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Biomass-based biosorbents potential for wastewater treatment

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Abstract

Biosorption is a cost-effective and eco-friendly method for removing pollutants from water, using agricultural waste, microbial biomass, and plant residues. Adsorbents like activated carbon, biochar, and modified biomass show promising results, with mechanisms like electrostatic interactions and hydrogen bonding playing key roles. Surface modification techniques, such as acid treatment and nanoparticle incorporation, enhance biosorption efficiency. Despite challenges in scalability and efficiency, research aims to enhance biosorption processes for widespread industrial success and cleaner water resources. Biomass materials, including bacteria, fungi, and algae, offer practical alternatives for wastewater treatment. Biopolymer-based porous carbon adsorbents, such as alginate, carrageenan, starch, cellulose, gelatin, and chitosan, demonstrate high biosorption capacities for pollutants. Physical and chemical pretreatment techniques, such as grinding, milling, pyrolysis, carbonization, ultrasonication, and heat treatment, enhance biosorption capacity. Characterization techniques like FTIR spectroscopy and SEM provide insights into biomass adsorbent structure and properties, aiding in optimization for practical applications in environmental remediation and water treatment.

Keywords: Bio sorption, Wastewater treatment

Review article

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1. Introduction

Wastewater development has increased due to population growth and industrialization, particularly in emerging nations where an estimated billions m^3/year of industrial and municipal wastewater is produced. This effluent frequently contains various contaminants, including chemicals, heavy metals, oil, and grease. Therefore, it requires thorough treatment to protect the environment and guarantee clean water supplies [1-2]. Traditional treatment techniques, such as primary and secondary treatments, have drawbacks because of their high energy requirements, need for land, and high operating expenses. So, a viable substitute for treatment is required, for removal of contaminants such as heavy metals and nutrients. Industries around the world struggle to implement suitable systems despite the urgent need for wastewater treatment because of financial constraints, physical limits, and loose regulations. The Water Pollution Control Action Plan in developed countries, which emphasizes treatment facilities and water reuse, is one initiative that demonstrates efforts to address this issue.

Although the effectiveness of wastewater treatment has increased due to technological breakthroughs, particularly in the field of nanomaterials, obstacles remain to be overcome, such as the emergence of new contaminants and the need for complete pollutant removal [3]. From outdated sanitation systems to contemporary international standards, wastewater management has become increasingly important for environmental preservation and public health. Research projects concentrate on innovative treatment methods and cultural changes toward sustainable water management as communities come to appreciate wastewater as a precious resource. Aiming to provide thorough insights into wastewater difficulties and evolution, efforts are being made to synthesize many study disciplines so that professionals and non-experts alike can make informed decisions [4]. Even though they play a vital role in reducing the environmental damage caused by untreated wastewater, conventional wastewater treatment techniques have significant negative effects on the environment.

These effects differ according to the treatment technique used, some systems have significant energy use, large land utilization, or high embodied energy reliance on materials like plastics. In the developed countries like UK's water sector, standard practices tend to prioritize more technical solutions over natural systems such as reed beds, often ignoring the comprehensive assessment of these consequences throughout a system's life cycle [5-6]. An approach for thoroughly assessing the environmental effects of wastewater treatment systems is life cycle assessment or LCA. It has been used to investigate the viability of different treatment techniques, emphasizing the necessity of a broader adoption in the water sector to direct initiatives for environmental policy and improvement. However, this approach is often quantitative instead of qualitative that shows significance of taking a variety of aspects into account when designing a system. Novel techniques present viable substitutes for traditional treatment techniques, with potential to lower energy usage and boost biomass production.

However, to evaluate viability of such technologies and pinpoint areas for development, a full assessment using techniques such as life cycle assessment (LCA) is necessary. Comprehensive assessment and mitigation techniques are required because presence of new contaminants, including pharmaceuticals, in wastewater creates additional dangers to the environment. Research has indicated that traditional treatment methods may not eliminate pollutants to full extent, which could have negative ecological effects. Environmental risk assessments are essential for comprehending how contaminants affect ecosystems and for directing the creation of efficient remediation strategies [7]. Optimizing wastewater treatment systems is crucial to reducing pollution and safeguarding the environment in particular areas, where water supplies are limited, and reuse of recovered water is crucial. The environmental consequences of traditional treatment techniques transcend beyond immediate objective of treating wastewater, stressing necessity of comprehensive evaluations and creative solutions to guarantee sustainable water management practices.

By implementing innovative technologies and sustainable practices, water treatment facilities in regions can not only improve water quality but also conserve precious resources for future generations [8]. An essential concept in wastewater treatment is biosorption, which uses materials derived from biomass. This is especially true regarding eliminating contaminants from industrial effluents, such as heavy metals and dyes. These effluents, which come from various industries, including food, plastics, textiles, and paper, contain dangerous materials that jeopardize human health and aquatic habitats. Particularly for low concentrations of contaminants, conventional techniques such as flocculation, coagulation, and activated carbon biosorption have drawbacks [9]. Therefore, there is growing interest in using accessible, affordable materials for biosorption. Using leftover algae from agar extraction procedures as effective biosorbents for removal of metal ions is a potential approach. Likewise, alternative biomass sources with ability to remove contaminants from wastewater include peanut hulls, rice husks, clay, and even agricultural by-products like guava seeds and date pits.

The surface area, porosity, and density of these biosorbents are physical properties that have a significant impact on the biosorption process [10]. The ability to biosorb is innate to both living and dead microbes and provides a straightforward but efficient method for eliminating pollutants. Despite a great deal of research in this field and the creation of numerous biomaterials, biosorption has not yet found widespread industrial success. There are still issues with scalability, efficiency, and financial viability that prevent it from being widely used in wastewater treatment procedures. However, research into and improvement of biosorption processes employing biomass-based materials is still ongoing to develop a more environmentally friendly and sustainable method of purifying water [11]. Identifying the potential of biomass-based adsorbents in wastewater treatment is the primary goal nowadays for researchers. Few important goals include tackling the issue of global water pollution and to highlighting the pressing need for long-term solutions to clean wastewater and lessen its negative effects on the environment and public health. [12].

The past analysis identified the drawbacks of existing wastewater treatment techniques, including membrane filtration, coagulation-flocculation, and precipitation. This paves the way for investigating alternative strategies, especially those using biomass-based adsorbents. If biomass-based adsorbents—such as those made of plant, animal, or microbiological cells—can be used as efficient adsorbents to remove contaminants from wastewater it will be very beneficial in near future because of its affordability, eco-friendliness, and biodegradability [13], Additionally, the significance of ongoing innovation and interdisciplinary collaboration in the field of biomass-based adsorbents for wastewater treatment, as well as future research directions and prospective improvements in the field is main objective of this review on unleashing potential biomass for wastewater treatment seeks to promote sustainable and efficient wastewater treatment solutions by offering a thorough understanding of the role that biomass-based adsorbents play in addressing the global challenge of water pollution [14-15].

2. Assessing the advantages and limitations of using biomass materials.

Understanding the properties of adsorbents is essential for understanding biosorption mechanisms and future material applications. Physical and chemical properties such as chemical composition, functional groups, surface area, porosity, and shape all have an impact on sorption. Chitin/chitosan, which is prevalent in nature and generated from a variety of sources, such as crustacean exoskeletons, has substantial biosorption qualities determined by its molecular structure, functional groups, and surface characteristics. Environmental variables and pretreatment methods have a significant impact on biosorption performance. Notably, lignocellulosic materials contain functional groups such as hydroxyl, carboxyl, and silanol, which are essential for adsorbent organic contaminants, as evidenced by many researches on seaweed powder and lignin polysaccharide interactions [16]. Understanding the nature, characteristics, and potential uses of biomass materials is essential for evaluating their benefits and drawbacks. Because it is renewable and can be turned into various CO_2-neutral biofuels and bio chemicals, biomass offers a replacement for fossil fuels.

Even though biomass has many advantages, there are some drawbacks that should be considered. The regenerative nature of biomass, which lowers CO_2 emissions compared with fossil fuels, is one of its main benefits in lessening the greenhouse impact. Furthermore, biomass includes a broad variety of resources, such as wood, organic residues, and agricultural waste, offering a variety of feedstock choices for the generation of bioenergy [17]. Moreover, a great deal of research has been conducted to improve the use of biomass and solve technical issues related to its conversion into biofuels and biochemicals. Nevertheless, these benefits, there are a few issues with biomass use that need to be resolved. Understanding the complicated composition of biomass, which varies depending on the source and includes both organic and inorganic components, is essential. Concerns about feedstock quality, processing effectiveness, and product consistency arise from these fluctuations [18].

The processes involved in the combustion and conversion of biomass may produce biomass ash, which needs to be managed properly to reduce any possible environmental hazards. The primary tools used to evaluate the environmental effects of biomass consumption are energy-based metrics and CO_2 emissions. However, these methods fall short of fully accounting for the environmental effects connected to the production and use of biomass. Because it considers several harmful domains, such as the depletion of mineral and fossil resource stocks, ecosystem quality, and human health, life cycle analysis (LCA) provides a more comprehensive assessment tool. In conclusion, evaluating the benefits and drawbacks of using biomass resources necessitates a comprehensive understanding of their makeup, characteristics, and effects on the environment. Although biomass has a lot of promise as a renewable energy source, its variability, processing difficulties, and environmental effects must all be carefully considered to reap the full benefits and ensure sustainable use. To accelerate the shift toward a more sustainable energy future, research and innovation in biomass conversion technology and sustainability evaluation methodologies are essential [19].

