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Sustainable Wastewater Treatment: Recent Progress in the use of Bio-Waste-Derived Adsorbents for Organic Dye Removal

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Abstract
There are serious health and environmental hazards associated with the growing amount of organic dyes in wastewater from sectors like food processing, leather, and textiles. These pollutants are frequently ineffectively removed by traditional wastewater treatment techniques. Adsorbents made from bio-waste have become a viable substitute because of their high removal efficiency, affordability, and sustainability. The adsorption of organic dyes is facilitated by the distinct surface chemistries of these adsorbents, which are made from a variety of biomass sources. Through synthesis and modification approaches, recent research has concentrated on enhancing these materials' adsorption capacity, selectivity, and overall performance. Adsorbents made from bio-waste have potential uses in pollutant degradation, nutrient recovery, and value addition in addition to dye removal. But issues like leaching and long-term stability need to be carefully thought out. This review highlights the recent advancements in the application of bio-waste-derived adsorbents for organic dye removal from wastewater, emphasizing their potential contributions to sustainable wastewater treatment and resource recovery.

Keywords: *Bio-Waste, adsorbents, organic dyes, wastewater, application*

1. Introduction

The increasing amount of synthetic colors in wastewater, especially from the food processing, leather, and textile sectors, is causing major environmental issues. These dyes contribute to the aesthetic contamination of water bodies and provide serious health risks due to their toxic and carcinogenic properties (1). Traditional wastewater treatment methods, like chemical coagulation and complex oxidation processes, often fall short in eliminating these pollutants and can result in undesirable byproducts. Therefore, there is an urgent need for innovative and sustainable solutions to address this issue. Consumers, businesses, and the government should all handle dye effluents properly to improve public health and safeguard the environment (2). Industrial wastewater treatment technologies are often divided into four stages: pre-primary, primary, secondary, and tertiary.

The first phase is a preliminary process that is used to crush and screen suspended and floating particles, as well as oil and grease traps, and to remove impurities (papers, grits, wood, plastics, textiles, etc.) with minimal effort. Flotation and sedimentation are the initial steps in the treatment process that remove organic pollutants, whereas skimming removes foamy solids (3). During secondary wastewater treatment, dissolved organic and colloidal components are broken down by microorganisms, maintaining the waste's stability. Many industries, particularly food processing, textiles, and cosmetics, heavily rely on organic dyes. Untreated discharge of wastewater containing these dyes into the environment results in significant contamination. These dyes pose a major threat to aquatic ecosystems and human health, and they are commonly poisonous and carcinogenic (4). For

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this reason, eliminating organic dyes from wastewater is a crucial aspect of environmental management.

Recent technological advancements in wastewater treatment have proved the effectiveness and promise of adsorption as a dye removal method. Among the several adsorbents being studied, materials made from biowaste have attracted attention due to their affordability, sustainability, and ease of availability. Because these materials are derived from organic sources like food waste and agricultural waste, they not only provide a useful method of removing dye, but they also contribute to the value of waste (5,6). Adsorbents made from bio-waste offer a sustainable substitute for traditional techniques. Even though they work well, traditional adsorbents like activated carbon are costly and involve energy-intensive procedures. On the other hand, bio-waste adsorbents are more affordable, renewable, and frequently more accessible, making them a more environmentally friendly choice. The study demonstrates how altering materials made from biowaste through chemical or physical processes can enhance their adsorption properties. These changes increase the surface area, porosity, and functional groups, which increases the dye removal efficiency. The ability to change bio-waste materials improves their performance to the level of commercial adsorbents, which is a major advancement. Scaling up the investigation of bio-waste-derived adsorbents is also possible, especially in areas where bio-waste generation is prevalent (e.g., agricultural or food-processing businesses). Utilizing waste materials that are readily available locally for treatment lessens reliance on expensive or imported technologies.

Recent years have seen the use of biowaste-derived adsorbents as a viable substitute for the removal of organic dyes from wastewater. As demonstrated in the following, these adsorbents, which are derived from food waste, agricultural waste, and other biomass materials, offer several advantages over more conventional adsorbents like activated carbon as shown in fig 1. Large-scale wastewater treatment applications find them appealing since they are generally inexpensive, plentiful, and eco-friendly (7).

