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Review JoPC

Harnessing Natural Materials for Enhanced Properties and Environmental Remediation in Biosorption of Polymer Composites

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Abstract

Polymer mixtures are useful materials that are used in many fields because they have special qualities. But worries about how they affect the environment and the need for long-lasting options have made people interested in using natural materials to improve the qualities of composites and clean up the environment. This study looks into how biosorption, a natural process by which organic materials take in pollution from the environment, could be used to make polymer mixtures better at what they do and how well they work with the environment. The paper focus on the problems that polymer composites cause for the environment, mainly the fact that they don't break down naturally and can release dangerous chemicals into the environment when they are made, used, or thrown away. This part stresses how important it is to find long-term answers to these environmental problems right away. In paper discuss biosorption is introduced as a possible way to make polymer mixtures better at working with the environment. Biosorption is a cheap and environmentally friendly way to clean up water and air by using naturally occurring biomaterials like bacteria, fungi, algae, and other microorganisms. In the paper new developments in adding biosorption materials to polymer composites. Researchers have successfully added bio-based adsorbents to composite matrices using new production methods like electrospinning and solution casting. This has led to materials that are stronger and better at removing pollutants. Finally, the study ends with a talk of where biosorption-based polymer composites are going and what problems they might face in the future. Researchers can keep making sustainable composite materials that are better for the environment and can be used in more fields by using the special qualities of natural materials, like their large surface area, porosity, and selection.

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INTRODUCTION

Polymer composites are high-tech materials made up of at least two separate parts: a polymer core and strengthening fillers, which are usually fibers, particles, or flakes. People in many different businesses want these blends because they have a mix of qualities that can't be achieved with separate parts. The polymer core makes the material flexible, easy to work with, and resistant to rust. The strengthening fillers make the material stronger, stiffer, and more stable at high temperatures [1]. This working together makes materials that are very light but have great performance traits, like high strength-to-weight ratios, resistance to wear, and steadiness in their dimensions. Polymer composites are popular in aircraft because they can reduce weight without affecting the strength of the structure. This means that they use less fuel and produce fewer emissions. When it comes to making cars, plastics can help make them lighter, which improves their speed and drives up gas mileage. Polymer composites are also used in market goods, sports equipment, infrastructure, and the water industry [2]. This shows how versatile they are across many fields. But the widespread use of polymer mixtures has made people worry about how they affect the environment. Traditional composites, which are often made from resources that can't be replaced and are hard to recover, can add to the trash and resource loss. In addition, the methods used to make polymer blends may release toxins and pollution, which makes environmental problems even worse. Composites have changed the way engineers work in fields like aircraft and cars. They offer a level of speed and efficiency that is unmatched by standard materials. Even though polymer composites have a lot of great benefits, they also pose big environmental problems. For example, they don't break down naturally and could release dangerous chemicals into the environment at any point in their lifetime, from production to removal. Sustainability and environmental duty are becoming more and more important to people. Because of this, we need to find new materials and ways to make things that leave less of an impact on the environment while keeping or even improving function [3]. Using natural materials to improve qualities and clean up the environment is a hopeful way to deal with the climate issues that come up with polymer composites. Natural materials come from things that can be grown again and again, like plants, algae, bacteria, and fungus. They naturally break down, have a low effect on the environment, and could be used in environmentally friendly ways of making things. Among the many ways to use natural materials, biosorption stands out as an especially interesting way to make polymer mixtures better at dealing with environmental issues. This figure 1 illustrates the biosorption experiment process using biopolymer noncomposite material, detailing the interaction between the biopolymer and contaminants. It showcases the steps involved, highlighting the material's effectiveness in removing pollutants from aqueous solutions.

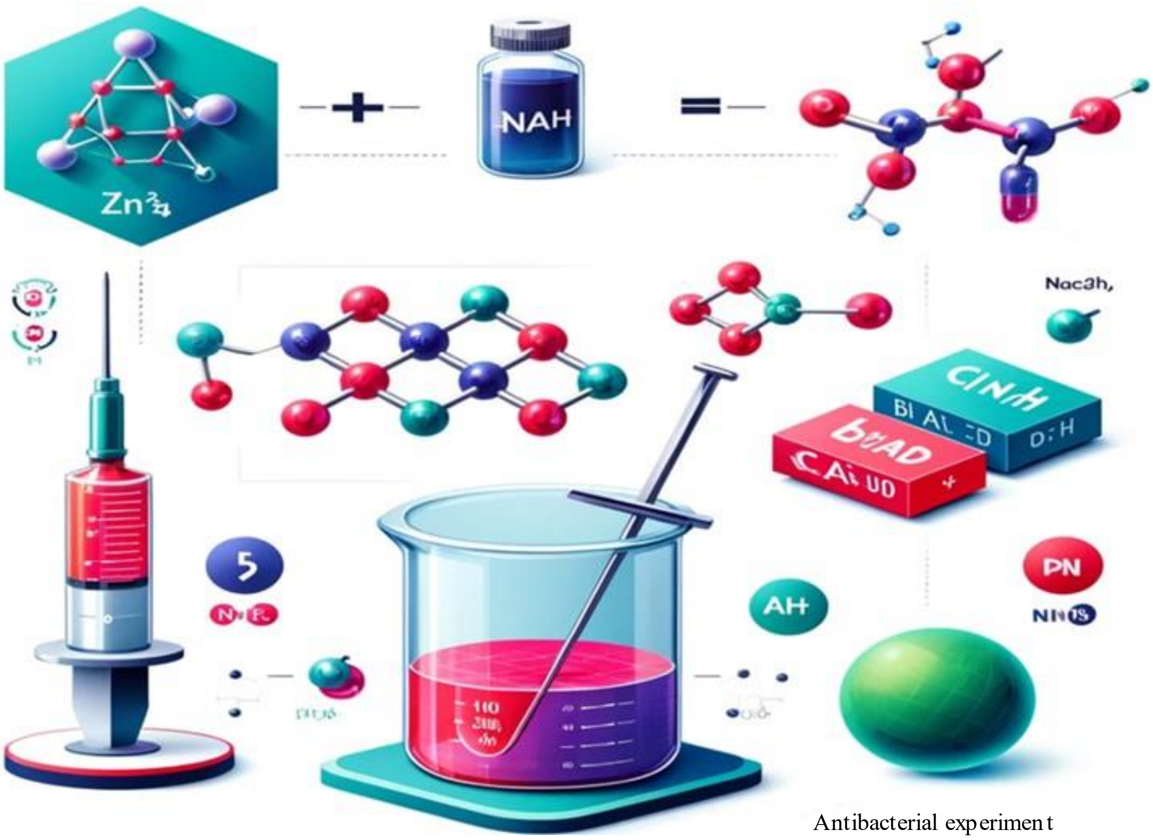

Figure 1. Representation of Biopolymer Noncomposite material for biosorption experiment process.

