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NEXT-GENERATION PLANT CELL IMMOBILIZATION FOR SUSTAINABLE WASTEWATER REMEDIATION

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ABSTRACT

Wastewater contamination by organic pollutants, heavy metals, nutrients, dyes, pharmaceuticals, and other emerging contaminants represents a significant environmental challenge. Conventional wastewater treatment technologies may encounter limitations in removing persistent pollutants, maintaining stable microbial populations, and achieving efficient treatment under variable operating conditions. Cell immobilization has emerged as a promising biotechnological strategy for improving wastewater treatment by retaining biologically active microbial or plant cells within or on suitable supporting materials. This approach can enhance biomass retention, facilitate cell recovery and reuse, improve operational stability, and support the removal or transformation of diverse contaminants. Microbial immobilization techniques include adsorption, entrapment, encapsulation, covalent attachment, and biofilm formation, whereas plant-cell immobilization involves the use of living plant cells, plant tissues, and plant-associated systems capable of accumulating, transforming, or detoxifying pollutants. Common immobilization matrices include alginate, chitosan, cellulose, silica, activated carbon, biochar, and synthetic polymers. Immobilized bacteria, fungi, algae, and plant cells have demonstrated potential applications in organic matter degradation, nutrient removal, heavy metal biosorption, dye decolorization, pharmaceutical removal, and the treatment of industrial effluents. However, treatment efficiency depends on cell viability, mass-transfer limitations, carrier properties, wastewater composition, and operating conditions. Additional concerns include carrier degradation, biomass leakage, regeneration costs, and the environmental risks associated with contaminated biomass. This review examines the fundamental principles, immobilization methods, supporting materials, pollutant-removal mechanisms, and applications of immobilized microbial and plant cells in wastewater treatment. It also discusses current technological limitations, scale-up challenges, and emerging approaches involving bio-based carriers, hybrid immobilization systems, and integrated treatment technologies. Future research should prioritize long-term performance evaluation, environmentally compatible materials, resource recovery, and pilot-scale validation to facilitate the sustainable implementation of immobilized-cell technologies in wastewater management.

KEYWORDS: Plant cell immobilization, wastewater remediation, heavy metal removal, pharmaceutical contaminants, emerging pollutants.

1. INTRODUCTION

With an increase in industrial, agricultural and municipal wastewater, wastewater now has a growing number of pollutants like heavy metals, dyes, organic materials, pharmaceuticals and other contaminants. As these pollutants continue to contaminate the wastewater, they also negatively affect the quality of water and cause potential risks to human health. While traditional wastewater treatment systems are used for most wastewater treatment applications, there are limitations. One such limitation is their ability to effectively remove contaminants of persistent nature. Another concern is that such systems generate secondary waste and often end up being costly when operated under different

conditions. For this reason, a lot of interest has been gained in creating new technologies of wastewater treatment that are sustainable and effective (Wang & Chen, 2009).

Another biotechnological innovation of interest is cell immobilization. The goal of this approach is to keep the cells within a support material or on top of one. When comparing such systems to free cells, the immobilized cells systems result in improved biomass retention, faster and easier cell removal, and reuse of cells and systems, and better systems for stability. As with any system, there is more than one way to immobilize cells. There are four immobilization systems: entrapment, encapsulation, adsorption and covalent attachment. In wastewater treatment systems, this technology allows for the incorporation of plant and/or microbial cells within the system design (Cassidy et al., 1996; Moreno-Garrido, 2008). Using immobilized plant and microbial cells for the removal of contaminants can be accomplished in multiple ways including biosorption, bioaccumulation, enzymatic transformation, and the assimilation of nutrients. How well the removal of contaminants can be performed using cells immobilized in matrices is largely influenced by what kind of support matrices (e.g. alginate, chitosan, cellulose, biocompatible) are chosen to keep the cells in place. Such a support matrix may also create additional hurdles, such as the potential for mass transfer limitations, matrix degradation, and/or toxicity towards cells. In addition, there is also the need for an efficient means for handling of the used (i.e. pollutant-loaded) biomass (Yaashikaa et al., 2022).

This review examines the fundamental principles, immobilization techniques, supporting materials, and pollutant-removal mechanisms associated with immobilized microbial and plant cells in wastewater treatment. It further evaluates applications involving heavy metals, synthetic dyes, organic pollutants, and pharmaceutical contaminants, while discussing technological limitations and future research directions (Yaashikaa et al., 2022; Moreno-Garrido, 2008). Particular emphasis is placed on sustainable immobilization materials, integrated treatment systems, resource recovery, and pilot-scale validation to support the practical implementation of immobilized-cell technologies in wastewater management.

2. FUNDAMENTALS OF CELL IMMOBILIZATION

Biological immobilization of microbial or plant cells involves fastening them to a solid substrate in such a way that they retain their biological activity. Immobilized cells are becoming a much more attractive tool as it provides improved biomass retention, less hassle with cell recovery, and better overall system stability. Biotransformation and biological removal of pollutants as well as biosorption and bioaccumulation can also be mediated by these immobilized cells. Plant cell cultures have all been utilized in biological waste management processes. A range of substrates from more classic examples of immobilized media (such as activated carbon and chitosan) to modern polymers can be employed. The design of an effective immobilized cell system takes into consideration the biology, material science, pollutant characteristics, and other ecological factors (Cassidy et al., 1996; Moreno-Garrido, 2008).