Figure 1. Activated carbon derived from bio-waste and its potential uses (2)

Large surface area and the presence of functional groups are two unique properties of bio-waste materials that enhance their adsorption capabilities and enable them to effectively absorb and remove various organic dyes. According to studies, adsorbents made from biowaste can remove popular colors like methylene blue and crystal violet with high levels of efficiency often more than 90%. Moreover, chemical or physical modification of these biosorbents can improve their effectiveness. As the demand for sustainable wastewater treatment solutions rises, the search for bio-waste-derived adsorbents is a critical step in the development of workable, reasonably priced, and ecologically friendly methods for lowering dye pollution in aquatic environments (8–10). The aim of this review is to discuss application of biowaste for the removal of organic dyes, with an emphasis on their potential contribution to the advancement of wastewater treatment technology.

2. Bio-Waste-Derived Adsorbents

The most promising method has been determined to be biological adsorbents that employ nonliving biomass because of their capacity to treat in an environmentally acceptable manner. Microorganisms' cell walls contain a variety of functional groups, including phenolic compounds, alcohol, aldehydes, ketones, carboxylic, ether, and others, which enable the special surface chemistry of bio-sorbents. These materials are desirable for the removal of organic dyes because of their high affinity for them (11). This makes it possible to effectively remove dyes from the wastewater. Chitin, peat, chitosan, yeast, and fungal biomass are examples of biological components that are frequently used in the chelation and complexion processes that remove dye from the solution. High adsorption capacity, vast surface area, high porosity, ease of availability, stability, viability, compatibility, environmental friendliness, ease of regeneration, and high selectivity in terms of removing various dye varieties are all necessary characteristics of a good adsorbent when it comes to removing organic dye. The key components in achieving high dye adsorption are the pore volume of the bio adsorbents and the functional groups of the dyes (12). A large pore volume allows the greatest amount of dye molecules to bind to the adsorbent. Low ash content, higher porosity, and increased surface area all contribute to high adsorption capacity. The functional groups (hydroxyl, carboxyl, etc.) on the surface of biomass-based adsorbents are significant factors affecting their hydrophobicity. Similarly, the diversity of microbes, including different types of bacteria, fungi, yeast, and algae, was examined in relation to the removal of dye molecules (13). The biosorption process and the live cell-based biodegradation process can be combined to improve dye removal performance in addition to having a high dye sorption capacity. Biomass biosorption capabilities are influenced by pH, initial dye concentration, temperature, contact time, and bio-sorbent dosage (14).

2.1. Bacterial

Bacteria can aid in bioremediation processes by adsorbing pollutants from aqueous media utilizing a variety of methods, such as dead biomasses. They are effective adsorbents due to their small size, wide distribution, and capacity to grow under a variety of environmental conditions. Under the correct circumstances, some bacterial species have been shown to efficiently absorb reactive pigments from wastewater (15). varying dyes decolorize at varying rates depending on the type of bacteria, dye reactivity, and operational factors such as pH, temperature, co-substrate, electron donor, and dissolved oxygen content. Textile dyes can be effectively cured by extremeophiles. The Langmuir adsorption isotherm shows that the basic blue dye has a maximum solubility capacity of 139.74 mg/g. Potential surface functional groups could be found on adsorbent surfaces with carboxyl and phosphonate groups with the ability to bind cationic pollutants. Biosorption fidelity depends on the type of bacteria as well as the group of ions because of their diverse cell wall compositions (16).