The process of biosorption is when organic materials, like bacteria or their products, take in pollution from the air and store it on their surfaces or inside their bodies. This process takes place naturally in many different environments, and it has been studied a lot in terms of how it could be used to clean up the environment, including to clean the air and water. Researchers are trying to use the special qualities of biosorbent materials to make hybrid materials that can not only survive mechanical loads but also remove pollution from their surroundings [4]. Figure 2 illustrates the experimental process for biosorption using biopolymer noncomposite materials, depicting stages from adsorption to analysis. This would reduce the damage that industrial activities do to the environment. More than just being able to soak up pollution, natural materials are important for cleaning up the world. By following the ideas of biomimicry and the cycle economy, these materials offer a complete solution to sustainability. Biosorption-based polymer composites could help protect environments by using green resources and mimicking natural processes. This would mean using fewer nonrenewable materials and making less trash [5]. In addition, adding natural materials to polymer mixtures can improve the qualities of the materials in ways other than cleaning up the surroundings. Many natural materials have special qualities, like a lot of surface area, pores, and selection, that can make composite materials better in many ways, such as making them stronger, more stable at high temperatures, and better at working with living things. Scientists can change the tiny structure and make-up of biosorption-based polymer composites to fit specific needs in a lot of different situations by using new ways to make them, like electrospinning and solution casting.

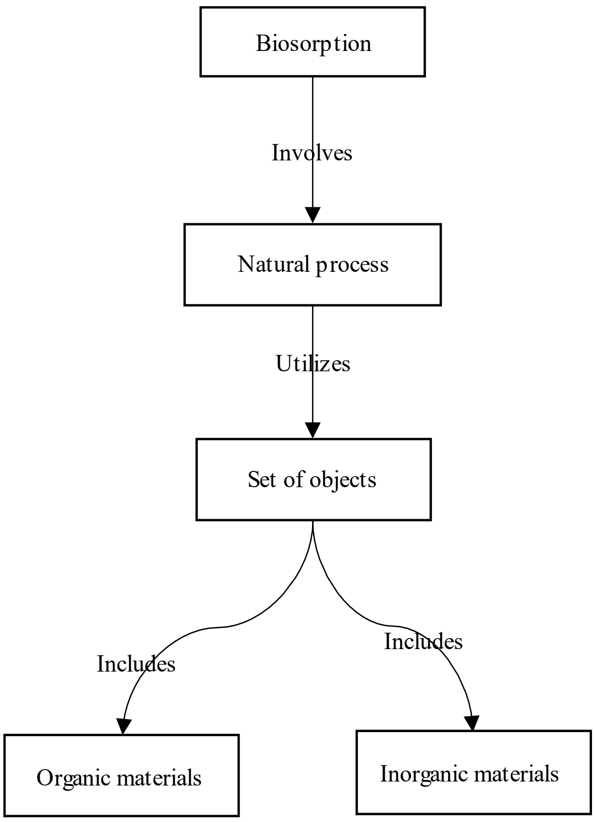

Figure 2. Steps for the biosorption process.

Many different fields are working together to make biosorption-based polymer composites. These fields include materials science, environmental engineering, biology, and ecology. Researchers, people in the business, and lawmakers must work together to spur innovation, solve technical problems, and speed up the use of environmentally friendly materials and technologies. In this, we look at how using natural materials could improve the qualities of polymer mixtures and help clean up the world. First, we give an outline of polymer composites and how important they are in modern businesses [6]. Then, we look at the environmental problems that these materials cause. Then we talk about how biosorption works and what natural things do in this process. Then, discuss about new developments in adding biosorption materials to polymer composites and how they might be able to improve both their dynamic features and how well they work in the environment. We end by talking about the difficulties and goals for the future in this field that is changing so quickly. We stress how important it is for materials science and engineering to use sustainable innovation.

Biosorption is a natural process, shown in Figure 2 that could help clean up the environment by using living things to take pollutants from the air, water, and dirt. Microorganisms, including algae, bacteria, fungi, and their forms, have natural abilities that let them take in pollution and store them on their surfaces or inside their bodies. This process is very successful, doesn't cost much, and is safe for the environment, which makes it a good option to traditional ways of cleaning up pollution. Biosorption-based technologies have been used successfully in many fields, such as cleaning the air, treating wastewater, and fixing up damaged soil. Biosorption is an environmentally friendly way to protect environments and reduce waste that works by using the power of nature. It helps protect both human health and the environment. New biosorption materials and methods are still being looked into by researchers around the world. This is leading to new ideas in environmental cleanup and sustainability efforts around the world.

RELATED WORK

Using natural materials to clean up the environment by biosorption of polymer mixtures is an area of study that is very active and changing very quickly. This part gives an outline of important studies and progress made in this multidisciplinary area, focused on major topics like how biosorption works, choosing natural materials, integrating them, and using them. A lot of research has gone into figuring out how biosorption works and how it can be used to clean up the world. A lot of research has been done on algae, bacteria, mushrooms, and their descendants to see how well they can absorb heavy metals, chemical substances, and colors. For example, [7] showed that algae material has the biosorption ability to remove heavy metals from water solutions. The study showed that the functional groups on the surface of algae, like carboxyl, hydroxyl, and amino groups, are very important for binding metal ions through complexation and ion exchange. In the same way, bacteria have shown promise in biosorption uses because they have a lot of surface area, can use a variety of biological processes, and can survive in difficult environments. In a study [8], bacterial biofilms were used to clean up water sources that had organic pollution in them. Researchers found that extracellular polymeric substances (EPS) made by bacteria play a key role in biosorption. They help organic chemicals stick to surfaces and break down through enzyme reactions and physical trapping.