2.1 Principles of Cell Immobilization

The basic idea behind cell immobilization is to physically confine cells, keeping them alive, while allowing the free exchange of matter between the cell system and its environment, the wastewater. The immobilized cells must have access to pollutants, nutrients, and other needed substances like oxygen, while their products must be able to escape the cell system, so that they may take part in further chemical reactions. Immobilization can be done in several ways including cells can be trapped, covalently linked to some carrier, or formed into a biofilm. Trapping techniques include absorption (cell attached to a carrier), entrapment (within some porous polymer), and encapsulation (semi-permeable protective matrix). Biofilm-based immobilization occurs when cells form a three dimensional structure with some polymer matrix. Different ways to immobilize cells can be more suitable depending on the particular cell type, the characteristics of the carrier, and the properties of the wastewater and operational parameters (Moreno-Garrido, 2008; Wang et al., 2006).

Carrier material can greatly influence cell performance. Immobilization in natural polymers like alginate or chitosan is often considered to be favourable, and cell entrapment with carbon-based carrier material such as activated carbon and biochar can further encourage cell immobilization by absorbing pollutants. Some synthetic polymers and inorganic carrier material offer greater cell immobilization and stability, though all carriers should be considered for cell immobilization after being assessed for durability and potential for regeneration (if possible) in terms of cost (Gadd et al., 2009). Another critical aspect of immobilized cells' functioning is mass transfer. Pollutants have to cross the bulk wastewater's liquid layer surrounding the carriers to reach the cells. When the matrices are thick, diffusion can cause uneven distribution of pollutants and even limit nutrients, especially in more active biofilms. If cell concentration gets too high, if carriers become too thick, or if there is not enough turbulence, treatment performance will suffer. This includes things like poor carrier selection, insufficient blending, or bad retention times (Wang et al., 2009; Gadd et al., 2009). Fungi have different modes of enzymatic and metabolic action when it comes to degradation of pollutants. For plants, cells in culture may actively bind, degrade, and transform different compounds in their surroundings. However, different degradation processes must be identified clearly. The distinctions of biological degradation, intracellular accumulation, passive biosorption on the surface of cell

walls, and the carrier adsorption must be made for the assessment of treatment performance.

2.2 Advantages of Immobilized-Cell Systems

Immobilization can be highly effective for cell retention, but it comes at the expense of high volume-based activities, lower cell yields, and reduced tolerance to environmental extremes. One potential benefit of immobilizing microbes in cell carriers is enhanced cell retention and higher concentrations of active microbes, although this isn't possible with some microbe types. For slow growing and specialized pollutants degrading cells, immobilized systems may even be required for operation of certain technologies (Wadhawan et al., 2026; Moreno-Garrido, 2008).

For many technologies, especially some types of treatment reactors, a substantial advantage of immobilized cell systems is the improvement of cell recovery and reuse. For cells to be reusable in many different treatments, the recovery must be simplified and efficient, with no substantial reduction in cell viability, function, or structural stability. Cells may be trapped within carriers and may need to be recovered using techniques like centrifugation or membrane filtration. Another possible advantage of immobilization is more flexible reactor design. Reactors can have fixed bed arrangements, moving bed designs, and continuous-flow types (Hou et al., 2024). In most cases, these designs can help capture more space while retaining cell masses and helping systems combine with existing treatment designs. Immobilization technologies can help improve the potential of resource recovery and better water recycling. Biogas can be produced, nutrients and metal recovered, and there are many carrier technologies that are sustainable (Gadd et al., 2009; Volesky, 2007). Although there are multiple advantages of cell immobilization, immobilization does not guarantee maximum performance in all situations. For immobilization to be applied practically, the disadvantages, such as cell leakage, carrier deterioration, and prepare costs must be mitigated. Thus, immobilization cell systems must be thoroughly assessed and compared, particularly in regards to the efficient removal of pollutants, safety, cell carrier reuse, and operating costs.

3. METHODS OF PLANT-CELL IMMOBILIZATION

Plant cells have potential applications in wastewater treatment as immobilized biocatalysts because of their potential to adsorb and accumulate different wastewater pollutants and detoxify other toxic substances by intracellular accumulation and enzymatically mediated processes. Immobilized plant cells have been extensively studied, and many factors affect the performance of different system types. Many factors include the plant cell type and health, the carrier material, and the nature of the target pollutants. Principal immobilizing systems include entrapment, encapsulation, adsorption, covalent attachment, and aggregation (Cassidy et al., 1996; Moreno-Garrido, 2008).

3.1. Entrapment and Encapsulation

Entrapment involves using a polymer that allows the passage of nutrients and toxic substances, while also holding onto cellular metabolic products. To trap cells with this material, they are first added to sodium alginate and then introduced to a calcium chloride solution. This creates cell-laden beads. Agar, carrageenan, and several types of synthetic polymers can also be used. The advantage of using entrapment is that the cells can be protected from high concentration contaminants while still being available for harvest. However, use of too dense a material can prevent oxygen and nutrients from diffusing to the cells, and long term use can degrade the integrity of the material, swelling the matrix. As a result, both polymer concentration and cell loading must be studied for their impact on cell viability, and then optimally combined (Moreno-Garrido, 2008; Bustos-Terrones, 2024).

