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A Review on Bioremediation of Tannery Effluent using Immobilized Bacteria

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ABSTRACT

Tannery effluent is a significant contributor to contaminants such as heavy metals within the ecosystem. Effluents generally contain heavy metals, and they also contain more bacteria that can thrive in such an environment. Bioremediation has ancestrally been performed using bacteria; in recent decades, the implementation of "immobilized" bacteria has acquired recognition as an intriguing technique due to manifold assistance. This review systematizes a humongous amount of extant literature on multifarious toxicants that can be tackled with immobilized bacteria. We further explore assorted deterministic facets using immobilized bacteria for environmental remediation with an emphasis on encapsulation in biomaterials and their role in detoxifying toxic compounds. We explore multiple techniques for immobilizing bacteria in numerous complementary arrays incorporating multiple species of bacteria, factors that influence the remediation process, such as bioreactor layouts used in pilot, lab-scale applications. Exploits and drawbacks of using immobilized bacteria in fermenters to treat tannery effluent are also described. The imperishable future aspects, recovery of significant commodities, in addition to bioremediation, represent an important incentive of the immobilized treatment process that makes more cost-effective, legitimate treatment enforcement that is also congruent with the precepts of the bioeconomy.

INTRODUCTION

Tannery effluent is one of the paramount defilements of the world (Suman et al. 2021). For the past few decades, a few treatments and entente were accomplished but still, waste production cannot be invalidated or overturned. Effective tannery effluent treatment and recovery approaches are indispensable and expository for an eco-friendly environment. Biological treatment systems were also superior to toxic chemical forms of treatment and mechanisms (Mehrotra et al. 2021). The Tannery sector has had a crucial impact in several countries, such as China, India, and Brazil. Fairly comprehensive tannery effluent trammels established a significant contribution greatly to economic development.

Moreover, inadequate disposal of tannery effluent poses global hazards, and intensifying emphasis has been placed on mitigating tannery effluent harmful emissions (Zhao et al. 2022). The outflow of tannery effluents without adequate treatment resulted in much greater levels of sources or areas of land (Maheshwari et al. 2017). Tannery effluent undergoes several processes that deodorize the effluent before it is extravasated into the environment. Tannery effluents include substantial quantities of contamination samples due to the comportment of colored and deleterious substances (Shaheen Fathima et al. 2020).

Heavy metals are substantial in manufacturing use and are the most massive environmental toxins (Haso et al. 2022). Heavy metal contamination of the environment poses a significant risk to living organisms that comprise an ecology. Due to various bioaccumulations and nonbiodegradability in origins, heavy metal contamination is a major threat to the environment. Pollutants like lead (Pb), cadmium (Cd), and mercury (Hg) have no process and are hazardous to microbes that live (Haso et al. 2022, Igiri et al. 2018). The Tannery industry is renowned for its high water usage and large discharge of effluent (Zhao et al. 2022). Biodegradation of effluents is a non-toxic, environmentally sustainable, ideal substitute. Current technological innovations in developments in biotechnology presently permit the adjustment of microbes such that one rudimentary method is streamlined, debases more multifaceted substances, and disposes of quantities (Maheshwari et al. 2017). Hence, these organisms (microbial consortia) have been isolated, identified, and used for treating the same (Suman et al. 2021, Maheshwari et al. 2017, Yusif et al. 2016).

Immobilized microbes have been utilized in an array of scientific and industrial initiatives since they were demonstrated to be extraordinarily beneficial in environmental remediation (Mehrotra et al. 2021). Immobilized microbes are utilized in organic compounds, diagnostic and contaminant analysis, food processing, pharmaceutics, and industrial remediation. The progression of bioengineering and anticipated advancements has incentivized repercussions to immobilize bacteria for attributed reasons. Immobilization of organic material inside determines the components that provide tangible assistance, optimum size, tensile stability, resistance, and highly permeable properties of the biomolecules (Maheshwari et al. 2017). Numerous developments of debilitated bacteria have surfaced, including tannery effluent, which has prompted more findings into core aspects of rendered immobile systems, particularly of immobilization on bacterial consortium in legion frameworks (Mehrotra et al. 2021).

In this review, we provide an overview of the present state of expertise about the use of immobilized bacteria for environmental bioremediation possibilities. We also cover various support matrices, immobilized bacterial cultures and communities, immobilization techniques, nutrients for immobilized bacteria, contaminants treated by immobilized microbes, transfer of mass factors (salinity, pH, and contaminants' toxic effects), and factors that affect the remediation process when using immobilized cells. We wrap up with a quick talk about the difficulties, most recent advancements, and potential future directions.

CATEGORIES OF CARRIERS OR SUPPORT MATERIALS

Inorganic materials, natural organic composites, and synthetic organic composites are three main types of carrier materials used for immobilization (Berillo et al. 2021) (Fig. 1). Ceramic materials, cellulosic, and polymer blends are prevalent as sustaining arrays for microbes or polymers in function (Mehrotra et al. 2021) (Berillo et al. 2021). Furthermore, the discovered bacteria are immobilized on the matrix. Multiple biological variations are induced to enable adjunct and cell expansion inside the rendered immobile lattice (Tuson & Weibel 2013). Multiple synthetic, natural organic substances were examined to determine their capacity to intervene as an impactful provider or layer for the stabilization of bacteria for environmental bioremediation.

Natural organic carriers have been readily accessible, reasonably priced, bio-based, innocuous, the residence of manifold unembellished on apparently biological pattern subsidiary to the assimilated scope. Materials constructed from naturally occurring polymers, including guar gum, pectate, agar, silica gel, chitin, charcoal, lignin, dextrose, hyaluronic, cellulose, and alginate (Fig. 1), have been made by gel formation (Mehrotra et al. 2021) of bioavailable composites mixture with different particle. During the immobilization process, xanthan gum-incapacitated bacteria will not experience rapid physical and chemical variations, and the gel is pliable and consistent (Mehrotra et al. 2021). Chitin is favorable long-term support because it provides presumably defensive peptide structural features that can optimize bacteria association to the identified areas that require it (Labus et al. 2016, Suhag et al. 2015).

Polyvinyl alcohol (PVA), polyacrylamide (PAM), polycarbamoyl sulfonate (PCS), and polyethylene glycol are widely used emulsifiers. Polyethylene (PE), polyurethane (PU), polypropylene (PP), polyacrylonitrile (PAN), and polyvinyl chloride (Fig. 1) are examples of well-known plastic substances (Mehrotra et al. 2020). Biomaterials, already renowned as hydrophilic polyimide emulsions, are increasing in popularity as sustainable formulations for cellular immobilization. Nanogels are just not coherent as a result of their configuration and interplaying structure. The polyimide distinction ascertains the demand for complex

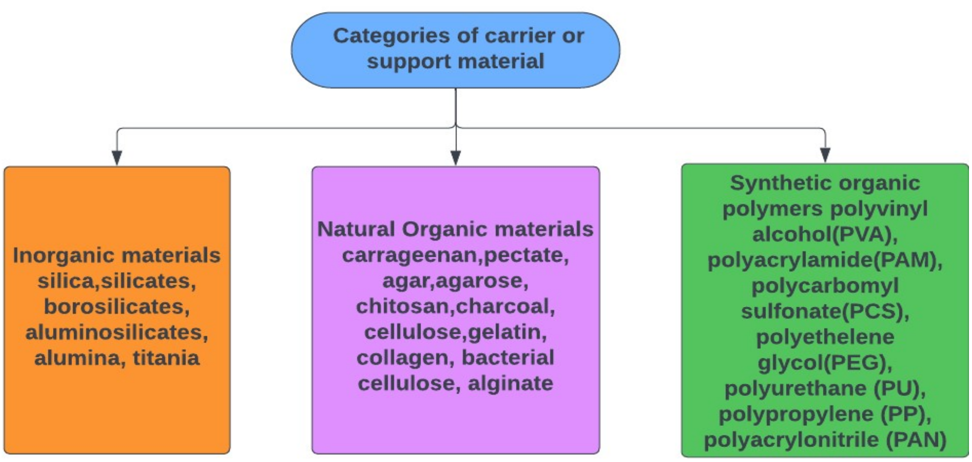

Fig. 1: Support materials.

intermediaries. As a consequence, biomaterials containing paralyzed bacteria are a palatable innovation for remediation implementation (Mehrotra et al. 2020).

