. The porous membrane with a pore diameter of 0.02 to 0.4 μm is used to isolate treated water and microorganisms in this method. Solid-liquid separation is efficient **[26, 55-59].**

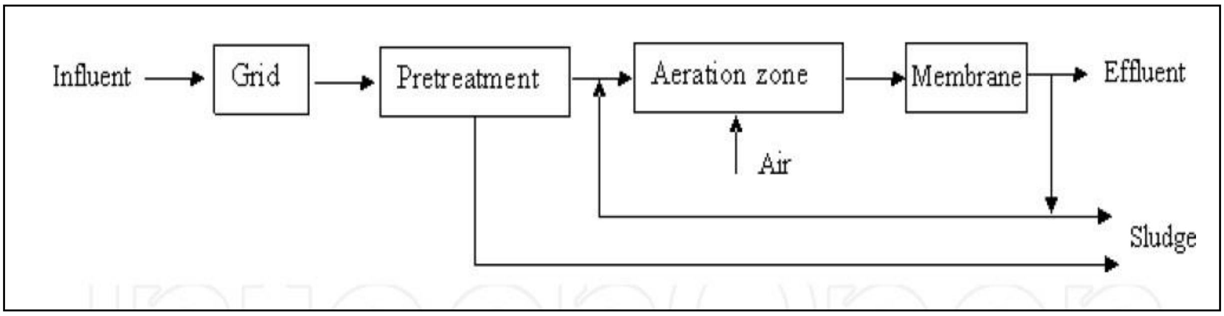

Figure 3: The scheme of MBR reactor (*Source: Zheng et.al, 2013*)

6.6 Anaerobic degradation

In the absence of oxygen, anaerobic degradation is a mechanism where biodegradable content is broken down by microorganisms. The anaerobic degradation theory involves the following process: first, insoluble organic pollutants are broken down into soluble substances and made available to other bacteria; second, sugars and amino acids are transformed into carbon dioxide, hydrogen, ammonia, and organic acid by acidic bacteria; third, organic acids are converted into acetic acid, ammonia, hydrogen. In contrast to aerobic degradation, anaerobic degradation processes are sluggish and inefficient. Moreover, some organic contaminants, such as lignin and high molecular weight PAH, may also break down anaerobic bacteria. They can be used to effectively handle wastewater from the sugar industry, slaughterhouses, the food industry, the paper industry, etc. with high organic pollutant loads. Example: Upflow reactor for anaerobic sludge blanket, anaerobic filter **[26, 36].**

6.6.1 Upflow Anaerobic Sludge Blanket Reactor (UASB)

At the start of the 1980s, Lettinga developed the UASB system **[60].** It is a type of suspended growth reactor that helps maintain a high microbial biomass concentration **[61].** It is a type of anaerobic digester that produces methane and then processes the anaerobic microorganisms to form a blanket of granular sludge. There are three UASB zones, the lower blanket zone of sludge, the middle dead zone, and the upper gas zone. The layer is evenly dispersed at the bottom of the reactor, where the anaerobic granules meet and degrade the organic matter. The substrate that is injected near Gas-Liquid-Solid (GLS) at the bottom of the reactor is discharged, while biogas evolved at the top of the reactor outlet comes out. Via a dense blanket of anaerobic granular sludge suspended in the device, liquid waste travels upwards. The production of methane inside the blanket achieves the mixing of sludge and wastewater. Large and dense granules remain suspended inside the sludge bed during these processes. In the gas-solid separator, where the gas bubbles detach, granules with gas trapped in them join. The granules slip back into the reactor afterward. Via a gas collection system, the biogas is then stored. The settling zone joins the liquid and smaller-size granules. This enables the settling back into the reactor of tiny and light granules. Effluent collection systems at the top of the reactor store the treated effluent **[26].**