Figure 1, Illustration of entrapment and encapsulation polymeric matrices used for the treatment of wastewater via immobilization of plant cells. Encapsulation uses a polymeric matrix, or shell, to wrap cells within. Cell encapsulation can be accomplished with alginate-based hydrogels and other biocompatible polymers. The method can help preserve plant cells during the wastewater treatment process. Since cells can be repeatedly used, as long as they stay alive and encapsulated, cell harvesting is made easier. There are several challenges that must be addressed, such as matrix resistance to material transfer, membrane permeability, shell strength, and overall material and construction costs. Finally, the encapsulation matrix must allow the cells to retain their metabolism and provide nutrients.

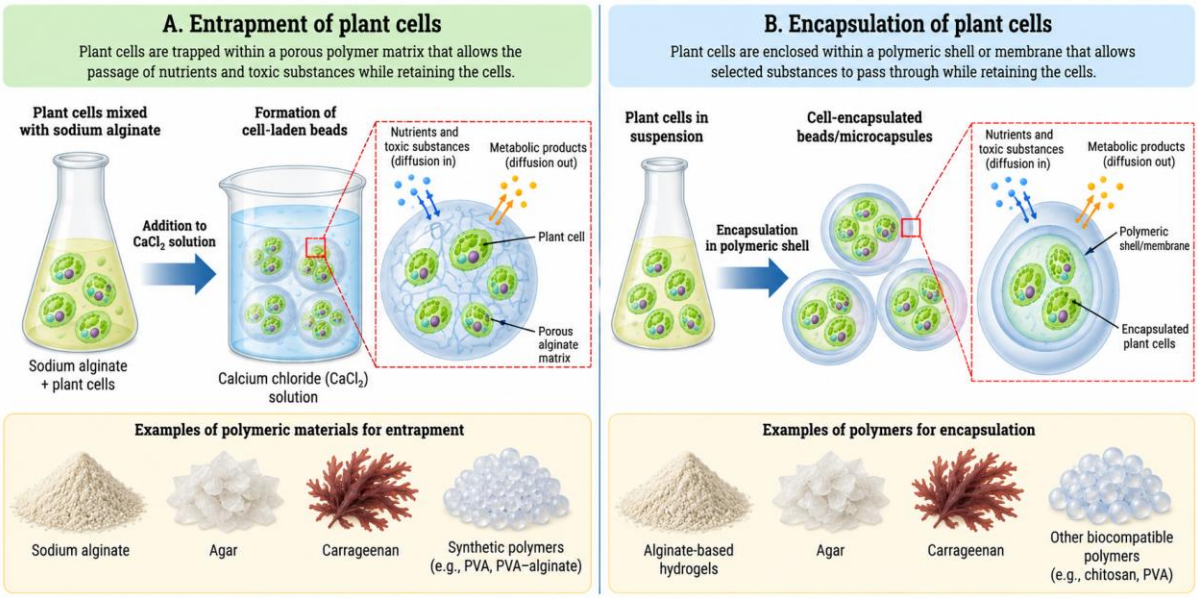

Figure 1: Schematic representation of plant-cell immobilization by entrapment and encapsulation using polymeric matrices for wastewater treatment.

3.2 Adsorption, Surface and Covalent Attachment

Adsorption-based cell immobilization involves the attachment of plant cells onto different surfaces with physical bonds such as electrostatic, hydrogen bonding, and hydrophobic bonding. For plant cell attachment, some examples of supportive material are porous ceramic, different forms of cellulose, and other forms of biocompatible materials. This technique is easy as it can skip the need for various chemical steps, or cell-supporting materials like different kinds of gel, while cell attachment also helps the contact of plant cells with pollutants in wastewater and supports biomass recovery. On the downside, cells can lose attachment because of weak binding under varying flow of wastewater. Therefore, consideration should be given to support materials based on the cell types to be immobilized and potential attachment of pollutants to the supporting materials. Different methods should be used to differentiate the role of supporting materials in pollutant removal (Leenen et al., 1996; Ghosh et al., 2019).

Unlike physical adsorption, covalent cell attachment can stronger bond cells to surfaces and helps with cells adhering even under harsh conditions. This chemical modification of carriers also introduces dangers for cells. Cells must first have the surface modifications carefully optimized so that their viability is not too significantly lowered. The process as a whole needs to be weighed against the additional cost and complexity of the process as well as its negative impacts on cell viability. **Figure 2** shows a comparison of adsorption-based immobilization and covalent attachment of plant cells on supporting materials.