2.1. Common Pollutants

Discuss the properties, sources, effects, and SOPs (Standard Operating Procedures) levels in the environment. (Targeted by Biomass-based Adsorbents in Wastewater Treatment)- Introduction Paragraph Table 1.

2.2. Biomass as a Source of Adsorbents

2.2.1. Living Biomasses for Pollutant Removal

Living biomasses are essential for the cleansing of water and air because they eliminate contaminants from the environment, since water pollution caused by industry and human activities is a major global issue, efficient pollutant removal procedures are necessary. Pollutants pose serious threats to ecosystems and human health, particularly heavy metals, and volatile organic compounds (VOCs). Traditional methods of eliminating pollutants are often expensive and harmful to the environment. However, living biomasses offer a practical alternative through processes like biosorption and bioaccumulation [20]. Biosorption is the process by which pollutants are passively adsorbed to inanimate materials, whereas toxicants are actively absorbed by living cells during bioaccumulation. The functional groups and surface properties of biomasses derived from algae, fungi, bacteria, and yeast enable them to effectively adsorb pollutants [21]. Chemical alterations can enhance their biosorption capacities even more. Because living biomasses are readily available, priced, and simple to regenerate, they present intriguing options for the removal of pollutants. Their ability to work in a range of situations also makes them versatile tools for environmental rehabilitation. Research and development on living biomasses is still in progress, which contributes to a cleaner and better environment by increasing their effectiveness in lowering air and water pollutants [22].

i. Bacteria biomass as adsorbents

Bacterial biomass, specifically leftover biomass from such as from *Saccharomyces pastorious* and *Saccharomyces cerevisiae* is used to remove pollutants and pharmaceuticals from water. Although the use of microorganisms as adsorbents in traditional wastewater treatment is promising, the process of removing free microbial cells from effluents is challenging. To evade this, the researchers immobilize the microbial biomass on different naturally occurring polymers like chitosan, and alginate. Distinct types of adsorbents are developed and evaluated by researchers, varied degrees of efficiency are demonstrated in removal of medications (such as antibiotics cephalexin, rifampicin, and disinfectant ethacridine lactate) and dyes (like orange II and indigo carmine) from water. The study found that the immobilization polymer selection significantly affects removal efficiency; for pharmaceuticals, range of removal efficiencies is 40.05% to 96.41%, and for dyes, it is 17.17% to 58.29%. These findings demonstrate the potential of biomass derived from immobilized bacteria as safe adsorbents for the environment, offering a potential solution to the issues caused by dyes and medications that contaminate water. The bacterial strains *Pseudomonas, Enterobactor, Streptomonas, Aeromonas, Acinetobactor, and Klebsiella* are frequently utilized for wastewater cleanup [23].

ii. Fungal biomass as adsorbents

A practical substitute for toxicity and carcinogenicity is biosorption. Because of their high biosorption capacity, fungi are useful adsorbents, and biological processes offer advantages over chemical ones. Metal and dye binding require the surface functional groups of fungal biomasses. Immobilized fungi also have the benefit of being easily separated from reaction solutions, allowing for repeated and continuous use. Many fungal pellet bioreactors have demonstrated potential, especially when utilized in continuous mode operations, which facilitates the easy scalability of biodegradation procedures. Waste fungal biomass, a byproduct of industrial operations that support the goals of a circular economy, offers a sustainable solution [24]. The removal of lead and cadmium from waste fungal biomass demonstrates its potential as an affordable and sustainable adsorbent when used for heavy metal biosorption. By defining the waste fungal biomass and utilizing pre-treatment procedures, the biosorption efficiency is increased.

Given the circumstances, the application of fungi in biosorption processes holds potential for the long-term and economically viable treatment of wastewater contaminated with dyes and heavy metals. Using *Aspergillus sydowii* and *Aspergillus destruens* under saline circumstances resulted in over 90% elimination of benzo-α-pyrene and phenanthrene through biodegradation and biosorption processes, as examples of fungus-based treatments for the sorption and removal of persistent organic pollutants (PACs) [25]. Diclofenac, gemfibrozil, ibuprofen, progesterone, and ranitidine all effectively eliminated by *Trametes versicolor* and *Ganoderma lucidum*, with the removal effectiveness of both fungi being enhanced when combined. Because white-rot fungi from the Basidiomycota family may degrade lignin, which can lead to the decomposition of PAC, they have been extensively researched for their potential in PAC removal. These fungi are appealing candidates for wastewater treatment because they use non-selective and non-specific enzymatic pathways for pollutant breakdown.

A few species that create fungal biomass are *Cunninghamella elegans, Aspergillus oryzae, Ganoderma lucidum*, filamentous fungus, micro fungi, fungal pellets, and the fungal-algal consortium [26]. These are used because they are effective in eliminating synthetic coloring, chromium, lead, and cadmium ions, as well as wastewater from wineries. These are employed in wastewater remediation, biomass harvesting, fungal biomass enhancement, and microalgae growth support via their cell walls. Overall, it has been demonstrated that certain fungal biomass species are effective at extracting various toxins from wastewater. By harnessing the power of these fungi, industries may effectively treat their wastewater in an environmentally beneficial manner. Moreover, the utilization of fungal-algal consortiums enhances the efficacy of the treatment process, making it a favored option for ecologically sustainable water management methodologies [27].

iii. Algal biomass

Algal biomass is a good adsorbent for eliminating heavy metals from aqueous solutions. It has been demonstrated that filamentous fungi may sorb a variety of heavy metals, such as Cu, Zn, Cd, Pb, Fe, Ni, Ag, Th, Ra, and U, to varied degrees. Variables, including pH, biomass content, metal ion concentration, and pre-treatment methods, control how effective this biosorption is. Fungal biomass outperforms both commercial ion-exchange resins and activated carbon in metal sorption, with the possibility for biomass renewal. The biomass's cell wall is crucial to the processes involved in heavy metal sorption, even though little is known about these mechanisms. Further research and development are continued to fully realize the potential of fungal biosorption technology [28]. Pharmaceutical microparticles pose a threat to conventional wastewater treatment methods as they are a primary source of aquatic contamination.

Phytoremediation, which employs plants to purify contaminated water, is one treatment. Phytoremediation has garnered interest from a multitude of organizations and specialists owing to its cost-effectiveness and minimal environmental disruption. Its use in wastewater treatment is becoming increasingly widespread because of rapid industrialization and urbanization. Heavy metal concentrations higher than 5 g/cm^3 pose major risks to both the environment and biological organisms. Effective treatment methods are needed for lead-contaminated soil and industrial effluent because lead has a negative impact on a range of animals and ecosystems. Aquatic plants like *Hydrilla verticillata, Eichornia crassipes* (water hyacinth), and *Lemna minor* (duckweed) are commonly used to remove lead from wastewater. These plants provide a cost-effective alternative to traditional treatment methods [29-31].

iv. Biosorption using chitin and chitosan/ Biopolymer-chitin and chitosan

Two crucial biopolymers that are required to remove pollutants from water are chitosan and chitin. These are plentiful, biodegradable biopolymers that provide inexpensive, green alternatives used for the biosorption of heavy metals from wastewater. In biosorption the importance of electrostatic interactions is often underestimated. To optimize biosorption processes and develop effective cleanup strategies, a thorough understanding of surface chemistry and metal ion adhesion to biopolymer surfaces is essential. These polymers offer exceptional mechanical and physical qualities in addition to being nontoxic, biodegradable, biocompatible, and bioactive. The electrostatic interactional behavior of functional groups that result in chitosan/chitin/cellulose composites—biodegradable adsorbents produced in an environmentally responsible manner with the use of ionic liquids—is also covered. The X-ray and infrared photoelectron spectra were used to demonstrate the strength of the hydrogen connection between chitosan and cellulose. This indicates that the metal ions are linked to the hydroxyl and amine groups. This chitosan-type adsorbent was made and assembled in a way that was unquestionably more ecologically friendly than some others.

2.2.2. Dead Biomasses from Argo-Wastes for Pollutant Removal

i. Agricultural residues (Crop residues, husks, and peels)

The triple growth in agricultural production that has taken place globally since the 1960s results in the generation of over one billion tons of agricultural waste annually. Poor handling of this waste can have negative effects on the environment, putting ecosystems and human health at risk as well as contaminating the air, water, and soil. Sustainable agriculture practices are essential to reducing these environmental effects since, by 2050, there will be more than ten billion people on the planet. One approach to solving this problem and promoting sustainable resource management and a circular economy is to value agricultural waste for the removal of contaminants. The use of agricultural waste as an affordable and environmentally friendly adsorbent to remove pollutants from wastewater has gained interest. Agricultural waste, husks, peels, and other byproducts are included. These waste products' unique chemical compositions, wide availability, renewable nature, and affordable price make them ideal for a range of wastewater treatment applications. Heavy metals, organic compounds (including insecticides, medications, and coloring agents), and other contaminants present in urban and industrial wastewater are commonly eliminated using agricultural waste.