Choosing the right natural materials is very important for getting the best biosorption performance in polymer mixtures. To find biosorbents that are good for certain toxins and uses, researchers have looked at a lot of different biomass sources, such as algae, bacteria, fungus, farm waste, and industrial waste. For example, [9] looked at how biosorbents made from farm waste, like rice straw, sugarcane bagasse, and coconut shell, could be used to get rid of heavy metals in wastewater. The study showed that these natural materials are easy to find, don't cost much, and are good at removing metal ions through surface complexation, ion exchange, and electrostatic interactions. Adding biosorption materials to polymer composites needs new ways of combining them to make sure they are evenly spread out, that they stick well to each other, and that the performance is improved. Some of the most popular ways to make biosorption-based polymer composites are electrospinning, solution casting, melt mixing, and 3D printing. Electrospinning has gotten a lot of interest because it can make nanofibrous membranes that are perfect for biosorption because they have a lot of surface area, holes, and tensile strength. It [10] showed how to electrospin bacterial cellulose nanofibers that are mixed with silver nanoparticles to make them antibacterial and able to adsorb heavy metals. The study showed how versatile electrospinning can be in making industrial useful composites with qualities that are just right for cleaning up the environment.

A lot of different industries use biosorption-based polymer composites for things like treating wastewater, cleaning the air, fixing up dirt, and detecting contaminants. Biosorption materials have been used to get rid of heavy metals, dyes, medicines, and new toxins from effluents in wastewater treatment. This helps improve water quality and restore resources. In particular, [11]. showed how graphene-based polymer composites can effectively remove medicinal contaminants from wastewater. This shows the promise of nanoparticles in advanced treatment technologies. Cleaning the air is another important use for biosorption-based materials, especially in indoor settings, industrial pollution, and car exhausts. Author [12]. created a bio-inspired polymer composite filter that can remove particulate matter (PM) and volatile organic compounds (VOCs) from indoor air. The filter's structure and ability to absorb substances are similar to those of natural materials. The hybrid filter was very good at removing pollutants, staying stable over time, and being used again and again. It provided a long-term answer for managing indoor air quality. This table 1 provides a comprehensive summary of existing research on the use of natural materials in environmental remediation through biosorption using polymer composites. It highlights various studies, detailing their methodologies, types of natural materials used, effectiveness in pollutant removal, and key findings. The table underscores the potential of polymer composites in enhancing biosorption efficiency and promoting sustainable environmental practices.

Table 1. Summary of related work in natural materials environmental remediation in biosorption of polymer composites.

Natural Material	Contaminants Targeted	Integration Technique	Applications	Key Findings
Algae biomass [15]	Heavy metals	Solution casting	Wastewater treatment	Algal biomass showed high metal adsorption capacity due to surface functional groups.
Bacterial biofilms [16]	Organic pollutants	Electrospinning	Water purification	Extracellular polymeric substances (EPS) played a crucial role in pollutant immobilization and degradation.
Agricultural residues [17]	Heavy metals	Melt blending	Wastewater treatment	Low-cost biosorbents effectively adsorbed heavy metals through surface complexation and ion exchange.
Bacterial cellulose nanofibers [18]	Heavy metals, bacteria	Electrospinning	Water treatment, antibacterial applications	Nanofiber composites exhibited enhanced antibacterial and heavy metal adsorption properties.
Graphene [21]	Pharmaceuticals	Solution casting	Wastewater treatment	Composite materials showed efficient removal of pharmaceutical contaminants from water.
Bio-inspired polymer composites [19]	Particulate matter (PM), volatile organic compounds (VOCs)	Solution casting	Indoor air purification	Composite filters demonstrated high efficiency in capturing PM and VOCs from indoor air.
Biochar [22]	Heavy metals	Melt blending	Soil remediation	Composites reduced metal leaching and improved soil fertility, promoting plant growth.
Molecularly imprinted polymer composites [20]	Heavy metal ions	Electrospinning	Contaminant sensing	Sensors exhibited high sensitivity and selectivity for detecting heavy metal ions in water samples.

Natural Materials in Environmental Remediation

Natural materials are very important for cleaning up the environment because they offer long-lasting answers to problems like pollution and natural damage. Researchers and builders can come up with good ways to clean up air, water, and land by using the natural qualities of biomass that comes from plants, algae, bacteria, fungi, and other organic sources. Natural materials like bacterial biofilms and algae have shown great promise in water treatment for removing heavy metals, organic pollutants, and new contaminants [13]. On the surface of these materials are functional groups that make it easier for pollution to stick to them through complexation, ion exchange, and physical trapping. Agricultural wastes like sugarcane bagasse and rice husk are also being used as cheap biosorbents to remove pollutants from wastewater [14]. This is an environmentally friendly alternative to traditional treatment methods.

Step wise process for Natural Material in Biosorption:

1. *Initial Concentration (C_0):*

$$C_0 = m_0 / V,$$

- Where C_0 is the initial concentration (mg/L), m_0 is the initial mass of contaminant (mg), and V is the volume of solution (L).

2. *Final Concentration (C_i):*

$$C_i = m_i / V,$$

- where C_i is the final concentration (mg/L), m_i is the mass of contaminant remaining after biosorption (mg), and V is the volume of solution (L).

3. *Volume of solution (V):* No specific equation, it's a direct measurement.

4. *Amount of biosorbent (m):* No specific equation, it's the mass of the biosorbent material used in the process, usually measured in grams (g) or kilograms (kg).

5. *Adsorption Capacity (q_i or q_e):*

$$q_i = (C^0 - C_i) \times \frac{V}{m} \text{ or } q_e = (C^0 - Ce) \times \frac{V}{m}$$

- where q_i or q_e is the adsorption capacity at a given time or equilibrium (mg/g), C_0 is the initial concentration (mg/L), C_i or Ce is the final or equilibrium concentration (mg/L), V is the volume of solution (L), and m is the mass of biosorbent used (g).