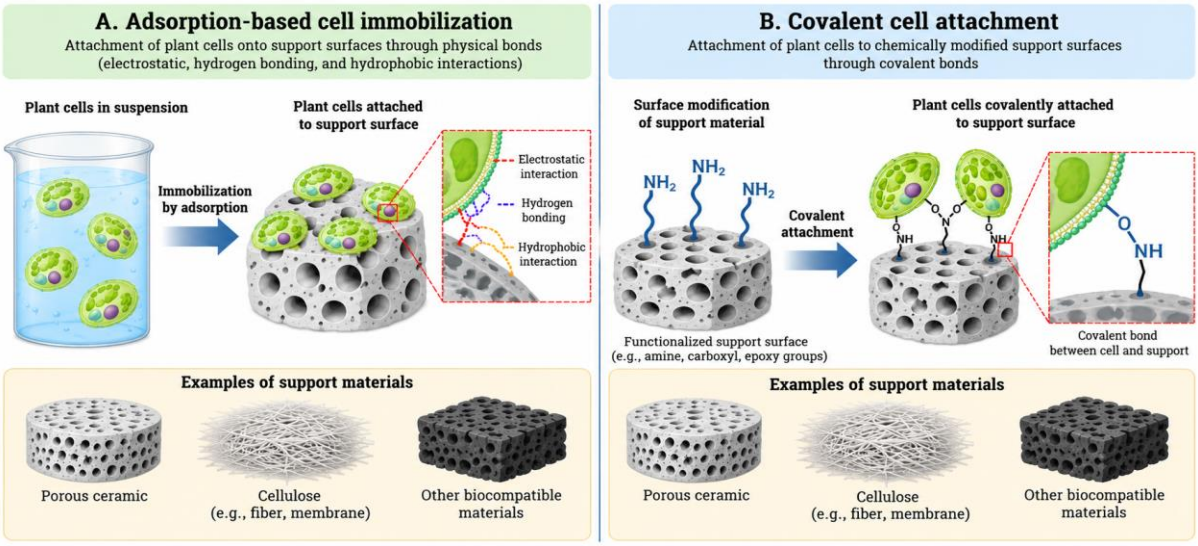

Figure 2: Comparison of adsorption-based immobilization and covalent attachment of plant cells on supporting materials.

3.3 Aggregation-Based Immobilization:

Plant cells can also be kept as aggregates or clusters within a reactor or other support. It's also common for plant-cell suspensions to consist of aggregates of many sizes and they may even be held inside porous carriers or specialized reactors. Using aggregation might help to easily capture cells with less trouble compared to using cell encapsulation. Although large aggregates can be troublesome in that there is a difference in oxygen, nutrients and pollution, reducing activity of cells located in the inner parts of the aggregates, this is often offset by the ability to capture cells more efficiently aggregate stability and resistance to shear forces must also be considered (Crini, et al., 2019; Leenen et al., 1996).

3.4 Selection of an Appropriate Immobilization Method

Selecting an immobilization technique relies on a variety of considerations, including plant species, target compound(s), effluent properties, and intended processing system. Both encapsulation and entrapment techniques offer cell protection and high levels of retention, while adsorption offers ease of implementation. In certain cases, more stringent retention, like that provided by covalent techniques, may be needed, although there is often a trade off in cell/reagent incompatibility. No immobilization technique is clearly superior. Research should evaluate cellular performance, pollutants degradation, mass-transport, carrier sustainability, regeneration, and economically feasible methods in typical wastewater. Prior to scale-up, safe storage, and final disposal of biomass loaded with pollutants must also be assessed (Crini, et al., 2019).

4. MECHANISMS OF POLLUTANT REMOVAL

Removal of pollutants by immobilized plant cells is done through processes involving both physical and biological activities. It incorporates both bio and non-bio based sorption, ion exchange, accumulation, sequestration inside cells, and cellular metabolism using enzymes. It depends on several variables such as plant species, cell viability, type of immobilization, pollutants, and operational conditions. Further, processes of mass transport determine the extent of contamination to reach both surfaces of the cells as well as systems inside. Optimal treatment performance of technologies using plant cell suspensions can only be accomplished once the different types of cell based processes are clearly understood (Yaashikaa et al., 2022; Radoor et al., 2024).

4.1 Biosorption and ion exchange

Biosorption is a physicochemical process involving the passive binding of pollutants to biological materials through interactions between contaminants and functional groups present on plant cell surfaces. Plant cell walls contain cellulose, hemicellulose, pectin, and other structural components bearing functional groups, particularly hydroxyl and carboxyl groups, that can interact with dissolved metal ions and selected organic compounds. Depending on the chemical properties of the pollutant and the surrounding medium, these interactions may involve electrostatic attraction, surface complexation, hydrogen bonding, and ion exchange. Biosorption can occur in both living and non-living plant biomass and does not necessarily require metabolic energy (Wang & Chen, 2009).

Ion exchange is particularly relevant to the removal of metal ions from wastewater. During this process, metal ions replace counterions associated with functional groups on the plant cell surface, facilitating their transfer from the aqueous phase to the biological material. The efficiency of this mechanism depends on solution pH, ionic strength, metal speciation, and the presence of competing ions. Immobilization can improve the practical application of biosorption by facilitating biomass recovery, reducing cell washout, and enabling repeated treatment cycles. However, the supporting matrix may also contribute to pollutant binding or introduce additional diffusion resistance. Consequently, the contributions of the plant cells and immobilization material should be considered separately when evaluating treatment performance (Wang & Chen, 2009; Radoor et al., 2024).