2.2. Fungus

Fungal biomasses include sugars, proteins, and lipids, but they also contain functional groups (alcohols, carboxyls, and alkanes) that provide them special qualities and uses in wastewater treatment. Fungal cells have been said to be an economical, simple, environmentally safe, and nutrient-free method of biotreating wastewater effluent that contains organic dyes (17). Numerous fungi, including Sarocladium sp., Trichoderma sp., and several kinds of white-rot fungi, have been employed as effective candidates to remove different colors from wastewater. It was shown that whereas the removal rate of anionic dyes rises in low-pH solutions, the removal rate of cationic dyes reduces. Conversely, a solution with a high pH encourages the removal of cationic dyes and produces a low percentage of anionic colors being removed. Understanding the adsorption mechanism and its favorability requires an understanding of the point of zero charges, or pHpzc. An example of adsorption mechanism is boron onto bentonite as shown in fig 2 (18).

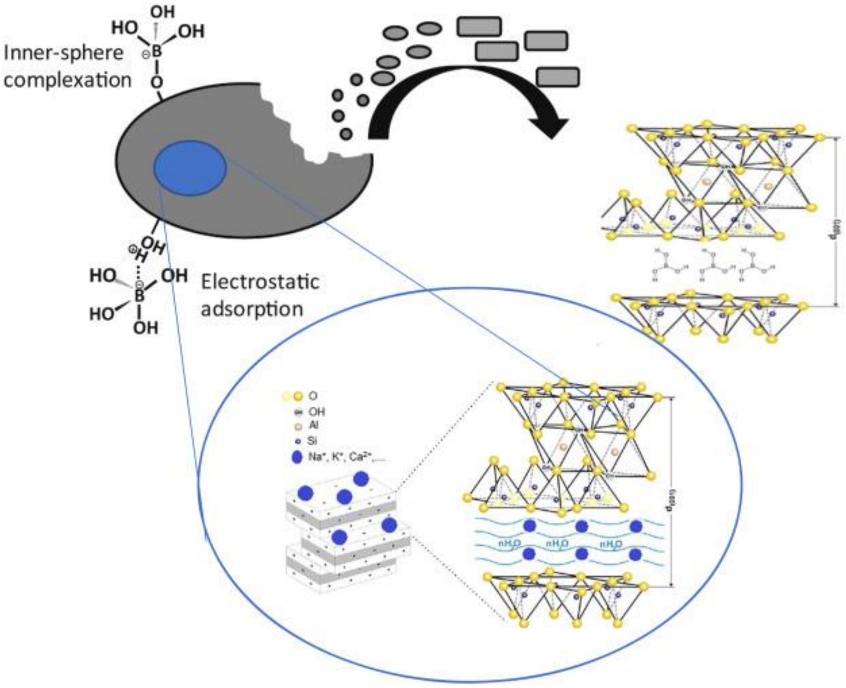

Figure 2. Adsorption mechanism of boron onto bentonite (66)

The pHpzc value reveals the active sites and adsorption capacity of the adsorbents. The presence of functional groups (OH−, COO−) makes cationic dye adsorption more beneficial when the pH is higher than the pHpzc, whereas the positively charged surfaces of the adsorbents make anionic dye adsorption more advantageous when the pH is lower than the pHpzc. Fungal biomass is generally a good substitute for current technology when used as an adsorbent and dye decolorizer. For the best dye-adsorption efficacy, the genotype and biomass preparation must be taken into account in addition to controlling ambient conditions (19).

2.3. Algae

Algae are one of the best sources of biosorbents because of their great ability for biosorption and accessibility. The algal cell wall is composed of polysaccharides such as mannan, xylan, chitin, and alginic acid. In addition to proteins, these constituents may consist of amino, amine, hydroxyl and imidazole, phosphate, and sulfate groups (20). Surface modification and encapsulation are examples of pretreatments that can increase algae's sorption capacity. The potential of brown algae functionalized with citric acid to extract the organic textile dye crystal violet from aqueous solutions was investigated. It was shown that uptake capacity increased by as much as 279.14 mg/g. This mechanism also involved electrostatic interactions (21).

2.4. Yeast

Yeast is a single-celled organism that presents numerous advantages over filamentous fungi in terms of pollutant adsorption and accumulation, growth rate, rate of decolorization, and toughness. The phosphate, polymer, carboxyl hydroxide, and amino groups on the yeast surface are the functional groups that alter the pH of the fluid being tested. There is proof that different colors can be bio-adsorbently absorbed by yeast biomass. Temperature, yeast mass, contact time, pH, and pollutant level all affect the bio-sorption process (22).