Since these contaminants seriously affect the environment and public health, getting rid of them is a key priority in wastewater treatment systems. Unprocessed agricultural waste may naturally have sorption properties, although it has less absorption capacity than commercial adsorbents that are made. Several pre-treatment methods have been employed to improve their capacity to bind pollutants, including chemical and physical treatments. Chemical reagents like calcium hydroxide, sodium hydroxide, and organic acids are commonly used to modify agricultural waste to enhance its sorption properties and for effective pollutant removal. A range of wastewater treatment processes, including municipal wastewater treatment, industrial effluent treatment, and agricultural runoff remediation, have used adsorbents produced from agricultural waste. Utilizing agricultural waste offers a long-term option for pollutant removal as well as assistance with waste management and resource recovery. Since these adsorbents may be specifically engineered and tailored to target specific contaminants, they also provide versatility and economic viability in wastewater treatment applications. One workable approach to the environmental contamination issues associated with agricultural production is the valuation of agricultural waste with goal of eliminating contaminants.

The application of agricultural waste as a resource for wastewater treatment can help achieve goals related to sustainable development, promote the ideas of the circular economy, and minimize the negative impacts of pollution on ecosystems and human health. Continued research and development in this area are essential to optimize the use of agricultural residue and increase its effectiveness in removing contaminants from wastewater. Agricultural waste residues such as Shell, Leaves, Seeds, Sawdust, Husk, Bran, Peel, Miscellaneous (as miscellaneous dead biomasses) provide an abundant source of biomass for a variety of uses, including wastewater treatment. The accumulation of organic matter from leaves, seeds, and shells creates waste management issues, but these materials also have the potential to be used for environmental restoration. Miscellaneous dead biomasses, such as forest waste products like grouts and crumbs, contribute to the varied range of low-cost adsorbents used to cleanse water and wastewater. The use of agricultural residues, such as seed remnants and husks left on fields after crop harvesting, shows inventiveness in transforming waste into beneficial resources for water treatment [32-33].

ii. Food waste biomass

Biomass from food waste offers a viable treatment option for wastewater due to its availability and distinct chemical makeup. The potential of food waste management in addressing environmental concerns is becoming increasingly recognized, with the global market predicted to be worth USD 34.22 billion in 2019. Food waste not only wastes resources but also fuels societal problems like hunger that impact millions of people globally. Food loss points are highlighted during the production, transportation, and consumption phases, underscoring the necessity of effective management techniques. Food waste makes up a substantial portion of greenhouse gas emissions, which emphasizes how urgently sustainable solutions are needed. While tackling environmental issues, enacting new environmental legislation, and implementing circular economies can boost economic growth. We can reduce pollution and provide a more sustainable future for the future generations by using the biomass from food waste for wastewater treatment [34-35].

iii. Forest and wood residues (Sawdust, bark, and wood chips)

Wood and forest waste, such as wood chips, bark, and sawdust, offer unique and sustainable alternatives to wastewater treatment. Due to their unique properties, these residues—which are commonly generated by forestry operations and the manufacturing of wood—find application in the water treatment sector. Sawdust, a byproduct of wood manufacturing, is an effective adsorbent for pollutants in water due to its high surface area and porosity. Bark is a common residue that can aid in pollution removal and water absorption. Wood chips are formed from several types of wood and have a porous structure, making them ideal for wastewater treatment via filtration and biosorption. Studies have suggested that the use of forest residues for wastewater treatment offers promise due to their low cost and favorable environmental effects [36]. Researchers evaluated different types of wooden forestry residues as adsorbents and demonstrated their usefulness in water purification methods [37]. For example, Nigeria generates a large amount of sawdust and wood debris each year, which presents an opportunity to reduce environmental pollution by treating wastewater with them.

In a similar line, wood debris, including bark and logging residues, has been studied in Poland for its ability to absorb toxins from water sources. To characterize the suitability of forest residues for wastewater treatment, studies assessing the chemical composition and quality features of these materials have been conducted. These programs aim to maximize the use of forest wastes in water treatment applications [38]. Evaluating side-stream production from forest enterprises offers light on the types and quantities of wastes that are readily available for wastewater treatment. Despite potential benefits, there remain barriers to effectively utilizing wood and forest wastes in wastewater treatment processes. Reliability issues with residue processing, collection, and compatibility with existing treatment systems must be resolved. However, with proper management and technological advancements, forest residues can be valuable resources in environmentally friendly wastewater treatment programs. To summarize, wood and forest residues are feasible solutions for wastewater treatment, promoting resource efficiency and environmental sustainability. By leveraging the intrinsic properties of these residues, such as their biosorption capacity and porous architecture, innovative techniques to address water pollution concerns can be developed with success [39].

iv. Industrial by-products (Coconut shell, olive pomace, brewery waste)

Industrial byproducts such as coconut shell, olive pomace, and brewery waste offer considerable prospects for long-term resource utilization and economic generation, particularly in developing countries like Nigeria. Currently, these materials are frequently disposed of at a cost, causing environmental degradation and economic inefficiency. However, through inventive ways, these byproducts can be converted into important activated carbon adsorbents for a variety of industrial applications, including water and wastewater treatment [40-41].

v. Activated carbon from biomass

Activated carbon, obtained from materials such as coconut shell, is extremely effective at removing harmful organic compounds, smells, and taste contaminants from water and industrial effluents. Its porous structure and wide specific surface area make it an excellent material for purification, decolorization, solvent recovery, and pollutant removal. Manufacturing of activated carbon from industrial byproducts is a profitable commercial opportunity with the potential to create substantial cash [42]. Other agricultural leftovers and waste products, such as brewery waste and olive pomace, show promise for activated carbon generation, thereby improving resource efficiency and waste management methods. The use of these byproducts to produce activated carbon adheres to the principles of circular economy and sustainable development, reducing environmental pollution while gaining value from waste. Locally produced activated carbon minimizes reliance on expensive imports, promoting economic growth and self-sufficiency in water treatment and industrial uses [43].

Through research and innovation, ideal production methods and process parameters can be established to maximize the efficiency and effectiveness of activated carbon production from industrial byproducts.

Developing countries may address environmental issues, boost economic development, and contribute to global sustainability initiatives by tapping into the potential of these resources. The manufacture of activated carbon from biomass sources such as coconut shells, wood, and agricultural leftovers has received a lot of interest because of the growing demand for water treatment and purification solutions. These renewable materials provide a more sustainable alternative to conventional activated carbon generated from non-renewable sources. Despite their vast availability and carbon-rich nature, issues like low strength and attritional resistance remain[44]. However, recent advancements in production techniques have addressed some of these constraints. The research focuses on optimizing granulation settings, investigating alternative activation methods, and understanding the biosorption mechanisms to improve the effectiveness of biomass-derived activated carbon in water treatment. Future developments in this subject will require more research into sustainable manufacturing methods and the biosorption behavior of new pollutants [45].

vi. Fruit Peels (Orange peel, banana peel)

Fruit peels, such as those from oranges and bananas, are emerging as valuable bio resources for a variety of environmental applications, including wastewater treatment. These agricultural wastes, formerly thought to be trivial byproducts, are increasingly recognized for their potential in water filtration due to their widespread availability and bio sorption capabilities. Research has shown that fruit peels have bio sorption mechanisms that can effectively remove heavy metals and colors from water. The use of fruit peels as natural coagulants, bio-adsorbents, and even sources of activated carbon synthesis, showed their wide range of applications in water treatment. Fruit peel valuation helps not only to purify water but also to promote sustainable waste management techniques [46]. Fruit waste can be converted into useful adsorbents such as activated carbon or bio char, can be used to remove contaminants from wastewater in an environmentally beneficial manner. Use of fruit peels to remove dye and adsorb metal ions demonstrates their potential as low-cost & effective industrial effluent treatment options. In water-scarce locations, such as Pakistan, where access to safe drinking water is limited, use of fruit peels in wastewater treatment offers a solution to water quality issues. Laboratory studies & research projects targeted at improving the treatment efficiency of fruit peels for home grey water highlight practical implications of using these bio resources for large-scale water purification. Overall, incorporating fruit peel-based bio sorption techniques into water treatment systems shows great promise for enhancing environmental sustainability and resolving water pollution issues [47].

vii. Plant and Animal Solid Waste Adsorbent

Plant and animal solid waste adsorbents offer a solution to waste disposal concerns while also addressing water contamination issues. These abundant and renewable waste resources are frequently disregarded, despite their high potential for reuse. Plant-derived waste, which contains cellulose, lignin, proteins, hemicellulose, sugars, lipids, and starch, has been found to successfully remove PACs (persistent organic pollutants) from water. The concentration of PACs in water influences biosorption capacity, with larger concentrations often resulting in increased capacity [48]. However, studies frequently use synthetic PAC solutions at higher concentrations than those found in natural environments, emphasizing the importance of conducting research at lower, more realistic levels. Adsorbents can have both biosorption and degradation capabilities, with modifications such as chemical treatments and the addition of nanomaterials improving their efficacy.