IMMOBILIZED BACTERIA

Immobilization of a culture or an experimental microbial consortium is simpler as well as more effective for an intended area than stabilization of leguminous microbes retrieved from a sophisticated polluted site having various recognized and unidentified bacteria (enteric pathogens to one another). *Agrobacterium radiobacter* J14a, plain atrazine denigrating custom, as well as an instinctual combination of resources of bacteria alienated from an atrazine-polluted particular crop, for instance, were adsorbed utilizing hydroxylation alcohol aerogel (Siripattanakul et al. 2008). A synthesized pathogenic bacteria alliance (comprising 17 isolates) immobilized in chitin beads was researched in yet another investigation for the rehabilitation of a hydrocarbon marshland. In fifteen days, the experimentally pathogenic syndicate healed the pollutant (Angelim et al. 2013, Dong et al. 2017).

Microbes from the rapidly increasing society have been cultivated, and the produced microbes were commodified. The mixture and de-ionized water were evaluated in a conical flask with a volume of 250 milliliters in a 20:80 ratio and emulsified to verify consistency. 3.063 g of sodium alginate was evaluated in the intensive organisms (Maheshwari et al. 2017). The concoction was once implanted using a disinfected hypodermic needle and syringe into a glass beaker of 70 mL of 0.12 M calcium chloride. Gelation appeared at ambient temperature as eventually, the molecular- droplets emerged into close interaction with the calcium solvent. Entire precipitation formed circular droplets with an average diameter of 3-4 mm. At 1-2 h, the granules are empowered to firm up totally and utterly. The micelles were cleaned with a complete calcium cross-integration remedy (Maheshwari et al. 2017). In another survey, Sergio and Bustos identified that sorbent entrapped in calcium-alginate particles was efficacious in ammonia bioremediation in effluent. Integrating transgenic bacteria has emerged as a subsequent mainstream thing to enhance biochips and biocontrol by adjusting the organisms' extant alleles to diagnose and deteriorate specific residues.

Benefits for Immobilized Bacteria

Nitrogen, carbon dioxide, and micronutrients are vital to the development, prevalence, and feature of various microorganisms (yet if liberated or entrapped). Throughout remediation employing incapacitated bacteria, attain these substances predominantly from either the effluent that is usually embellished in these supplements in addition to the multiverse in which they have been adsorbed. Saez et al. investigated Streptomyces strains to devalue lindane with immobilized bacteria in various matrices. The strains, both free and incapacitated, seemed to be capable of evolving in varying concentrations with contaminants that they utilized as both sources of energy and carbon (Saez et al. 2012). Lindane (Fig. 2) exclusion was reported to be greater in biomolecules than it is in suspended cells. The largest increase of Pseudomonas species. A2, A5, but rather A11 might have been ascertained in a polycrystalline capsule substrate surface, which may have contributed to sufficient permeation of oxygen and precursors proffered by the conduit (Saez et al. 2012). Prolonged access to nitrogen and carbon is compelled throughout wastewater, but permeation and allocation of such supplements should be appropriate and unhindered (Suzana et al. 2013). Table 1 shows the immobilization matrix and pollutant removal performance of various baterias.

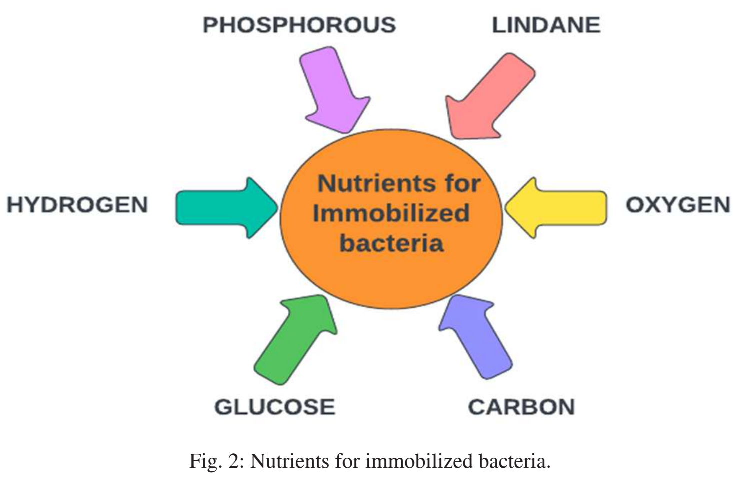

Fig. 2: Nutrients for immobilized bacteria.

Table 1: Immobilization on copious matrix and performances for removal.

Bacteria	Immobilizing matrix	Methods	Pollutants	Performance	References
Klebsiella variicola strain SKV2, *Sphingomonas* sp.	Polyurethane Calcium-alginate	Entrapment	polycyclic aromatic hydrocarbons Chlorpyrifos	44.3%,71.8%	(Dai et al. 2020; Santillan et al. 2020)
Bacillus pseudomycoides	PVA-Glutaraldehyde	Entrapment	BOD COD	86% 71%	(Mehrotra et al. 2020)
Pseudomonas putida *Bacillus cereus*	Sodium Alginate, Calcium Chloride	Entrapment	BOD, COD BOD, COD Cr	79% ,84%, 16-65% 83%,89% 86%,91%	(Maheshwari et al. 2017)
Pseudomonas putida YNS1	Alginate	Encapsulation	Phenol Cadmium copper	92% 99% 97%	(Namane et al. 2020)
Arsenic oxidizing bacteria	PVA	Entrapment	Arsenic	~ 80%	(Labus et al. 2016)
Selenastrum capricornutum	Alginate	Entrapment	Copper, cadmium, nickel, zinc	99%	(Partovinia & Rasekh 2018)
Bacillus sp., *Serratia* sp.	Alginate, Polyacrylamide	Entrapment	Chromium, mercury, nickel	-	(Suhag et al. 2015)
E. coli MG1655	Agar and alginate	Entrapment and Encapsulation	Arsenic	-	(Qiu et al. 2022)
Arthrobacter chlorophenolicus A6	Calcium Alginate	Entrapment	4-chlorophenol	98.6%	(Sahoo & Panigrahy 2018)
Bacillus licheniformis	Iron oxide magnetic	Biosorbent	Pb (II)	98%	(Wen et al. 2018)
Saccharomyces cerevisiae	Synthesized titania	Optimization and Modeling by Response Surface	Cr (VI)	99.92%	(Choudhury et al. 2017)
Fusarium verticillioides, Pencillium funiculosum	Nanosilica	Biosorption	Cr (III) Cr (VI)	128.26, 138.66 336.24, 332.77	(Mahmoud et al. 2015)
Arthrospira platensis	Alginate, Silica gel, Agarose	Biosorption	Pb (II)	65.85 $mg.g^{-1}$, 2.58 $mg.g^{-1}$	(Duda-Chodak et al. 2013)
Bacillus cereus RC-1	Biochar derived from sewage sludge	Biosorption	Cd (II)	158.77$mg.g^{-1}$ 127.71 $mg.g^{-1}$	(Huang et al. 2020)
Sulfate-reducing bacteria	Sodium alginate	Entrapment	Fe Zn Cd Pb Ni	85–95% 85–95% 85–95% 85–95% 75-95%	(Gopi Kiran et al. 2018)
Pseudomonas putida	Agar beads	Entrapment	Cu (II) Zn (II)	0.28 $mg.g^{-1}$ 0.25 $mg.g^{-1}$	(Meringer et al. 2021)
Escherichia coli, *Staphylococcus epidermidis*	Kaolin	Biosorption	Cr Zn Cr Zn	89 $mg.g^{-1}$ 68 $mg.g^{-1}$ 46 $mg.g^{-1}$ 48 $mg.g^{-1}$	(Quiton et al. 2018)
Chlorella sorokiniana	Loofa sponge	Biosorption	Cr	69.26 $mg.g^{-1}$	(Nasreen et al. 2008)
Saccharomyces cerevisiae Sr(II)	chitosan beads	Biosorption	Sr (II) Co (II) s(I)	34.96 $mg.g^{-1}$ 28.90 $mg.g^{-1}$ 17.62 $mg.g^{-1}$	(Yin et al. 2017)
Bacillus drentensis	Bio-carrier Beads	Biosorption	Pb Cu	0.3332 $mg.g^{-1}$, 0.5598 $mg.g^{-1}$	(Seo et al. 2013)

