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REVIEW ARTICLE

Industrial wastewater treatment using extracellular polymer substances/bioflocculants: a review

Bishwambhar Mishra[1] · Parashuram Kallem[2,3] · Rajasri Yadavalli[1] · Sanjeeb Kumar Mandal[1] · C. Nagendranatha Reddy[1] · B. Sumithra[1] · N. S. V Lakshmayya[1] · Fawzi Banat[3]

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Abstract

The treatment of industrial wastewater, containing various contaminants like chemicals, dyes, and heavy metals, has emerged as a significant environmental issue. Traditional treatment procedures, although successful, frequently include synthetic chemicals that are non-biodegradable and present hazards to both ecosystems and human health. Bio-flocculants, especially those originating from extracellular polymeric substances (EPS) generated by microorganisms, provide an environmentally benign and sustainable option. These bioflocculants utilize microbial enzymes and polymeric substances to efficiently agglomerate and eliminate contaminants, adhering to the principles of green chemistry. Recent studies have concentrated on enhancing bioflocculant manufacturing technologies and their utilization in industrial wastewater treatment. Research is directed on improving biodegradability, cost-efficiency, and pollutant removal efficacy. This paper analyzes the function of microbial-based bioflocculants in industrial wastewater treatment, emphasizing their ecological advantages, biodegradability, and economic efficiency. It also examines progress in bioflocculant synthesis, concentrating on the production and application of EPS. Contemporary research trends focus on enhancing bioflocculant manufacturing technologies and broadening their industrial uses. Future initiatives focus on improving the efficiency and scalability of bioflocculants to facilitate new and sustainable wastewater management solutions.

Keywords Contaminants · Pollutant removal · Biodegradability · Sustainability · Floculation

Introduction

Water pollution arises as a consequence of the persistent release of industrial wastewater and effluents into aquatic ecosystems, including rivers and lakes. Annually, a significant quantity of hazardous substances such as toxic sludge, heavy metals, solvents, suspended solids, and other biological wastes are released into neighboring ecosystems by industrial establishments worldwide (Choudhary et al. 2020; Briffa et al. 2020). The majority of the pollutants included in these effluents consist of dissolved and emulsified natural compounds, suspended materials, such as clays and silica, sulfur, asbestos, lead, mercury, nitrates, phosphates, toluene, dyes, alkalis, acids, benzene, pesticides, chlorobenzene, polychlorinated biphenyls, volatile organic compounds, carbon tetrachloride, and hazardous solvents, (Tong et al. 2022; Nagendranatha Reddy et al. 2022; Briffa et al. 2020; Bhadauria et al. 2017; Kolya et al. 2017). Toxic metals pose a significant threat to both living organisms and the environment when their concentration exceeds a particular threshold. In

✉ Parashuram Kallem
parshukallem@gmail.com

✉ Rajasri Yadavalli
rajasriy_biotech@cbit.ac.in

✉ Fawzi Banat
fawzi.banat@ku.ac.ae

1 Department of Biotechnology, Chaitanya Bharathi Institute of Technology (CBIT), Gandipet, Hyderabad, Telangana 500075, India

2 Department of Environmental and Public Health, College of Health Sciences, Abu Dhabi University, PO Box 59911, Abu Dhabi, United Arab Emirates

3 Department of Chemical Engineering, Khalifa University of Science and Technology, PO Box 127788, Abu Dhabi, United Arab Emirates

drinking water, for example, the permissible thresholds are Lead (Pb): 0.01 mg/L, Arsenic (As): 0.01 mg/L, Cadmium (Cd): 0.003 mg/L, and Mercury (Hg): 0.006 mg/L. Globally, a significant number of dyes, estimated to be approximately one million annually, are utilized by various organizations (Zaynab et al. 2022; Santhosh et al. 2024). Regrettably, a substantial proportion of these dyes ultimately find their way into wastewater, posing severe environmental risks and causing detrimental effects on both human beings and aquatic organisms (Briffa et al. 2020). Similarly, the presence of radioactive elements and other recalcitrant and complex pollutants generated from industrial wastewater poses potential risks involved to both environment and humans, such as carcinogenic effect (asbestos and other heavy metals), eutrophication and low dissolved oxygen content (nitrates, phosphates, sulfur, etc.), impaired metabolism and other disorders (solvents), (Reddy et al. 2018; Jorge et al. 2023). Addressing hazardous contaminants in industrial waste and sewage is crucial to protect ecosystems and public health, as changes in the nutritional composition of water can disrupt ecological balance. The ecology can have significant consequences as a result of water pollution originating from industrial facilities (Nagendranatha Reddy et al. 2022).

Conventional methods and approaches, viz., chemical precipitation, coagulation, oxidation processes, membrane filtration, adsorption processes, evaporation recovery, flocculation, etc., are employed for the purification of industrial wastewater and the treatment of sewage (Zhang and Jiang 2019; Zhang et al. 2021, 2022; Rajoria et al. 2022). Among these several technologies available for water treatment, the flocculation process stands out as a highly efficient and economically viable option as it is employed for the separation and recovery of dispersed or finely fractionated particles present in wastewater. According to Chibowski (2011), the fragmented particles spread and then aggregate into bigger clusters known as flocs, which can easily separate from the surrounding water (Chibowski 2011). Chemical flocculants are frequently employed in fermentation, post-fermentation processing, and wastewater treatment due to their cost-effectiveness and superior flocculation capabilities (Okaiyeto et al. 2016; Agunbiade et al. 2022). Similarly, the chemical flocculants too pose serious health impacts and environmental issues which is evident from the literature, viz., nervous system breakdown, development of cancers and Alzheimer's disease by usage of chemical flocculants, such as aluminum salts and polyacrylamide monomers. Hence, the potential hazards associated with chemical flocculants can be overcomed by utilizing the green, sustainable and biodegradable flocculants (Klotz et al. 2017; Salehizadeh et al. 2018).

The current necessity of wastewater treatment focusing on reduced ecological footprint has shifted attention toward the alternative usage of bioflocculants or biopolymers derived from various organisms, viz., microbes, plants, etc., (Castiello et al. 2023; Yang et al. 2024; Edo et al. 2024). Bioflocculants have gained significant interest from the scientific community due to their sustainable and renewable nature, low toxicity, eco-friendly, biodegradability, and low cost (Chen et al. 2019; Castiello et al. 2023; Nkosi et al. 2024; Orchard et al. 2024). In recent years, microbial-based bioflocculants have emerged as a noteworthy subset of bioflocculants, showcasing significant innovation. The use of microorganisms' metabolic activity enables the effective utilization of biopolymers in wastewater treatment procedures, showcasing their significant potential. Microorganisms, including bacteria, fungi, yeasts, and actinomycetes, produce bioflocculants as a byproduct of their growth and metabolic processes (Agunbiade et al. 2017). The utilization of the innate capacities of these bacteria to generate bioflocculants offers a potentially fruitful approach for achieving sustainable wastewater treatment. Microbial-derived bioflocculants exhibit significant versatility, since their ability to effectively aggregate a diverse range of pollutants, such as suspended particles, heavy metals, and organic compounds, has been extensively described in scientific literature. Gaining a comprehensive comprehension of the fundamental processes involved in microbial bioflocculation is crucial for effectively exploiting their complete capabilities in the context of industrial wastewater treatment. These processes encompass the production of extracellular polymeric substances (EPS) by microbes, enzymatic activity, and physicochemical interactions.

The contamination levels of heavy metals in Indian water bodies are of serious concern, with widespread occurrences exceeding acceptable limits and arising primarily from anthropogenic activities such as industrial discharge, agricultural runoff, and domestic waste disposal. Continuous monitoring and effective remediation strategies are essential for safeguarding public health and ecological integrity. Regular evaluations emphasize the need for stringent policies and enforcement of existing regulations to manage and mitigate heavy metal contamination effectively. The permissible quantities of heavy metals in water bodies can fluctuate dramatically given the site and origin of the contaminants, nevertheless in broad terms, the safe levels for widespread heavy metals such as lead, arsenic, chromium, copper, and cadmium are calculated in parts per billion (ppb), with the majority of regulations establishing a threshold less than 100 ppb for each particular metal; for instance the EPA primarily establishes the upper limit of contamination level for lead in water for consumption at around 0.01 mg/L (Singh et al. 2024). At 37 monitoring stations, it was noted that the concentrations of metals exceeded safe limits. For instance, mercury levels were found to be nine times higher than the Bureau of Indian Standards (BIS) recommended limit of 1 µg/L in samples from the Yamuna River (Zhang et al. 2023).

This review aims to address the challenges posed by industrial wastewater, which poses significant risks to ecosystems and human health. Among the available solutions, bioflocculants derived from natural or biological sources have gained attention for their eco-friendly, biodegradable, and cost-effective properties. However, the mechanisms and potential of microbial-based bioflocculants remain underexplored, highlighting the need for a comprehensive review of their applications in industrial wastewater treatment. This paper provides a comprehensive analysis of their applications in industrial wastewater treatment, emphasizing their role in advancing sustainable water treatment strategies globally. It delves into recent advancements, challenges, and future prospects in microbial bioflocculant research, aiming to bridge knowledge gaps and foster sustainable innovations in water treatment technology.