Researchers found that pretreatment fish bones from bluefish (*Pomatomus saltotrix*), bogue (*Boop boops*), European anchovy (*Engraulis encrasicolus*), and gilthead seabream (*Sparus aurata*) are effective low-cost adsorbents. Animal waste, such as fish bones, crab shells, and cow dung, has shown promise as adsorbents due to its abundance, low cost, and eco-friendliness, making it an appealing option. The use of waste materials for water treatment is important for sustainable practices in addressing environmental challenges [49-50]. Plant and animal solid waste are easily available, inexpensive, and renewable resource materials. They are manufactured in vast quantities each year and are typically difficult to dispose of. Finding relevant applications for these materials is an important field of research [51-52]. Making use of these waste materials can assist in minimizing waste while also producing commercially viable products [68-69]. Plant-derived wastes are mostly constituted of cellulose, with lignin, proteins, hemicellulose, carbohydrates, lipids, and starch acting as structural components [53-70].

2.2.3. Biopolymer-based Porous Carbon Adsorbents

i. Alginate-based Adsorbents

Alginate, an anionic linear polysaccharide with two monomeric units, β-D-mannuronic acid (M) and α-L-guluronic acid (G), is commonly used to create hydrogels due to its structural diversity and capacity to include other adsorbents. Several applications for the removal of contaminants from water have previously been developed using alginate immobilization systems. Because of their unique structural features and capacity to integrate a variety of adsorbent materials, alginate-based adsorbents have emerged as a promising alternative for pollutant removal in water. By mixing alginate with lignocellulosic materials such as lignin and olive pomace, innovative hybrid biopolymers with increased biosorption capabilities can be created, providing benefits from both components. These hybrid adsorbents are prepared using the ionotropic gelation process, which allows for adsorbent tuning by integrating variable percentages of low-cost agro-industrial ingredients. In response to increased concerns about heavy metal contamination, alginate and chitosan derivatives have gained favor as adsorbents for water treatment.

Grafting, functionalization, copolymerization, and cross-linking have all been investigated as ways to improve their bio sorption properties. These improvements increase the physical strength and thermo stability of alginate-based polymers, making them more effective at removing heavy metal ions from aqueous solutions. Several studies have looked at the biosorption mechanisms of alginate-based composites for the removal of heavy metals such as Cu (II), Pb (II), and Cd (II). These composites improve bio sorption performance and can be customized to individual application requirements. Furthermore, alginate-based adsorbents are more abundant, renewable, and selective for contaminants than other materials such as activated carbon or zeolites. Functionalized alginate adsorbents, such as alginate-biuret and alginate-urea, show high metal ion bio sorption capabilities, including Ni (II) and Zn (II). The inclusion of second components in the polymer chain improves functionality and mechanical strength, which are critical for adsorbent recyclability.

ii. Innovative modifications with alginate

Innovative modifications, such as the combination of alginate and polyethyleneimine, have demonstrated promising results in heavy metal removal from aqueous solutions. The development of alginate-based composites and their modifications as heavy metal adsorbents in aqueous media is a rapidly evolving subject of study. Through comprehensive characterization and assessment, these adsorbents provide efficient & cost-effective water filtration solutions that solve the problems faced by hazardous contaminants in industrial effluents and wastewater. Continued investigation and development of alginate-based adsorbents holds great promise for future sustainable water treatment systems. Alginate-based adsorbents have received a lot of attention for their performance in wastewater treatment applications. These adsorbents produced from alginate show promising bio sorption capacities for a variety of pollutants found in wastewater. Recent research has investigated unique techniques for improving the efficacy of alginate-based adsorbents.

For example, the development of sericin and alginate particles has proven effective in extracting precious metals from wastewater. Alginate-based bio-composite materials, particularly low-cost adsorbents like alginate-based bio-composite beads, have been proven useful in wastewater remediation. Development of magnetic alginate-based adsorbents has opened possibilities for the treatment of anionic organic pollutants in wastewater. The use of alginate-based adsorbents derived from seaweed and other natural sources has shown promise for adsorbing metal ions and radionuclides from aqueous solutions. Recent advances in alginate-based nano adsorbent materials demonstrate their promise for bioremediation of environmental contaminants. These studies demonstrate the adaptability and usefulness of alginate-based adsorbents in tackling wastewater treatment difficulties. Adsorbents have been created in a variety of ways, including droplet polymerization and immobilization procedures employing calcium ions and modified sludge biomass. Alginate-based adsorbents have shown exceptional biosorption capacities for the removal of direct dyes, heavy metals (such as copper, cadmium, and lead), and other pollutants from wastewater. These adsorbents have been used in a variety of applications, including the treatment of industrial wastewater, metal plating effluents, acid mine drainage, and ammonia and phosphorus removal in aquaculture systems.

Cross-linking, composite synthesis with other materials such as hydroxyapatite or sepiolite, and the incorporation of magnetic characteristics have all been investigated as ways to improve the effectiveness and adaptability of alginate-based adsorbents. Studies have also focused on the regeneration and reuse of these adsorbents, ensuring their long-term viability and cost-effectiveness across numerous cycles of use. Comparative studies have been done to evaluate the efficacy of alginate-based adsorbents against other materials such as ion-exchange resins, activated carbon, and chitosan-based adsorbents, with results indicating competitive or higher bio sorption capabilities. The ongoing research aims to optimize fabrication techniques, improve mechanical qualities, and investigate innovative formulations to improve the performance of alginate-based adsorbents for wastewater treatment and environmental remediation. Overall, alginate-based adsorbents offer considerable potential as long-term and efficient solutions to water pollution problems, with current research pushing their further development and application in a variety of scenarios.

iii. Carrageenan-based adsorbents

Carrageenan-based adsorbents have emerged as a viable alternative for wastewater treatment, taking advantage of the unique features of this natural polymer generated from seaweed. These adsorbents provide significant advantages, making them suitable for a wide range of water remediation applications. Primarily, carrageenan-based adsorbents effectively remove pollutants from wastewater. These contaminants include heavy metals, organic dyes, medicines, and other pollutants. Studies have repeatedly demonstrated that carrageenan-based adsorbents have significant biosorption capabilities, successfully lowering pollutant concentrations in water to satisfy regulatory criteria. One major advancement in this sector is the creation of magnetic carrageenan-based adsorbents [54]. Researchers have developed compounds that can be easily extracted from water using magnetic separation techniques by adding magnetic nanoparticles or carbon dots into carrageenan matrices. This property increases the adsorbents' reusability, making them more practical and cost-effective for large-scale wastewater treatment applications. Carrageenan-based adsorbents use is an environmentally friendly and long-term solution for wastewater treatment. These adsorbents, derived from natural sources, are biocompatible and environmentally benign, making them an appealing alternative to traditional treatment procedures that use synthetic ingredients.

This element is consistent with the expanding global emphasis on sustainable practices and the shift to eco-friendly solutions in a variety of industries. Carrageenan-based adsorbents have also been coupled with other biopolymers or nanomaterials to produce composite materials with superior biosorption and durability [55]. Chitosan-crosslinked carrageenan bio nanocomposites and alginate-carrageenan hybrid shells, for example, have increased water contaminant removal performance. These synergistic combinations demonstrate carrageenan-based adsorbents' versatility and adaptability to solve a wide range of wastewater treatment difficulties. Carrageenan-based adsorbents have potential applications in a variety of industries, including water treatment, medicines, textiles, and agriculture. Their ability to remove toxins from wastewater makes them valuable tools for ensuring water quality and environmental sustainability across a variety of industries. Continued research in the field of carrageenan-based adsorbents has the potential to advance wastewater treatment technology while also tackling the serious global concerns of water pollution. Researchers can help to make the environment cleaner and healthier for present and future generations by utilizing carrageenan's natural qualities [56].

iv. Starch-based adsorbents

Starch-based adsorbents have emerged as attractive water treatment materials due to their ubiquitous availability, low cost, and eco-friendliness. These adsorbents have received attention for their ability to efficiently remove a variety of pollutants from water, so contributing to pollution control and environmental preservation. Modified starch flocculants have been created to improve their effectiveness in water purification by overcoming the limitations of existing inorganic and synthetic polymeric flocculants. Starch-based flocculants' structural qualities, such as chain topologies and charge properties, have a significant impact on their flocculation efficiency [57-58]. Different types of starch-based flocculants, such as linear, grafting/branching, and star-like structures, perform differently in applications, emphasizing the need of understanding structure-activity connections when designing high-performance flocculants. The invention of starch-based hydrogel microspheres via spray drying provides an efficient way for water treatment applications by combining abundant raw materials with easy production scalability. Furthermore, starch-based flocculants show potential in combination flocculation processes with other coagulants, improving efficiency of removing contaminants such as humic acid from water. Overall, starch-based adsorbents are a sustainable and effective solution for water pollution reduction, taking advantage of polysaccharide's unique features to develop environmentally friendly water treatment solutions [59-60].

v. Cellulose-based Adsorbents

Cellulose-based adsorbents have emerged as potential materials for tackling environmental contamination issues, particularly in water and wastewater treatment. These adsorbents, generated from abundant and renewable cellulose sources, provide an environmentally benign option for removal of different pollutants from aqueous solutions. Cellulose's unique qualities, such as its large surface area, biodegradability, and abundance in nature, make it an appealing choice for bio sorption applications. Researchers have concentrated on separating cellulose nanofibers from agricultural byproducts such as banana peels, soy hulls, wheat straw, and maize husks, to mention a few. These agricultural byproducts not only provide a renewable source of cellulose, but they also help to address environmental concerns related to waste disposal [61]. Development of cellulose nanofiber-based composites, particularly with polysaccharides such as starch, has yielded encouraging results in terms of mechanical and barrier properties, making them appropriate for a wide range of environmental remediation applications.