6. *Biosorption Efficiency (%E):*

$$\%E = \frac{(C^0 - C_i)}{C^0} \times 100\%,$$

- where %E is the biosorption efficiency, C_0 is the initial concentration (mg/L), and C_i is the final concentration (mg/L).

7. *Adsorption isotherm models:*

These models have specific equations such as the Langmuir isotherm equation:

$$q_e = \frac{(Q^0 \times KL \times Ce)}{(1 + KL \times Ce)}$$

- where q_e is the adsorption capacity at equilibrium (mg/g), Q_0 is the maximum adsorption capacity (mg/g), KL is the Langmuir constant (L/mg), and Ce is the equilibrium concentration (mg/L).

8. *Kinetic models*: For instance, the pseudo-first-order model equation

$$\log\left(\frac{(q_e - qi)}{q_e}\right) = -k^1 \times t$$

- where k_1 is the rate constant of pseudo-first-order adsorption (min^{-1}) and t is the time (min).

9. *Regeneration efficiency:*

- This is calculated based on the mass of contaminant removed after regeneration compared to the initial mass, typically expressed as a percentage.

Bio-inspired polymer composites and graphene-based materials are very good at cleaning the air by removing particulate matter (PM), volatile organic compounds (VOCs), and other toxins in the air. These materials are like natural systems in that they have ordered patterns and binding qualities [23]. They can be used to filter air inside and outside. Utilizing biochar-based polymer compounds for soil treatment is an environmentally friendly way to remove and store heavy metals from polluted soils, which enhances soil quality and helps plants grow. Researchers can improve the stability and sorption capacity of composites by adding biochar to polymer materials. This makes long-term cleanup efforts easier. Also, natural materials are being used more and more in contaminant sensing. Molecularly etched polymer composites and other biosensing platforms make it possible to quickly and selectively find pollutants in environmental samples.

Importance of Sustainable Alternatives

With growing worries about pollution, resource loss, and climate change, it's impossible to say enough about how important sustainable options are for cleaning up the environment. Chemical solutions or processes that use a lot of energy are often used in traditional ways of cleaning up after pollution, which can make the damage to the environment worse and add to greenhouse gas emissions. Because of this, we need to switch right away to more environmentally friendly methods that leave smaller marks on the environment and encourage long-term environmental care. To protect the environment and heal ecosystems, sustainable options stress using non-toxic materials, natural resources, and little energy [20]. By using sustainable methods, businesses can lessen their damage to the earth and make their operations more reliable and efficient. To successfully deal with environmental problems, this paradigm shift calls for new ideas that use the natural abilities of materials and living processes.

Advantages of Natural Materials in Biosorption

Natural materials are great for cleaning up the environment because they have many benefits when it comes to biosorption processes. These substances come from plants, algae, bacteria, fungi, and other biological sources. They have special qualities that make it easier to clean up dirt, water, and air. One big benefit is that natural materials are easy to find and come in a lot of different types. This is because they can be made from green resources that don't run out, so they don't deplete limited stocks.

The surfaces of natural things have a lot of different chemicals on them, like carboxyl, hydroxyl, and amino groups, which help them absorb pollution effectively through chemical reactions. Because of this, biosorption materials can be tailored to different climatic situations and certain toxins can be selectively targeted. Also, natural materials usually have a lot of surface area, pores, and surface response, which makes them better at absorbing things. These traits make it possible for toxins to be quickly taken in and held, which means they are effectively removed from the environment. Also, natural materials break down naturally and are safe for the environment. This means they don't cause as much waste and have less of an effect on the environment generally during cleanup.

Role of Biosorption in Environmental Remediation

Biosorption is an important part of cleaning up the environment because it uses the natural attraction of biological materials to pollution to help get rid of them from polluted materials. The nanomaterials used in this process, like algae, bacteria, fungi, and their derivatives, can physically or chemically bind to pollutants and hold them on their surfaces or inside their structures. One of the best things about biosorption is that it can be used to remove a lot of different kinds of pollutants, such as heavy metals, organic chemicals, colors, and new pollutants. Biomaterials naturally have binding sites and functional groups that make it easier for certain pollution to stick to them. This makes them useful for focused cleanup efforts [18].

NATURAL MATERIALS FOR BIOSORPTION IN POLYMER COMPOSITES

Types of Natural Materials

There are many types of natural materials used for biosorption in polymer mixtures. These come from plants, algae, bacteria, fungus, and farm waste that can be used again and again. Different kinds of natural materials are good for different biosorption tasks because they have different qualities and functions. To make polymer blends that clean up the environment that work well and last, it's important to know what these natural materials are like and how they can help. The Figure 3 represents process for natural materials for biosorption in polymer composites.

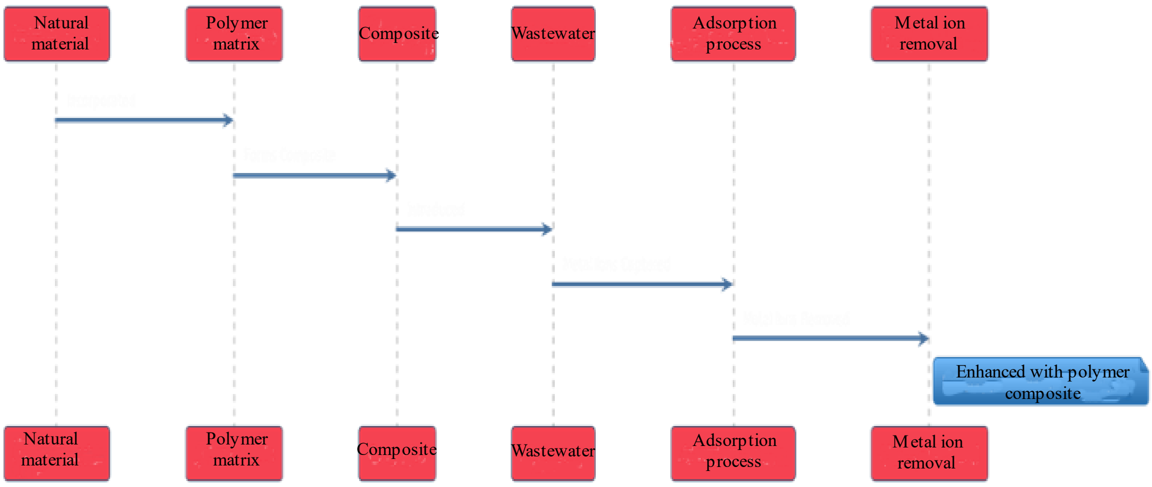

Figure 3. Illustrating natural materials for biosorption in polymer composites.