3. Recent Developments in the Synthesis and Modification of Bio-Waste-Derived Adsorbents

Adsorbents made from bio-waste have drawn a lot of interest because of their affordability, environmental advantages, and sustainability. Enhancing these materials' adsorption capacity, selectivity, and general effectiveness in eliminating pollutants from diverse settings has been the main focus of recent advancements in their synthesis and modification. A promising method for environmental remediation, especially in wastewater treatment and pollutant removal, is combining 3D printing technology with adsorbents made from bio-waste. Adsorbents with intricate geometries can be precisely fabricated via 3D printing, greatly improving their effectiveness in adsorption applications. For example, porous carbon monoliths with high surface areas and adjustable porosity have been investigated for use in gas separation and adsorption processes using direct ink 3D printing (23). The ability to repurpose these materials not only contributes to waste reduction but also promotes sustainable practices in material production (24). 3D-printed adsorbents can enhance mass transfer and adsorption capacity, particularly in CO_2 capture and catalytic reactions (25). (26) presented a novel approach to wastewater treatment by integrating advanced materials and 3D printing technologies. The combination of Sr-doped TiO_2, biowaste-derived adsorbents, and polymeric matrices provides a sustainable and efficient method for mitigating dye contamination in water. This method suits small-scale facilities and rural communities lacking access to sophisticated water treatment technologies.

Activated carbon preparation and regeneration via microwave heating has become more popular recently, mostly because of its novel heating technique. By means of dipole rotation and ionic conduction within the particles, microwave devices provide energy directly to the carbon bed, in contrast to traditional systems that depend on conduction or convection (27). Utilizing food waste especially, noodles (NOD) to produce activated carbon (NODAC) by microwave-induced KOH activation has been investigated recently. NODAC was tested for its capacity to absorb water-soluble brilliant green (BG) dye. By applying response surface methodology (RSM) to a variety of agricultural wastes, including c, the study was able to optimize important parameters like dosage, pH, and contact time. Adsorption fit well to Freundlich and Langmuir isotherms and followed a pseudo-second-order kinetic model (28) by applying this technique to various agricultural wastes, such as c with high surface area and significant adsorption capabilities. Enhanced adsorbent properties, including better methylene blue adsorption and carbon yield, are the consequence of optimizing variables including radiation time, power, and impregnation ratio (29). The activated carbon produced by microwave-assisted synthesis has improved pore volume and surface area, among other physical and chemical characteristics. It is also more environmentally friendly because it produces less harmful emissions. Adsorbents with improved adsorption capabilities and economic feasibility are produced by precisely controlling the activation process through the use of microwaves' special heating mechanism, which is based on dipole rotation and ionic conduction (30).

For the synthesis of solid-state materials, mechanochemical techniques in particular, high-energy ball milling are becoming more and more feasible (31). These approaches provide cost-effective machinery solutions, excellent efficiency, and simple designs. High-energy ball milling improves the adsorption qualities of materials like chitosan by decreasing particle size, increasing surface area, and causing physicochemical changes. Ball milling chitosan enhances its surface area and lowers its molecular weight, while adding a mild oxidizing agent increases its adsorption capability by producing oxygenated groups, according to research (32). Waste seashells, such scallop shells, have been successfully converted into adsorbents using ball milling by reacting with sodium oxalate. In order to improve the shells' capacity to absorb heavy metals like lead ions from aqueous solutions, this technique alters their surface by adding carboxyl groups.

The adsorption behavior was well described by the Langmuir isotherm model, and the produced adsorbents demonstrated enhanced adsorption kinetics and equilibrium properties (33). Significant progress has been made recently in the mechanochemical synthesis of bio-waste adsorbents, especially in improving the performance of chitosan, a biopolymer derived from crab shells. Researchers have successfully cross-linked chitosan with a variety of polyanionic linkers, such as tripolyphosphate (TPP), dextran sulfate (DS), and poly [4-styrenesulfonic acid-co-maleic acid] (PSSM), employing a solvent-free mechanochemical technique with high-energy ball milling. The resulting cross-linked chitosan adsorbents have increased mechanical strength, greater adsorption capabilities for pollutants, especially in wastewater treatment, and dramatically improved stability in acidic conditions.