The use of cellulose-based adsorbents emphasizes the relevance of sustainable and green technology in tackling water pollution issues, helping to preserve freshwater resources for future generations[62]. Polysaccharides are natural biopolymers formed by living organisms and consist of repeated monosaccharide units ($C_n(H_2O)_n$) [63]. They are regarded as sustainable and environmentally favorable materials. Examples include chitin/chitosan, cellulose, starch, pectin, alginate, guar gum, and xanthan gum. Among these, cellulose is the most common biopolymer on Earth. Chitosan, the second most prevalent, is highly valued for a variety of environmental uses. This study discusses the current advances in leveraging natural biopolymer resources to remediate and eliminate contaminants from aquatic settings [64].

vi. Gelatin-based Adsorbents

Gelatin-based adsorbents have emerged as a viable alternative for eliminating contaminants from diverse industrial wastewater streams, such as those from textile, plastic, paper and pulp, printing, culinary, tannery, cosmetic, mineral processing, and chemical facilities. These companies frequently discharge contaminants, particularly colors, into wastewater, causing serious environmental concerns. Dyes, including cationic, anionic, and non-ionic forms, are notoriously difficult to biodegrade due to their complex structures, thus their removal is a top concern. Bio sorption is a simple yet effective method for dye removal that has been investigated [65]. Gelatin, generated from collagen, has various advantages, including biodegradability and hydrophilicity; nevertheless, its low mechanical qualities and quick disintegration in moist circumstances limit its application.

However, by reinforcing gelatin with carbon nanotubes (CNTs), its mechanical characteristics can be increased, and its degradation rate reduced, making it more suitable as an adsorbent. Furthermore, the introduction of magnetic nanoparticles (MNPs) into gelatin-CNT composites allows for facile separation from solution by magnetic separation techniques, surpassing limitations of traditional filtration and centrifugation methods. This study focuses on the synthesis of nanocomposite beads made of gelatin, CNTs, and MNPs with strong saturation magnetization characteristics, demonstrating their potential as anionic and cationic dye adsorbents. This study intends to help design efficient wastewater treatment solutions by assessing the sorption process under various parameters such as contact time, temperature, and initial dye concentration.

vii. Chitosan -based Adsorbents

The extensive contamination of water bodies with heavy metal ions, which poses serious risks to human health and the environment, has motivated the development of effective remediation solutions. Chitosan-based adsorbents are particularly promising because of their abundance, low toxicity, and varied chemical characteristics. Chitosan, generated from chitin, has a high affinity for heavy metal ions, making it useful in wastewater treatment applications. The importance of chitosan-based adsorbents in tackling heavy metal pollution, particularly their role in bio sorption methods for removing harmful pollutants from aqueous solutions [66-68].

3. Pretreatment Methods

3.1 Physical Pretreatment Techniques

Physical pretreatment procedures are critical phases in the pretreatment of biomass to improve the quality and yield of pyrolysis products. Grinding and milling, pyrolysis, carbonization, ultra sonication, and heat treatment are some of the important processes. Grinding and milling are required to ground the biomass feedstock and achieve high-quality pyrolysis product yields. It is a pricey and resource-intensive technique that consumes a large amount of energy. During pyrolysis, decreasing the feedstock size reduces polymerization and crystallinity of biomass components while boosting heat transfer between substrates[69]. The yield and content of bio-oil are significantly impacted by particle size. Smaller particles boost bio-oil yield by allowing for more efficient heat transmission, whereas larger particles produce charring rather than volatile formation. The composition of bio-oil compounds is similarly affected by particle size; with lower particle sizes, lighter compounds increase while heavy compounds decrease. Particle size influences the physical properties, energy content, biomass pyrolysis behavior, and organic content of bio-oil. Heating smaller particles uniformly produces more bio-oil than heating larger particles unevenly.

The effect of particle size on bio-oil yield varies with temperature, heating rate, biomass type, and other variables. The type of reactor used in the pyrolysis process determines the optimal particle size [70]. Pyrolysis and carbonization entail heating biomass in the absence of oxygen to generate bio char, bio-oil, and syngas. They are critical steps in turning biomass into lucrative goods and can help improve biofuel efficiency and quality. Ultra sonication is the use of high-frequency sound waves to alter biomass structure. It can improve enzyme accessibility to biomass substrates, resulting in higher enzymatic hydrolysis efficiency. Ultra sonication is used to reduce lignocellulosic biomass to smaller particles, which aids in subsequent processing procedures. Heat treatment includes heating biomass at high temperatures to change its structure and qualities. It can increase biomass digestibility, decrease recalcitrance, and improve enzymatic hydrolysis efficiency. Heat treatment is used to remove moisture, volatile components, and hemicellulose from biomass, which increases biofuel output. It can also improve the energy density and stability of biomass feedstock, making it better suited for biofuel production [71].

Wet torrefaction (WT) is a biomass treatment method that utilizes hydrothermal media or hot compressed water. To keep water in the liquid phase, WT is commonly conducted at temperatures ranging from 180 to 260 °C while under pressure. The procedure produces solid hydrochar, gases, and liquid products. Which have major portion of energy and mass of raw biomass. WT alters biomass composition, reducing hemicellulose content while increasing cellulose and lignin content, which effects subsequent pyrolysis. Studies show that WT affects biomass characteristics and pyrolysis kinetics. Variations in WT conditions influence biomass composition and pyrolysis products. Other media used for WT include HCl, acetic acid, and aqueous ammonia, which improve fuel characteristics and biochar quality. Ammonia fiber expansion (AFE) is another pre-treatment approach that improves biomass characteristics, influencing biomass structure and biofuel production. However, its impact on biomass pyrolysis and bio-oil composition needs more investigation [72-73].

3.2. Chemical Pretreatment Techniques for Adsorbents

Chemical pretreatment techniques are frequently used to improve the efficiency of adsorbents by eliminating contaminants from their surfaces and increasing the number of biosorption sites available. Several approaches are used for this aim. Acidic and alkaline treatment involves treating adsorbents with acids (e.g., H2SO4, HCl, HNO3) or bases (e.g., KOH, NaOH) to eliminate contaminants and boost biosorption capacity [74-75].

3.3. Biological Pretreatment Techniques

Biological pretreatment approaches present promising opportunities for removing antibiotics from wastewater by utilizing natural processes to breakdown or eliminate pollutants. Enzymatic therapy, microbial fermentation, biochemical transformation, and phytoremediation are some of the most effective procedures. Enzymatic therapy is the employment of enzymes to degrade antibiotics into simpler molecules. Algae have stress response mechanisms that enable the enzymatic breakdown of antibiotics, ensuring their survival. Enzymatic degradation has been used by algal species such as Chlamydomonas sp. Tai-03 to completely remove drugs such as tetracycline. This approach uses algae's enzymatic activity to catalyze the degradation of antibiotics into non-toxic metabolites. Microbial fermentation uses microbial metabolism to convert complex organic molecules, such as antibiotics, into simpler ones. Algae-bacteria consortiums have been studied for their potential to breakdown antibiotics in wastewater [76]. Synergistic effects are achieved by combining algae with bacteria, which leads to increased antibiotic breakdown. For example, Chlorella sp., coupled with isolated bacterial strains, efficiently degraded ketoprofen. Biochemical transformation is the conversion of complex chemicals into simpler molecules via metabolic processes.

Algal-mediated biodegradation is an important process for removing antibiotics from wastewater. Several algae species have been demonstrated to metabolize antibiotics such as ciprofloxacin, erythromycin, and azithromycin, converting them into non-toxic forms. This approach uses algae's metabolic activity to convert antibiotics into harmless components. Phytoremediation uses plants to absorb, digest, or detoxify pollutants from the environment. Algal biochar, generated from algae, has emerged as a viable sorbent for removing antibiotics from water [77]. Algal biochar has a high surface area and porosity, which allows for effective antibiotic biosorption. The inclusion of elements like iron salts or fertilizers can improve the antibiotic removal capacity of algae-based systems. Finally, biological pretreatment techniques provide long-term and successful options for removing antibiotics from wastewater. These approaches, which use the enzymatic, metabolic, and sorption properties of algae and other microorganisms, show considerable potential for reducing antibiotic pollution in aquatic ecosystems. Additional research and development in this sector are required to optimize and scale up these biological treatment technologies for practical use in wastewater treatment plants [78].