4.2 Enzymatic transformation

Enzymatic transformation involves the conversion of contaminants into chemically different products through reactions catalysed by enzymes present in plant cells. Depending on the substrate and the metabolic capabilities of the selected plant material, enzymatic reactions may include oxidation, reduction, hydrolysis, and conjugation. These processes can alter the chemical structure, solubility, mobility, or biological activity of selected organic pollutants. Certain phenolic compounds, synthetic dyes, and pharmaceutical contaminants may undergo biological transformation under suitable conditions. However, the efficiency and pathways of these reactions are compound-specific and depend on enzyme activity, pollutant accessibility, temperature, pH, and cellular viability. Immobilization may improve the operational retention of biological material, although diffusion resistance within the supporting matrix can limit the accessibility of contaminants to active cellular systems (Radoor et al., 2024; Yaashikaa et al., 2022). **Figure 3,** shows Mechanisms of enzymatic transformation of wastewater contaminants by immobilized plant cells.

An important consideration is that the disappearance of a parent contaminant does not necessarily demonstrate complete degradation or detoxification. Transformation products may remain in the treated water and may possess biological activities different from those of the original compounds. Therefore, reliable evaluation requires chemical identification of transformation products, appropriate mass-balance assessment, and toxicity testing. Research on enzyme-mediated wastewater remediation similarly identifies operational

stability, mass-transfer limitations, and the environmental assessment of transformation products as important considerations (Bilal et al., 2019; Yaashikaa et al., 2022).

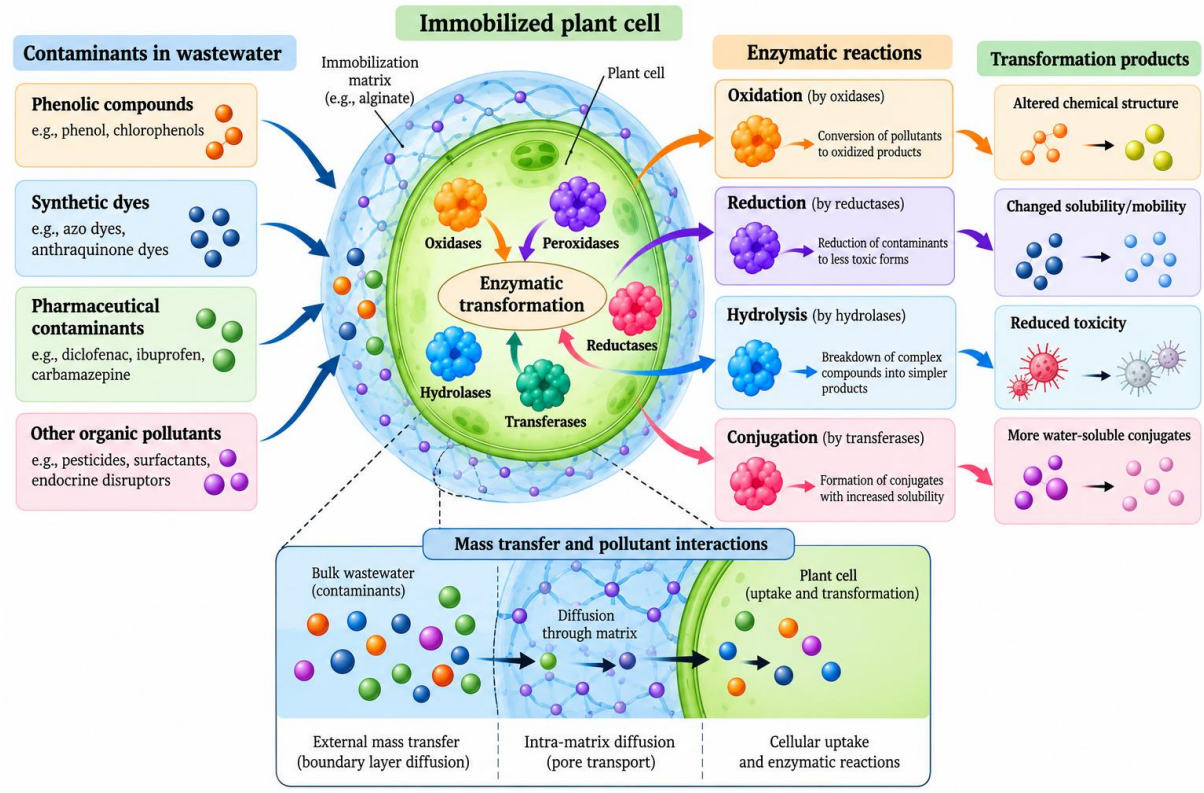

Figure 3: Mechanisms of enzymatic transformation of wastewater contaminants by immobilized plant cells.

4.3 Mass transfer and pollutant interactions

Mass transfer governs the movement of contaminants from bulk wastewater to active sites within an immobilized system. The process generally involves transport through the surrounding liquid boundary layer, diffusion across the immobilization matrix, and interaction with cellular surfaces or intracellular metabolic systems. For living plant cells, membrane transport may subsequently be required for intracellular sequestration or enzymatic transformation. Mass-transfer efficiency depends on matrix porosity, bead dimensions, cross-linking density, agitation, hydraulic conditions, and pollutant characteristics (Radoor et al., 2024; Ghosh et al., 2026).