Various sources of industrial effluents and their treatment

Industries promote the economic development of any nation. On the other hand, the spread of industry into the global ecosystem, generating harmful pollutants, has become a key problem (Manisalidis et al. 2020). The loss of biological properties is caused by industrial waste emissions, and the resulting toxins have negative impacts on human health, food security, ecosystems, economy, and culture (Abalansa et al. 2021). The oil and gas market, mining companies, chemical industry, food and beverage industry, energy industry, textile industry, leather industry, automotive industry, and many more all contribute to the production of industrial wastewater. All biotic and abiotic pollutants generated by manufacturers must be appropriately treated before being discharged into the various waterways (Crini et al. 2020; Walling et al. 2022). Figure 1 describes the sources of wastewater, the major pollutants associated with them, and the established treatment methods.

Paper industry effluent

Wastewater from the pulp and paper industry is usually significant, requiring effective treatment before it is discharged into surrounding ecosystems (Hossain and Ismail 2015). The dark brown color of the effluent released during the pulping process is largely due to lignin and its contemporaries (Prasongsuk et al. 2009; Śliżewska et al. 2022). High concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), chlorinated mixtures classified as incorporated natural halides, attached solids, fibers, lignin and its constituents, fatty acids, tannins, resin acids, sulfur-containing derivatives, etc., in untreated wastewater pose a significant hazard to receiving water if released unattended. It is generally accepted that many of these contaminants are

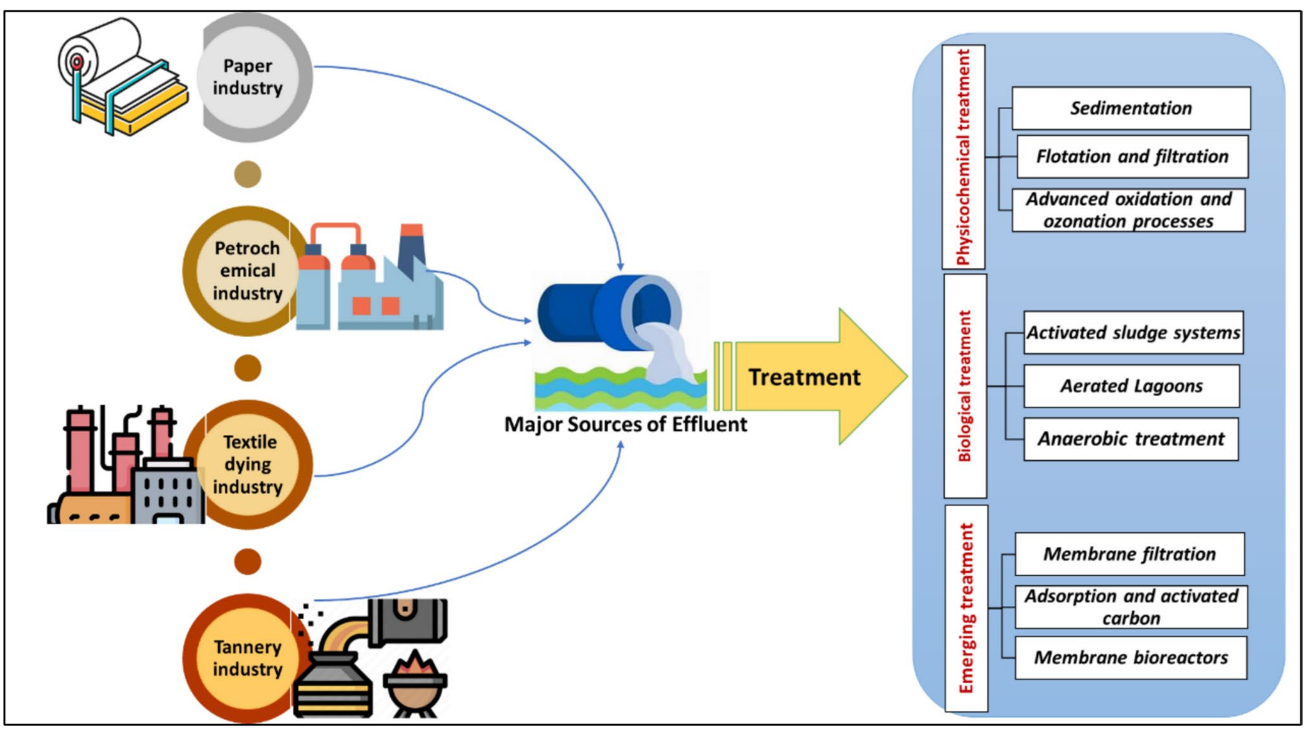

Fig. 1 Sources of effluents, major pollutants associated with the respective effluents and its treatment

toxic either in the short or long term. In the organisms studied, chlorinated biological components, such as dioxins and furans hold the potential to jeopardize genotypic changes. The potential of genotoxic to harm marine ecosystems and human welfare through pollution of water sources used for human consumption, recreation, or industrial agriculture is of increasing concern (Chandra et al. 2017; Kumar and Chandra 2020; Islam et al. 2022). The pulping process generates wastewater that is difficult to treat biologically due to the numerous wood components such as cellulose, hemicellulose, lignin, pectin, carbohydrates, and extractives. In addition, various harmful components such as resin acids, unsaturated fatty acids, diterpene alcohols, juveniles, and chlorinated resin acids can enter the treatment effluent (Kumar and Chandra 2020; Ojha and Tiwary 2021). Chlorine oxidation is the most important reaction in bleaching, and chlorinated organic compounds, also known as AOX, are the most problematic components of the effluent. The harmful effects of these by-products on the ecosystem have been evaluated in wastewater (Bokhary et al. 2018). Daphnia, shrimp, and plankton in waters receiving effluents from the pulp and paper industry have been the subject of numerous studies documenting toxic/lethal effects. The pulp and paper market generate many wastes, most of which are usable only as liquids, and their disposal is a major environmental problem. However, groundwater pollution from conventional solid waste treatment and disposal methods is a major environmental problem due to oxidation and leaching of various heavy metals and other compounds (Dixit et al. 2015). Therefore, powdered activated carbon with a diameter of less than 200 meshes can benefit from a dual treatment strategy consisting of aerobic (for the degradation of low molecular weight compounds) and anaerobic (for the further degradation of metabolites).

Petrochemical, petroleum, and petroleum derivatives effluent

The production of liquid fuels, waxes, petrochemical products, and their metabolites is the focus of the petroleum refining and petrochemical plants (PRPP) industry group (Jain et al. 2020). There is great potential for PRPP goods because of growing population and global financial expansion (Jain et al. 2020; Varjani et al. 2021). Global economic development and population growth have created significant demand for PRPP products. Large amounts of water are consumed in the various stages of petroleum production and processing, resulting in significant wastewater generation (Ng et al. 2022). The amount of wastewater generated by PRPP is about 0.4–1.6 times that of crude oil produced (Jain et al. 2020). Given this sudden increase in demand for PRPP products, scientists are increasingly concerned about environmental stability. Various hazardous organic chemicals found in PRPP effluents pose an immediate threat to aquatic habitats. Therefore, it is critical to develop state-of-the-art methods to treat PRPP wastewater. PRPP wastewater contains large amounts of aromatic and aliphatic hydrocarbon molecules that can potentially impact marine habitats (Diya'uddeen et al. 2011; Ulloa-Saavedra et al. 2022). In addition, oil is an immiscible liquid, so it forms a blanket on the surface of waters that blocks sunlight and oxygen, resulting in lower dissolved oxygen levels (DO) and higher mortality rates for marine life (Royer et al. 2020; Radji et al. 2022).

Various techniques can be used for wastewater treatment, including membrane bioreactors, moving bed bioreactors, activated sludge processes, up-flow anaerobic sludge blankets, anaerobic membrane bioreactors, hybrid anaerobic reactors, up-flow anaerobic fixed bed reactors, anaerobic–aerobic biofilm reactors, microaerobic hydrolysis acidification, membrane sequencing batch processes. However, the corresponding common techniques are characterized by inherent limitations, such as high investment and operation/maintenance costs, technological complexity, etc. These limitations affect the practicality and financial plausibility of the operational protocols, especially for underdeveloped countries (Jafarinejad and Jiang 2019). Another major problem with traditional treatment methods is how to dispose of the large amounts of oily sludge that remain. PRPP wastewater contains organic matter that is difficult to degrade and incompatible with current treatment methods. Thus, sustainable and environmentally friendly, affordable and easy-to-use methods and protocols are needed that can help alleviate the multiple aspects of PRPP wastewater and also overcome the production of toxic pollutants and leachate.