The mechanochemical process not only increases the efficiency of chitosan as an adsorbent but also provides a cost-effective and scalable approach to producing high-performance bio-waste-derived adsorbents, making it a promising technique for industrial applications in removing toxic pollutants like heavy metals and PFAS from contaminated water sources (34).

Non-thermal plasma technology has been used to modify agricultural wastes, including sawdust from Moabi and Sapelli woods, to improve their adsorption properties. The process changes the surface chemistry and microstructure of the sawdust, increasing its roughness, porosity, and reactivity, which improves its ability to remove pollutants like Reactive Blue 2 dye from aqueous solutions. The process effectively produces adsorbents with a higher affinity for contaminants, making it a promising and environmentally friendly alternative to conventional wastewater treatment methods (35). Plasma treatment can make the surface more hydrophilic by adding polar functional groups and increasing surface roughness. Low-temperature plasma (LTP) technology has also become an effective way to modify the surface properties of carbon materials, including those derived from bio-waste, by introducing oxygen-containing functional groups and increasing surface roughness. These modifications enhance the hydrophilicity and adsorption capacity of the adsorbents, making them more effective at capturing water vapor, even in low humidity conditions (36). Recent studies have demonstrated the effectiveness of cold plasma (CP) treatment in regenerating adsorbents like carbonized rice husk (CRH), significantly reducing the need for new materials and eliminating the use of washing solutions. CP-treated CRH retained over 70% of its initial methylene blue (MB) adsorption effectiveness in trials with five successive regeneration cycles, but untreated CRH only retained 9–13%. Its promise as a low-energy, economical technique for adsorbent recovery was highlighted by the discovery that the energy consumption for CP treatment was roughly 6.4 times lower than that needed for carbonizing new rice husks (37).

The potential for improving adsorption capacities and efficiencies for a variety of contaminants, including heavy metals and dyes, has drawn a lot of interest recently to surface modification techniques of bio-waste-derived adsorbents. These adsorbents must be modified in order to improve their surface properties, which have a direct impact on how well they interact with wastewater pollutants. Adding functional groups to bio-waste-derived adsorbents to increase their affinity is a common modification for specific pollutants. A significant advancement is the use of ZnO modification on date pits, which has shown considerable improvement in the adsorption capacity for metals like Cu^{2+}, Ni^{2+}, and Zn^{2+}. The modification involves loading ZnO onto the surface of the bio-waste followed by thermal treatment, resulting in a material with increased surface area and enhanced functional groups, which promote better adsorption performance (38). Similarly, (39) highlighted the use of phosphoric acid to activate palm fiber waste (PFW), producing both activated carbon and bio-sorbents. As confirmed by SEM and FTIR analyses, the surface modification through acid activation significantly improved the adsorbent's surface characteristics, including pore cleanliness and surface area. This modification increased the adsorption capacity, with the bio-sorbent achieving a higher methylene blue removal efficiency than the activated carbon.

Adsorbents generated from bio-waste are also frequently modified by chemical activation shows that the properties of activated carbon made from leftover fruit peel may be changed by using chemical activating agents, which improves the material's adsorption capacity for removing aqueous dyes. Superior adsorption capabilities for copper ions can be produced by chemically modifying licorice residue with NaOH and citric acid to produce bio-adsorbents (41). Physical changes including composite creation and trapping have also been investigated in addition to chemical changes. the creation of composite adsorbents by cross-linking and physically altering chitosan with citrus reticulata peel waste (CRPW). Ultrasonic irradiation and glutaraldehyde cross-linking were two of the procedures used to create these composites, which improved their surface area, pore structure, and functional groups. The modifications substantially increased the adsorbents' capacity to remove pollutants, such as Congo red dye, from aqueous solutions (42).