Interactions among pollutants and the surrounding wastewater matrix can further influence treatment efficiency. Dissolved organic matter, salts, and competing contaminants may occupy binding sites, modify surface charge, or alter contaminant availability. Changes in pH and ionic strength can also influence functional-group ionization and pollutant speciation. These effects are especially important in real wastewater, where multiple contaminants coexist. Optimizing mass transfer requires balancing matrix stability, cell retention, and the accessibility of active sites. Appropriate particle dimensions, immobilization materials, reactor configurations, and hydraulic retention times should be selected according to the target pollutant and treatment objectives. Integrating mass-transfer analysis with chemical measurements and biological activity assessments can help distinguish diffusion limitations from insufficient adsorption capacity or reduced cellular activity (Radoor et al., 2024; Yaashikaa et al., 2022).

5. APPLICATIONS OF IMMOBILIZED PLANT CELLS IN WASTEWATER TREATMENT

Plant cell immobilization is an emerging biotechnological approach for wastewater remediation that combines the biological properties of plant cells with the operational advantages of supporting materials. Immobilized plant cells can facilitate the removal of selected contaminants through biosorption, bioaccumulation, enzymatic transformation, and nutrient assimilation. Common immobilization materials, including calcium alginate, agar, and carrageenan, and cellulose-based polymers, can retain biomass within treatment systems and facilitate its recovery. The potential applications of this technology include heavy metal removal, synthetic dye treatment, organic pollutant remediation, and the treatment of pharmaceutical contaminants. However, treatment efficiency depends on the plant species, immobilization matrix, pollutant characteristics, and operating conditions (Fomina et al., 2014; Ahluwalia, et al., 2007).

5.1 Heavy Metal Removal

Heavy metal contamination is caused by many industries, including electroplating, mining, battery production, and others. Many heavy metals such as cadmium, lead, nickel, and copper are durable and cause health issues to humans, and ecological disruption. With immobilization, plant cells have been known to biosorb and bioaccumulate metal. For biosorption, functional groups on plant cell walls such as carboxyl, and hydroxyl, help the immobilization matrix bond metal ions. On the other hand, bioaccumulation relies on biological processes within living cells to retain and take up metal ions (Mukherjee et al., 2022). Although polymer-based matrices can accommodate and keep plant cells active, there are several things that can affect how well they perform. This includes pH, the metal concentrations, the amount of metal that competitor cells use up, the pore sizes of the matrix, and how well plant cells survive in the environment. A noteworthy thing is that because metals cannot be decomposed, you have to find some way to regenerate the cells or dispose of the metals safely. This means that researchers must find some way to measure biological uptake and bio adsorption separately from the absorption that occurs within the matrix material (Fomina et al., 2014; Ahluwalia, et al., 2007).

5.2 Removal of Synthetic Dyes

A broad range of synthetic dyes are utilized in numerous industries such as the textile, leather, paper and printing, among others. Due to this, these synthetic dyes have the potential to pose great danger to different environments if discharged as untreated wastes into bodies of water, primarily through the limitation of light, and the effect it has on aquatic life and the introduction of pollutants into the water. There are several different aspects that are involved in the overall adsorption process and the combination of different variables like the dyes and different plant cell structures determines the overall degradation process of dyes through the use of plant cells. For example, different matrices and composite polymers are being investigated for different uses, particularly as a way to hold plant cells for various reasons. For plant cell applications, many different types of polymers have the capability of being used in plant cell retention.

In particular, both calcium alginate and composite polymer matrices are good options as far as holding plant cells (Konar et al., 2026; Wang et al., 2009). These different options have some benefit, such as different levels of performance as well as various levels of cost efficiency. Of course, each individual matrix can only do so much and if too many different things are going on than even the most effective of the matrices could break down. Some of the most extreme cases could even mean that the plant cells would be affected. The adsorption or transformation of dyes, such as when they are adsorbed by some materials, doesn't mean that the dye molecules have been totally broken down, as it can just mean that the visible colour has been altered. This includes checking for the presence of the original dye and any possible newly formed compound as well as the concentration of total organic carbon in the wastewater. Measuring any potential toxicity to plants can provide more clarity on whether the process used to treat wastewater, such as immobilised plant cells, really did something positive for the quality of wastewater (Wang et al., 2009). **Figure 4,** shows mechanism of Synthetic Dye Removal from Wastewater Using Immobilized Plant Cells: Adsorption, Biotransformation, and Environmental Toxicity Assessment.

