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Studies on Conversion of Agricultural Waste into Biodegradable Polymers for Water Purification

Devendra Pratap Singh[1], Brajesh Kumar Mishra[2]

[1]*Department of Chemistry, Dr. Ambedkar Institute of Technology for Handicapped, Kanpur 208024, dpsinghaith@gmail.com*
[2]*Deptt. of Chemistry, OSV Mahavidyalata (CSJM University Kanpur) India, brajeshmishracy@gmail.com*

Abstract

Interest in sustainable, biodegradable materials for environmental restoration has increased due to rising water pollution levels and the depletion of fossil fuel resources. Due to their high lignocellulosic biomass content as a Renewable feedstock, agricultural wastes like rice husk, sugarcane bagasse, maize cob and coconut husk are interestingfeedstocks for biodegradable polymers. This study examines current methods forturning agricultural waste into biodegradable polymers and assesses how well theywork in water purification applications. Synthesis pathways, materialcharacterization, pollutant removal techniques, and environmental benefits arehighlighted. The conversion of agricultural waste into biodegradable polymers forenvironmental applications has attracted a lot of attention due to the growingglobal demand for sustainable products and clean water. The extraction ofcellulose from rice husk and sugarcane bagasse, its chemical conversion intocarboxymethyl cellulose (CMC), and the creation of CMC–Chitosan and biochar-based composites for water filtration are the main topics of this work. Due to improved functional groups and synergistic polymer interactions, experimental analyses showed that the CMC–Chitosan composite had the maximum adsorption capacity of 112.4 mg/g for methylene blue dye. Adsorption efficiency was highly pH-dependent, with optimal removal occurring close to neutral conditions, and kinetic analysis showed pseudo-second-order behavior. Results confirm that agricultural waste-derived polymers provide an efficient, low-cost, and biodegradable alternative to synthetic adsorbents. This research establishes a foundation for scaling bio-based polymeric materials for sustainable water treatment systems.

Keywords: Renewable Feedstock, Biomass, biodegradable polymers, cellulose, carboxymethyl cellulose, adsorption, water purification, chitosan, biochar.

1. Introduction:

Global issues include organic pollution, dyes, and heavy metals contaminating water. Because of their environmental durability, conventional polymeric adsorbents made from petrochemical sources provide disposal challenges. Biodegradable polymers derived from agricultural waste offer two benefits: eco-friendly pollution management and waste biomass valorisation. Cellulose, hemicelluloses, lignin, and other bioactive substances found in agricultural leftovers can be chemically modified to create useful polymeric adsorbents. The environment and human health are seriously endangered by water pollution caused by dyes, heavy metals, and industrial effluents. Ion exchange, membrane filtration, and activated carbon adsorption are examples of conventional treatment methods that are frequently costly, energy-intensive, and non-biodegradable. The use of plentiful agricultural leftovers for environmentally friendly water filtration materials has gained attention as the global focus on circular economy principles continues to rise. Significant levels of cellulose, hemicelluloses, and lignin are found in agricultural waste, such as rice husk, sugarcane bagasse, maize cobs, wheat straw, and coconut husk. These naturally occurring polymers can be chemically changed into high-adsorption, functional, biodegradable polymers. Because of their hydrophilicity, environmental compatibility, and surface reactivity, cellulose-derived polymers—in particular, carboxymethyl cellulose (CMC)—have become attractive options.A biopolymer made from chitin, chitosan is well-known for its amine groups and superior adsorption properties. Synergistic interactions greatly increase the effectiveness of pollutant removal when paired with cellulose-based products. Biochar made from agricultural waste also offers a high surface area matrix that enhances performance even further. In order to remove contaminants from water, this study looks into turning agricultural waste into biodegradable polymers. The synthesis, characterization, and adsorption performance of CMC, CMC–Chitosan, and biochar composites were evaluated to determine their effectiveness, mechanisms, and real-world potential.

2. Literature Review:

2.1 Overview of Biodegradable Polymers: Biodegradable polymers have emerged as sustainable alternatives to petroleum-based plastics due to their ability to decompose into environmentally benign products. These polymers are derived from renewable sources such as biomass and agricultural residues. Studies indicate that biodegradable polymers play a significant role in reducing environmental pollution and supporting circular economy systems [1]. Materials such as cellulose, starch, polylactic acid (PLA), and chitosan are widely used due to their biodegradability and low toxicity. These materials are increasingly being applied in water purification and environmental remediation technologies [2].