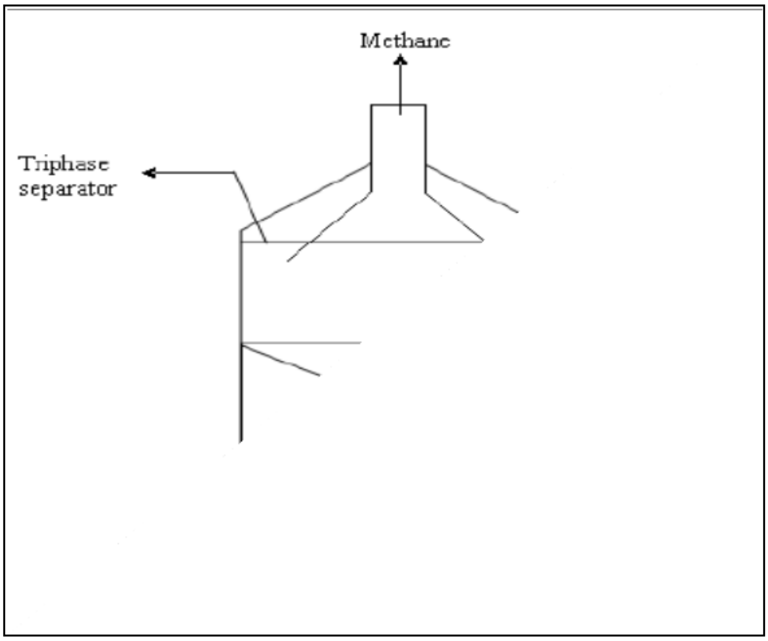

Figure 4: The scheme of up-flow anaerobic sludge blanket reactor (*Source: Zheng et.al, 2013*)

6.6.2 Anaerobic biofilter

In 1960, the anaerobic filter bioreactor was created. These are also known as fixed-film anaerobic reactors, which are highly effective anaerobic therapies. This reactor consists of a fixed bed where bacterial biofilm is formed. This fixed bed is made up of various inert materials such as pumice, gravel, crushed rock, a stone of pumice, etc. These materials range in size from 12-55 mm. Such materials provide a surface for anaerobic bacteria to grow. The organic contaminants in wastewater are decomposed or contaminated in the system by bacteria present within the fixed bed as water flows through the fixed bed, and then methane gas is emitted from the top of the system **[26, 62].**

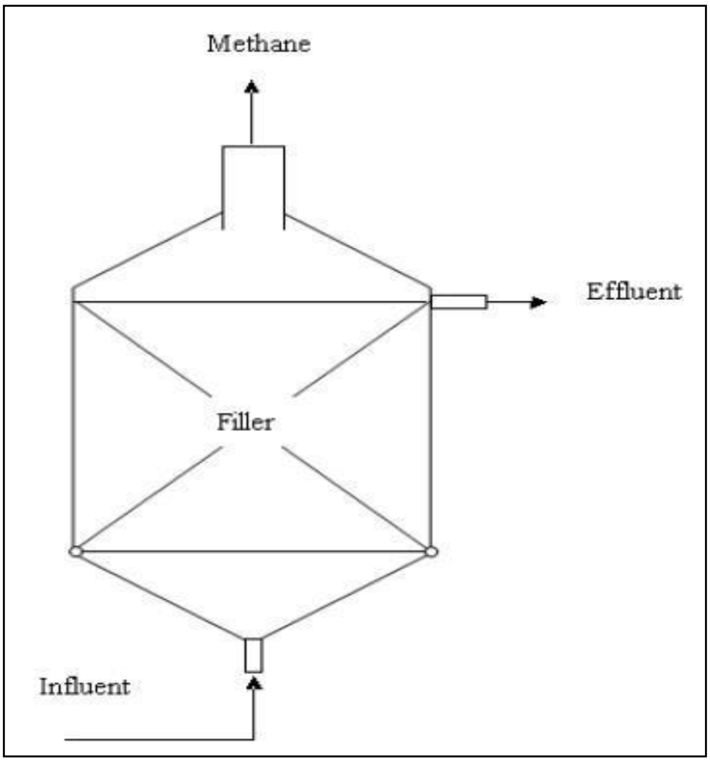

Figure 5: The scheme of the anaerobic biofilter (*Source: Zheng et.al, 2013*)