Textile dying effluent

The textile industry is one of the oldest and most important trade markets in the world. It has helped many countries grow and provides employment to more than 35 million people around the world (Atkar et al. 2021). Although the textile industry is very important, it is regrettably one of the most polluted. The garment company's wet market is responsible for the initial steps, such as mordanting, cleaning, bleaching, coloring, and finishing (Stone et al. 2020). These processes require chemicals, such as dyes, minerals, detergents, coloring agents, tints, and fresh water (Abdulkadhim and Abdulameer 2021). Projections state that the fabric and coloring industries consume more than 700,000 tons of dyes each year, with 10–15% of all dyes ending up in water bodies untreated (Hamad et al. 2022). Due to the hazards that these fluorescent toxins pose to both humans and marine life, the management of unprocessed textile dyes has become an important issue in many countries. Some of the physicochemical, electrochemical, and biological methods for removing dyes in textile wastewater include adsorption, coagulation-flocculation, membrane technology, Fenton oxidation, ozonation, and electrolysis. Each in itself has its advantages and disadvantages in terms of how it works, how much it costs, and how much waste it leaves behind. These include the need for a good environment, a maintenance schedule and improvements, sensitivity, chemical costs, and equipment breakage (Khan et al. 2022). Therefore, a mix of methods is usually used to achieve the best results in the treatment of industrial textile wastewater.

Tannery effluent

Leather tanning is the process of transforming the outer fur of animals that decomposes into leather that does not decompose and has certain physical, chemical, and natural properties that can be used in daily life and factories (Nur-E-Alam et al. 2020; Nigam et al. 2022a). This is a complicated process that requires a lot of time and a lot of chemicals, salts, and other ingredients. The processes in panel houses, tanyards, and post-tanning areas are often referred to as "wet processes" because they take place outdoors in treatment containers such as barrels. After the leather is re-tanned, it goes through the dry processing steps. The techniques used in each of the upstream stages depend on the primary resources used and the desired end products. For this reason, the impact of wastewater constituents on the environment varies from tannery to tannery (Ariram et al. 2020). Some industrial processes release chemicals into the air that are bad for the environment. These pollutants, which are present in wastewater in varying amounts, have either direct or indirect effects on the atmosphere. The most common processes used in the world for tanning leather are the use of chromium and plants. Today, 80–90% of the leather produced worldwide is chrome tanned leather. Chrome tanning requires about 2% or more of the hides and skins to be chromium, but only about 60–70% of the chromium needs to be immobilized. For this reason, about 0.5 kg of chromium can remain in the tanning liquid for every 1000 kg of hides tanned. This makes things weaker and throws nature out of balance. Impurities in tannery effluents are a problem because they accumulate and are not easily degraded (Saxena et al. 2016; Nur-E-Alam et al. 2020; Krithiga et al. 2022). There are several physicochemical methods for treating tannery waste, such as coagulation-flocculation and biological treatment, but all of them are associated with major problems, such as the formation of a large amount of concentrated sludge. Large-scale dewatering of tannery sludge has historically been done with membranes. How well membranes work depends on how well the wastewater is treated before it is used. Chromium, in particular, needs to be removed from the liquids generated during leather tanning (Goh et al. 2021; Nigam et al. 2022b).

Bioflocculants-sources, types, and constituents

Bioflocculants are a type of extracellular polymeric substances (EPS) that are produced by the process of cell lysis and secretion by various microorganisms, including bacteria, algae, fungi, actinomycetes, activated sludge, and palm oil mill effluents, among others (Shahadat et al. 2017). Various microorganisms are responsible for the production of different types of bioflocculants. Several bacterial strains, including *Bacillus licheniformis*, *Nocardia amarae* YK1, *Pacilomyces* sp., and *Rhodococcus erythropolis* S-I, have been found to possess the ability to generate proteins that exhibit flocculating properties. The production of polysaccharide bioflocculants is observed in several species, such as *Bacillus subtilis* IFO3335 and *Alcaligenes latus* KT201. Additionally, glycoprotein bioflocculants are produced by *Arathrobacter* sp. and *Arcuadendron* sp. TS-4, as reported by Abu Tawila et al. (2018). The treatment of wastewater has become a subject of significant scientific interest because of the notable properties exhibited by natural flocculants, also known as bioflocculants. These qualities include biodegradability and a strong aptitude to induce flocculation (Abu Tawila et al. 2018). The issue of industrial wastewater has gained significant attention in global research. Bioflocculants have emerged as a viable solution for the elimination of various contaminants, such as heavy metals, suspended particles, dyes, and turbidity (Alias et al. 2022).

The appropriate selection of microorganisms and the manner in which they are cultivated are crucial factors in ensuring optimal growth. These bacteria have the ability to generate oxygen, which can facilitate the degradation of many contaminants, including phenolic hydrocarbons and organic solvents. Several strains of bioflocculant-producing bacteria (BPB), including *Bacillus licheniformis* NJ3, *Bacillus nitratireducens*, *Bacillus* sp. DAS10-1, and *Arthrobacter* spp., have been found to be effective in the removal of heavy metals, specifically arsenate, from wastewater (Abu Tawila et al. 2018; Alias et al. 2022). Several bioreactor designs have been discussed in the scientific literature (Ogbonna and Nwoba 2021) for the purpose of acquiring bioflocculants. Several elements play a crucial role in bioflocculant bloating. The factors that have been identified as influential in this study are pH, carbon concentration, nitrogen concentration, phosphorus concentration, dissolved oxygen levels, trace element presence, carbon dioxide levels, and temperature. The bioflocculants that have been identified exhibit a composition comprising polysaccharides, uronic acids, sugars, and proteins. The chemical composition and flocculating efficiency of bioflocculants are subject to various factors, such as the environmental conditions in which the bioflocculant-producing microorganisms were obtained, the composition of the medium used for their cultivation, and the bioflocculant's functional groups, morphology, crystallinity, and pyrolysis profile. The wastewater containing activated sludge has the ability to harbor microorganisms that produce unique metabolites. Furthermore, the present environment encompasses macromolecular substances that play a crucial role in bioflocculants, including proteins, polysaccharides, nucleic acids, and cellulose (Nkosi et al. 2021). Figure 2 illustrates various types of bioflocculants, along with examples and their structures.

Bioflocculation depends on many factors, such as nutrient conditions, pH, type of microalgae, and type and amount of flocculants. For this reason, the process is difficult to control (Ummalyma et al. 2017). Even within the same species, microbes have different characteristics depending on how they are cultured, making bioflocculation difficult to predict (Venkata Mohan 2014; Li et al. 2020) conducted nine different tests with pH values ranging from 8 to 12. For *Skeletonema Costatum*, pH was best when it was 11.5; for *Chaetoceros Gracilis*, it was best when it was 10.5 (Pérez et al. 2017). Different types of crop cultivation increase the risk of contamination and cause additional costs for additional nutrients (Mathimani and Mallick 2018). Figure 3 presents the physical characterization of bioflocculants based on experimental analysis.

It is known that when pH changes, charges on the surface of microalgal cells also change, altering flocculation efficiency. Many studies have shown that as pH increases, zeta potentials of freshwater microalgae first decrease and then increase (Ummalyma et al. 2016; Aljuboori et al. 2016). Precipitation has to do with the removal of charges. It is worth noting that above the ideal dosage, flocculation frequency decreases dramatically because that is the only place where maximum flocculation rates and efficacy can be achieved. After testing the flocculation coherence of two strains (*B. braunii* strains Kossou-4 and Overjuyo-3) at six different ratios, the best ratio was found to be 1:40 (Al-Hothaly et al. 2015). It is not clear why this is so, but it may have something to do with the ratio of microalgae to flocculant doses (Zhang and Jiang 2019). Experiments have shown that the addition of metal cations to the medium makes it easier for microalgae to stick together. Vandamme et al. (2015) found that flocculation worked much better when calcium and magnesium were present in the medium (Vandamme et al. 2015). Metal cations help the fragments stick together by balancing the remaining negative charge. As a result, flocculation works better (Guo and Chen 2017). The long-term performance of microbial-based bioflocculants under optimized conditions showcases their sustained efficacy in applications like wastewater treatment and bioremediation. Over extended periods, these bioflocculants have demonstrated remarkable efficiency in aggregating suspended particles and effectively removing contaminants from water sources. The general mechanism of the bioflocculation process is shown in Figure 4.

Recent studies highlight the enduring viability of the microbial cultures responsible for bioflocculant production, ensuring consistent performance. Moreover, ongoing research emphasizes the economic viability of this approach, making it an environmentally sustainable choice for water treatment. These findings underscore the enduring potential of microbial-based bioflocculants in providing reliable and efficient solutions for clean water and environmental remediation challenges (Shahadat et al. 2017). Table 1 summarizes the reported studies highlighting the source of the bioflocculant from bacteria, algae, fungi and mixed cultures.