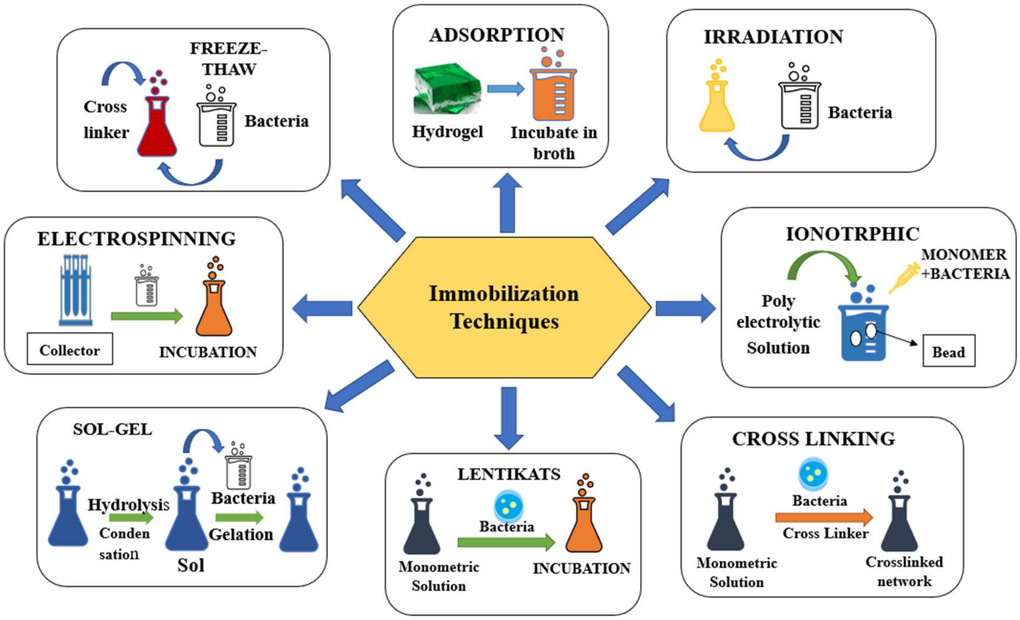

Fig. 3: Numerous methods and support materials used in the bacterial immobilization process.

BACTERIAL IMMOBILIZATION METHODS

A lot of changes over the decades: a numerous approach for isolating bacteria in biopolymers were created over time (Fig. 3). Several myriad processes evolved for inactivating bacteria in biopolymers (Mehrotra et al. 2021). Ligand binding and polymeric bond formation on solid substrates are among the most prevalent and significant procedures. Cross-linking among biomolecules/biocatalysts/bacteria and the viscoelastic insurer is another tactic, as is virtualization by vesicles and entanglement in a composite membrane (Mehrotra et al. 2020).

Adsorption

Ligand binding of molecules on alginate for biotechnological implementations constitutes a basic, reduced, ubiquitously utilized insertion method. It is premised on the transient intimate contact of bacteria with the transmission exterior via low intermolecular influences (Suzana et al. 2013). Even though feeble conversations are embroiled in the adsorbents, there's a strong probability of bacterial attachment oozing away from endorsements further into the ecosystem; thereby, this substrate procedure has specific applicability (Dzionek et al. 2016).

Covalent Bonding

Covalent binding symbiosis, on the reverse side, is potent for peroxidase confinement and yet is seldom often used for disorienting bacteria. The organic solvents in use for inter-molecular are broadly highly toxic, minimizing bacteria and survivability and subsequently causing cells to perish (Dzionek et al. 2016).

Cross Linking

Cross-linking is an illustration strategy of cell disruption that requires the establishment of chemical bonding between the stimulated biodynamic assist and bacteria employing functionalized homologous recombination entities, including solvent, hexyl, diphenyl, and many others. Mehrotra et al. previously entrapped an untrodden type of bacteria, *Bacillus pseudomycoides*, in an Extracellular matrix and agglomerated to fumaric acid for the biotreatment of tannery effluents and revealed not only majestic biological membranes for about 2 months and also impactful disinfectants of effluents without bioleaching (Mehrotra et al. 2020) Bai et al. observed alloying of Polyvinyl alcohol biomaterials in the mere existence of acetic anhydride as a merge intermediary to inactivate nitrifying bacteria in the hopes of evaluating the matrix's capacity to maintain bacteria productivity. Based on the report's positive findings, the technique might be employed in a diverse selection of bioactivities (Bai et al. 2010). Another additional benefit of this technique is that it makes it possible for synchronous polycondensation without the necessity for a compatibilizer or innovator (Bai et al. 2010). Singh et al. previously reviewed 5 bacteria isolated on beta alginate for physicochemical expulsion of heavy metals; 62-71 percent of total rehabilitation of 10 $g.mL^{-1}$ strontium has been demonstrated out of conduit (Singh et al. 2020). Some cross micelles can also be complexed utilizing radio waves, individuals that have been indicated to be using ultra-violet (UV) irradiation-induced pictures of oxidative damage. Hsueh et al. presented Ultraviolet light glycerine immobilized bacteria, a technique that augmented the brewing process in the biomedicine, pharmacological, and industrial products (Hsueh et al. 2017).

Ionotropic Gelation Method

Ion channel phase transition accumulation of bacterium in granules employing varied chelating and polyatomic cations must have observed substantial application to the innovation of incapacitating colony forming units. The biggest drawback of calmodulin emulsions is their own destruction and successive volatilization by oxalate, leading to decreased intensity and tensile stability. The problem was conquered across polymer chains copolymerization and emulsifier transplantation with polymeric materials including Composite, along with additional rehabilitation to polyethylene and dimerization. Bhabha Atomic Research Centre (BARC) in Bombay, the beta copolymer, has been employed to sustain hydrocolloid particles to oxalate catalysts (Mehrotra et al. 2021). In addition to their greater recompression and o_2 propagation prospects, barium-alginate particles are additionally indicated as nitrogen fixation under hypoxic conditions.