6.7 Biosorption

New biotechnological processes, such as bioaccumulation and biosorption, are used to remove heavy metals from industrial waste. Due to its numerous properties such as cost-effectiveness, highly efficient, highly precise, less chemical or sludge formation, no additional nutrient requirements, biosorbent regeneration, and eco-friendly in nature, this is an attractive technology **[63].** It is an alternative strategy to traditional methods used to remove heavy metals from wastewater. The approach uses biological materials (microbial biomass) as biosorbents for the treatment of water sources polluted with heavy metals **[64].** Biosorption relies on the pH, temperature, initial dye concentration, and dosage of the solution **[43].** Due to their diversity, adaptability, and flexibility, several microorganisms such as bacteria, yeast, algae, protozoa, and fungi are effectively used to extract heavy metals like arsenic, mercury, lead, copper, cadmium, and their cyanide complexes, etc. Heavy metal biosorption using Actinobacteria biomass is a promising agent in the development of green technology that aids in the control of heavy metal emissions. *Bacillus, Pseudomonas, Streptomyces, Aspergillus, Trichoderma, Yarrowia lipolytica, Rhizopus, and Penicillium* are examples of such microbial metal biosorbents. As possible biosorbents, they are considered **[63, 65].** Because of several features, including metal detoxification mechanisms that can withstand high heavy metal concentrations, actinomycetes play a unique role in bioremediation. They can alter the toxicity of heavy metals and create a wide range of biologically active compounds. In biosorption metal ions bind with metal-binding proteins that are present on the cell wall. In this method heavy metals, present in wastewater are accumulated via various processes like spontaneous physiochemical pathways, by use of energy i.e., ATP, or by property of various non-living or inactive microbial biomass that binds with heavy metals. **[63, 66]**

6.8 Phytoremediation

In situ bioremediation is referred to as phytoremediation. **[36].** It is an evolving technology that makes use of microorganisms associated with some higher living plants to extract pollutants from water. In 1991, the word "phytoremediation" was coined **[2, 67].** They use rooted plants and trees to assimilate, metabolize, degrade, or detoxify metal contamination and organic chemical contamination **[67, 68].** Heavy metals, aromatic, chlorinated solvents, petroleum hydrocarbons, pesticides, explosives, crude oil, and other organic and inorganic pollutants have also been considered as possible targets for phytoremediation technologies. This approach is focused on the use of various plant interactions at contaminated sites, such as physical, biochemical, biological, chemical, and microbiological, to reduce the toxic effects of pollutants **[4, 67].** Phytoremediation is a method of bioremediation that uses different types of plants to extract, shift, stabilize, and/or kill water pollutants **[5].** Phytoremediation is well suited for use in the field at very large sites where other remediation methods are either not feasible or cost-effective.

Aquatic plants are capable of consuming excess contaminants that are found in agricultural, domestic, and industrial wastewater, such as heavy metals, organic and inorganic waste, and pharmaceutical pollutants. Salvinia molesta and Pistia stratiotes are among the aquatic plants used in the treatment of this wastewater. Plant roots consume these toxins and help to restore them **[69].**

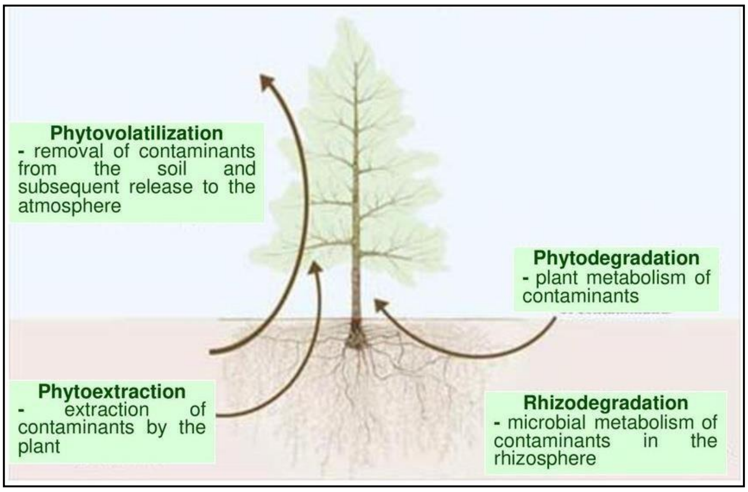

Figure 6: Phytoremediation techniques involved in wastewater remediation (*Source: Zouboulis et.al, 2011*)