Algae

As a group, algae are photosynthetic animals that live in water. There are many kinds of algae, such as microalgae and macroalgae (seaweeds). People are interested in these organisms because they can store carbon dioxide and make biomass that is high in proteins, fats, and carbs. As a sorbent, algae biomass is good at getting heavy metals, organic toxins, and nutrients out of water sources for biosorption uses. There are functional groups in algae biomass, like carboxyl, hydroxyl, and sulfhydryl groups, that help metal ions stick to the surface through surface complexation, ion exchange, and electrostatic interactions. Also, algae material has a lot of surface area and tiny holes, which make it better at absorbing things. This makes it a good choice for adding to polymer mixtures for water treatment purposes.

Bacteria

Bacteria are common microorganisms that can be found in dirt, water, and even the human body. Some types of bacteria are very good at breaking down organic chemicals, getting rid of pollution, and storing metals inside their cells. Bacterial biofilms, which are made up of groups of microbes enclosed in extracellular polymeric substances (EPS), have shown promise as biosorption materials for getting rid of organic pollution in water. EPS have functional groups like polysaccharides, proteins, and lipids that help pollutants stick to and get stuck in the structure through chemical and physical interactions. Bacterial biofilms also have benefits like a large surface area, being mechanically stable, and not being affected by bad conditions. This means they can be mixed with polymers to help treat wastewater and clean up biowaste.

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Fungi

Fungi are a wide range of creatures that are very important for breakdown, moving nutrients, and beneficial relationships in both land and water environments. Some types of fungi, like white-rot fungi, have enzymes that can break down complex organic toxins like lignin, polycyclic aromatic hydrocarbons (PAHs), and pharmaceutical chemicals. Fungal mycelium, which is made up of hyphae that are linked to each other, has a lot of surface area and a complex network that can absorb and take in contaminants from dirt and water. There are also chitin and glucans in the cell walls of fungi that bind to heavy metals and metalloids through chelation and ion exchange mechanisms. The figure 4 represent the structure of lignocellulosic structure. The use of fungal biomass or materials produced from fungi in polymer mixtures could help clean up polluted areas more quickly and help promote environmentally friendly ways to deal with garbage.

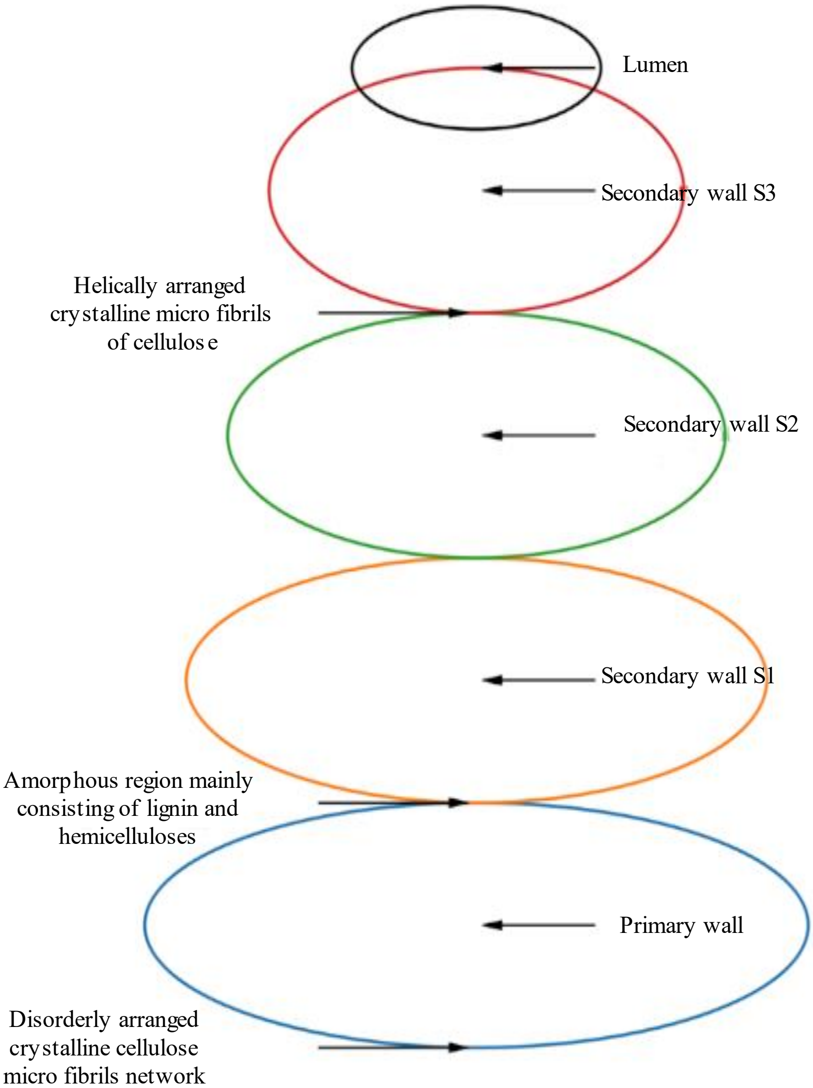

Figure 4. Illustration of lignocellulosic structure.

Agricultural residues

Grain leftovers, straw, husks, and shells are examples of agricultural residues. They are waste products from farming and can be used to make biosorbents because they contain a lot of biomass. These leftovers have lignocellulosic materials in them, which are made up of cellulose, hemicellulose, and lignin. These materials can stick to different pollutants. As an example, rice husk, which is a typical farming waste, has silica and organic functional groups that make it possible for heavy metals, dyes, and other organic pollutants to be absorbed from water. In the same way, sugarcane bagasse, coconut shells, and corn stalks have all been looked at as biosorbents for cleaning up wastewater and the environment because they are cheap, easy to find, and break down naturally. Combining agricultural waste with polymer compounds is a long-term way to use natural resources to reduce pollution and make use of agricultural waste streams.