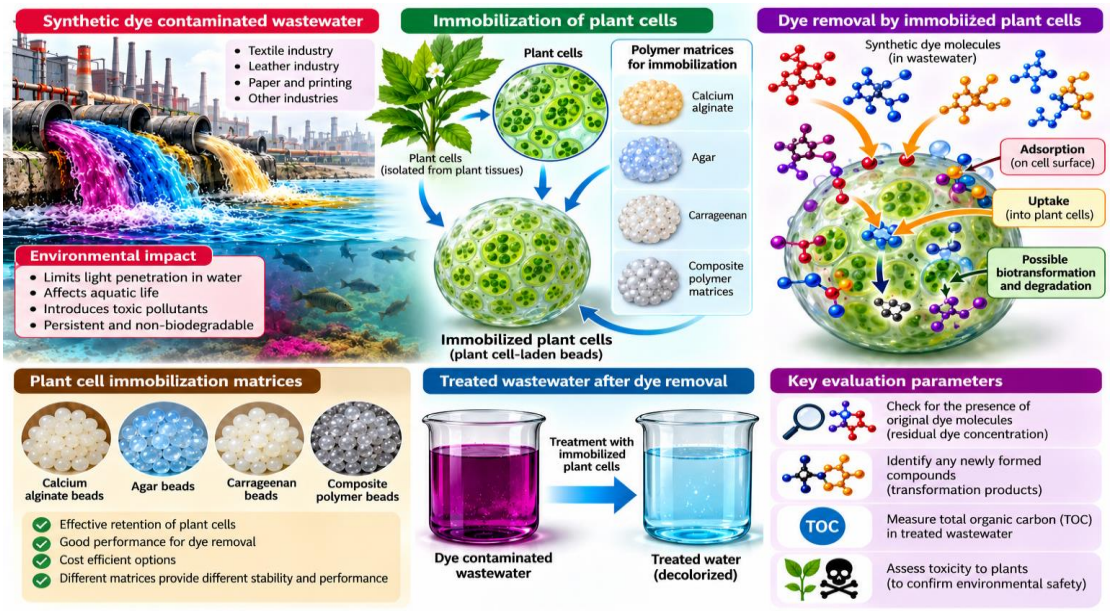

Figure 4: Mechanism of Synthetic Dye Removal from Wastewater Using Immobilized Plant Cells: Adsorption, Biotransformation, and Environmental Toxicity Assessment.

5.3 Removal of Organic Pollutants

Wastewater from industries and agricultural practices can be loaded with organic pollutants, including phenolic compounds, pesticides and herbicides. Some pollutants are very resistant to conventional methods of biological treatment and can remain active and toxic. Cells from plants that are trapped on a matrix, such as agar, can aid in the elimination of particular types of organic pollutants. This can happen by adsorption, through cellular uptake, or via enzymatic action. Many plant cell types have processes for altering organic compounds through reactions of reduction, oxidation, hydrolysis and conjugation. Being trapped helps cells maintain their mass and can allow for the development of experiments that investigate cellular reactions in a well-defined setting (Pantha, et al., 2025; Wang et al., 2009). Some cells can have their metabolism impaired by some pollutants, and some cells cannot transform certain pollutants. In some cases, the immobilization matrix, which is used to traps the cells, may bind organic pollutants independent of the trapped cells. In combination with other treatment processes, such as the use of other types of biomass or different methods, immobilized plant cells could have an additive effect in the elimination of certain types of pollution, particularly mixtures of pollutants. But the usefulness of such treatment combinations must be determined under actual wastewater treatment conditions (Hai et al., 2007; Wang et al., 2009).

5.4 Pharmaceutical Contaminant Treatment

Pharmaceutical residues are becoming known as dangerous contaminants in water systems. This includes municipal, hospital and manufacturing systems, as well as discharge systems. Treatment systems leave antibiotics, pain relievers and other types of drugs, which can remain and enter ecosystems, causing exposure to wildlife, and leading to antimicrobial resistance, which is an important threat to public health. There is the potential for research on plant cell immobilization systems to find ways to remove pharmaceutical contaminants from wastewater. This depends on both the type of plant cell as well as the pharmaceutical contaminant, but plant cell immobilization offers a variety of means of removal, such as the absorption and accumulation of compounds by plant cells, or the breakdown of pharmaceuticals by the enzymes produced by plant cells. Furthermore, plant cells that are immobilized are easy to capture and reclaim (Pantha, et al., 2025).

Although plant cells can immobilize some drugs, the efficacy of each drug is specific. The ability of plant cells to absorb one drug cannot be generalized to absorb others. There are other limitations such as very low concentrations of drugs in wastewater, and competing waste water components. The unknown breakdown pathways of different drugs also present some challenges. Different studies that aim to address environmental levels of pharmaceutical pollution must investigate the potential environmental effects of each drug individually and of combinations of drugs in Realistic environmental concentrations. Techniques such as high performance liquid chromatography (HPLC) and liquid chromatography mass spectrometry (LCMS) are useful for investigating parental drugs and their breakdown products, while toxicity studies can clarify the environmental effects of various processes for pharmaceutical wastewater treatment (Khasawneh et al., 2021; Tapera, et al., 2026). Using immobilized plant cells as a method of removing pharmaceuticals from wastewater can offer more advantages over the current processes, but more safety, piloting, and mechanistic studies must be done before widespread adoption (Tapera, et al., 2026). **Table 1**, Major Applications, Removal Mechanisms, and Challenges of Immobilized Plant Cells in Wastewater Treatment.

Table 1: Major Applications, Removal Mechanisms, and Challenges of Immobilized Plant Cells in Wastewater Treatment.