4. Effects of Pretreatment on Biosorption Capacity

Pretreatment plays a significant role in improving the biosorption capability of materials utilized for pollution removal. Several effects can be noticed upon pretreatment. Pretreatment methods, such as physical or chemical treatments, might lead to an increase in the surface area of the adsorbent material. This increase allows for more active sites available for pollutant biosorption, hence boosting the overall biosorption capacity. Pretreatment procedures can also boost the porosity of the adsorbent material, creating more room for pollutant molecules to adsorb onto surface. Increased porosity promotes greater absorption of contaminants into adsorbent, therefore boosting efficacy of biosorption process. Pretreatment can modify surface functional groups of adsorbent material, making them more receptive to pollutant biosorption [79]. This alteration can involve introducing or boosting certain functional groups that have a high affinity for target contaminants, thereby raising biosorption capability. Pretreatment procedures can boost accessibility of active sites on adsorbent material, guaranteeing, pollutants can easily interact with and bind to these sites. Enhanced accessibility boosts the effectiveness of pollution removal and increases biosorption capacity. In summary, pretreatment of adsorbent materials results in enhanced surface area, increased porosity, modification of surface functional groups, and improved accessibility of active sites, all of which collectively contribute to higher biosorption capacity & more efficient removal of environmental pollutants [80-81].

5. Biosorption Mechanisms

Biosorption is a fundamental biological physico-chemical mechanism applied for the removal of target species like metal ions or dyes from aqueous solutions. This process involves the interaction between a solid phase, known as the adsorbent, and a liquid phase containing the target species, referred to as the sorbate. Common adsorbents include algae, bacteria, fungi, and plants, with their cell walls serving as the major site for biosorption. Some predominant mechanisms are complexation, chelation, coordination, precipitation, and reduction. Complexation includes the creation of coordination complexes between the adsorbent and the metal ions present in the aqueous solution. Functional compounds such as hydroxyl, carboxyl, amino, ester, sulfhydryl, carbonyl, and phosphate groups present in the adsorbent's cell wall help this process [82]. Chelation is a specific sort of complexation where numerous coordination sites on the adsorbent simultaneously bond to a metal ion, generating a ring-like structure known as chelate. This improves the stability of the metal-adsorbent combination. Coordination involves the direct coordination of metal ions with certain functional groups found in the adsorbent's cell wall, such as hydroxyl and amino groups.

This coordination can occur through lone pair-electron interactions. Ion exchange happens when metal ions in the aqueous solution replace ions of similar charge bound to the functional groups on the adsorbent's surface. This mechanism is regulated by parameters, including pH and the concentration of competing ions [83]. Precipitation entails the development of insoluble metal complexes on the surface of the adsorbent due to chemical interactions between metal ions and functional groups. This leads to the elimination of metal ions from the aqueous phase. Reduction involves the enzymatic or chemical reduction of metal ions to lower oxidation states by functional groups contained in the adsorbent's cell wall. This process can result in the immobilization of metals in a less hazardous state. Biosorption capacity, determined by criteria like equilibrium time and biosorption capacity values, is significant in determining the success of biosorption processes. Biosorption capacity refers to amount of metal ions adsorbed per unit mass of adsorbent under specified conditions. Analytical approaches such as titration, infrared spectroscopy (IR), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), energy-dispersive X-ray spectroscopy (EDS), and X-ray absorption fine structure spectroscopy applied to explore the functional groups contributing to biosorption [84].

6. Applications of adsorbents for the removal of pollutants

Biosorption, the process by which biological materials such as agricultural waste, plant residues, and microbial biomass are exploited to remove contaminants from water, has attracted substantial interest in recent years due to its effectiveness, cost-efficiency, and eco-friendliness. One area where biosorption has shown promising results is in the removal of numerous pollutants, including heavy metals, dyes, polycyclic aromatic hydrocarbons (PAHs), oils, and the simultaneous removal of many contaminants. Heavy metal pollution in water bodies owing to industrial and agricultural activity poses a substantial hazard to both aquatic ecosystems and human health [85]. The textile business generates huge quantities of effluent containing synthetic colors, which are detrimental to the environment. PAHs are persistent organic pollutants with major environmental concerns due to their resistance to degradation. Oil spills pose a tremendous threat to marine ecosystems, necessitating efficient cleanup procedures. Industrial effluents may contain numerous contaminants, requiring simultaneous removal for successful wastewater treatment. Real-world uses of adsorbents require treating wastewater containing complicated combinations of contaminants [86]. Adsorbents have developed as excellent tools for the removal of various pollutants from contaminated water sources, offering sustainable and eco-friendly solutions to environmental remediation concerns.

Activated carbon derived from palm kernel shells and coffee husk bio char, for instance, has demonstrated successful removal of heavy metals such as Cd (II), Pb (II), and Cr (VI) through modifications aimed at enhancing their biosorption capacities, with factors like pH playing pivotal roles in the biosorption process. Mechanisms such as electrostatic interactions, surface complexation, and reduction are implicated in heavy metal biosorption by these adsorbents. Similarly, adsorbents like banana peels, watermelon rind-based activated carbon, and modified bamboo bio char have shown effectiveness in removing both anionic and cationic dyes from wastewater, with electrostatic interactions, hydrogen bonding, and π-π interactions serving as key biosorption mechanisms [87-88]. Adsorbents derived from coconut shells and pinewood sawdust have been utilized for the removal of polycyclic aromatic hydrocarbons (PAHs), with biosorption capacities varying based on PAHs' molecular weights and mechanisms primarily involving π-π interactions and hydrophobic interactions.

Moreover, adsorbents produced from fish scales, maize stalk pith, and nettle fiber assembly have shown high oil biosorption capabilities, through physical adhesion by van der Waals force and hydrophobic interactions. Notably, adsorbents have been studied for their potential to simultaneously remove different contaminants, including dyes, heavy metals, & PAHs, showing encouraging results with high removal efficiencies [89]. Adsorbents produced from banana peels, *Parthenium hysterophorus*, and *Tinospora cordifolia* have proven successful in removing contaminants from actual industrial effluents, indicating their potential for practical applications in industrial wastewater treatment. In conclusion, biosorption offers a diverse and sustainable technique for contaminant removal from wastewater. With continued research and development efforts, adsorbents continue to improve as effective tools for environmental remediation, meeting critical need for sustainable water treatment solutions [90-91].

7. Establishing the relationship between biomass properties and functional groups

The link between biomass qualities and functional groupings can be determined using Pearson correlation and regression analysis. In reported research on rice straw-derived biomass, pH correlated negatively with aliphatic O-alkylated (HCOH) carbons and anomeric O-C-O carbons but positively with fused-ring aromatic structures and aromatic C-O groups. The electrical conductivity (EC) of rice straw biomass is negatively correlated with aliphatic O-alkylated carbons but positively correlated with fused-ring aromatic structures and aromatic C-O groups. Similarly, in rice bran-derived biomass, pH is associated negatively with aliphatic O-alkylated and anomeric O-C-O carbons but favorably with fused-ring aromatic structures and aromatic C-O groups. Regression analysis revealed fused-ring aromatic structures and anomeric O-C-O carbons had significant effects on pH for rice straw biomass, whereas fused-ring aromatic structures and aliphatic O-alkylated carbons had an impact on rice bran biomass.

These findings highlight the importance of functional groups in regulating the pH and EC of biomass, offering insights into tailored biomass synthesis and applications. Functional groups play an important role in the biosorption of heavy metals and contaminants by biomass materials. Hydroxyl groups, which widely found in cellulose and lignocellulosic materials, help to create chemical bonds or coordinate interactions with ions, increasing biosorption capacity and selectivity. Biomass materials have numerous functional groups such as hydroxyl, amino, and carboxyl groups, allowing them to preferentially adsorb ions from multi-ionic systems, hence enhancing enrichment and separation efficiency. Biomass materials include a variety of physical properties, such as porosity and high surface area, which provide a large number of biosorption sites and routes. These properties improve biosorption capacity and response rates, making biomass materials useful adsorbents for a variety of contaminants.

Biomass materials are renewable, environmentally benign, cost-effective, and widely available, making them attractive candidates for biosorption applications when compared to other adsorbents. Uranium enrichment and separation using biomass functional materials has made substantial progress, with studies looking into microbial materials, plant & household biomass, biopolymer materials, and biomass carbon. Environmental elements that influence biosorption efficiency have examined, as well as practical applications and future research initiatives, with goal of inspiring further advancement in materials and environmental remediation domains. Carboxyl groups, which are abundant in biomass sources such as algae, play an active role in biosorption processes,involve mechanisms such as passive electrostatic attraction, ion exchange, & metal complexation. Studies have shown that metal ions may be effectively removed from aqueous solutions utilizing a variety of biomass sources, including agricultural and food sector bio wastes, fungal biomass, and algal biomass, demonstrating potential of biomass materials in environmental remediation.