3.1 Mechanisms of Organic Dye Adsorption onto Bio-Waste-Derived Adsorbents

The adsorption of organic dyes onto bio-waste-derived adsorbents is a critical area of research in wastewater treatment, primarily due to synthetic dyes' environmental and health hazards. Various mechanisms underpin this adsorption process, which the characteristics of both the adsorbent and the dye molecules can influence. The adsorption of organic dyes onto bio-waste-derived adsorbents typically involves mechanisms such as electrostatic interactions, π–π stacking, and hydrogen bonding. For example, when adsorbents undergo deprotonation, their surface becomes more negatively charged, significantly enhancing electrostatic attraction between the adsorbent and positively charged dye molecules like methylene blue (MB). The large surface area and porosity of bio-waste-derived adsorbents provide ample active sites for these interactions, further improving their effectiveness in capturing dye molecules. The presence of oxygen-containing functional groups on the adsorbent's surface also plays a crucial role in facilitating these interactions (43).

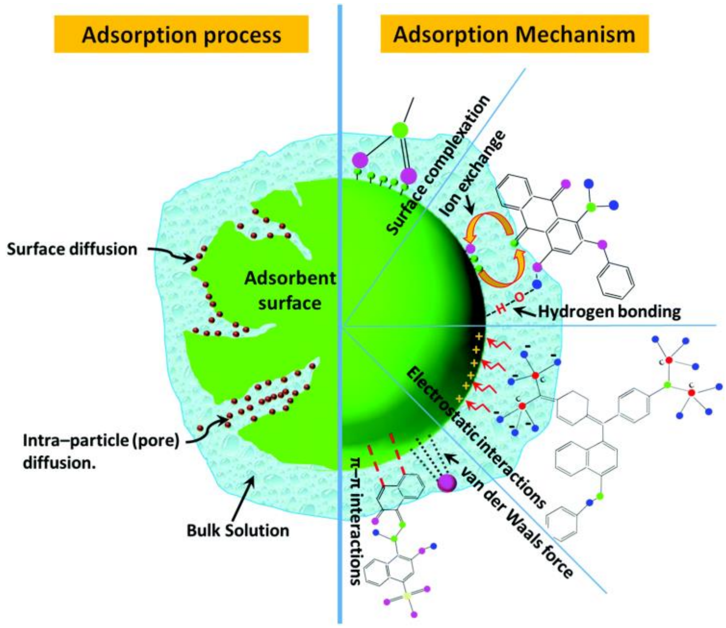

Figure 3. Mechanism of adsorption process (55)

As seen in Figure 3, the adsorption process usually comprises a number of mechanisms, such as ion exchange, chemical adsorption, and physical adsorption. Van der Waals forces are the main force behind physical adsorption, also known as physisorption, which is defined by a comparatively weak connection between the dye molecules and the adsorbent surface. Chemical adsorption, also known as chemisorption, on the other hand, is frequently more selective and entails the creation of stronger covalent connections. The composition of the dye and adsorbent, as well as ambient factors like pH and temperature can all have a substantial impact on the precise interaction processes (44–45). The functional groups such as hydroxyl, carboxyl, and phenolic groups that are present on the surface of the adsorbent primarily control these mechanisms. The method by which methylene blue (MB), a commonly studied organic dye, primarily occurs through hydrogen bonding and electrostatic attraction. The hydroxyl groups on the surface of the adsorbent, such as date pits, form hydrogen bonds with the nitrogen atoms in MB. At the same time, electrostatic attraction occurs between the negatively charged sites on the adsorbent and the cationic dye molecules. The bio-waste adsorbent's high surface area and porous structure assist this interaction by increasing its ability to absorb dye molecules from aqueous solutions. Particle size, pH, and dye concentration are some of the variables that might affect the effectiveness of the adsorption process; the ideal circumstances will vary based on the particular characteristics of the adsorbent and the dye being removed (46). For example, the initial dye concentration in the solution may have an impact on the adsorption efficiency of adsorbents made from bio-waste. According to studies, the percentage removal effectiveness of organic dyes usually falls as the initial concentration rises. The reason for this phenomenon is because increased concentrations cause the available active sites on the adsorbent surface, resulting in a lower percentage of dye removal despite potentially higher total amounts of dye being adsorbed (47- 48). For example, in a study involving bio-hydroxyapatite/chitosan hydrogel beads, the removal efficiency of Orange G dye dropped from 98.66% to 44.85% as the initial dye concentration increased from 5 to 80 mg/L (49).

