# Biomaterials for Sustainable Water Treatment: A Review of Modification Strategies and Removal Mechanisms

**Monika Yadav, Deeksha Ranjan, Saloni Singh**

Department of Applied Sciences and Humanities (Environmental Science), Faculty of Engineering and Technology,
Rama University, Kanpur 209217

## Abstract:

Water pollution is a major global challenge demanding innovative and sustainable solutions. Biomaterials, with their inherent advantages, offer a promising alternative to conventional water treatment methods. This review explores the potential of modified biomaterials for water pollutant removal. We discuss various modification strategies such as surface modification, porosity control, functionalization, and composite formation, explaining how they enhance the interaction between biomaterials and pollutants. The primary removal mechanisms, including adsorption, chelation, and size exclusion have been addressed. Additionally, the review explores biodegradation, a unique advantage offered by biomaterials derived from living organisms, and its role in achieving complete pollutant removal. This review underlines the exciting potential of biomaterials in addressing the global water pollution crisis and paving the way for a cleaner future.

Keywords: Biomaterial, Adsorption, Biodegradation, Pollution

## 1. Introduction:

Biomaterials are a fascinating class of materials designed to interact with biological systems for a specific purpose, most commonly in a medical context [1]. These engineered materials can be used to address medical conditions by delivering drugs, promoting tissue regeneration, or aiding in wound healing. Enhance or replace damaged tissues or organs with artificial implants like artificial joints or stents. Facilitate the repair of damaged tissues using scaffolds that guide cell growth and tissue formation. Assist in medical diagnosis through the creation of biosensors or imaging contrast agents.

Biomaterials come in a variety of forms, broadly classified by their origin such as **Metals and Alloys:** Stainless steel, titanium alloys, and nitinol are some examples used in implants due to their strength, durability, and biocompatibility (ability to coexist with living tissue without causing harm). **Ceramics and Glasses:** Biocompatible ceramics like hydroxyapatite (a component of bone) are ideal for bone replacements due to their similarity to natural bone tissue. Bioactive glasses can even stimulate bone growth. **Polymers:** Natural polymers like collagen (a major component of skin) and synthetic polymers like polyethylene (used in heart valves) offer versatility and can be tailored for specific applications [2]. Biodegradable polymers are particularly useful for temporary implants or scaffolds that degrade as the body heals.

The success of a biomaterial hinges on several key properties like **Biocompatibility:** the material shouldn't trigger an adverse immune response or harm surrounding tissues. **Bioactivity:** Some materials can actively interact with living tissue, promoting cell adhesion, growth, and differentiation (specialization into different cell types). **Mechanical Properties:** The material's strength, elasticity, and wear resistance must be suitable for its intended function. For example, a bone replacement needs to withstand significant loads. **Surface Properties:** The surface characteristics like roughness and topography can influence how cells interact with the material.

Biomaterials are proving to be a promising alternative for water treatment due to several advantages. Many biomaterials are derived from natural resources like agricultural waste, making them a sustainable choice compared to traditional methods. They generally pose minimal risk to the environment and human health. Utilization of abundant and often waste materials can lead to lower treatment costs. Biomaterials usually have a high surface area and functional groups that can effectively capture pollutants through adsorption. Agricultural Waste like Rice husk, straw, and other agricultural byproducts can be modified to remove heavy metals and organic contaminants [3]. Natural Polymers such as Chitosan, derived from chitin (a component of crustacean shells), is a popular biomaterial for removing dyes, heavy metals, and other pollutants [4]. Live or processed biomass from these organisms can capture pollutants through biosorption and bioaccumulation mechanisms [5]. Biomaterials offer an eco-friendly and potentially cost-effective solution for water treatment at various scales, from centralized plants to household filters. They can be particularly effective in removing specific pollutants like heavy metals, dyes, and organic contaminants.