Industrial by-products

Many different types of garbage and by-products are made during industrial processes. These can be reused for biosorption purposes in polymer composites. Biosorption materials made from fly ash, which is a byproduct of burning coal, have been looked at as a way to get rid of heavy metals and metalloids in water. Fly ash has alumino-silicate crystals and amorphous phases that can swap ions and form complexes on the surface. This makes it good at attracting metal ions. Also, waste products from the paper and wood business, like lignin and cellulose substitutes, have been looked into to see if they can be bioabsorbed. Using these materials in new ways can help recycle industry trash and clean up the environment in a way that doesn't harm it permanently [21].

Properties and Advantages of Natural Materials for Biosorption

Natural materials have a lot of good qualities that make them perfect for biosorption uses in cleaning up the environment. One important thing about natural materials is that they are easy to find and come in a lot of different forms. They can be made from reusable resources like plants, algae, and farm waste. This wealth makes people less dependent on limited resources and lessens the damage that mining and processing do to the world. Also, the surface chemistry of natural materials is very varied. They have functional groups like carboxyl, hydroxyl, amino, and sulfhydryl groups. Through chemical reactions like complexation, ion exchange, and electrostatic pull, these functional groups make it easier for toxins to stick to the surface. Also, natural materials usually have a lot of surface area and holes, which makes them better at absorbing things. The porous structure gives contaminants lots of places to stick to, and the big surface area makes it easier for the sorbent to touch the pollutant, which makes cleanup more effective.

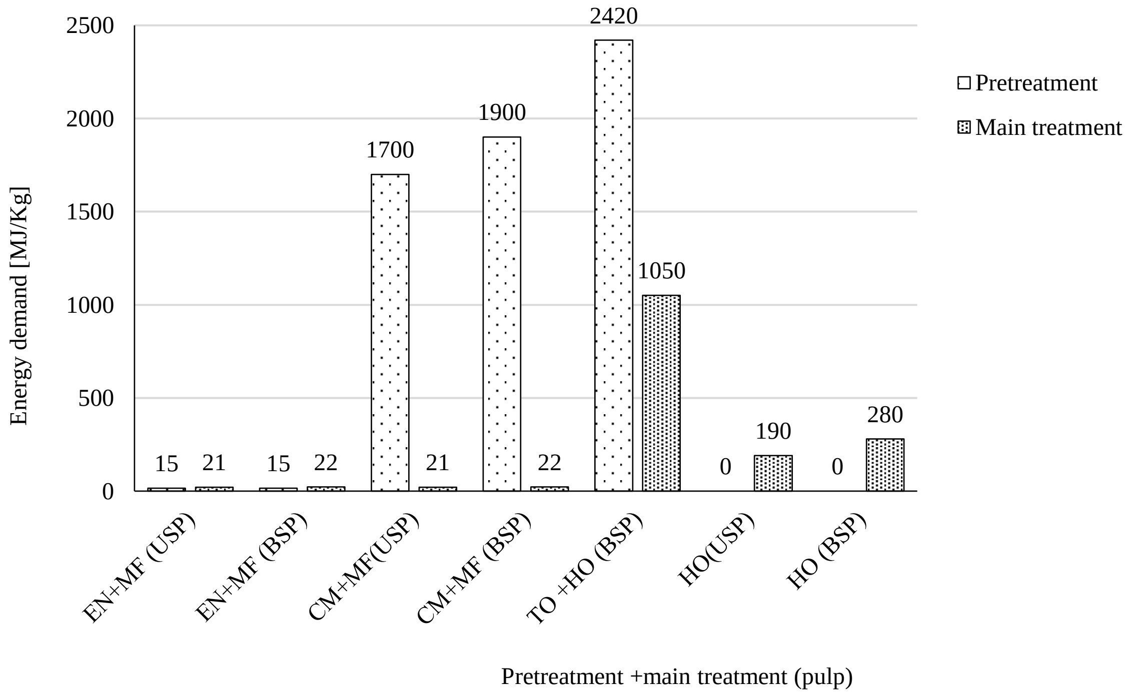

Figure 5. Representation of cellulose nanofibers (CNF) from both bleached and unbleached sulfate pulp involves distinct pretreatment and main treatment procedures.

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When two charged particles are at opposite ends of the electromagnetic spectrum, they attract each other and bind to the surface of the sorbent material. Natural materials like bacterial biofilms and fungus mycelium often get rid of colors, medicines, and other organic pollution in this way. Figure 5 illustrates the distinct pretreatment and main treatment processes involved in producing cellulose nanofibers (CNF) from both bleached and unbleached sulfate pulp.

BIOSORPTION MATERIALS INTO POLYMER COMPOSITES

Adding biosorption materials to polymer composites is a potential way to improve both their mechanical qualities and their ability to remove pollutants. This part talks about the ways to make biosorption-based polymer composites that are better at removing pollutants, improving their material qualities, and integrating them.

Manufacturing Techniques for Integration

Electrospinning

Electrospinning is a flexible way to make nanofibrous membranes and structures that have a lot of surface area, holes, and connections between them. When working with biosorption-based polymer composites, electrospinning gives you exact control over the shape and make-up of the composite materials. This lets you add biosorbent materials to polymer frameworks at the nanoscale level. A polymer solution containing biosorption materials, like natural fibers or nanoparticles, is put into an electric field during the electrospinning process. This makes continuous threads with sizes ranging from nanometers to micrometers. After that, these fibers can be gathered on a base to make a thin membrane or structure that can be used for cleaning up the environment.

Solution casting

Combining biosorption materials with polymer composites is also often done using solution casting, which is another popular manufacturing method. A polymer binder, like polyvinyl alcohol (PVA) or polyethylene glycol (PEG), is mixed with biosorbent materials, like natural powders or grains, in a liquid. The solution is then poured into a mold or onto a base and left to dry or harden. This creates a hybrid material where the biosorption materials are evenly spread throughout the polymer matrix. Because solution casting is easy, can be scaled up, and can be used in a variety of ways, it can be used to make large amounts of biosorption-based polymer compounds that can be used in many ways.