Microbial-based bioflocculant mediated treatment of industrial effluents

In the fields of treatment and bioprocesses, much attention is paid to microorganisms, and people are actively searching for powerful microorganisms that give good results. Exopolysaccharides, enzymes, proteins, surfactants, and emulsifiers are all products of microbes that are used both biologically and physically in treatment processes (Devi et al. 2015). Over time, several researchers found that microbes make bioflocculants along with other metabolites. Microbes make this metabolite for unknown reasons. (Abu Bakar et al. 2021).Researchers are exploring ways to create bioflocculants that are more effective than before. They do this by using a variety of substrates, from synthetic nutrients to the most complex biomaterials and waste biomaterials. Several researchers have written on how bacteria that generate bioflocculants can employ odd food sources to increase the effectiveness of bioflocculants and to clean up industrial effluent (Alias et al. 2022). Again, it is often said that various bacteria use sources with high hydrocarbon content for their growth. When hydrocarbons enter naturally occurring substrates, they cause microbial populations to grow. These microbes can use petroleum hydrocarbons as their sole carbon food source and degrade them by converting the pollutants into minerals (Xu et al. 2018). Researchers are looking for species of bacteria that can metabolize oils. A type of Bacillus was observed to metabolize oily wastewater, however, no evidence of metabolites such as bioflocculant production was discovered. Treatment of petroleum and petroleum-based contaminants has been a focus of interest in recent years as spills occur throughout the world using microorganisms and bioflocculants. Numerous isolated and combined bacterial conglomerates have been explored and evaluated for useful and formal applications (Arora 2018). Microorganisms that degrade oil often produce extracellular

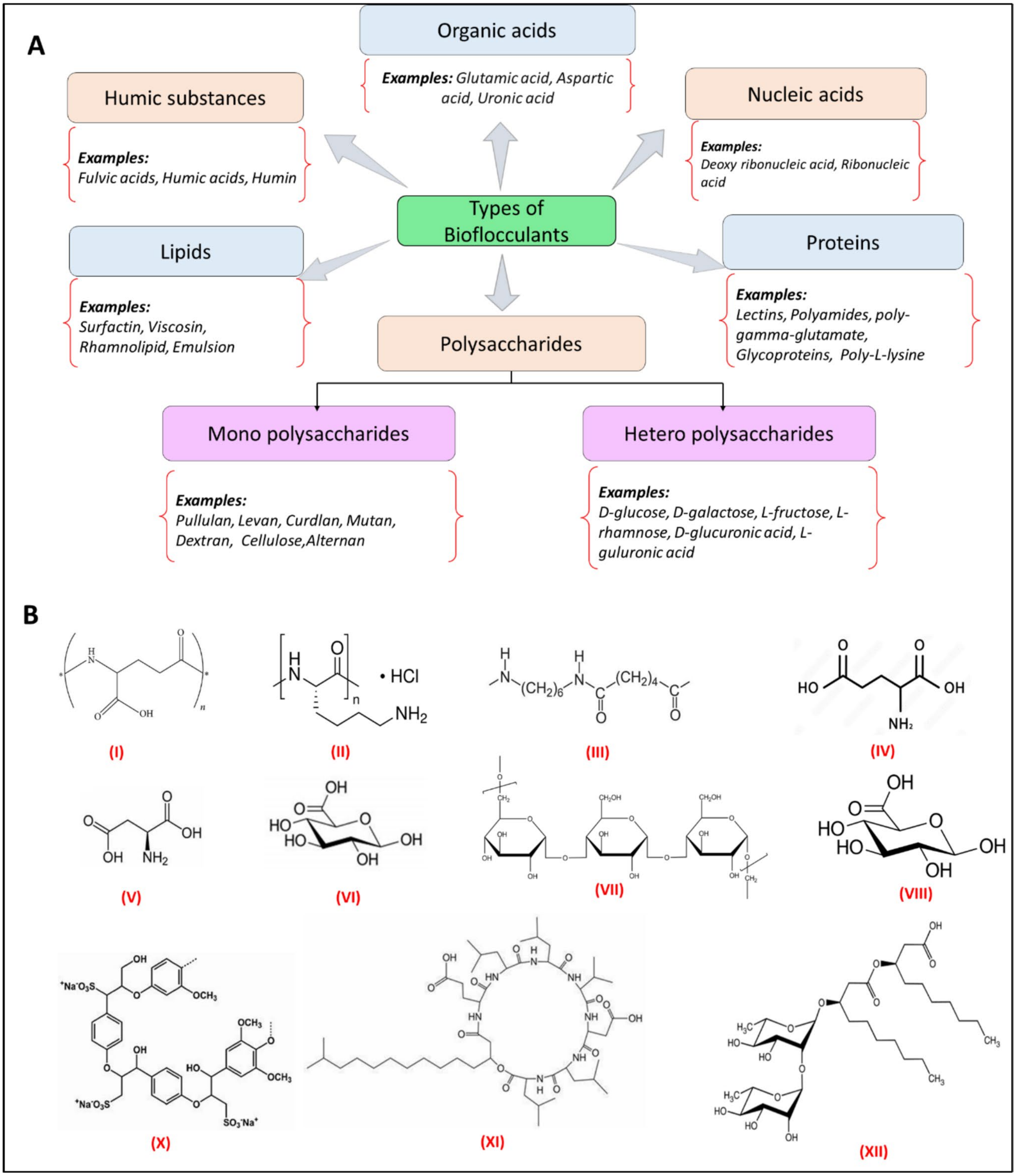

Fig. 2 **a:** Different types of bioflocculants and its examples; **b:** Chemical structure of variousbioflocculants (i: poly-gamma-glutamate; ii: Poly-L-lysine; iii: Polyamides IV: Glutamic acid V: Aspartic acid VI: Uronic acid VII: Pullulan VIII: Glucuronic acid X: Humic acid; XI: Surfactin; XII: Rhamnolipids)

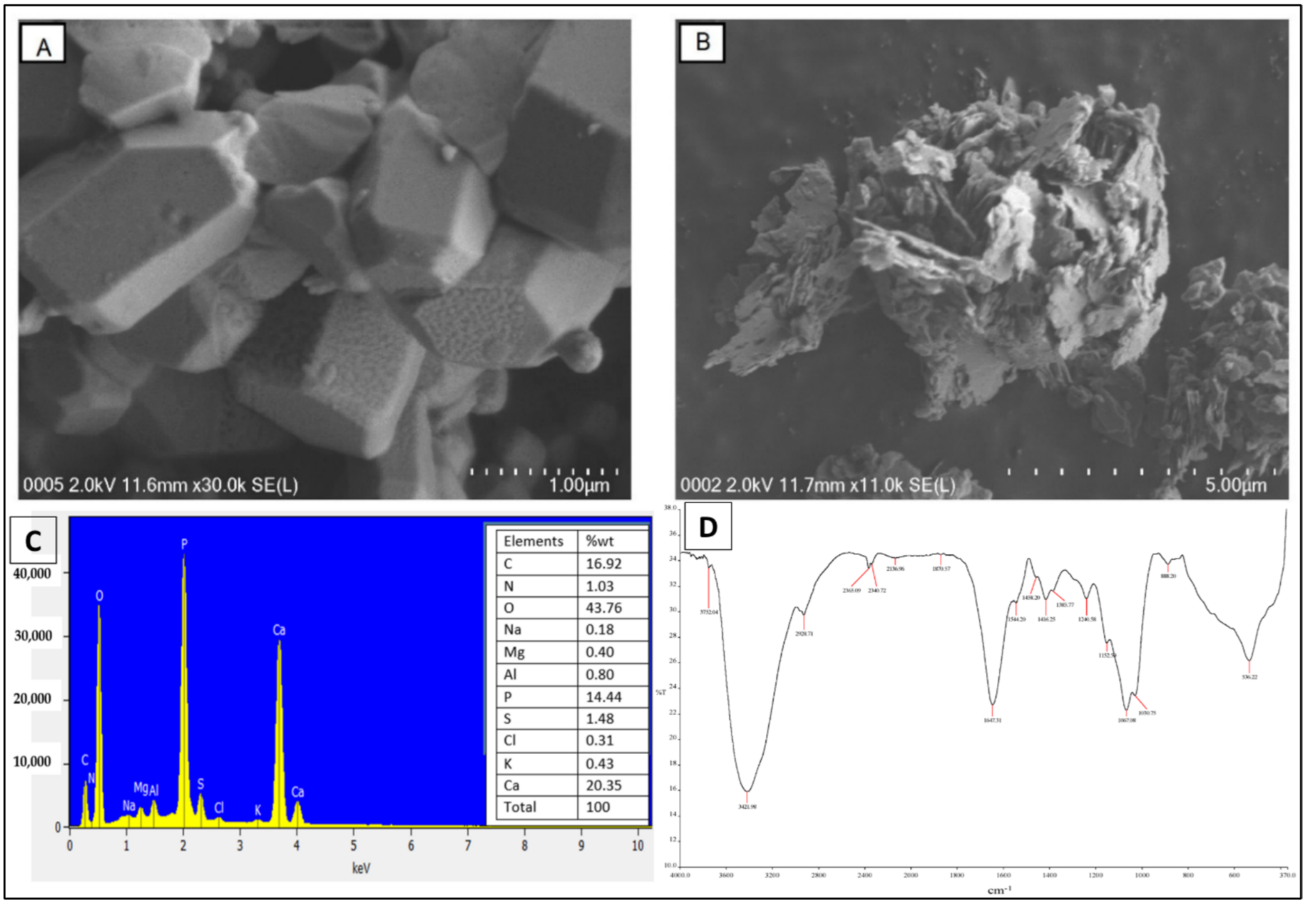

Fig. 3 Physical characterization of bioflocculants (Scanning Electron Microscopical analysis for (A) purified bioflocculant; (B) bioflocculant aggregation with kaolin clay (Abu Tawila et al. 2018); (C) Elemental analysis of the bioflocculant (Tsilo et al. 2022)(D) Fourier Transform Infrared Spectrophotometry (FTIR) spectra of the purified bioflocculant (Makapela et al. 2016)