Application	Target pollutants	Removal mechanisms	Major challenges
Heavy metal removal	Cadmium, lead, nickel, copper	Biosorption and bioaccumulation	Metal toxicity, competing ions, and safe disposal
Synthetic dye removal	Textile, leather, and paper dyes	Adsorption and enzymatic transformation	Incomplete degradation and toxic intermediates
Pharmaceutical treatment	Antibiotics, analgesics, anti-inflammatory drugs	Biosorption, cellular uptake, and potential biotransformation	Compound-specific removal and unknown transformation products
Integrated treatment	Mixed industrial and pharmaceutical contaminants	Combined biological and physicochemical processes	Process compatibility and variable treatment efficiency
Organic pollutant removal	Phenols, pesticides, herbicides	Biosorption, cellular uptake, and enzymatic transformation	Cellular toxicity and limited degradation capacity

6. CHALLENGES AND LIMITATIONS

Even though it holds great promise for sustainable wastewater treatment, plant cell immobilization faces a variety of technological, biological and economical constraints, most of which might even curtail the possibilities of industrial utilization. If the immobilization matrix has dense polymer networks and large beads, then the pollutant and nutrient accessibility to the cells decreases, and in turn, the treatment efficiency (Wang & Chen, 2009). There is the constant struggle of sustaining the cellular viability and metabolic activity of plant cells in wastewater. Pollutants like heavy metals and persistent synthetic dyes can be toxic to the plant cells and create an imbalance within the plant cells' metabolism. Therefore, the efficacy of the wastewater treatment using plant cells depends on the type of plant species used, the concentrations of pollutants, pH levels, temperature, and nutrient availability.

Another factor impacting treatment effectiveness is the stability and durability of the immobilization matrices. For example, some natural polymers such as alginate are susceptible to swelling and structural degradation, which causes cell leaching. This reduces treatment effectiveness and requires regular treatment. Repeated use of the same material leads to further degradation of the adsorption or metabolic properties of the cells and the material must be replaced or regenerated (Yaashikaa et al., 2022). Pollutant-loaded biomass is an issue in the design and construction of wastewater treatment systems. In addition, the safe disposal of recovered persistent organic compounds and accumulated heavy metals must be considered. Moreover, transformation of a pollutant may occur and result in compounds that are more toxic than the original compound. In this case, an additional step to analyse the products of the transformation and assess toxicity must be included in the design. Finally, the economics and technological issues surrounding immobilization must be fully addressed (Wang & Chen, 2009; Yaashikaa et al., 2022).

7. FUTURE PERSPECTIVES

Future research on plant cell immobilization must focus on the development of low cost, environmentally friendly wastewater treatment technologies. In this context, improvements to matrix systems in terms of biocompatibility and mechanical strength may aid cellular activities. Pollutant accessibility and cell activities are also to treatment effectiveness. Use of biopolymers or composite matrices has the potential to minimize the negative impacts of treatment on the environment. The optimum operational performance of immobilized cell systems is related to bead size, polymer concentration, cell loading, and the conditions used for cross-linking (Radoor et al., 2024).

Integrating immobilized cells with complementary wastewater treatment technologies may also be a worthwhile area for research. Adsorption, membrane filtration, or other types of oxidation technologies may enhance treatment processes of mixed pollutants including persistent organic pollutants and various drugs and medicines. Hybrid treatment systems using immobilised cells can also use treatment processes that optimize pollutant contacting, biomass retention and continuous processes (Yaashikaa et al., 2022). With the advent of high-resolution analytical technologies, researchers can investigate the mechanisms underlying pollutant removal. With the integration of metabolite and enzyme analysis, along with advanced analytical techniques, the potential pathways and products of pollutant degradation can be determined. These tools will enable the identification and use of plants and cell cultures that are both resilient and able to tolerate the pollutants in the wastewater. One of the main things researchers should consider is the way in which cells remove pollutants through both adsorption and metabolism, and should differentiate between them (Yaashikaa et al., 2022; Radoor et al., 2024).

8. CONCLUSION

Cell immobilization technology is one method of advancing wastewater treatment by improving biomass retention and operational stability, as well as enabling reuse of active materials. With this technology, different microbes or plant cells can be immobilized to treat various contaminants such as heavy metals, dyes, organic pollutants, and pharmaceuticals. Techniques and materials used in cell immobilization will dictate the overall system's performance, but cells with the correct biology, combined with efficient immobilization and appropriate supporting materials and operational parameters, will lead to a more successful removal system. Alginate, chitosan, and other natural polymers have low cost and are abundant and available.

However, their use in industrial scale pollutant treatment still has many challenges, most importantly their mass transfer limitations. Pollutants should be distinguished from pollutants fully transformed. While biosorption and partial transformation are valuable, the products must be assessed to determine the potential risk they may pose. Additionally, after a pollutant treatment system has been implemented, it must be ensured that the biosorbents, transformed pollutants, and treated biomass do not cause pollution in the environment. Research on pollutant treatment using cell immobilization technology must focus on the design of robust and sustainable matrices at a large scale, while considering integrated treatment systems at an operational level. Furthermore, fundamental mechanisms of the pollutant removal systems must be understood, as well as the practicality and the economics of the system, including the system's ability to be recycled. Future research should be geared towards systems that facilitate pollutant removal and nutrient and material recovery while considering the system's environmental footprint.

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Conflict of interest
The author declares no conflict of interest.

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