Phytoextraction, phytodegradation, phytovolatilization, and rhizofilteration are some phytoremediation techniques used in wastewater remediation **[2].**

Phytoextraction or phytoaccumulation- Plants use this method to accumulate contaminants in their roots and aboveground shoots or leaves. Heavy metals are extracted from wastewater using this process, which involves metal absorption by roots and transfers to shoots or leaves above ground. They must be harvested and stored as plants decompose, preventing pollutants from being recycled. **[2, 70].**

Phytotransformation or phytodegradation- This is the process of organic compounds being absorbed and transformed from water into more stable, less mobile, and less harmful forms. For example, metal chromium can be reduced from hexavalent to trivalent chromium, which is non-carcinogenic and less mobile. Organic pollutants such as nitroaromatics and aliphatic organic compounds are extracted using this method. Within the plant, they are phytodegraded. **[2, 71].**

Phytovolatilization- This method necessitates the absorption of certain metals, such as mercury or selenium, in groundwater, accompanied by their conversion to volatile chemical species and release into the atmosphere. **[2, 72].**

Rhizofiltration-It is a method used to minimize pollution from flowing water for water remediation. This includes the filtering and sorption by plant roots and by microorganisms present in the rhizosphere of wastewater pollutants. Metals, radionuclide, and hydrophobic organic compounds are primary pollutants that can be extracted by this process. Certain plants may be used in this technique, such as water hyacinth and duckweed. Duckweed has been used in industrial wastewater treatment plants **[2].**

To extract heavy metals from wastewater, some of the other plants used for treatment can include macrophytes. For the removal of Pb and Cd, *Salvinia minima* (Seguier.), a tropical water fern, is used. Alvarez et al. (2004) suggest that the water lily is efficiently used for tannery removal of Cr. The source of E. crassipes (Mart) can easily adsorb metals **[73].**

TABLE 2. Bioremediation techniques, types of industrial waste, & their outcomes.

Bioremediation Techniques	**References**	**Type of Industrial waste**	**Outcomes**
Bacteria	[33-38]	Textile Pharmaceuticals	Removal of heavy metals like Hg, Cr, Cu, Cd, Zn, dyes, color, pesticides, dyes.
Algae	[1,39, 40-45]	Sewage wastewater Textile wastewater	Used for sorption of poisonous, heavy metals, and radioactive metal ion. Gold and Silver metal ion recovery. Reduction of N, P, and COD by microalgae. 68.4% BOD and 67.2% COD removal
Fungi	[5,6,10,46-50]	Olive mill wastewater	Reduction of heavy metals like Pb, Fe, Ni, U, Zn, Cd, Ag, Th, & Ra

			Used to remove radionuclides from polluted waters. The removal of COD, total nitrogen, ammonium nitrogen, and phosphate removal varied from 0 to 72%, 22 to 93%, 27 to 90%, and 12 to 100%.
Yeast	[5,43,50]	Textile	Helps in reducing COD levels and removing mono- and polyphenols, organic matter, heavy metals, & degrade dyes. They remove 98% of oils and 94% of COD.
Aerobic biodegradation			
1)Activated sludge reactor (Ardern and Lockett invented this method).	[7,26,51-54]	Organic matter, nitrogenous matter, and phosphate in the wastewater are eliminated.	For treatment of secondary wastewater. Removal of organic carbon substances and nutrients such as nitrogen (N) and phosphorus (P). 80 to 90 % BOD removal.
2)Membrane bioreactor	[26,55-59]	Food processing, pulp and paper, textile, tannery, landfill leachate, pharmaceutical, oily, and petrochemical wastewaters	Removal of organic compounds. Removal efficiency of COD is 98% and 100%