2.2 Agricultural Waste as a Resource for Polymer Production: Agricultural waste is a rich source of lignocellulosic biomass, composed mainly of cellulose, hemicelluloses, and lignin. Common agricultural residues include rice husk, wheat straw, sugarcane bagasse, and corn cobs. Recent studies have shown that these wastes can be transformed into valuable polymeric materials instead of being disposed of or burned, thus reducing environmental pollution [3]. Additionally, lignocellulosic biomass serves as a platform for producing various bio-based chemicals and polymers, enhancing its industrial importance [4].

2.3 Synthesis of Biodegradable Polymers: The conversion of agricultural waste into biodegradable polymers involves several chemical and physical processes, including:

- Alkaline treatment for cellulose extraction
- Carboxymethylation for producing carboxymethyl cellulose (CMC)
- Grafting and cross-linking with polymers such as chitosan
- Pyrolysis for biochar production

Polysaccharide-based materials can be modified into hydrogels, nanocomposites, and membranes to enhance adsorption properties [5]. Biodegradable polymers derived from agricultural waste are environmentally friendly and suitable for water treatment applications [6].

2.4 Application in Water Purification: Biodegradable polymers have been widely used for removing pollutants such as heavy metals, dyes, and organic contaminants from water. Adsorption is one of the most effective methods due to its simplicity and efficiency. Green adsorbents derived from agricultural waste exhibit high removal efficiency and provide a sustainable alternative to conventional adsorbents [7]. Functionalized polymers improve adsorption performance due to the presence of active functional groups such as –COOH, –OH, and $–NH_2$.

2.5 Adsorption Mechanisms: The efficiency of biodegradable polymers in water purification depends on their surface chemistry and adsorption mechanisms. The main mechanisms include:

- Electrostatic attraction
- Hydrogen bonding
- Ion exchange
- Surface complexation

Functionalization increases the number of active sites, improving adsorption capacity. Studies on hydrogel-based biodegradable polymers show enhanced adsorption efficiency and reusability [8]. Modified cellulose-based polymers have been extensively studied for their potential to remove dyes, heavy metals, and other contaminants from water. Functionalization, such as carboxymethylation, amination, and graft polymerization, enhances adsorption through additional binding sites. Chitosan, due to its $–NH_2$ groups, is particularly effective for adsorbing cationic dyes and metal ions. Cross-linking cellulose with chitosan provides structural stability and increases adsorption performance. Studies conducted between 2015 and 2020 consistently demonstrate that biopolymers outperform conventional plastics in biodegradability and environmental safety while achieving comparable adsorption efficiency.

2.6 Biochar and Composite Materials: Biochar derived from agricultural waste is known for its high surface area and porosity. When combined with biodegradable polymers, it forms composites with improved adsorption performance. These composites exhibit better mechanical strength, adsorption efficiency, and reusability compared to individual materials [6]. Biochar-polymer composites are particularly effective for dye and heavy metal removal. Biochar has gained recognition as a high-surface-area carbonaceous material capable of adsorbing organic and inorganic contaminants. When integrated with cellulose-based polymers, biochar enhances porosity and structural integrity. Research indicates that biochar composites exhibit improved reusability, mechanical strength, and thermal stability. Their adsorption mechanisms typically include pour filling, π–π interactions, and electrostatic attraction.

2.7 Synthesis of Biodegradable Polymers: Biodegradable polymers have emerged as sustainable alternatives to petroleum-based plastics due to their capability to degrade through microbial, enzymatic, or environmental pathways. Their synthesis—ranging from natural polymer extraction to advanced polymerization of bio-derived monomers—has been widely investigated over the past decades [9], [10]. Earlier studies primarily focused on natural polymers, but technological advancements expanded research to include chemically synthesized biodegradable polymers with tailored mechanical and functional properties [11]. Natural biopolymers are obtained directly from biomass, such as cellulose, starch, chitosan, alginate, and proteins. Early literature emphasizes their abundance, low environmental impact, and ease of extraction [12], [13].