7.1. Mechanism of Pollutants Biosorption on Adsorbents

SOP biosorption on adsorbents involves a variety of physical and chemical interactions, including van der Waals forces, hydrogen bonding, electrostatic forces [92] and weak intermolecular connections. Studies have demonstrated that FTIR analysis, SEM, XRD, biosorption energy models, pH, contact time, dose, and aqueous solution concentration all play important roles in determining the biosorption process. In addition, mechanisms such as partition, diffusion, cation exchange, hydrogen bonding, &electrostatic forces are used to explain biosorption. For example, elimination of pollutants with chitosan revealed changes in amide and amine groups, showing electrostatic interactions with the pollutants. Studies consistently reveal, partition mechanism dominates SOP elimination by adsorbents, as evidenced by sorption isotherm measurements. E.g., as evidenced by research on removal of phenol by chitin and polycyclic aromatic hydrocarbons (PAHs) by plant residue adsorbents. Electrostatic force of attraction, London dispersion force, and Debye force are 3 major contributors to biosorption processes.

Electrostatic interactions, whether strong in chemisorption or weak in physisorption, are defined by the attraction of opposing charges on the functional groups of the adsorbent and bio sorbate [93-94]. London dispersion force (dipole-induced dipoles interaction) caused by fluctuating dipole-induced dipole interactions, come from non-zero instantaneous dipole moments in atoms and molecules, making them the most important component related to all materials' polarizability [95]. Debye (permanent-induced dipoles) force is created when a molecule with a permanent dipole generates a dipole in an adjacent molecule through interactions between permanent dipoles and the polarizability of atoms and molecules. These forces play an important role in regulating the type and strength of interactions between adsorbents and bio sorbates, which influences the overall biosorption process [39].

7.2 Surface Modification Techniques to Enhance Biosorption Efficiency Acid Treatment

Acid treatment increases the positive charge on the adsorbent surface, which improves selectivity for metal oxyanions but decreases it for metal ions. In contrast, base treatment raises negative charge on surface, resulting in better selectivity for metal cations due to electrostatic attraction [96-97]. Base Treatment: Bases also introduce hydroxyl groups, which enhance biosorption ability. In oxidation-reduction processes, the Fenton method includes treating adsorbents with a solution of hydrogen peroxide and ferrous ions [74]. This method eliminates contaminants, expands biosorption sites, and oxidizes the adsorbent surface, hence improving metal binding functional groups. While effective, hydrogen peroxide's harmful nature limits its widespread use [75-98]. Chemical modification using functional groups: Chemical modification involves adding functional groups to adsorbents to improve their biosorption capabilities.

This approach improves the selectivity and affinity of adsorbents for certain metals [99-100]. Chelation and Complexation: Chelating or complexing substances are sometimes employed to improve adsorbents' ability to bind metals. These agents generate stable complexes with metal ions, increasing the biosorption capability of the material. Chemical pretreatment procedures are critical to improving the efficacy of adsorbents for metal removal applications. However, several chemical therapies have significant downsides, such as bulk loss and toxicity. Physical procedures such as thermal treatment can also be used for adsorbent pretreatment because they are simple and effective at eliminating contaminants [70-101]. Nanoparticle Incorporation: Integration of nanoparticles to improve biosorption properties [102-103].

7.3 Parameters of Biosorption

7.3.1. pH of the solution Temperature and Contact time

Optimizing parameters including pH, temperature, contact time, and adsorbent dosage can boost biosorption ability. The choice of adsorbent should examine characteristics including biosorption capability, removal efficiency, sustainability, and the possibility of regeneration and reuse. [104]. In summary, knowing the mechanisms and improving the conditions of biosorption processes is vital for effectively removing heavy metals from aqueous solutions, contributing to environmental remediation efforts, and safeguarding human health [105-107].

7.3.2. Biosorption Isothermal Study

Isotherm studies use equilibrium data to study the biosorption process. Several isotherm models are employed, including Langmuir, Freundlich, Sips, and Redlich-Peterson. The Langmuir isotherm is often employed for biosorption because it fits experimental data well. The Langmuir model predicts that biosorption sites on the adsorbent surface are equivalent, resulting in a single layer of adsorbate. However, the Freundlich model implies a heterogeneous surface with different affinities for the adsorbate. Both models have successfully described the biosorption isotherms of Ni (II) ions on various adsorbents.

7.3.3. Biosorption Kinetic Study

Kinetic studies offer data on the biosorption rate and time required to reach a specific clearance percentage. The pseudo-second-order model is extensively used for heavy metals biosorption kinetics, showing a chemical bonding mechanism between heavy metals ions and biosorption sites. This method involves electron sharing or exchange b/w adsorbent and adsorbate. While pseudo-first-order model is simpler and more often employed, it may not fully describe entire biosorption process. Despite its shortcomings, several researchers have used pseudo-first-order model to investigate heavy metals ion biosorption kinetics, particularly during the earliest stages of biosorption processes. Overall, isotherm and kinetic studies provide critical insights into biosorption behavior of biomass for heavy metals such as heavy metals, allowing for optimization of biosorption methods for practical applications in water treatment. Kinetics of metal removal by adsorbent and biomass (time of removal): Rates of particulate matter (PM) and heavy metal removal by adsorbents and biomass are regulated by metal ion transport from bulk solution to sorption sites on biomass material's surface. This transfer process involves 2 basic mechanisms: intra particle diffusion within sorbents and film diffusion in surrounding aqueous phase, referred to as mass transfer. Among these mechanisms, intra particle diffusion is frequently regarded as rate-limiting stage of sorption. As a result, regulating intra particle diffusion is critical for increasing efficacy of metal removal by adsorbents and biomass [108-109].

8. Potential methods of characterization

Characterization approaches are critical in understanding the structure and characteristics of biomass-based adsorbents & membranes, allowing for more effective usage and for Elucidating the Role of Functional Groups in Biomass Materials (Hydroxyl Groups, Common in cellulose and lignocellulosic materials [69], Carboxyl Groups: Present in various biomass sources, including algal biomass [110-111], Amino Groups: Found in microbial biomass and certain agricultural residues [112-113] and Phenolic Groups: Abundant in wood-derived biomass [114]. Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDX), Brunauer-Emmett-Teller (BET) analysis, X-ray diffraction (XRD), Raman spectroscopy, thermogravimetric analysis (TGA), X-ray photoelectron spectroscopy (XPS), and transmission electron microscopy (TEM) are all common characterization techniques. Fourier transform infrared (FTIR) spectroscopy: This technique is used to identify functional groups on the surface of biomass-based adsorbents and membranes. It gives information on chemical bonding and molecular structure, which can be used to identify potential interaction sites with adsorbates or pollutants.

8.1 Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDX)

SEM provides a thorough analysis of the surface morphology and microstructure of biomass-based materials. EDX analysis offers elemental composition information, which is critical for understanding the chemical makeup of adsorbents and membranes. Brunauer-Emmett-Teller (BET) Analysis: BET analysis is used to calculate the specific surface area and pore size distribution of biomass-derived materials. This information is critical for determining biosorption capacity and surface accessibility for adsorbates.

8.2. Scanning electron microscopy (SEM) and energy-dispersive X-ray microanalysis (EDAX)

SEM with EDAX is used to examine the surface morphology and elemental content of the adsorbent material. Microscopic surface images and EDAX spectra are obtained with a scanning electron microscope equipped with an energy-dispersive X-ray micro analyzer.

8.3. X-ray diffraction analysis

X-ray diffraction (XRD) is a technique used to determine the crystalline phases in biomass-derived materials. It aids in understanding the structural features of materials, which is especially useful for applications involving crystalline compounds or composites.

8.4. Raman Spectroscopy

Raman spectroscopy reveals molecular vibrations and structural properties of biomass-based materials. It enhances FTIR analysis by providing information on chemical bonding and composition [115-116].

8.5. Fourier transforms infrared analysis

FTIR analysis is useful in identifying functional groups implicated in lead (II) sorption. It offers information on the chemical properties of the biomass prior to and following sorption. FTIR spectra are recorded using FTIR equipment, with materials produced as KBr discs, in the 400-4000cm^{-2} wavenumber range [117-118].

8.6. 13C cross-polarization magic angle spinning nuclear magnetic resonance analysis

The role of functional groups in biomass materials is investigated using one-dimensional (1D) and two-dimensional (2D) 13C nuclear magnetic resonance (NMR) spectroscopy. The 1D NMR spectra of biomass shows considerable changes in functional groups as the charring temperature increases, shifting from aliphatic O-alkylated carbons to fused-ring aromatic structures. This change is supported by elemental analysis and prior research on charred agricultural residues. However, due to overlapping bands in the 1D spectra, additional analysis is enabled by 2D correlation spectroscopy. The synchronous and asynchronous maps derived from 2D NMR indicate the sequential changes in functional groups during charring, indicating the cleavage of aliphatic O-alkylated and anomeric O-C-O carbons prior to the formation of fused-ring aromatic structures and aromatic C-O groups. Regression research verifies the linear relationship b/w functional groups & changing temperatures, implying that aromatization is faster than dealkylation and dehydroxylation. Overall, 2D NMR spectroscopy sheds light on the precise sequencing of functional group changes in biomass materials during charring, which aids in the development of biomass for a variety of uses [119].

8.7. Thermo gravimetric analysis

TGA is used to study the thermal stability and degradation of biomass-based materials. It aids in finding appropriate temperature ranges for pyrolysis or thermal treatment processes.

8.8. X-ray photoelectron spectroscopy

XPS is a technique used to determine the elemental composition and chemical state of surface species in biomass-based materials. It gives useful information on surface functional groups and the chemical environment [120].