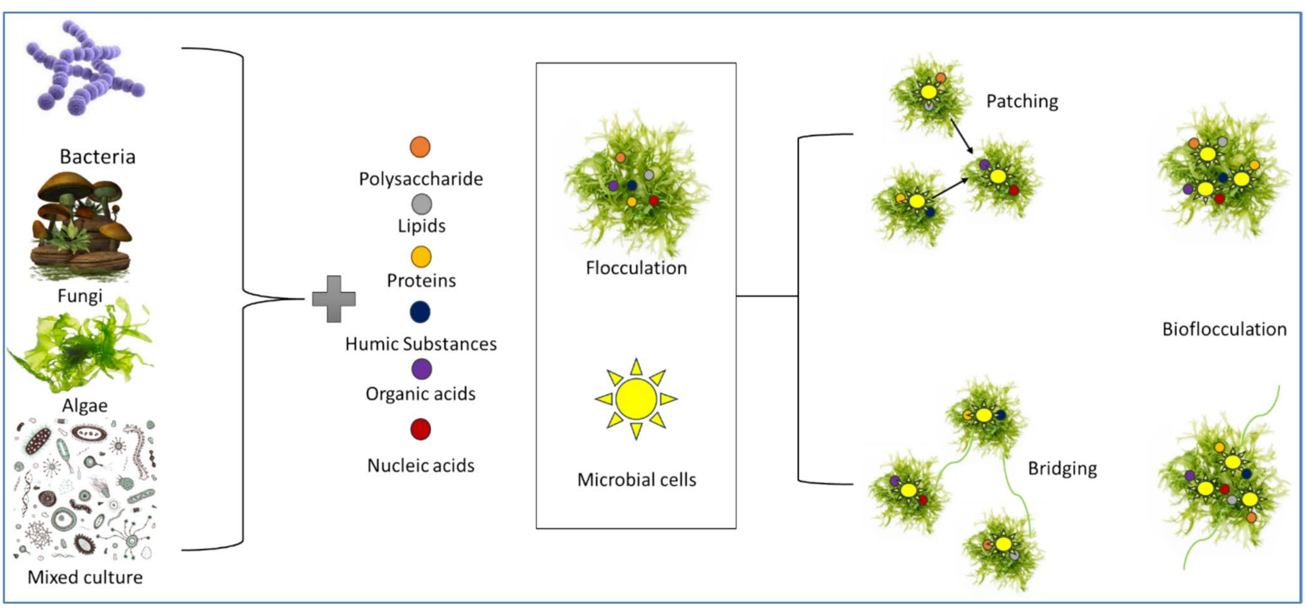

Fig. 4 General mechanism for bioflocculation process

Table 1 List of some reported studies highlighting the source of bioflocculant from bacteria, algae, fungi and mixed culture

S.L No	Consortium (Source)	Carbon/nitrogen sources	FA and flocculant composition (PS and P)	References
Bacterial strains				
1	*Corbetia* sp.OAUIFE, *Bacillus* sp. MAYA (Sediment)	Glucose, Urea, Yeast extract, $(NH_4)_2SO_4$	FA: 90% Uronic acid: 66% P: 31%	Ugbenyen and Okoh (2014)
2	*Corbetia* sp. OAUIFE, *Bacillus* sp. MAYA and *Bacillus* sp. Gilbert (Sediment)	Glucose, Urea, Yeast extract, $(NH_4)_2SO_4$	FA: 87.4% (kaolin) FA: 96.4% (river water) FA: 93.7% (brewery wastewater) FA: 82.2% (diary wastewater) PS and P	Ugbenyen et al. (2015)
4	*Halomonas* sp. Okoh and *Micrococcus* sp. Leo (Sediment)	Glucose, Yeast extract	FA: 86% Polycoprotein	Okaiyeto et al. (2013)
6	*Streptomyces* sp. Gansen and *Cellulomonas* sp. Okoh (River)	Sucrose, Peptone	FA: 98.9% PS and P	Nwodo et al. (2014)
7	Biological sludge (Municipal sewage)	NI	FA: 98.5% Amino-polysaccheride	Zhang et al. (2013)
8	*Bacillus agaradhaerens* C9 (Alkaline lake)	Glucose, yeast extract	FA: 80.6% PS: 65.4% P: 4.7%	Ben Rebah et al. (2018)
9	*Bacillus mojavensis* 32A (Salt production pond)	L-glutamic acid, ammonium chloride	FA: 96.1% PS: 98.4% P: 1.60%	Ben Rebah et al. (2018)
10	*Bacillus* sp. TERI VB2 (Soil from India Habitat Centre)	Glucose, yeast extract, urea	FA: 99% PS: 97.13% P: 1.46%	Bisht and Lal (2019)
11	*Pseudomonas* sp. HP2 (Forest soil)	Yeast extract, peptone, rice straw biomass	FA: 92.5%	Qi et al. (2019)
Algal and fungal strains				
12	*Pichia kudriavzevii* MH545928.1 (Kombucha SCOBY)	Lactose, Peptone	FA: 80.2%	Tsilo et al. (2021)
13	*Streptomyces* sp. hsn06 (Freshwater)	Glucose, NH_4Cl	FA: 60.3%	Li et al. (2018)
14	*Scenedesmus acuminatus*	Glucose, Peptone	FA: 90%	Yang et al. (2020)
15	*Aspergillus flavus*	Sucrose	FA > 90%	Aljuboori et al. (2013)
16	*Talaromyces trachyspermus* OU5	Glucose, Urea	FA > 92.5% PS: 84.6% P: 15.2%	Fang and Shi (2016)
18	*Phanerochaete chrysosporium*	Glucose, Potatoes	FA: 93.5% (coal slurry) Acidic polysaccharide	Zhang et al. (2013)
19	*Aspergillus flavus*	Sucrose, Peptone	FA: 97.4%	Aljuboori et al. (2013)
20	*Aspergillus niger*	Palm oil mill effluent, Glutamic acid	FA: 81% PS: 66.8% P: 31.4%	Aljuboori et al. (2013)
21	Filamentous fungal strain (River water)	Potato dextrose agar	FA: 59.4–99.18%	Jebun et al. (2015)
22	*Penicillum* strain HHE-P7	Glucose, Yeast extract	FA: 93%	Liu and Cheng (2010)
23	*Rhizopus* sp. M9 *Rhizopus* sp. M17 (Soil)	Potato starch wastewater, Urea	FA: 90.2%	Pu et al. (2014)
24	*Scenedesmus quadricauda*	Nitrate	FA: 86.7% PS: 56.7% P: 41%	Aljuboori et al. (2016)
Mixed culture/microbial consortium				
25	*Corbetia* sp.OAUIFE, *Bacillus* sp. MAYA (Sediment)	Glucose, Urea, Yeast extract, $(NH_4)_2SO_4$	FA: 90% Uronic acid: 66% P: 31%	Ugbenyen and Okoh (2014)
26	*Corbetia* sp. OAUIFE, *Bacillus* sp. MAYA and *Bacillus* sp. Gilbert (Sediment)	Glucose, Urea, Yeast extract, $(NH_4)_2SO_4$	FA: 87.4% (kaolin) FA: 96.4% (river water) FA: 93.7% (brewery wastewater) FA: 82.2% (diary wastewater) PS and P	Ugbenyen et al. (2015)
28	*Halomonas* sp. Okoh and *Micrococcus* sp. Leo (Sediment)	Glucose, Yeast extract	FA: 86% Polycoprotein	
29	*Halobacillus* sp. Mvuyo and *Oceanobacillus* sp. Pinky (Sediment)	Sodium carbonate, Urea, Yeast extract, $(NH_4)_2SO_4$	FA: 98.3% PS and P	Ugbenyen and Okoh (2014)
30	*Streptomyces* sp. Gansen and *Cellulomonas* sp. Okoh (River)	Sucrose, Peptone	FA: 98.9% PS and P	Nwodo et al. (2014)

Table 1 (continued)

S.L No	Consortium (Source)	Carbon/nitrogen sources	FA and flocculant composition (PS and P)	References
31	Biological sludge (Municipal sewage)	NI	FA: 98.5% Amino-polysaccharide	Zhang et al. (2013)
32	*Aspergillus flavus* (Source NI[3])	Sucrose	FA > 90%	Aljuboori et al. (2013)
33	*Talaromyces trachyspermus* OU5	Glucose, Urea	FA > 92.5% PS: 84.6% P: 15.2%	Fang and Shi (2016)
35	*Phanerochaete chrysosporium*	Glucose, Potatoes	FA: 93.5% (coal slurry) Acidic polysaccharide	Zhang et al. (2013)
36	*Aspergillus flavus*	Sucrose, Peptone	FA: 97.4%	Aljuboori et al. (2013)
38	Filamentous fungal strain (River water)	Potato dextrose agar	FA: 59.4–99.18%	Jebun et al. (2015)
39	*Penicillum* strain HHE-P7			
	Glucose, Yeast extract	FA: 93%	(LIU and CHENG 2010)	
40	*Rhizopus* sp. M9 *Rhizopus* sp. M17 (Soil)	Potato starch wastewater, Urea	FA: 90.2%	Pu et al. (2014)
41	*Scenedesmus quadricauda*	Nitrate	FA: 86.7% PS: 56.7% P: 41%	Aljuboori et al. (2016)

F.A: Flocculating activity; P.S: Polysaccharides; P: Proteins

surface-active products that facilitate the use of oily substrates by making the oil more soluble or dispersing it. Pseudomonas aeruginosa is a top candidate in this area and has been extensively tested to see if it can degrade petroleum hydrocarbons on-site or off-site and leave behind useful or harmless metabolites (Patowary et al. 2017) (Table 2).