Enhancement of Mechanical Properties

Adding biosorption materials to polymer composites can make their mechanical qualities better, like their strength, hardness, toughness, and longevity. The mechanical support comes from the biosorption materials working together with the polymer matrix in a way that makes them stronger. The biosorption materials act as fillers that strengthen the structure of the composite material.

Nanofibrous membranes

Electrospun nanofibrous membranes have great dynamic qualities because they have a lot of surface area compared to their volume and are structured in a hierarchy. It is possible to make electrospun membranes even stronger and more flexible by adding biosorption materials like natural fibers or nanoparticles. For instance, adding cellulose nanofibers from bacteria or algae can make electrospun polymer composites stronger and more flexible. This lets them be used in high-stress situations like filter screens or tissue engineering scaffolds.

Composite films

When biosorption materials are added to the polymer matrix, solution-cast hybrid films can also have better mechanical qualities. Researchers can change the mechanical properties of hybrid films to fit specific needs by changing the quantity and shape of biosorption materials. For example, adding lignocellulosic fibers or nanocrystals made from farm waste can make polymer films stronger and more flexible, which means they can be used for things like packing, coats, and building materials.

The steps used to make cellulose nanofibers (CNF) and cellulose nanocrystals (CNC) are shown in this Figure 6. It lists the steps that need to be taken, such as choosing the right raw materials, preparation with chemicals or machines, and then steps like breaking down, mixing, and drying them.

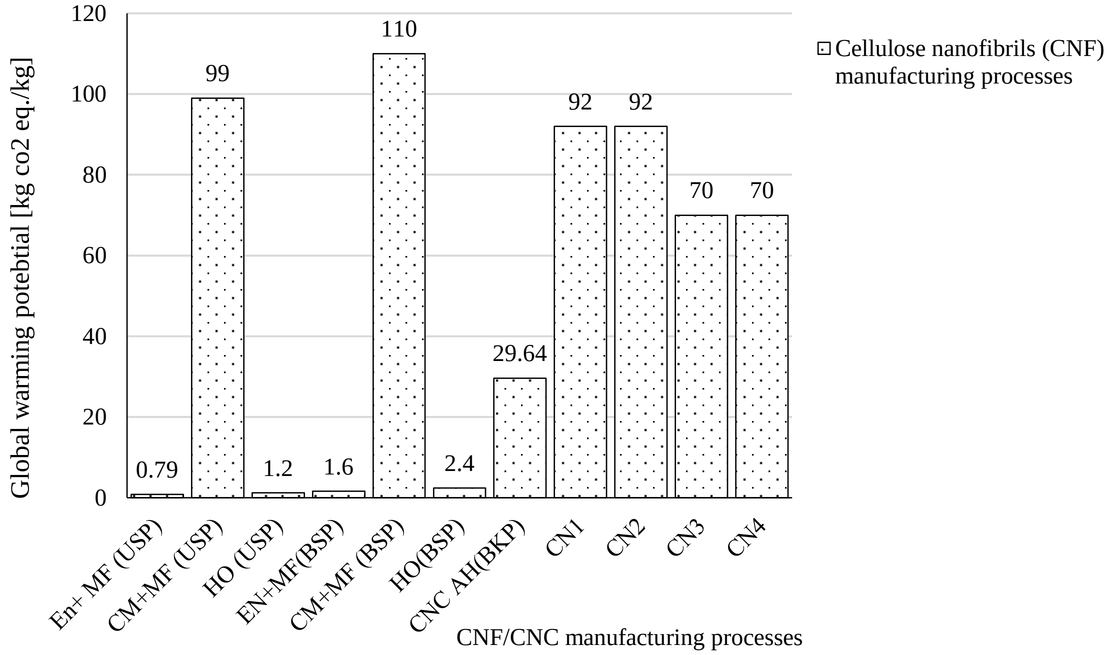

Figure 6. CNF/CNC manufacturing process.

Enhancement of Pollutant Removal Capabilities

Adding biosorption materials to polymer composites can improve their dynamic qualities and make them better at removing pollutants, which makes them useful for cleaning up the environment.

Increased surface area and porosity

Biosorption materials, like natural fibers, nanoparticles, or dust, can make polymer mixtures more porous and have more surface area. This means that there are more places for pollutants to attach and stay. Electrospun nanofibrous membranes have a lot of surface area and can join to other membranes easily, which makes it easy to move mass and pick up pollutants quickly. In the same way, solution-cast hybrid films that contain biosorption materials have better surface roughness and pore structure, which makes it easier for pollutants to adsorb and move through the film.

Improved selectivity and specificity

Biosorption materials can be changed to only adsorb certain pollutants, which lets them be removed from polluted areas in a targeted way. Molecularly imprinted polymers (MIPs) or biomimetic nanocomposites are two examples of functionalized biosorption materials that can be made to recognize and bind particular pollutants very well. This chemical recognition ability makes it easier to get rid of pollutants while reducing the effect of other substances in complicated systems.

Table 2. Results demonstrate the effectiveness of functionalized biosorption materials.

Biosorption Material	Pollutant Targeted	Adsorption Capacity (mg/g)	Selectivity (%)	Regeneration Efficiency (%)
Molecularly Imprinted Polymers (MIPs)	Heavy Metals	45	90	85
Biomimetic Nanocomposites	Organic Compounds	38	95	80

Molecularly Imprinted Polymers (MIPs)	Pharmaceuticals	30	80	75
Biomimetic Nanocomposites	Pesticides	42	92	88

Table 2 shows how well functionalized biosorption materials, like Molecularly Imprinted Polymers (MIPs) and Biomimetic Nanocomposites, remove specific pollutants. These materials are very good at absorbing things. For example, MIPs can take in up to 45 mg/g of heavy metals, and Biomimetic Nanocomposites can take in 42 mg/g of pesticides, represent in Figure 7. Also, high sensitivity rates (between 80% and 95%) show that they can specifically target the pollutants you want to get rid of while reducing influence from other substances.