3.2 Application of Bio-Waste-Derived Adsorbents in Real Wastewater Treatment

The application of bio-waste derived adsorbents in real wastewater treatment offers a sustainable and cost effective solution for pollutant removal, nutrient recovery and treatment process optimization (50). These adsorbents do not only ensure effective treatment but also contribute to waste valorization and resources recovery.

3.2.1. Application as a Catalyst

Once the adsorption process is complete, the adsorbents can be used as catalysts for photodegradation, hydrocarbon oxidation, nitrophenol reduction to aminophenol, xylose and xylan conversion to furfural, and phenylacetylene conversion to acetophenone (51). Nuclear magnetic resonance (NMR) spectroscopy, high-performance liquid chromatography (HPLC), gas chromatography, ultraviolet spectroscopy, and Fourier-transform infrared spectroscopy (FTIR) can all be used to further examine the final product, depending on the type of pollutant. The position of the metal ion on the adsorbent, the conversion and selectivity during the oxidation of cyclohexanol, and the rise in ethyl benzene can all affect the metal ion's catalytic activity (52).

The leachability of the pollutant or other materials from the adsorbent during their use as catalysts is the most important problem to be addressed, notwithstanding the enormous potential of spent adsorbents to induce catalysis. For leaching assessment, most studies used the Toxicity Characteristic Leaching Procedure (TCLP) or the California waste removal test (53). Wasted adsorbent frequently contains hazardous materials, and environmental agencies (such as the USEPA in the US, the CPCB in India, and DEFRA in the UK) enforce stringent disposal regulations. Therefore, expanding the usage of nontoxic waste adsorbents can solve this issue (54).

3.2.2. Application as Fertilizer

Fertilizers and other user-friendly materials can be made from the spent adsorbent. Long-term stability in a variety of conditions and affinities for anions and cations are among the qualities needed for fertilizer manufacturing. The primary use of charcoal is as fertilizer. Biomass is rich in calcium (Ca), nitrogen (N), potassium (K), and phosphorus (P) (55). By using this technique, nutrients are replenished in the soil, which may increase soil fertility. Biodegradable organic adsorbents can be used as fertilizers. According to one report, the breakdown of carboxymethyl cellulose, a chitosan that removes copper, takes 20 days (56).

Charcoal, biochar, and other products with varying economic values are produced by the pyrolysis of waste bio-sorbent, which happens when pollutants are adsorbed in biochar or when biochar is applied directly to soil. Charcoal can be used to minimize the amount of toxic chemicals in soil. It was discovered that applying 15 g/kg of charcoal reduced a plant's chromium and cadmium concentrations by 33.50 and 28.73 percent, respectively (57). Furthermore, charcoal is ineffective in providing the nitrates and phosphates that crops require for growth. Therefore, it is possible to add metal ions like Ca, Mg, and Al to charcoal. These substances enhanced precipitation or the creation of H bonds in the case of phosphate, whereas nitrate increases electrostatic attraction.

Meanwhile, the nonfuel fraction gases (carbon monoxide (CO), methane (CH_4), and other hydrocarbons) may be utilized to synthesize various chemical reagents in order to synthesize biofuels (58). Adsorbents can also be used as fertilizer to promote metal sequestration, increase soil organic carbon (SOC) (from the application of activated carbon), improve the nutritional value of the soil, and boost the soil's ability to hold water. Each heavy metal's concentration in charcoal has a threshold value. Basic and premium biochar should have less lead than 120 and 150 g/t. This includes requiring more charcoal than commercial fertilizer and releasing nutrients in a controlled manner to avoid soil contamination and metal ion buildup. During biomass feedstocks, this has affected the initial capital cost of recovering all pyrolysis products, including heat and gases (59).