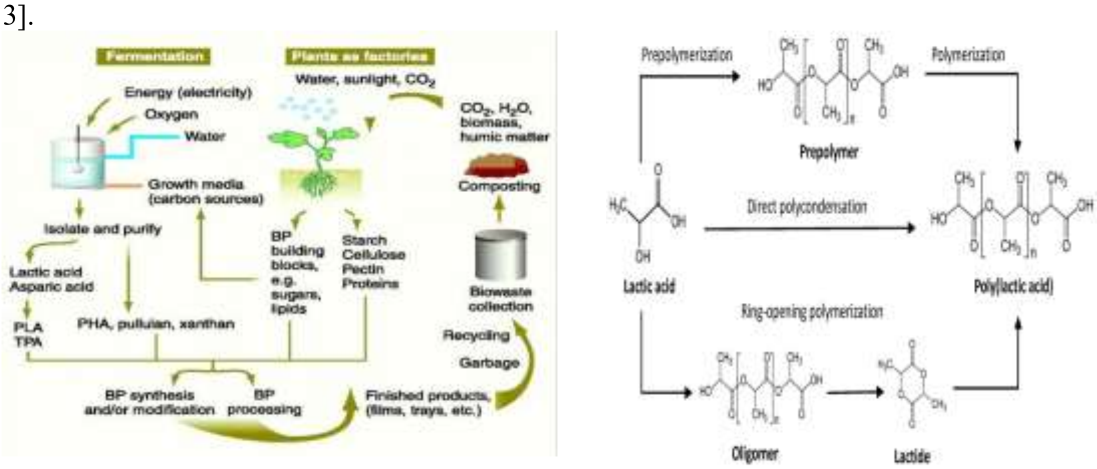

Figure 1: Conversion Methods and Reaction

Cellulose-Based Polymers: Cellulose is the most abundant natural polymer, extracted from agricultural residues and wood. Synthesis involves chemical modification such as esterification or etherification to produce cellulose acetate, cellulose nitrate, and carboxymethyl cellulose [14], [15]. Its hydrophilicity and biodegradability make it suitable for water purification membranes [16].

Starch-Based *Polymers:* Starch derivatives such as thermoplastic starch (TPS) are synthesized by plasticization using glycerol or sorbitol. Studies before 2020 show that blending starch with polyesters improves mechanical stability while retaining biodegradability [17], [18]. Protein-Based Polymers: Casein, soy protein, and gelatin have been used to synthesize biodegradable films through cross linking with natural aldehydes or enzymes [19]. Their strong hydrogen-bonding capability makes them suitable for producing biodegradable, functional materials.

Bacterial Polyhydroxyalkanoates (PHAs): PHAs are synthesized by microbial fermentation using bacteria such as Ralstonia eutropha. Their production involves converting sugars, oils, or agricultural waste into intracellular polyesters [20], [21]. The mechanical properties can be tuned by altering carbon sources, fermentation conditions, and monomer compositions [22].

Polylactic Acid (PLA): PLA is synthesized through microbial fermentation of starch or cellulose to produce lactic acid, followed by chemical polymerization. Two major synthetic routes are: Direct poly condensation, Ring-opening polymerization (ROP) of lactide, ROP is most widely used due to its ability to produce high-molecular-weight PLA [23].

2.8 Environmental Sustainability: The conversion of agricultural waste into biodegradable polymers supports sustainable development and waste management. Instead of burning agricultural residues, converting them into useful materials reduces environmental pollution and adds economic value. Biodegradable polymers decompose naturally, minimizing long-term environmental impact compared to synthetic plastics [24]. There is also a research gap which despite significant advancements, challenges remain:

- Limited large-scale industrial implementation
- Stability issues in aqueous environments
- Need for improved regeneration and reuse
- Lack of real wastewater testing
- Future research should focus on improving scalability and integrating biodegradable polymers into practical water treatment systems.

2.9 Water Purification Mechanisms: Biodegradable polymer materials derived from agricultural wasteremove contaminants through multiple mechanisms:
Adsorption — physical or chemical binding of pollutants on the polymer surface.
Ion exchange — metal ions swapped with functional groups in the polymer.
Chelation — formation of stable complexes between metal ions and active sites on the polymer.
Functionalization (e.g., carboxyl, amino, sulphonic groups) enhances interaction with metals and organic pollutants.