Heavy metal removal

A strain that produces bioflocculants was found in biological sludge and used to produce bioflocculants from swine wastewater. After 60 h of fermentation at 30ºC and 150 rpm, a bioflocculant with a base of polysaccharides and a larger molecular mass of about 426 kDa was produced. The addition of 3 × 10–2% + 2 × 10–2% (w/w) of the bioflocculant appeared to be an effective microbial flocculant removing arsenite. After 60 min, 99.2% of arsenite was removed (Guo and Chen 2017).

Klebsiella oxytoca GS −4-08, grown in acetonitrile (ACN) as the sole source of nitrogen, produced a new bioflocculant called A-GS408. Chemical tests showed that the bioflocculant was mainly composed of polysaccharides (46.3% of the substance) and proteins (20.6% of the substance). A-GS408s has many carboxyl, amine, and hydroxyl groups, which play a major role in how Pd^{2+} and Cu^{2+} adhere to it (Fan et al. 2019). In this work, the phenol-degrading strain *Stenotrophomonas maltophilia* ZZC-06 was found to be able to utilize phenol-accommodating wastewater to produce the bioflocculant MBF-06. The test results showed that the flocculation activity increased to more than 90% when phenol was used as carbon. The ability of MBF-06 to remove cadmium was investigated, and 81.43% was the best flocculation efficiency for cadmium (Chen et al. 2016, 2017). Hazardous heavy metals can be removed from contaminated commercial pollutants and water using bioflocculants. The preliminary content of metals, ionic strength, temperatures, bioflocculant dosage, charge distribution, and variety of polymeric alignments with deposited ions affect how quickly and how accurately 959 bioflocculants absorb metals (Shahadat et al. 2017). The metals that the *P. aeruginosa* bioflocculant was able to absorb the most of were Cu^{2+} (87.39%) at a bioflocculant concentration of 20 mg/L; Cd^{2+} (79.93%) and Pb^{2+} (79.7%) at a bioflocculant concentration of 40 mg/L; and arsenate (72.96%) and Zn^{2+}. The bioflocculant of *R. philippinarum* was found to be capable of removing 19.2 and 69.3% of Ni^{2+} and $Cr_2O_7^{2-}$, respectively (Wang et al. 2022). It was found that the generated hydrogen bonds between the hydroxyl groups of the bioflocculant had a higher removal rate for $Cr_2O_7^{2-}$ than for Ni^{2+}. This means that the removal efficiency is different for Ni^{2+} and $Cr_2O_7^{2-}$. *Achromobacter* sp. has shown great promise for the removal of lead from wastewater and sewage, and the highest flocculation activity was 95% (Subudhi et al. 2014). After 60 min, a bioflocculant prepared from a variegated inoculum of *R. radiobacter* F2 and *B. sphaeicus* F6 was used to remove Pb^{2+} from aqueous solutions with an optimum pH of 7. Based on the magnitude of its effect, it was found that the most important parameters for adsorption of lead were pH, initial Pb (II) concentration, stirring rate, and temperature, in that order. The bioflocculant *Herbaspirillum* sp. was able to get rid of up to 66% of the Cd^{2+}. The researchers found that most bioflocculants are better at handling heavy metals at low concentrations than at higher concentrations (Abbas et al. 2015).

Table 2 Summary of effluent treated by bioflocculants for the removal of turbidity, organic pollutant, and other hazardous components

S.L no	Source of effluents	Type of bioflocculant and operating conditions	Key findings	References
1	Municipal Wastewater TS[4]: 340 mg/L COD: 193 mg/L Turbidity: 58 NTU pH: 6.7	Mixture of strains isolated from secondary municipal sludge and cultivated in sterilized sludge. Flocculant: 2 mg brothexopolysaccharide/L + (20mg /L Fe^{3+}; 20mg/L Al^{3+}; 200mg/L Ca^{2+}; 200mg/L Mg^{2+})	COD was reduced as follows: 80.4% (20mg/L Fe^{3+}) 78.1% (20mg/L Al^{3+}) 74.5% (200mg/L Ca^{2+}) 74.6% (200mg/L Mg^{2+})	More et al. (2016)
2	Brewery wastewater TS: 2362 mg/L COD: 1985 mg/L Turbidity: 4063 NTU pH: 4.5	Mixture of strains isolated from secondary municipal sludge and cultivated in sterilized sludge. Flocculant: 12.4 mg B-EPS/L + 40mg/L Fe^{3+}; 40mg/L Al^{3+}; 250mg/L Ca^{2+}; 250mg/L Mg^{2+}	COD was reduced as follows: 87.4% (40mg/L Fe^{3+}) 86.2% (40mg/L Al^{3+}) 88.4% (250mg/L Ca^{2+}) 85.7% (250mg/L Mg^{2+})	More et al. (2016)
3	Aquaculture wastewater COD: 35.6 mg/L NH_4^+-N: 6.43 mg/L SS[5]: 27.1 mg/L	*Bacillus megaterium* SP1 Inoculation: 1 × 104 CFU/mL, 30°C, pH 7	Removal efficiency: COD: 64% NH_4^+-N: 63% SS: 83.8%	Luo et al. (2016)
4	Potato starch wastewater COD: 7965 mg/L Turbidity: 712 NTU pH: 6	*Rhizopus* sp. M9 + *Rhizopus* sp. M17 Flocculant: 0.1mL/L (0.5mL M17: 0.5mL M9) + 5mL/L10% $CaCl_2$	Removal efficiency: COD: 54.09% Turbidity: 92.11%	Pu et al. (2014)
5	Landfill leachate wastewater COD: 1944mg/L Turbidity: 1440 NTU Chromaticity: 512 times SS:11.04g/L pH: 6.5	*Pichia membranifaciens* Flocculant: 2% v/v + $CaCl_2$	Removal efficiency: COD: 42% Turbidity: 44% Chromaticity: 41% SS: 51%	Zhang et al. (2015)
6	Landfill leachate wastewater COD: 1944mg/L Turbidity: 1440 NTU Chromaticity: 512 times SS:11.04g/L pH: 6.5	*Bacillus cereus* Flocculant: 2% v/v + $CaCl_2$	Removal efficiency: COD: 45% Turbidity: 48% Chromaticity: 58% SS: 59%	(Zhang et al. 2015)
7	Landfill leachate wastewater COD: 1944mg/L Turbidity: 1440 NTU Chromaticity: 512 times SS:11.04g/L pH: 6.5	*Bacillus cereus* and *Pichia membranifaciens* Flocculant: 2% v/v + $CaCl_2$	Removal efficiency: COD: 73% Turbidity: 50% Chromaticity: 70% SS: 74%	Zhang et al. (2015)
8	Starch wastewater COD: 9660 mg/L Turbidity: 2098 NTU Chromaticity: 320 times SS: 1.094 g/L pH: 2.3	*Pichia membranifaciens* Flocculant: 2% v/v + $CaCl_2$	Removal efficiency: COD: 58% Turbidity: 54% Chromaticity: 57% SS: 34%	Zhang et al. (2015)
9	Starch wastewater COD: 9660 mg/L Turbidity: 2098 NTU Chromaticity: 320 times SS: 1.094 g/L pH: 2.3	*Bacillus cereus* Flocculant: 2% v/v + $CaCl_2$	Removal efficiency: COD: 81% Turbidity: 59% Chromaticity: 69% SS: 36%	Zhang et al. (2015)
10	Paper mill wastewater pH: 8.57	Crude and Purified bioflocculant from *Paenibacillus mucilaginosus* GIM1.16 Flocculant: 0.5–4 mg/L	Removal efficiency: COD: 70–75.2% SS: 81.5–88%	Tang et al. (2014)
11	Biological product factory wastewater pH: 7.11	*Paenibacillus mucilaginosus* GIM1.16 Flocculant: 0.5–4 mg/L	Removal efficiency: COD: 83.2–86.9% SS: 88.8–92%	Tang et al. (2014)
12	Tannery wastewater COD: 1082.2 mg/L Chrominance: 2410.8 mg/L Nt: 452.83 mg/L	*Bacillus cereus* CZ1001, *B. subtilis* CZ1002, *B. fusiformis* CZ1003 Flocculant: 0.2 g/L for COD, 0.11g/L for Chrominance, 0.11 g/L for Nt	Removal efficiency: COD: 22.71–97% Chrominance: 2.74–70.97% Nt: 22.71–38.43%	Yang et al. (2015)
13	Ash-flushing wastewater SS: 18.33 g/L pH: 9.88	*Pseudomonas veronii* L918 Flocculant: 2.83 mg/L, Jar tester: rapid mixing for 2 min, followed by slow mixing for 1 min	Removal efficiency: FA: 92.5%	Liu et al. (2016)
14	Simulated electroplating wastewater	*Rhizobium radiobacter* and *Bacillus sphaericus* Flocculant: 374 mg/L, pH: 6, Contact time: 40 min	Removal efficiency: Zn^{2+}: 90% Cu^{2+}: 90% Cr^{6+}: 30% Ni^{2+}: 65%	Zhao et al. (2017)