Sol-gel Method

Sol-gel implementation including whole bacteria, has served as a traditional procedure for over a half century. Nevertheless, there are certain boundaries to this approach, including the requirement for excessive pH conditions as well as the initiation of liquor during the transesterification reaction - both are detrimental towards the immobilized bacteria but instead impede biological conflict, and pathogenic cells were siphoning out from a dimensional analog. This seems to have a substantial influence on profitability (Eleftheriou et al. 2013). The curing scheme (vapor or defrost), retained hydraulic conductivity and extension of nanofiller (e.g., porcelain fibrils), and risk factors for the development of papule ingredients (e.g., xylitol), or even the amalgamation of liquid composites also including propylene glycol which can significantly affect such considerations (Eleftheriou et al. 2013).Utilizing porcelain granules, particulate Silicon dioxide, and the bicomponent in an amorphous form approach to create 'biocers' (biological ceramic composites), which are highly permeable, flexural copolymers of almost zero deformation (Pannier et al. 2012).

LentiKats Technology

The cryo technique was applied to the gelatinization of widely utilized polymer matrix, including Copolymer, which resulted in the development of bonds, more durable, harder biopolymers. Numerous different techniques for Polyaniline hydrogel were evolved, like polypropylene establishment to oxalic acid, however, the materials seemed to be fragile and precarious (Mehrotra et al. 2021). LentiKats® technique is feasible despite the destructive substances. The delicate phase transition strategy for use by LentiKats® technology (optics carriers) has been previously amplified to production usages. That has been sufficiently integrated to resist heavy temperatures of upwards of 50 with a diverse variety of ionic strengths but also merge the economic advantages between both big and tiny beads. The Polyvinyl alcohol LentiKats® procedure of elevated chemical and physical predictability permits the incapacitation of bacteria in their own initial dimensions and form. Because of the enhanced durability and resistance of the LentiKats®, diverse effluent could be depicted (Mehrotra et al. 2021).

Electrospinning Method

Bacterial implementation normally happens in arrays that seem to be many times heavier than nanomaterials, creating supplements. Still, instead, retentate complicated to deflect through into a range of immobilized bacteria, decreasing overall productivity. Utilizing a mixture that includes the bacteria of intrigue, an electromagnetic mandate will be employed to turn and emit adhesive strands. The above technique is simple, cost-effective, and versatile, with promising prospects for inactivating sustainable bacterial species (Zamel et al. 2019). Nevertheless, due to polyvinyl alcohol and the bond being water-based in the environment, they couldn't operate precisely for tannery effluent. In order the purpose of eliminating the blue-colored pigment substance cetyl/poly monomer (ethylene oxide) microfibers were electrospun alongside DMSO (dimethyl sulfoxide) as a carrier fluid to inhibit acceptable *Bacillus mycoides* (Zamel et al. 2019). Hardick et al. showed an electrically spinning framework that includes cellulose acetate, a polymer (that is recyclable, bioabsorbable, ethyl-insoluble, and extremely penetrable) for bacteria suspension, produces the development of nanofibers with immobilize many different bacteria for productive biological remediation. The structure might serve commercial uses because of numerous benefits involving simple interaction with affordability and its potential to be repurposed multitudinous (Aliheidari et al. 2019).

ASPECTS THAT INFLUENCE REMEDIATION USING IMMOBILIZED BACTERIA

Mass Transfer Limitation

Bacteria immobilized in water-based gel possess an enhanced resistance for hazardous substances owing to their defensive encasing, yet also exhibit an extended transmission of development advertising components (such as oxygen and dietary supplements) in part due to the additional weight that serves as a conveyance challenge. In one instance, investigations on the biological breakdown of gasoline through bound organisms demonstrated that their tiny permeability and brittle arrangement of calcium chloride beads impeded matter transfer (nutrient, diesel). This issue was eliminated through the mixture of fiber with a substance called sodium alginate, leading to straw-alginate beads (Xue et al. 2019, 2020). This might promote retention throughout cells that function. The multiple functions of the substrate (carrier and adsorbent) in embedded *Bacillus* cells adsorbed ions of Cd (II) were researched (Huang et al. 2020).

Toxicity of Pollutants

For the breakdown of chlorophenol, three distinct polyvinyl confined systems utilizing activated sludge have been examined (cryogel strands alongside biomass production merely, cryogel beads about PAC with edges and material, and cryogel beads with pulverized PAC and propyl (Xue et al. 2020). The most recent research on the consequences and breakdown of sulfamethoxazole (SMX) throughout analogously eliminated emphasize (ADC) rehabilitation in a photobioreactor contrasted three distinct types of microalgal-bacterial consortium: at ease levity, CA immobile fragments, and CA bound pieces alongside a powdered form of activated carbon (Xue et al. 2020).

Salinity

A variety of halophilic bacteria to endure salt is crucial for fluid breakdown in elevated humidity effluent, and efficiency is usually compromised over a particular threshold. A continuous breakdown utilizing cell debris demonstrated that input concentrations of TDS above 145,000 $mg.L^{-1}$ substantially decreased the proliferation of bacteria. In another investigation, the shell of walnuts (WS) was utilized to inhibit halophilic bacteria for use in the biological processing of tannery effluent (Pendashteh et al. 2018). While the effluent contaminants were more than 90,000 $mg.L^{-1}$, it was determined which WS enhanced the system's susceptibility to salt content astonishment as well as exacerbated its biological importing pace. In a large-scale experiment, bacteria trapped on the polypropylene material surpassed independent cells by four to seven instances at the finest water content assessed (180 $g.L^{-1}$) (Hasanzadeh et al. 2020).

Co-Contaminants

Immobilization has additionally been demonstrated to defend cells that exist compared to harmful impacts of materials beyond the desired pollutants. Heavy metals, for instance, have been experimentally illustrated to impede nitrification bacteria. In a recent research investigation, the impacts of multiple frameworks upon encapsulation of a Pseudomonas fatigue that shields denitrification species from the hazardous effects of Cr (VI) were evaluated (Yu et al. 2020). Free cells eliminated only 4% of the nitrogen oxides -N, but tissue trapped removed 86%, 88%, and 100%, correspondingly. Immobilization alongside retention transporters (biochar activated carbon, ceramsite) proved to have been inadequate. The initial amount of the substances may be elevated to 800 $mg.L^{-1}$ utilizing CA immobilized bacteria removed from effluent, though the appropriate fatal dosage over cell liberation was just 400 $mg.L^{-1}$. However, there have been situations during which substance amount hasn't been considered to be the most crucial aspect. Ji and Wang implemented a *Shigella fergusonii* demand immobilized over CA blend beads to eliminate Se (VI) within PBR (Ji & Wang 2020). The reactor levels and HRT have been demonstrated to regulate the process's elimination efficacy, and the influential Se level did not impact these.

pH

In biosorption procedure and metabolism, the acidity of the environment contributes to the magnetic attraction among bacteria as well as substances through determining substance differentiation as well as the physical and chemical characteristics (e.g., zeta) that impact the variety of receptors on the bacteria. For instance, ecological remediation of Cr (VI) employing CA-anchored yeast used for baking has been investigated by ranging the acidity level of the mixture from 1.5 to 7.5, at pH 3.5, suffering its greatest consumption abilities (Mahmoud & Mohamed 2017). Further investigations demonstrate an analogous degree of addiction (Dhanarani et al. 2016). The pH level of the substrate affects the functioning of enzymes and the development of bacteria evaluated throughout decomposition. The ideal pH value for biological remediation in a specific biomass reactor might be established with an empirical procedure. Usually, bound cells revealed a broad desirable pH examined by defending the organic matter about detrimental conditions for growth. As an instance, at pH 3, a *Sphingomonas* strain's phenol breakdown capacity proved entirely impeded, though poly vinyl ethyl-alginate-kaolin confined cells retained 95% effectiveness in elimination (Zhang et al. 2017). In extremely alkaline circumstances, like pH 10 and 12, independent cells solely eradicated 70% and 50% of the phenol, which is, accordingly, while bound cells currently ditched 95% of the phenol, despite at a slightly slower pace. Another investigation gazed into the way temperatures and pH levels impacted the ecological restoration of polluted soil by deploying imprinted bacteria.