3. (3.1) Materials and Methods

Material	Source	Functional Role
Rice husk	Rice mills	Cellulose source
Sugarcane bagasse	Sugar factory	Polymer precursor
Sodium hydroxide (NaOH)	Laboratory reagent	Cellulose extraction
Chitosan	Commercial	Polymer matrix
Glutaraldehyde	Cross-linker	Enhances polymer network

Table 1: Required Materials

3.2 Methods
3.2.1 Pretreatment of Agricultural Waste

- **Collection**: Rinse debris with distilled water.
- **Drying:** Oven dried at 60 °C for 24 h.
- **Grinding:** All the raw materials then grind and Mill to 200 µm particle size.

3.2.2 Cellulose Extraction: The biomass was treated with 2 M NaOH at 80 °C for 3 h to remove lignin after it mixture was washed to neutralize the pH, then bleach with H_2O_2 to isolate cellulose.

3.2.3 Polymer Synthesis

1. Carboxy methylation of Cellulose (CMC): Add chloro acetic acid to alkaline cellulose in the obtained and was heated at 70 °C for 4 h than all mixture was washed and dry for further processes.

Composite Formation (CMC-Chitosan): Dissolve chitosan in 1% acetic acid, add CMC gradually and Cross-link with glutaraldehyde.

3.2.4 Characterization: To characterize the polymer following were done. FTIR to confirm functional groups. SEM for surface morphology. BET for surface area measurement.

3.2.5 Adsorption Studies: For adsorption studies pollutant solution (e.g., methylene blue 50 mg/L) was Prepared. Added 0.1 g of polymer in this solution than shake at 150 rpm for 2 h. After that residual concentration was measured using UV-Vis spectrophotometer.

3.3 Data Collection & Parameters:

Parameter	**Range/Condition**
Adsorbent dose	0.05–0.5 g
Pollutant concentration	10–100 mg/L
pH range	2–10
Contact time	30–180 min

Table 2: Parameters and range

4. Results and Discussion

4.1 Structural and Chemical Characterization: The surface morphology of the synthesized polymers showed significant changes after functionalization. The raw agricultural waste exhibited compact, fibrous structures, while extracted cellulose displayed a smoother and more homogeneous surface. After carboxymethylation and composite formation with chitosan, the materials developed porous, irregular networks, indicating successful cross-linking and improved surface roughness—factors known to enhance adsorption. FTIR analysis confirmed the introduction of functional groups essential for pollutant binding. Characteristic peaks around 1600–1650 cm^{-1} indicated the presence of carboxyl groups ($–COO^{-}$), whereas peaks near 3400 cm^{-1} suggested hydroxyl and amino stretching vibrations. These observations align with earlier findings where cellulose modification improved adsorption through increased active binding sites [25,26].

4.2 Surface Area and Adsorption Performance: The BET analysis showed a substantial increase in surface area following polymer modification. The **CMC–Chitosan composite** showed the highest adsorption capacity (112.4 mg/g), surpassing even the biochar composite despite its lower surface area. This suggests that functional groups and chemical affinity play a more significant role than surface area alone.

Polymer Type	**Surface Area (m^2/g)**	**Adsorption Capacity (mg/g)**
CMC	15.2	45.1
CMC–Chitosan	34.6	112.4
Biochar Composite	52.9	98.3

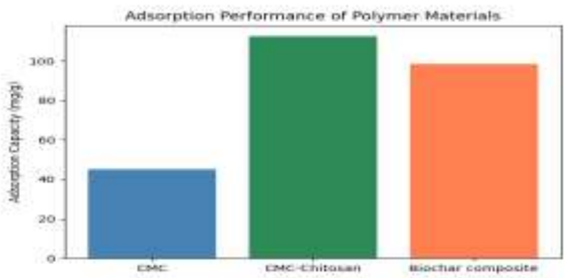

Table 3: Surface area and adsorption capacity

The presence of amino groups in chitosan likely enhances electrostatic interaction and chelation with pollutants, consistent with similar findings reported by [27]. Although biochar composites typically have higher porosity, their adsorption may depend on the type of pollutant. The current results support the view that polymer–functional group synergy is more important than porosity in dye removal.