Table 2 (continued)

S.L no	Source of effluents	Type of bioflocculant and operating conditions	Key findings	References
15	Arsenite solution $NaAsO_2$: 1.00 ppm	*Turicibacter sanguinis* ZCY8 Culture broth: 1g/L, 20°C Jar tester: 2 min at 200 rpm followed by 40 rpm for 30 min, settlement period: 1–6 min	Removal efficiency: Arsenite: 86.1%	Cao et al. (2015)
16	Primary treated wastewater Ni:48mg/L; Al:26.9mg/L; Fe: 14.2mg/L; Zn:17.4mg/L; Cu:76mg/L	*Cloacibacterium normanense* NK6 Broth-EPS: 35 or 50mg/L, 250 rpm, and 30°C, 0–12 h	Removal efficiency: Ni: 85% Al: 73% Fe: 71% Zn:65% Cu: 36%	Nouha et al. (2016)
17	Synthetic Wastewater Fe^{3+}: 171-999mg/L Pb^{2+}: 88–917 mg/L	*Bacillus mucilaginosus* Flocculant: 40% v/v, 29°C, 150 r/min, 15 min	Removal efficiency: Fe^{3+}: 15–27% Pb^{2+}: 30–78%	Yao et al. (2013)
18	Synthetic Wastewater Arsenate: 0.5mg/L Arsenite: 05.mg/L	*Paenibacillus polymyxa* ZCY-79 Flocculant: 120mg/L, pH 7, 60 min	Removal efficiency:Arsenate: 98.9% Arsenite: 84.6%	Zhao et al. (2016)
19	Chromium solution Cr (VI): 10–100 mg/L, pH 4–8	*Bacillus licheniformis* Flocculant: 2g/L, 150 rpm, 1–2 h	Removal efficiency: Cr (VI): 88% (at pH 7)	Natarajan (2015)
20	Chromium solution Cr (VI): 10–100 mg/L, pH 4–8	*Bacillu firmus* Flocculant: 2g/L, 150 rpm, 1–2 h	Removal efficiency: Cr (VI): 77% (at pH 7)	Natarajan (2015)
21	Aqueous solution Pb $(NO_3)_2$: 1g/L	*Paenibacillus polymyxa* CCTCC M206017 Flocculant: $4 \times 10{-}3$(w/w) Jar tester: 1 min at 1500 rpm followed by 40 rpm for 2 min, Settlement period: 1–6 min, pH: 8–9	Pb: 99.85%	Feng et al. (2013)

Removal of organic chemicals

Bioflocculants can remove harmful organic compounds from wastewater, sludge, and soil. Microorganisms are believed to be the most practical way to degrade polycyclic aromatic hydrocarbons (PAHs). It is said that PAHs can be removed from contaminated soils using bacteria that produce EPS (Kanaujiya et al. 2019). Inoculating soils and sediments where PAHs are a problem with bacteria that can degrade PAHs and produce EPS is a good way to clean them up. EPS is an important component in the degradation of PAHs. The relationship between EPS and PAHs is considered consistent and heat-releasing, with PAHs primarily attaching to EPS through hydrophobic interactions. EPS can display various surface properties that aid in dissolving hydrophobic substances, as demonstrated by Xu et al. in their 2022 study. In the context of phenanthrene (PHE) biodegradation, this process predominantly occurs at the interface of silicone oil and water. Bacteria overcome the challenge of limited PHE mass transfer by producing EPS, which facilitates the movement of dissolved PHE within the silicone oil phase (Xu et al. 2022). The EPS make it easier for PHE to move in the water (Bianco et al. 2022). This makes PHE more available in the water. It was found that soil-bound phenanthrene is released more when bacteria that form EPS are present. It was found that more than 30% of the pyrene had been degraded by *Zoogloea* sp. and *Aspergillus niger* after 35 days. For these two microbes, the rate of pyrene degradation increased with the number of EPS (Liu and Cheng 2010). Pyrene was degraded faster when more EPS surface area was present in association with the pyrene. To date, most research on how EPS can be used to degrade toxic organic compounds has been conducted in the laboratory (More et al. 2014).

Removal of colorant/dyes

Depending on the type of dye, ionic strength, temperatures, agglomeration of the flocculant, and its ranges of action, bioflocculants have different decolorization effects (Buthelezi et al. 2012). For example, the bioflocculant of *A. parasiticus* was able to remove anionic dyes from a watered solution. At a flocculant dose of 50 mL/L, the highest decolorization value was over 92% for Reactive Blue 4 and Acid Yellow 25 (Buthelezi et al. 2012). When the ability of the bioflocculant produced by *R. philippinarum* to remove color was tested, it was found to remove 86.1% methylene blue, 97.84% crystal violet, and 99.49% malachite green (Barathi et al. 2022). The bioflocculant produced by *S. ficaria* was 99.9% effective in removing color from pulp wastewater and 90.4% effective in removing color from low turbidity river water (Salehizadeh and Yan 2014). The polygalacturon of *Corynebactrium glutamicum* was suitable to efficiently decolorize ink wastewater. Decolorization competence of 48.9, 31.2, 30.6, and 26.0% was observed when the bioflocculant was mixed with 0.5, 1, 3, and 5% molasses wastewater, respectively, in the eidolon of 2 mM $CaCl_2$ as co-flocculant (Salehizadeh and Yan 2014). The polysaccharide flocculant of *P. elgii* could absorb cationic dyes better than neural and anionic dyes. For methylene blue and Red X-GRL, the decolorization rates were 65 and 72%, respectively (Li et al. 2013). A bioflocculant produced by *Bacillus* sp. was sufficient to remove 93% of the color of 925 basic fuchsin (100 mg/L) and 35% of the color of reactive black (Shahadat et al. 2017). Buthelezi et al. (2012) concluded that *B. subtilis*, *Exiguobacterium acetylicum*, K. *terrigena*, *Staphylococcus aureus*, *Pseudomonas pseudoalcaligenes*, and *Pseudomonas plecoglossicida* were able to treat textile wastewater; the decolorization efficiency achieved was up to 97.04% (Buthelezi et al. 2012).

The bioflocculant produced by *R. philippinarum* was very good at removing color from dye solutions such as methylene blue, crystal violet, malachite green, and ink blue. The decolorization efficiencies were 97.73, 95.91, 94.85 and 94.20% after 8 h of standing time at an initial dye concentration of 10 mg/L, a bioflocculant concentration of 1–3 mL (2 g/L The decolorization rate increased as the treatment progressed. For methylene blue, crystal violet and malachite green, equilibrium was reached after 8 h. For the inky blue solution, it took 12 h (Wei et al. 2011). The bioflocculant from bio-aerated filter backwash sludge was able to get rid of the color of methylene blue at an initial dose of 10 mg/L and of fast blue at a dose of 50 mg/L. The results were 82.9% and 77.8%, respectively (Mohammed and Dagang 2019). *Klebsiella* sp. produced a bioflocculant that was very capable of absorbing sulfamethoxazole in water. The decolorization efficiency was 67.82% under the best conditions, i.e., an initial pH of 5, a bioflocculant dose of 5 mg/L, a coagulant dose of 0.5 mg/L, and a reaction time of 1 h. The bioflocculant was 53.27% effective in removing the effluent (Yang et al. 2012).

Dewatering and settling of sludge

The process of sludge dewatering holds significant importance in both wastewater treatment and sludge recycling. For a considerable period of time, researchers have tried intending to aggregate the sludge by utilizing microorganisms. Microorganisms have the ability to thrive in diverse environmental conditions and synthesize secondary metabolites comprising carbohydrates, proteins, lipids, and nucleic acids. The chemical composition of bioflocculant is a significant factor in the process of sludge settling.

Bioflocculation has been referred to as a simple and important method for biomass recovery because it is cheap and does not produce additional impurities. Conventional methods for extracting cell mass from algae to produce biodiesel are too expensive, and bioflocculation can be an important component of commercial algal biomass extraction to reduce the expense of producing biodiesel from algae (Ummalyma et al. 2017). There are a handful of studies on how bioflocculation is used to get rid of microalgae. Bioflocculant from *P. polymyxa* was used to separate high density cells from *Scenedesmus sp*. The greatest flocculating activity (up to 95%) was found for high density algal cultures when the concentration of bioflocculant, the proportion of $CaCl_2$ and $FeCl_3$ were 1%, 8.5 mM and 0.2 mM, respectively (Kim et al. 2011).