3.2.3. Application in Ceramic Production

As fillers in the cement industry, the waste-derived adsorbents can also be used as ingredients in the production of ceramic materials. By using the adsorbent in the production of ceramics and in the construction of roads, the problem of its dangerous character may be lessened (60). With the right preparation conditions, the leaching of hazardous compounds from the utilized adsorbent can be controlled. The adsorption capacity of the loaded adsorbent (61–63) was matched by the ratio of 3/97 between the spent adsorbent (zeolite- and perlite-supported magnetite after molybdenum adsorption) and sludge. The leaching of other heavy metals (such as nickel, chromium, copper, zinc, arsenic, and cadmium) that increase when the ceramic synthesis technique is applied may also be prevented by ceramic products. The treatment of contaminated eluent produced during desorption operations benefits from this. Furthermore, the used adsorbent can be disposed of by immobilizing it within the matrix of phosphoric glass. It was also demonstrated that throughout the glassmaking process, about 20% of the discarded adsorbent could be integrated (64–65).

Conclusions

The increasing amount of synthetic dyes in wastewater, especially from the leather, textile, and food processing industries, presents significant environmental issues because of their toxic and cancer-causing properties. In addition to producing undesirable byproducts, conventional wastewater treatment methods including chemical coagulation and complex oxidation processes frequently fall short of eliminating these contaminants. The proper handling of dye effluents by consumers, businesses, and the government is necessary to improve public health and safeguard the environment. Industrial wastewater treatment technologies are often divided into four stages: pre-primary, primary, secondary, and tertiary. The use of biowaste-derived adsorbents has gained acceptance as a substitute for conventional methods of removing organic dyes from wastewater in recent years. Produced from food scraps, agricultural waste, and other biomass products, these adsorbents have several benefits over more traditional adsorbents like activated carbon. Large-scale wastewater treatment applications find them appealing since they are generally inexpensive, plentiful, and eco-friendly. Studies have shown that adsorbents generated from biowaste can achieve high levels of dye removal efficiency, often more than 90% for common dyes like crystal violet and methylene blue.

The most promising method has been determined to be biological adsorbents that employ nonliving biomass because of their capacity to treat in an environmentally acceptable manner. Alcohol, aldehydes, ketones, carboxylic, ether, and phenolic chemicals are among the several functional groups found in microorganisms' cell walls, and their distinct surface chemistry determines how well dyes are removed from the effluent. Because of their affordability, environmental advantages, and sustainability, bio-waste-derived adsorbents have drawn a lot of interest. The goal of recent advancements in the synthesis and modification of these materials has been to enhance their overall performance, selectivity, and adsorption capacity in the removal of pollutants from diverse environments.

Bio-waste-derived adsorbents offer a sustainable and cost-effective alternative for pollutant removal, nutrient recovery, and treatment process optimization in actual wastewater treatment. They contribute to waste valorization and resources recovery. Photodegradation, nitrophenol reduction, hydrocarbon oxidation, xylose and xylan conversion, and phenylacetylene conversion are among processes in which adsorbents can be used as catalysts. Leaching of pollutants or other compounds from the adsorbent is a serious problem, though. Charcoal, which has long-term stability and may be utilized to increase soil fertility, is one example of an adsorbent that can be transformed into fertilizer. Adsorbents can be used as fertilizers to enhance water-holding capacity, soil nutritional value, metal sequestration, and soil organic carbon. Waste-derived adsorbents are also useful in ceramic manufacture, such as fillers in the cement industry and road building. With the right preparation conditions, it is possible to control the leaching of hazardous compounds from the utilized adsorbent. Ceramic products can avoid the leaching of extra heavy metals during the use of ceramic synthesis techniques, which is advantageous in treating polluted eluent created during desorption operations.

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Conflicts of Interest

The authors declare no conflict of interest.

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