## 2. Modification strategies:

Biomaterials offer a promising and sustainable approach for water treatment due to their inherent properties. However, to maximize their pollutant removal efficiency, various modification strategies can be employed.

i. **Surface Modification:** This approach involves altering the surface chemistry of the biomaterial to enhance its interaction with pollutants. Techniques like **Chemical Treatment:** Using acids or bases to alter surface charge and create functional groups that attract specific pollutants [1]. (e.g., introducing amine groups for heavy metal removal) and **Grafting:** Attaching specific molecules (ligands) to the biomaterial surface that have a high affinity for target pollutants [2]. (e.g., grafting thiols for mercury removal) have been extensively utilized and reported by researchers [6].

ii. **Porosity Control:** Modifying the pore size and distribution within the biomaterial can significantly impact its pollutant capture capacity. Increased porosity allows for deeper penetration of pollutants into the biomaterial, leading to higher adsorption capacity. Techniques involve creating pores using controlled chemical reactions and utilizing heat to modify pore structure [7].

iii. **Functionalization:** This strategy involves introducing specific functional groups onto the biomaterial surface that can directly bind pollutants through mechanisms like chelation (complex formation) or electrostatic interactions. Functionalization allows for targeted removal of specific pollutants. Such as introducing thiol groups for heavy metal removal attaching imine groups for organic contaminant capture [8].

iv. **Composite Formation:** Combining biomaterials with other materials like inorganic nanoparticles or synthetic polymers can create synergistic effects for enhanced performance. Advantages includes increased surface area for adsorption, improved mechanical strength and stability, introduction of additional functionalities for broader pollutant targeting [9].

## 3. Mechanism of Pollutant removal:

Modified biomaterials for water treatment primarily remove pollutants through a combination of physical and chemical mechanisms. Some of highly investigated mechanisms have been discussed below:

i. **Adsorption:** This is the dominant mechanism for most modified biomaterials. Modified surfaces with high affinity functional groups create attractive sites for pollutants to bind through: **Van der Waals forces:** Weak attractive forces between molecules. **Hydrogen bonding:** Formation of a specific type of intermolecular bond between the biomaterial and pollutant. **Electrostatic interactions:** Attraction between oppositely charged biomaterial surfaces and pollutants [10]. The most practical, affordable, and simple technique for removing colors from aqueous solutions is adsorption. A wide range of adsorbents, including agricultural wastes, seaweeds and bioadsorbents have been reported by researchers to date in relation to the removal of contaminants from wastewater [11, 12].

ii. **Chelation:** This mechanism is particularly effective for removing heavy metals. Certain modifications introduce functional groups (e.g., thiol groups) that form strong complexes (chelates) with metal ions, effectively capturing them from the water [13].

iii. **Size Exclusion:** For biomaterials with well-defined pore structures, size exclusion can play a role. Modified biomaterials with controlled porosity can act like filters, allowing water molecules to pass through while larger pollutant molecules become trapped within the pores [14].

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v. **Biodegradation:** Some biomaterials, particularly those derived from living organisms (e.g., algae, bacteria), can degrade certain pollutants through enzymatic processes. The specific details vary depending on the organism and pollutant, but the general process involves **Biosorption:** The pollutant first comes into contact with the surface of the live biomaterial and gets adsorbed. **Enzymatic Breakdown:** Enzymes secreted by the organism break down the complex pollutant molecules into smaller, simpler units. **Metabolic Utilization:** The breakdown products are then taken up by the organism and used as a source of energy and nutrients. Species like Chlorella vulgaris have been shown to degrade phenolic compounds present in industrial wastewater. Pseudomonas sp. bacteria can degrade various petroleum hydrocarbons, making them useful for bioremediation of oil spills [16, 17].

## 4. Conclusions:

The ever-growing concern over water pollution necessitates the development of efficient and sustainable treatment solutions. Biomaterials, with their inherent renewability, biocompatibility, and tunability, present a promising alternative to conventional methods. This review explored various modification strategies for biomaterials, including surface modification, porosity control, functionalization, and composite formation. These modifications enhance the interaction between biomaterials and pollutants, leading to improved removal efficiency through mechanisms like adsorption, chelation, and size exclusion. For specific cases, biomaterials derived from living organisms offer an additional advantage: biodegradation. Overall, biomaterials offer a versatile and sustainable approach to water treatment. By optimizing modification strategies and exploring the potential of biodegradation from living organisms, scientists can create tailored solutions for removing a wide range of pollutants from water. Biomaterials research is a rapidly evolving field with continuous advancements. From developing smart materials that respond to biological cues to creating 3D-printed scaffolds for complex tissue engineering, biomaterials hold immense potential for revolutionizing healthcare. Further research is crucial to address existing challenges and ensure the large-scale, cost-effective application of these promising biomaterials for a cleaner and healthier future.

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