DESIGN OF BIOFILTRATION SYSTEMS BY IMMOBILIZED BACTERIA

The implementation of immobilized bacteria in the bioretention of tannery effluent (Pathak et al. 2020, Li et al. 2016, Tong et al. 2013) varied in commercial and residential sources, like quarrying (Ma et al. 2020), petroleum (Dev et al. 2017), pharmacological, fabric, paper and pulp industries, livestock production, and sludges, has received considerable interest. Diverse fermenter kinds, along with packed-bed bioprocesses, fluidized bed bioreactors, hybrid fermentation, anaerobic membrane processes, and continuously stirred tank bioreactors, had also investigated the potential that use of paralyzed bacteria in particles for wastewater treatment from diverse sources (Table 2).

Packed-bed Bioreactor (PBR)

The PBR usually consists of a hollow tube filled with bacteria-immobilized water-based gels, which can function using an up-flow or down-flow arrangement. PBR with *Bacillus cereus* confined is employed for disinfecting wastewater produced by the industry (Banerjee & Ghoshal 2017). The researchers indicated that over ninety percent of COD, 96% of TOC, 100% of phenol compounds, 49% of ammonia nitrogen, and 42.6% of phosphates had been eliminated from wastewater. A further investigation indicated a complete elimination of the phenol about a water-based solution utilizing *Bacillus cereus* bound in CA beads (Banerjee & Ghoshal 2016). Another investigation utilized a variety of cultures retained in Ca-alginate beads to disinfect artificial metal-polluted effluent in an identical way (Gopi et al. 2018).

Fluidized Bed Bioreactor (FBR)

The FBR is composed of bound bacteria in hydrophilic gels, which are embedded in a tube that is inflated by the upflow of polluted water at an appropriate acceleration that encourages effective blending. A pure culture for *Bacillus cereus* imprisoned in CA was implemented to purify polluted water generated by hydrocarbons (Banerjee & Ghoshal 2017, 2016). Researchers disclosed eliminating over ninety-five percent of COD and phenol compounds in petroleum refineries, the effluent *Rhodococcus* rubber and *Rhodococcus* opacus had been suspended for the purification of 72-98% volatile organic compounds from artificially lined up fluids in an identical investigation. The FBR arrangement permits immediate mass movement to the paralyzed bacteria gel/beads, leading to an immediate proliferation of biomass and elevated pollutant rate of elimination throughout the disinfection of effluent (Bello et al. 2017).

Hybrid Bioreactor (HBR)

To enhance biological reactor effectiveness, the hybrid reactor encompasses either a halted or connected bed for the growth of bacteria. HBR implemented metabolic bacteria debris immobilized in PVA to process artificial effluent. This recently disclosed that this HBR system, which is comprised of anaerobic waste immobilized in polyvinyl alcohol beads, dissolved material, and biofilm transport resources, eradicates 80% of nitrogen and 72-90% (Wu et al. 2018). A separate investigation discovered that HBR performed from biological reactors compacted with PVA eliminated 89% COD from effluent wastewater within 72 hours of the process (Pandey & Sarkar 2017). The HBR arrangement might shield immobilized bacteria from being exposed directly to particular impurities yet improve the treatment process (Grandclément et al. 2017)

Table 2: Immobilized bacteria in various bioreactor types for the treatment of tannery effluent.

Bioreactors	Immobilizing matrix	Bacteria	HRT (h)	Performance	Reference
FBR	Ca- alginate	*Bacillus cereus*	-	> 95%, COD	(Banerjee & Ghoshal 2016)
		Rhodococcus ruber,		100% removal of alkanes.	
	PVA-cryogel	*Rhodococcus opacus*	-	65–72% removal of PAH	(Bello et al. 2017)
HBR	PVA	Sludge from tannery effluent	-	67–80% inorganic nitrogen	(Wu et al. 2018)
	PVA	Anaerobic microbe from upflow bioreactor	72	89% COD removal	(Pandey & Sarkar 2017)
MBR	PVA	Mixed microbial community from anaerobic	24	84.7% COD removal	(Juntawang et al. 2017)
	triacetate	Microbial community from marine sediment	40	78% COD removal 22% removal.	(Ng et al. 2016)
CSTR	PEG	*Afipia* sp.	16	2–99% dioxane removal	(Isaka et al. 2016)

Anaerobic Membrane Bioreactor (AnMBR)

The AnMRB consists of a barrier immobilized upon fluids over the process of treatment of pollutants pursuant to anaerobic circumstances using an up-flow or down-flow arrangement in Anaerobic debris immobilized in polyvinyl alcohol was demonstrated to eliminate 84.7% COD compared to electronically lined up domestic wastewater throughout AnMBR execution at 24 h HRT (Juntawang et al. 2017). In further investigation, the community of bacteria that originated in marine debris proved imprisoned in the material triacetate for the purification of effluent(Ng et al. 2016). The interaction among immobilized beads, as well as their membrane exterior, diminishes the development of cakes on the barrier of the substrate and enhances MBR effectiveness for tannery effluent (Juntawang et al. 2017)

Continuously Stirred Tank Bioreactor (CSTR)

To overcome the conveyance of mass constraints, the CSTR incorporates bacteria-immobilized water-based gels, which are precisely transformed with pollutants employing constant swirling and ventilation. At a duration of sixteen hours (Isaka et al. 2016), HRT, an intact culture of *Afipia* sp., encased polyethylene glycol (administered in CSTR to eradicate 85-91% dioxin about the water-based solution. Anammox debris immobilized in polyvinyl alcohol was initially applied by CSTR for the disinfection of the wastewater treatment facility, disregarding fluid. The researchers indicated that functioning the CSTR at 3 h HRT in nitrate deletion of 88-92% (Hsieh et al. 2015). A further investigation adopting sewage effluent immobilized in polyethylene glycol conveyed a total nitrogen reduction of 92% throughout the conduct at 1.5 h HRT.

FUTURE PERSPECTIVES AND POSSIBILITIES

The progress made in immobilizing bacterial cells with different polymers, untested bacterial strains, and novel cell immobilization methods for the bioremediation of environmental pollutants is covered in this review. As this article discusses, the use of immobilized bacteria in the bioremediation of industrial wastes has demonstrated promising performance in the removal of contaminants; however, the majority of existing work has been primarily restricted to laboratory-scale studies. The complexity of operations, matrix stability, characteristics, presence of multiple contaminants, mass transfer limitation of substrates into immobilized cells, build-up of toxic metabolic products around the cells due to low dispersion level, which may prevent microbiological growth, and thick biofilm formation, which may obstruct the beads' pores and prevent the transfer of substrate from the bulk liquid to the immobilized cells. Despite these obstacles, this field of study keeps developing to better understand and develop these procedures.