S. silvestris has been found to produce a bioflocculant that can be used for the recovery of marine microalgae. When marine microalgae named *Nannochloropsis oceanic* were extracted, the maximum flocculating activity of up to 90% was achieved at pH 8.7 and 25 °C (Wan et al. 2013). *K. pneumoniae* produced a new biopolymeric flocculant that was used to remove *Acanthamoeba cysts*, a dangerous amoeba species found in water. For *Acanthamoeba cysts*, the best removal rate was 84% when the optimal dose of the bioflocculant, temperature, and pH were 129.73 mg/L, 30.75 °C, and 4.36, respectively (Salehizadeh and Yan 2014). The extracellular biopolymer flocculant of *K. terrigena* was very good at removing *Cryptosporidium oocysts* from water. At a dose of 2 mg/L, the purified bioflocculant was sufficient to eliminate 62.3% of *C. oocysts* from tap water (Salehizadeh and Yan 2014; Salehizadeh et al. 2018). *Salmonella sp.* was removed from chicken farm wastewater containing 3 log CFU cells of Salmonella using a bioflocculant of *K. terrigena*. At an optimal dose of 2 mg/L and room temperature, the refined bioflocculant was able to remove 80.3% of *Salmonella sp.* in 30 min (Joshi et al. 2020).

Cost analysis of bio flocculants

Chemical coagulants/flocculants for wastewater treatment vary in expense every m3. For example, alum costs USD 0.10 and ferric chloride costs USD 0.15 for animal husbandry effluent (Hamawand et al. 2017), alum costs USD 19 for palm oil mill effluent and PAC costs up to USD 1.80 for treating leachate (Aziz et al. 2018).

Table 3 compares the costs of chemical coagulants and indicates that the cost of using biocoagulants/bioflocculants is competitive with that of using traditional chemical coagulants.

Although biocoagulants/bioflocculants are more expensive than traditional treatments like alum or ferric chloride, the information reported purely compares resource employed. Another factor that may influence treatment decision-making is the expense of sludge management. Chemicals, aluminum, and iron in sludge make it harder to

Table 3 Cost analysis of bioflocculants for wastewater treatment

S.No	Treated water	Type	Estimated cost (USD/m^3)	Source
1	Drinking water	Chitosan	0.0025	Kangama et al. (2018)
2	Wastewater	*Moringa oleifera*	2	Yin (2010)
		Azadirachta indica	6.8	Ali et al. (2019)
		Moringa oleifera	5.2	
3	Wastewater (Domestic)	Chitosan	0.015	Hamawand et al. (2017)
4	Wastewater (Leachate)	*Tamarindus indica*	19.50	Aziz et al. (2018)
5	Wastewater (Palm Oil Mill Effluent)	Water-soluble chitosan from mushrooms	1.25	Lichtfouse et al. (2019)
		Acid-soluble chitosan from mushrooms	1	
6	Wastewater (Paper Mill Effluent)	Starch	1–2.85	Amaro et al. (2017)

treat employing biological methods like anaerobic digestion, which is cheaper than landfilling. However, this increases operational costs. The increased digestibility of aluminum and iron in sludge causes a harmful effect on microorganisms in anaerobic digestion, leading to poor digestion performance (Barakwan et al. 2019). The use of biocoagulants/bioflocculants diminishes the presence of aluminum and iron in sludge, increasing the biodegradability of the resulting sludge that will be processed biologically. As previously stated, anaerobic digestion has a lower operating cost than landfilling or more complex technologies like as electrochemical processes (Lichtfouse et al. 2019).

Current research trends and future aspects

In the dynamic realm of microbial-based bioflocculants for industrial wastewater treatment, scholars are in the frontier of pioneering and sustainable approaches to address an immediate global environmental concern. The fundamental objective of ongoing research is to isolate and purify newly discovered microbial strains that have the ability to produce bioflocculants with remarkable efficacy. These strains are highly desirable in diverse ecological habitats, and researchers are actively engaged in enhancing their growth circumstances and metabolic pathways to achieve optimal bioflocculant output and efficacy. The current endeavor to explore microbial variety and genetic adaptation is facilitating the development of customized bioflocculants that can effectively treat certain industrial wastewater streams, like those originating from textiles, mining, or food processing sectors. Furthermore, there is a growing emphasis on investigating the molecular complexities of bioflocculation in current research endeavors. This includes a focus on understanding the genetic factors, enzymatic activities, and intermolecular associations that serve as the foundation for this phenomenon. Looking toward the future, the incorporation of advanced technologies such as artificial intelligence (AI) and machine learning (ML) presents significant potential. The utilization of these technologies will play a crucial role in enhancing the overall efficiency of the bioflocculant manufacturing process, encompassing various stages such as strain identification and selection, optimization of fermentation conditions, and the ability to forecast the performance of bioflocculants in diverse environmental settings. The utilization of predictive modeling has the potential to greatly improve the efficiency and cost-effectiveness of wastewater treatment operations. In addition to the aforementioned points, the emerging future orientation indicates that current scientific investigations on bioflocculants are mostly concentrated on the following aspects. (a) The quest for functional strains that exhibit strong performance in both single and mixed cultures, while also generating an ample supply of bioflocculants, is a constant pursuit. (b) Individuals are actively seeking cost-effective methods to cultivate functional strains, such utilizing starch-rich wastewater and hydrolysates derived from waste biomass. Figure 5 illustrates the progress and potential of microbial bioflocculant advancements in wastewater treatment research and future prospects.

A noteworthy advancement in scientific research involves the formation of distinct assemblages of microorganisms capable of decomposing lignocellulosic biomass and synthesizing *bioflocculants* in situ. The research is centered toward the cultivation of self-flocculating specimens that may be cultivated under cost-effective circumstances, with a particular emphasis on acquiring high-value, non-flocculating kinds such as some microalgae. It is logical to cultivate both self-flocculating strains and strains requiring culture in the same reactor, as this practice effectively minimizes operational expenses. It is of practical significance to consider the utilization of bioflocculants in conjunction with commercially available flocculants to generate efficient and economically feasible combinations that facilitate the extraction of water from sludge. It is important to note that a single bioflocculant

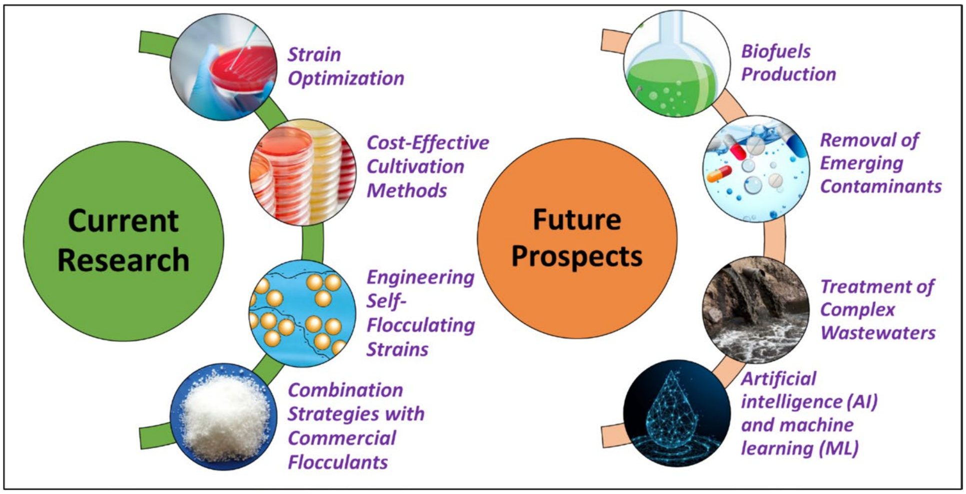

Fig. 5 Microbial bioflocculant advancements in wastewater treatment research and future prospects

may not possess universal suitability for various conditioning activities. This is mostly due to the inherent variability observed in different types of sludge, as well as the dynamic nature of these sludge compositions over time. The utilization of EPS derived from actively proliferating cells is often regarded as a viable option for the application of flocculants in practical settings. The utilization of waste sludge as a primary resource for expanded polystyrene (EPS) production is a topic of attention in terms of its practicality. This is due to the fact that the appropriate management and utilization of waste sludge is advantageous for the effective administration of contemporary urban areas.

Conclusion

The renewable nature, biodegradability and sustainable nature of Bioflocculants makes them a prominent alternative to chemical flocculants. Bioflocculants derived from microorganisms aptly addresses the mitigation of pollution by employing the fundamental tenets of green chemistry in terms of low cost and eco-friendly nature, and sustainable technology. The microbial-derived biopolymers can effectively remove majority of the pollutants produced by various industries. However, certain issues, viz., integration of Bioflocculants with existing systems, their life cycle analysis, environmental impact in larger usage, ensuring compliance with regulations, obtain consistency, etc. have to be addressed for unlocking their full potential for sustainable future usage.

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Declarations

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