Anaerobic biodegradation			
1)Upflow Anaerobic Sludge Blanket Reactor (UASB) Lettinga developed the UASB system.	[26,60,61]	Organic pollutants, chemical, petrochemical, textile, dairy, brewery, sugarcane	Reduction of organic contaminants. 75% COD removal
2)Anaerobic biofilter	[26,62]	Organic	COD concentration decreased COD from day 0 to day 20 with a removal efficiency of 91.73%.
3)Biosorption	[43,63-66]	Heavy metals	Removal of heavy metals ions like Ni, Cd, Hg, Co, etc.
4)Phytoremediation	[2,5,36,67-69]	Organic and inorganic contaminants, including heavy metals, aromatic, chlorinated solvents, and petroleum hydrocarbons, pesticides, explosives, crude oil, etc.	They use rooted plants and trees to assimilate, metabolize, degrade, or detoxify metal contamination and organic chemical contamination. Reductions in BOD (82%), EC (86%), TDS (68%), & COD (78%),

7.0 Conclusion

Water contamination is of great concern around the world nowadays. Due to increased human activities on energy reserves, environmental degradation has arisen through unhealthy agricultural practices and rapid industrialization. For a key alternative approach to overcoming problems, microorganisms are therefore critical. Bioremediation is an emerging and revolutionary technique that is used for polluted water remediation. It is a natural method for waste disposal. It is a very efficient and favored instrument for the cleaning of polluted areas. They use living microorganisms that exist naturally, such as bacteria, yeast, fungi, algae, and some plants, to improve normal biological degradation. They are sustainable approaches to the control of environmental pollution. Appropriate microbial communities can degrade, modify, extract, immobilize, mineralize, detoxify, or convert a wide range of pollutants or hazardous compounds into harmless or non-toxic conditions. As they degrade pollutants, microbes obtain energy. Eventually, simpler molecules, such as carbon dioxide or water, but also cell biomass, can be part of the residues of the procedure. The risk of potential risks in the handling and disposal of hazardous material is thus effectively eliminated. Bioremediation may also be carried out on-site, thus minimizing the associated costs and risks for shipping, as well as the possible threats to human health and the environment related to the transport of hazardous materials.

It is also applied as technology in-situ. It is ecologically appropriate since the treatment of polluted water is a cost-effective, safe, low-risk, reliable and eco-friendly technique. There is the destruction of pollutants and therefore the disruption of the site is reduced. They also help to control waste and environmental toxins using chemical and physical processes. Finally, bioremediation can be integrated into a process chain with other technologies, thus increasing the performance of the whole procedure.

As bioremediation is a natural process that uses living microbes for the degradation of toxic pollutants into non-toxic forms. But besides this, there are certain limitations associated with this method. As we use microbes for degradation; microbial population should have metabolic capacity to degrade contaminants, environmental conditions should be proper for their growth and activity e.g. temperature, pH, etc., there should be the right amount of contaminants and nutrients, if the process is not controlled then there are chances that those organic contaminants may not be degraded completely and may result in toxic by-products, controlling of volatile organic compounds may be difficult in ex-situ process, only those contaminants can be treated which are biodegradable, sometimes bioremediation may take more time for treatment than other methods, limitation of nutrients, low population or absence of microbes which have the biodegradative capability, the bioavailability of pollutants, the complexity of contaminants mixture may hinder the success of bioremediation. So, for the bioremediation method to be successful is site characterization which helps to establish a more suitable and feasible technique.

We can create organisms specifically for the bioremediation process using genetic engineering techniques. By this technique, we can insert two types of genes in the organism: First it can be degradative genes that may encode protein required for degradation of contamination, and second it can be reporter genes that may help in monitoring pollution levels.

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