The study of various composite materials, such as biodegradable sponge-polycaprolactone, water-soluble sponge-NaCl-PEG, and Pb-contaminated water, respectively, is one of the most recent advancements in the field of immobilized bacteria for bioremediation. Furthermore, the process of immobilizing bacteria on matrices has been shown to aid in the remediation of contaminated sites by increasing the rate at which pollutants can be biodegraded, enhancing the durability of the immobilized strains, increasing their tolerance to high pollutant loads, and increasing bacterial enzyme activity.

The production of suitable substrates to immobilize affordable bacteria, have stable physical and chemical properties, have high porosity and surface area, and are non-toxic should be one of the main topics of future research. Future studies could also look into the proper ratios of biological biomass and immobilizing substance applied to stop cell overcrowding, which is the cause of high biofilm formation and pore-clogging. To prevent pore clogging, another tactic to slough off the mature and overgrown biofilms is to optimize the flow rate through the bioreactor. The immobilized cell-based treatment process could be made more sustainable by recovering value-added products through simultaneous bioremediation processes, such as recovering the metals during the biological treatment of wastewater that is high in metals. Ultimately, immobilized microbes could become a common bioremediation tool with the standardization of bead-formation techniques and the development of basic, theory-based engineering design principles, governing equations, and recommendations. All things considered, the idea of immobilizing microbes is fascinating and keeps drawing attention from researchers looking to remediate a wide range of contaminants using reusable matrix materials and next-generation smart materials. In the upcoming decades, we predict that research in this field will continue to expand quickly and that there will be more instances of this technology being used in the field and on a commercial scale.

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REFERENCES

Aliheidari, N., Nojan, A., Mangilal, A. and Hamid, D. 2019. Electrospun nanofibers for label-free sensor applications. Sensors, 19(16): 44-48.

Angelim, A. L., Costa, S. P., Farias, B. C. S., Aquino, L. F. and Melo, V. M. M. 2013. An innovative bioremediation strategy using a bacterial consortium entrapped in chitosan beads. J. Environ. Manag., 127: 10-17. doi: 10.1016/j.jenvman.2013.04.014.

Bai, X., Ye, Z. F., Li, Y. F., Zhou, L. C. and Yang, L. Q. 2010. Preparation of crosslinked macroporous PVA foam carrier for immobilization of microorganisms. Process Biochem., 45(1): 60-66. doi: 10.1016/j.procbio.2009.08.003.

Banerjee, A. and Ghoshal, A. K. 2016. Biodegradation of real petroleum wastewater by immobilized hyper phenol-tolerant strains of Bacillus cereus in a fluidized bed bioreactor. 3 Biotech, 6(2): 447. doi: 10.1007/s13205-016-0447-1.

Banerjee, A. and Ghoshal, A. K. 2017. Biodegradation of an actual petroleum wastewater in a packed bed reactor by an immobilized biomass of Bacillus cereus. J. Environ. Chem. Eng., 5(2): 1696-1702. doi: 10.1016/j.jece.2017.03.008.

Bello, M. M., Raman, A. A. A. and Purushothaman, M. 2017. Applications of fluidized bed reactors in wastewater treatment – A review of the major design and operational parameters. J. Cleaner Prod., 141: 1492-1514.

Berillo, D., Al-Jwaid, A. and Caplin, J. 2021. Polymeric materials used for immobilisation of bacteria for the bioremediation of contaminants in water. Polymers, 13(15): 466. doi: 10.3390/polym13152466.

Choudhury, P. R., Bhattacharya, P., Ghosh, S., Majumdar, S., Saha, S. and Sahoo, G. C. 2017. Removal of Cr (VI) by synthesized titania embedded dead yeast nanocomposite: Optimization and modeling by response surface methodology. J. Environ. Chem. Eng., 5(1): 214-221. doi: 10.1016/j.jece.2016.11.041.

Dai, X., Lv, J., Yan, G., Chen, C., Guo, S. and Fu, P. 2020. Bioremediation of intertidal zones polluted by heavy oil spilling using immobilized laccase-bacteria consortium. Bioresour. Technol., 309: 123305. doi: 10.1016/j.biortech.2020.123305.

Dev, S., Roy, S. and Bhattacharya, J. 2017. Optimization of the operation of packed bed bioreactor to improve the sulfate and metal removal from acid mine drainage. J. Environ. Manage., 200: 135-144. doi: 10.1016/j.jenvman.2017.04.102.

Dhanarani, S., Viswanathan, E., Piruthiviraj, P., Arivalagan, P. and Kaliannan, T. 2016. Comparative study on the biosorption of aluminum by free and immobilized cells of bacillus safensis KTSMBNL 26 isolated from explosive contaminated soil. J. Taiwan Inst. Chem. Eng., 69: 61-67. doi: 10.1016/j.jtice.2016.09.032.

Dong, H., Wang, W., Song, Z., Dong, H., Wang, J., Sun, S., Zhang, Z., Ke, M., Zhang, Z., Wu, W. M., Zhang, G. and Ma, J. 2017. A high-efficiency denitrification bioreactor for the treatment of acrylonitrile wastewater using waterborne polyurethane immobilized activated sludge. Bioresource Technol., 239: 472-481. doi: 10.1016/j.biortech.2017.05.015.

Duda-Chodak, A., Wajda, Ł. and Tarko, T. 2013. The immobilization of arthrospira platensis biomass in different matrices - A practical application for lead biosorption. j. environ. sci. health - Part A Toxic/Hazard. Subst. Environ. Eng., 48(5): 509-17. doi: 10.1080/10934529.2013.730425.

Dzionek, A., Wojcieszyńska, D. and Guzik, U. 2016. Natural carriers in bioremediation: A review. Electron. J. Biotechnol., 23: 28-36.

Eleftheriou, N. M., Ge, X., Kolesnik, J., Falconer, S. B., Harris, R. J., Khursigara, C., Brown, E. D. and Brennan, J. D. 2013. Entrapment of living bacterial cells in low-concentration silica materials preserves cell division and promoter regulation. Chem. Mater., 25(23): 4798-4805. doi: 10.1021/cm403198z.

Gopi Kiran, M., Pakshirajan, K. and Das, G. 2018. Heavy metal removal from aqueous solution using sodium alginate immobilized sulfate reducing bacteria: Mechanism and process optimization. J. Environ. Manage., 218: 486-496. doi: 10.1016/j.jenvman.2018.03.020.

Grandclément, C., Seyssiecq, I., Piram, A., Wong-Wah-Chung, P., Vanot, G., Tiliacos, N., Roche, N. and Doumenq, P. 2017. From the conventional biological wastewater treatment to hybrid processes, the evaluation of organic micropollutant removal: A review. Water Res., 111: 297-317.

Hasanzadeh, R., Souraki, B. A., Pendashteh, A., Khayati, G. and Ahmadun, F. R. 2020. Application of isolated halophilic microorganisms suspended and immobilized on walnut shell as biocarrier for treatment of oilfield produced water. J. Hazard. Mater., 400: 21397. doi: 10.1016/j.jhazmat.2020.123197.