8.9. Transmission electron microscopy

TEM allows for high-resolution imaging of microstructure and morphology of biomass-derived materials on nanoscale. It is especially effective for analyzing minute structural features and nanoparticle distributions. These characterization approaches provide detailed information on the structural, morphological, chemical, and elemental properties of biomass-derived adsorbents and membranes. This information makes them more suitable for a variety of applications, such as wastewater treatment, environmental remediation, and biomedical applications. Several analytical methods are used to characterize biomass, particularly to understand its interaction with heavy metals [121].

8.10. Zeta Potential Analysis

Zeta Potential Analysis assesses the surface charge of biomass, providing information on its electrostatic properties. The surface charge of the biomass is determined with a Zeta potential analyzer (Malvern Zetasizer Nano ZS). These techniques allow researchers to better understand how biomass interacts with heavy metal ions by identifying functional groups involved in sorption, examining surface shape, calculating surface charge, and comparing changes in elemental composition before and after sorption. Isotherm and kinetic studies are critical for determining the equilibrium relationship and biosorption rate b/w adsorbent (biomass) and adsorbate (heavy metals in constant circumstances.

9. Desorption versus disposal

Adsorbents can be desorbed and regenerated after biosorption to keep pollutant levels in effluent below the allowable limit. The old adsorbent can be recycled for a variety of purposes, including catalyst synthesis, ceramic production, and pollutant removal, or it can be discarded. Pollutant desorption can be accomplished using an alkali or acid reagent, a chelating agent, or salt; for organic pollutants, chemical, thermal, microwave, or other methods can be used. Alkali was shown to be most effective method of removing heavy metals from chemical adsorbents. The employment of an acid, alkali, chelating molecule, or chemical as a desorbing agent result in waste (secondary pollution) in the polluted effluent. As a result, this technology has the same disposal issues as the other methods, such as the unused adsorbent, which has both the environmental and the economic ramifications.

- ***Limitations and Strategies***

The primary limitation of previously published biosorption research is that it is primarily undertaken on a laboratory scale, with no pilot studies or commercial-scale column filtration systems. Aside from the limitations of the adsorbents utilized, most of the research used batch mode studies with simulated mono-pollutant solutions, with only a handful using real wastewater. Most investigations on bio-waste biosorption focused on removing a single contaminant from dye-containing effluents. To satisfy the needs of wastewater treatment, more research should be conducted on multi-pollutant systems with actual textile wastewater. Furthermore, the analysis demonstrates that recent innovations in the use of activated carbon have inherent limitations in terms of operating efficiency, total costs, energy consumption, and the potential to produce hazardous byproducts, even when these approaches work well against a specific pollutant. Although most bio-wastes have a high elimination efficiency of up to 99%, previous studies used a range of markers, limiting the opportunities for comparison research. Finally, earlier research on biomass-based biosorption was conducted on a laboratory scale using simulated wastewater, limiting ability to do the cost assessments.

10. Future recommendations

Bio waste is the most cost-effective source of carbon synthesis and is commonly transformed into activated carbon. In the previous decade, bio-waste has emerged as a low-cost, efficient, and sustainable source of activated carbon for dye removal. Bio sorbents can be defined and described according to their low cost, local availability, stability, environmental friendliness, transportation, treatment methods used, recycling, lifespan issues, regeneration capabilities, and pore volume after deactivation. In terms of performance variables, the pH level has the greatest influence on the biosorption of cationic dyes; high pH values are necessary for maximum dye uptake. Dye biosorption capability is influenced by several parameters, including beginning dye concentration, temperature, adsorbent dose, type, & contact length. Thermal and nitric acid, sodium hydroxide, organic solvents, vacuum, and biological operations are examples of regeneration desorption methods. Considerations for a cost-effective system include the amount of adsorbent used, the simplicity of preparation or processing, green chemistry ideas, and the activation mechanism used. Furthermore, catalytic, ceramic, and fertilizer applications show promise for managing post-biosorption materials. Briefly, the adsorbent's durability and cost are two additional factors that influence its suitability for efficient on-site treatment. Local availability, transportation, economic feasibility, regeneration potential, and longevity issues can all be investigated in future research.

Table 1. Common Pollutants: Discuss the properties, sources, effects, and SOPs (Standard Operating Procedures) levels in the environment. (Targeted by Biomass-based Adsorbents in Wastewater Treatment)- Introduction Paragraph

Pollutant	Properties	Sources	Effects	SOPs Levels in Environment
Hardness	Dissolved minerals, primarily calcium and magnesium ions	Groundwater	Scaling in pipes and appliances, Soap scum formation, Reduced efficiency of soaps	Depends on local regulations and standards
Heavy Metals	High atomic weights and densities, toxic to living organisms	Industrial wastewater, Mining runoff	Bioaccumulation in organisms, Toxicity to aquatic life	Varies widely depending on the specific metal and location
Organic Pollutants	Diverse group including dyes, pesticides, pharmaceuticals, hydrocarbons, herbicides	Agricultural runoff, Industrial discharge	Toxic to aquatic life, Disruption of ecosystems, Health risks to humans	Regulated by environmental agencies based on specific compounds
Pathogens	Microorganisms such as bacteria, viruses, protozoa	Municipal wastewater, Agricultural runoff	Spread of waterborne diseases, Contamination of drinking water sources	Regulated by health departments for safe drinking water
Nutrient and Non-Nutrients	Nitrogen and phosphorus as examples, crucial for plant growth but can cause eutrophication in excess	Municipal wastewater, Agricultural runoff	Algal blooms, Oxygen depletion in water, Harm to aquatic life	Regulated based on nutrient criteria for water bodies
Acidic or Basic Compounds	Ca and Mg excess intakes	Agricultural runoff, Industrial discharge	Alters pH of water bodies, Corrosion of infrastructure	Regulated based on pH standards and local regulations
Other Inorganic Pollutants	Chlorides, fluoride, arsenic, selenium	Industrial discharge, Agricultural runoff	Health risks to humans and animals, Toxicity to aquatic life	Regulated based on specific compound standards

To summarize, future of wastewater treatment is introduction of emerging technologies such as microalgae-based systems into decentralized water treatment systems. However, significant barriers persist, hindering the widespread use of these technologies [122-123] . To address these issues and enhance micro algal-based wastewater treatment, numerous recommendations and future directions are given. Primarily, the economic feasibility of microalgae technology must be addressed by finding suitable strains and optimizing growth conditions for optimal productivity and pollution removal effectiveness. Furthermore, further research on efficacy of microalgae-based approaches for removing specific pollutants, particularly heavy metals, required. And practical implementation of biosorbents, particularly microalgae, for heavy metal wastewater treatment necessitates resolving complications associated with actual effluent treatment and optimizing separation procedures to reduce excessive sludge development. Strategic combinations with different materials should be investigated to increase adsorption efficiency and biosorbent strength. Furthermore, to accelerate development of micro algal immobilization in wastewater treatment, future research should focus on optimizing immobilization technologies, preventing leakage, conducting comprehensive contaminant studies, elucidating substance transfer mechanisms, and conducting techno-economic analyses. Integration with other technologies and enhanced monitoring techniques are also required for practical application. To summarize, implementing these recommendations will help to overcome current problems and advance practical implementation of microalgae-based wastewater treatment, ensuring availability of high-quality water resources for future generations[124-125].

11. Conclusion

Wastewater treatment is crucial due to rising pollution from industrial and municipal sources, necessitating effective alternatives to traditional methods. Biosorption using biomass-based adsorbents presents a promising avenue for addressing affordability and eco-friendliness, but scalability and efficiency barriers persist. Environmental risk assessments are needed to understand impact of contaminants on ecosystems and develop efficient remediation strategies. Biomass materials, including living biomasses like bacteria, fungi, and algae, as well as dead biomasses from agricultural, food, and industrial waste, present cost-effective, environmentally friendly alternatives for pollutant removal in wastewater treatment. These diverse biomaterials offer cost-effective, environmentally friendly alternatives with potential applications in heavy metal and dye removal, as well as in addressing water scarcity and pollution challenges. Various biopolymer-based porous carbon adsorbents, including alginate, carrageenan, starch, cellulose, gelatin, and chitosan, offer effective solutions for water pollution.

Physical pretreatment techniques, chemical pretreatment methods, and biological pretreatment techniques enhance biomass quality and yield in pyrolysis processes, while characterization techniques provide insights into biomass structure and properties. Biosorption, utilizing biological materials like agricultural waste and microbial biomass, is an effective, cost-efficient, and eco-friendly method for removing pollutants such as heavy metals, dyes, PAHs, oils, and multiple contaminants simultaneously from water sources. Adsorbents derived from various biomass sources demonstrate high effectiveness in pollutant removal through mechanisms such as electrostatic interactions, surface complexation, and hydrophobic interactions. Regeneration methods include thermal and chemical treatments, while future research should focus on optimizing microalgae-based systems for decentralized water treatment, addressing economic feasibility, pollutant specificity, and practical implementation challenges for effective wastewater treatment. Future research should focus on optimizing microalgae-based systems for decentralized water treatment, addressing economic feasibility, pollutant specificity, and practical implementation challenges for effective wastewater treatment.

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