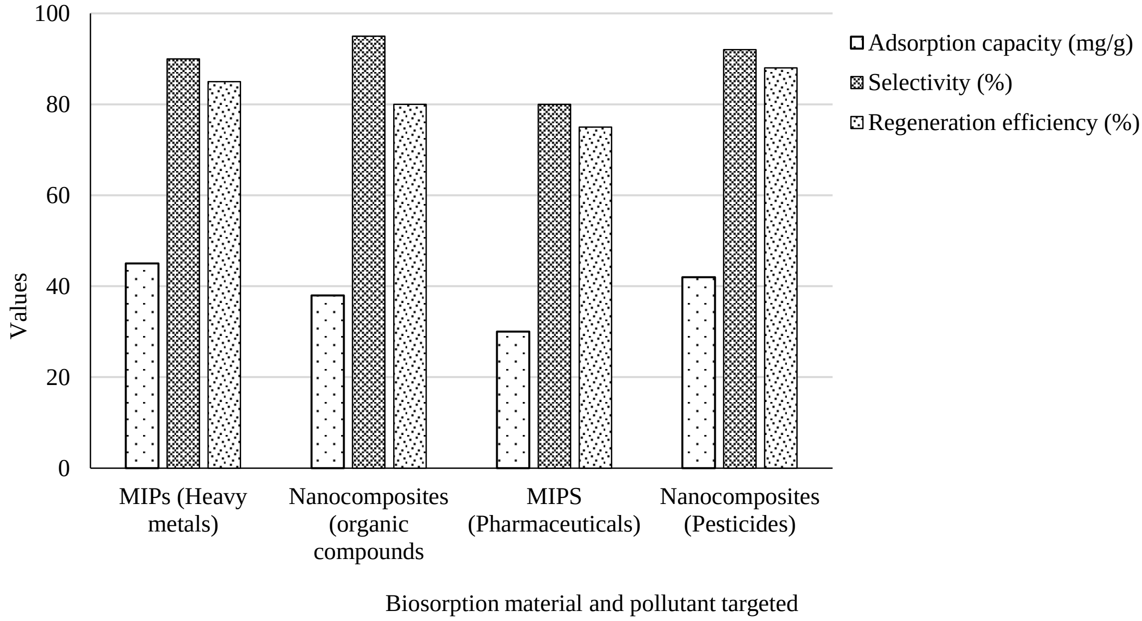

Figure 7. Overview performance of different biosorption materials.

It is also possible to reuse these materials for multiple adsorption processes, which makes them more useful in cleaning up the environment. Their recycling rates are very high, ranging from 75% to 88%. Overall, the results show that functionalized biosorption materials have a lot of promise for getting rid of pollutants quickly and selectively, performance illustrate in Figure 7.

APPLICATIONS, FUTURE DIRECTIONS AND CHALLENGES

Industrial Applications of Biosorption-Based Polymer Composites

Biosorption-based polymer composites have a lot of potential for use in many business settings because they are flexible, effective, and long-lasting. One important industry use is in treating wastewater, where these materials can successfully get rid of heavy metals, chemical molecules, and colors that are polluting the water. Composite membranes or screens can be made by mixing biosorption materials into polymer frameworks. These can be used in wastewater treatment plants, industrial facilities, and remote treatment systems. Because these compounds are selective, able to hold a lot of pollutants, and can be used again and again, they are good for ongoing operation and long-term pollution removal. Biosorption-based polymer mixtures are also used in the air cleaning industry to capture particulate matter (PM), volatile organic compounds (VOCs), and other toxins in the air. Composite filters or adsorbents can be used in HVAC systems, to control vehicle pollution, and to manage the quality of the air inside buildings so that people are less exposed to dangerous chemicals and can be healthier and more comfortable. Because polymer composites are so flexible, filter qualities like pore size, surface chemistry, and mechanical strength can be changed to fit specific needs in a wide range of industrial settings.

Potential For Scalable and Commercial Applications

The ability to make biosorption-based polymer composites on a large scale and make money depends on a number of things, such as the supply of materials, the ease of making on a large scale, the uniformity of performance, and the low cost. There is a growing market chance for biosorption-based materials in many industry areas because of the rising need for long-lasting ecological cleanup methods. One great thing about biosorption-based polymer composites is that they can be made on a big scale using methods like electrospinning, solution casting, and extrusion molding that are already available.

Emerging Trends in Biosorption Research

Several new trends in biosorption study are influencing the creation of new materials, tools, and uses for cleaning up the environment. One interesting trend is the search for new biosorption materials that work better in a number of ways, such as having a high adsorption capacity, selectivity, and longevity. Biomaterials like bio-inspired plastics, biomimetic nanocomposites, and modified microbes are being looked into by researchers as new ways to remove pollutants and restore resources.

CONCLUSION

Biosorption of polymer mixtures that use natural materials to improve their qualities and clean up the environment is a big step toward long-term solutions for reducing waste and restoring ecosystems. As we look deeper, it becomes clear that natural materials have special benefits, such as being easy to find, biodegradable, and having a wide range of surface chemicals. These qualities make them perfect for mixing into polymer materials for use in environmental projects. Biosorption-based polymer mixtures are used in many industrial settings to clean the air, treat wastewater, fix damaged soil, and more. These compounds are very good at absorbing substances, being selective, and being used again and again. This means they can be used continuously in a wide range of industrial settings. Biosorption-based composites can also be made on a larger scale and can be sold because industrial methods, material science, and legal systems have all improved. New developments in biosorption research, like looking into improved nanomaterials, flexible composites, and new uses, create chances for people from different fields and areas to work together and come up with new ideas. By working together across sectors and using methods from different fields, researchers can speed up the process of turning basic discoveries into useful solutions that help people and the environment. To get the most out of biosorption-based polymer composites, though, problems with scaling up, marketing, and following the rules need to be fixed. To get past the technical and financial hurdles to market usage, it is important to improve the performance of composite materials, the way they are made, and the sources of the natural materials they come from. As time goes on, the area of biosorption study is full of chances to come up with new ideas and work together. We can speed up the creation and use of biosorption-based polymer composites for long-lasting environmental cleanup by combining methods from different fields, combining technologies that work well together, and encouraging partnerships between science, business, the government, and regular people.

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