Haso, H. W., Dubale, A. A., Chimdesa, M. A. and Atlabachew, M. 2022. High performance copper based metal organic framework for removal of heavy metals from wastewater. Front. Mater., 9: 16-25. doi: 10.3389/fmats.2022.840806.

Hsieh, Y. L., Tseng, S. K. and Chang, Y. J. 2015. Nitrogen removal from wastewater using a double-biofilm reactor with a continuous-flow method. Senors, 11: 54-69.

Hsueh, Y. H., Liaw, W. C., Kuo, J. M., Deng, C. S. and Wu, C. H. 2017. Hydrogel film-immobilized Lactobacillus Brevis RK03 for γ-aminobutyric acid production. Int. J. Mol. Sci., 18(11): 2324. doi: 10.3390/ijms18112324.

Huang, F., Li, K., Wu, R. R., Yan, Y. J. and Xiao, R. B. 2020. Insight into the Cd^{2+} biosorption by viable Bacillus cereus RC-1 immobilized on different biochars: Roles of bacterial cell and biochar matrix. J. Clean. Prod., 272: 2743. doi: 10.1016/j.jclepro.2020.122743.

Igiri, B.E., Okoduwa, S.I.R., Idoko, G.O., Akabuogu, E.P., Adeyi, A.O. and Ejiogu, I.K. 2018. Toxicity and bioremediation of heavy metals contaminated ecosystem from tannery wastewater: A review. J. Toxicol., 54: 1145-1153.

Isaka, K., Udagawa, M., Kimura, Y., Sei, K. and Ike, M. 2016. Biological wastewater treatment of 1,4-dioxane using polyethylene glycol gel carriers entrapping Afipia sp. D1. J. Bioosci. Bioeng., 121(2): 203-208. doi: 10.1016/j.jbiosc.2015.06.006.

Ji, Y. and Wang, Y. T. 2020. Se(VI) reduction by continuous-flow reactors packed with Shigella fergusonii strain TB42616 immobilized by Ca2+-alginate gel beads. Process Biochem., 91: 46-56. doi: 10.1016/j.procbio.2019.11.031.

Juntawang, C., Rongsayamanont, C. and Khan, E. 2017. Entrapped cells-based-anaerobic membrane bioreactor treating domestic wastewater: Performances, fouling, and bacterial community structure. Chemosphere, 187: 147-155. doi: 10.1016/j.chemosphere.2017.08.113.

Labus, K., Drozd, A. and Trusek-Holownia, A. 2016. Preparation and characterisation of gelatine hydrogels predisposed to use as matrices for effective immobilisation of biocatalysts. Chem. Papers, 70(5): 523-530. doi: 10.1515/chempap-2015-0235.

Li, C., Wang, S., Du, X., Cheng, X., Fu, M., Hou, N. and Li, D. 2016. Immobilization of iron- and manganese-oxidizing bacteria with a biofilm-forming bacterium for the effective removal of iron and manganese from groundwater. Bioresour. Technol., 220: 76-84. doi: 10.1016/j.biortech.2016.08.020.

Ma, H., Wei, M., Wang, Z., Hou, S., Li, X. and Xu, H. 2020. Bioremediation of cadmium polluted soil using a novel cadmium immobilizing plant growth promotion strain Bacillus sp. TZ5 loaded on biochar. J. Hazard. Mater., 12: 388. doi: 10.1016/j.jhazmat.2020.122065.

Maheshwari, U., Ali, A. J. and Jain, M. K. 2017. Bioremediation by free and immobilized bacteria isolated from tannery effluent, 5: 75-90.

Mahmoud, M. S. and Mohamed, S. A. 2017. Calcium alginate as an eco-friendly supporting material for baker's yeast strain in chromium bioremediation. HBRC J., 13(3): 245-254. doi: 10.1016/j.hbrcj.2015.06.003.

Mahmoud, M. E., Yakout, A. A., Abdel-Aal, H. and Osman, M. M. 2015. Speciation and selective biosorption of Cr(III) and Cr(VI) using nanosilica immobilized-fungi biosorbents. J. Environ. Eng., 141(4): 899. doi: 10.1061/(asce)ee.1943-7870.0000899.

Mehrotra, T., Dev, S., Banerjee, A., Chatterjee, A., Singh, R. and Aggarwal, S. 2021. Use of immobilized bacteria for environmental bioremediation: A review. J. Environ. Chem. Eng., 9(5): 121-136.

Mehrotra, T., Zaman, M. N., Prasad, B. B., Shukla, A., Aggarwal, S. and Singh, R. 2020. Rapid immobilization of viable Bacillus pseudomycoides in polyvinyl alcohol/glutaraldehyde hydrogel for biological treatment of municipal wastewater. Environ. Sci. Pollut. Res., 27(9): 9167-9180. doi: 10.1007/s11356-019-07296-z.

Meringer, A., Liffourrena, A. S., Heredia, R. M., Lucchesi, G. I. and Boeris, P. S. 2021. Removal of copper and/or zinc ions from synthetic solutions by immobilized, non-viable bacterial biomass: Batch and fixed-bed column lab-scale study. J. Biotechnol., 328: 87-94. doi: 10.1016/j.jbiotec.2021.01.011.

Namane, A., Amrouche, F., Arrar, J., Ali, O. and Hellal, A. 2020. Bacterial behaviour in the biodegradation of phenol by indigenous bacteria immobilized in Ca-alginate beads. Environ. Technol. (United Kingdom), 41(14): 1829-836. doi: 10.1080/09593330.2018.1551427.

Nasreen, A., Muhammad, I., Iqbal, Z. S. and Javed, I. 2008. Biosorption characteristics of unicellular green alga Chlorella sorokiniana immobilized in loofa sponge for removal of Cr(III). J. Clean. Prod., 20: 616.

Ng, K. K., Shi, X., Ong, S. L., Lin, C. F. and Ng, H. Y. 2016. An innovative of aerobic bio-entrapped salt marsh sediment membrane reactor for the treatment of high-saline pharmaceutical wastewater. Chem. Eng. J., 295: 317-25. doi: 10.1016/j.cej.2016.03.046.

Pandey, S. and Sarkar, S. 2017. Anaerobic treatment of wastewater using a two-stage packed-bed reactor containing polyvinyl alcohol gel beads as biofilm carrier. J. Environ. Chem. Eng., 5(2): 1575- 1585. doi: 10.1016/j.jece.2017.02.013.

Pannier, A., Mkandawire, M., Soltmann, U., Pompe, W. and Böttcher, H. 2012. Biological activity and mechanical stability of sol-gel-based biofilters using the freeze-gelation technique for immobilization of Rhodococcus ruber. Appl. Microbiol. Biotechnol., 93(4): 1755-1767. doi: 10.1007/s00253-011-3489-7.

Partovinia, A. and Rasekh, B. 2018. Review of the immobilized microbial cell systems for bioremediation of petroleum hydrocarbons polluted environments. Crit. Rev. Environ. Sci. Technol., 48(1): 1-38.

Pathak, U., Banerjee, A., Roy, T., Das, S. K., Das, P., Kumar, T. and Mandal, T. 2020. Evaluation of mass transfer effect and response surface optimization for abatement of phenol and cyanide using immobilized carbon alginate beads in a fixed bio-column reactor. Asia-Pac. J. Chem. Eng., 15(2). doi: 10.1002/apj.2405.

Pendashteh, A. R., Chaibakhsh, N. and Ahmadun, F. R. 2018. Biological treatment of high salinity produced water by microbial consortia in a batch stirred tank reactor: Modelling and kinetics study. Chem. Eng. Commun., 205(3): 387-401. doi: 10.1080/00986445.2017.1398742.

Qiu, Y., Yu, S. and Li, L. 2022. Research progress in fluorescent probes for arsenic species. Molecules, 27(23): 25-36.

Quiton, K. G., Doma, B., Futalan, C. M. and Wan, M. W. 2018. Removal of chromium(VI) and zinc(II) from aqueous solution using kaolin-supported bacterial biofilms of gram-negative E. coli and gram-positive Staphylococcus epidermidis. Sustain. Environ. Res., 28(5): 206-213. doi: 10.1016/j.serj.2018.04.002.

Saez, J. M., Benimeli, C. S. and Amoroso, M. J. 2012. Lindane removal by pure and mixed cultures of immobilized actinobacteria. Chemosphere, 89(8): 982-987. doi: 10.1016/j.chemosphere.2012.06.057.

Sahoo, N. K. and Panigrahy, N. 2018. Biodegradation and kinetic study of 4-chlorophenol in bioreactor packed with stabilized bacteria entrapped in calcium alginate beads system. Environ. Processes, 5(2): 287-302. doi: 10.1007/s40710-018-0294-7.

Santillan, J. Y., Rojas, N. L., Ghiringhelli, P. D., Nóbile, M. L., Lewkowicz, E. S. and Iribarren, A. M. 2020. Organophosphorus compounds biodegradation by novel bacterial isolates and their potential application in bioremediation of contaminated water. Bioresour. Technol., 12: 317. doi: 10.1016/j.biortech.2020.124003.

Seo, H., Lee, M. and Wang, S. 2013. Equilibrium and kinetic studies of the biosorption of dissolved metals on Bacillus drentensis immobilized in biocarrier beads. Environ. Eng. Res., 18(1): 45-53. doi: 10.4491/eer.2013.18.1.045.

Shaheen Fathima, A., Bhuvaneswari, R. and Jeyanthi, J. 2020. Characterization of tannery effluent and synthesis of natural coagulant. AIP Conf. Proc., 312: 2270.

Singh, R., Shitiz, K. and Singh, A. 2020. Immobilization of bacterial cells in hydrogels prepared by gamma irradiation for bioremoval of strontium ions. Water, Air, Soil Pollut., 231(1): 4374. doi: 10.1007/s11270-019-4374-8.

Siripattanakul, S., Wirojanagud, W., McEvoy, J. and Khan, E. 2008. Effect of cell-to-matrix ratio in polyvinyl alcohol immobilized pure and mixed cultures on atrazine degradation. Water, Air, Soil Pollut. Focus, 8(3–4): 257-266. doi: 10.1007/s11267-007-9158-2.

Suhag, D., Bhatia, R., Das, S., Shakeel, A., Ghosh, A., Singh, A., Sinha, O.P., Chakrabarti, S. and Mukherjee, M. 2015. Physically cross-linked pH-responsive hydrogels with tunable formulations for controlled drug delivery. RSC Adv., 5(66): 53963-53972. doi: 10.1039/c5ra07424j.

Suman, H., Sangal, V.K. and Vashishtha, M. 2021. Treatment of tannery industry effluent by electrochemical methods: A review. Mater. Today: Proc., 47: 1112.

Suzana, C. S. M., Claudia, M., Martins, M. C., Fiuza, L. G. and Santaella, T. 2013a. Immobilization of microbial cells: A promising tool for treatment of toxic pollutants in industrial wastewater. Afr. J. Biotechnol., 12(28): 4412-18. doi: 10.5897/ajb12.2677.

Tong, K., Zhang, Y., Liu, G., Ye, Z. and Chu, P. K. 2013. Treatment of heavy oil wastewater by a conventional activated sludge process coupled with an immobilized biological filter. Int. Biodeterior. Biodegrad., 84: 65-71. doi: 10.1016/j.ibiod.2013.06.002.

Tuson, H. H. and Weibel, D. B. 2013. Bacteria-surface interactions. Soft Matter, 9(17): 4368-80.

Wen, X., Du, C., Zeng, G., Huang, D., Zhang, J., Yin, L., Tan, S., Huang, L., Chen, H., Yu, G., Hu, X., Lai, C., Xu, P. and Wan, J. 2018. A novel biosorbent prepared by immobilized Bacillus licheniformis for lead removal from wastewater. Chemosphere, 200: 173-79. doi: 10.1016/j.chemosphere.2018.02.078.

Wu, N., Zeng, M., Zhu, B., Zhang, W., Liu, H., Yang, L. and Wang, L. 2018. Impacts of different morphologies of anammox bacteria on nitrogen removal performance of a hybrid bioreactor: Suspended sludge, biofilm and gel beads. Chemosphere, 208: 460-468. doi: 10.1016/j.chemosphere.2018.06.012.

Xue, J., Wu, Y., Fu, X., Li, N., Sun, J. and Qiao, Y. 2020. Study on degradation characteristics and bacterial community structure changes of immobilized cells in straw-alginate beads in marine environment. Bioresour. Technol. Rep., 10: 402. doi: 10.1016/j.biteb.2020.100402.

Xue, J., Wu, Y., Shi, K., Xiao, X., Gao, Y., Li, L. and Qiao, Y. 2019. Study on the degradation performance and kinetics of immobilized cells in straw-alginate beads in marine environment. Bioresour. Technol., 280: 88-94. doi: 10.1016/j.biortech.2019.02.019.

Yin, Y., Hu, J. and Wang, J. 2017. Removal of Sr2+, Co2+, and Cs+ from aqueous solution by immobilized Saccharomyces cerevisiae with magnetic chitosan beads. Environ. Prog. Sustainable Energy, 36(4): 989-996. doi: 10.1002/ep.12531.

Yu, X., Shi, J., Khan, A., Yun, H., Zhang, P., Zhang, P., Kakade, A., Tian, Y., Pei, Y., Jiang, Y., Huang, H., Wu, K. and Li, X. 2020. Immobilized-microbial bioaugmentation protects aerobic denitrification from heavy metal shock in an activated-sludge reactor. Bioresour. Technol., 307: 12738. doi: 10.1016/j.biortech.2020.123185.

Yusif, B. B., Bichi, K. A., Oyekunle, O. A., Girei, A. I., Garba, P. Y. and Garba, F. H. 2016. A review of tannery effluent treatment. J. Clean. Prod., 2: 29.

Zamel, D., Hassanin, A. H., Ellethy, R., Singer, G. and Abdelmoneim, A. 2019. Novel bacteria-immobilized cellulose acetate/poly(ethylene oxide) nanofibrous membrane for wastewater treatment. Sci. Rep., 9(1): 5265. doi: 10.1038/s41598-019-55265-w.

Zhang, K., Liu, Y., Luo, H., Chen, Q., Zhu, Z., Chen, W., Chen, J., Ji, L. and Mo, Y. 2017. Bacterial community dynamics and enhanced degradation of di-n-octyl phthalate (DOP) by corncob-sodium alginate immobilized bacteria. Geoderma, 305: 264-74. doi: 10.1016/j.geoderma.2017.06.009.

Zhao, J., Wu, Q., Tang, Y., Zhou, J. and Guo, H. 2022. Tannery wastewater treatment: Conventional and promising processes, an updated 20-year review. J. Leather Sci. Eng., 4(1): 72.

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