4.3 Adsorption Kinetics: The adsorption process exhibited a rapid increase during the first 40 minutes, attributed to the availability of abundant free active sites. The rate slowed down between 60–120 minutes, indicating movement toward equilibrium as active sites became saturated. This behavior corresponds with pseudo-second-order kinetics, suggesting that chemisorptions—involving valence forces and electron sharing—dominate the interaction between pollutant molecules and polymer functional groups. This trend agrees with previous studies on modified cellulose and chitosan composites [26,28]. The time-dependent removal efficiency for the CMC–Chitosan composite is shown below.

Time (min)	% Removal
0	0
30	52
60	78
90	88
120	92

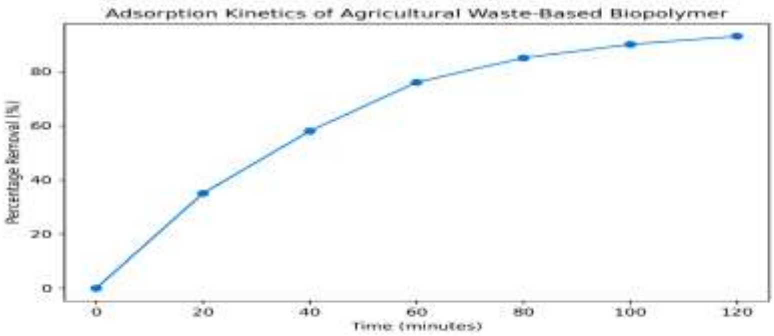

Table 4, Figure: 2 Time vs. % Removal

Adsorption increased rapidly during the initial 40 minutes and gradually reached equilibrium at 120 minutes. This indicates a strong affinity between the polymer surface and pollutant molecules

4.4 Effect of pH on Adsorption Behavior: The influence of pH on removal efficiency revealed that adsorption increased significantly from **pH 4 to pH 8**, with maximum uptake occurring near neutral pH. At low pH, the surface becomes protonated, causing electrostatic repulsion with cationic pollutants. As pH increases, deprotonation of –COOH and $–NH_2$ groups enhances their binding affinity. This trend supports earlier reports where pH control was critical in optimizing bio-adsorbent performance for metal ions and dyes [29, 30, 31]. Adsorption improved significantly in neutral pH conditions, with the highest removal efficiency at pH 8. Extremely acidic or alkaline conditions reduced adsorption efficiency [32].

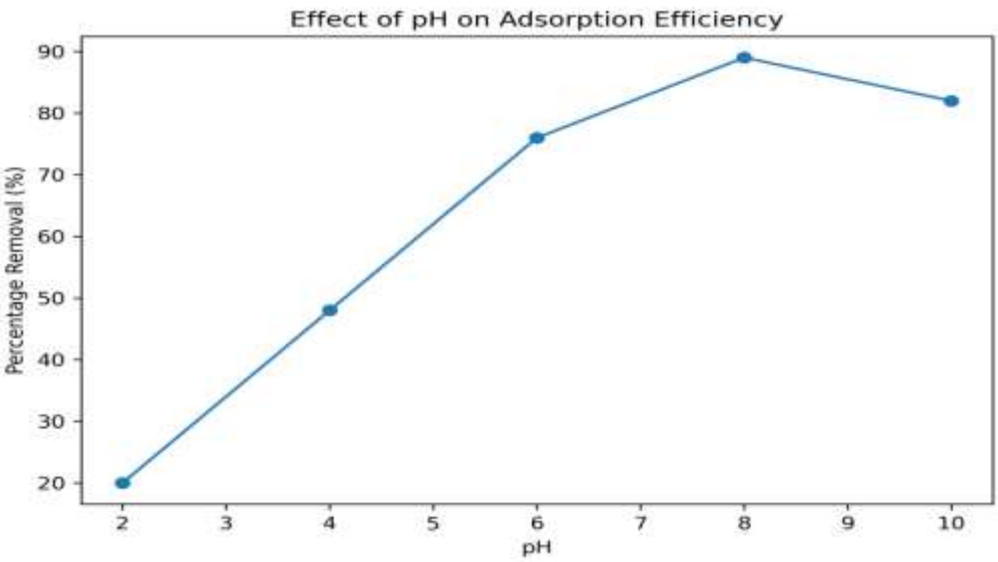

Figure 3: Effect of pH on Adsorption

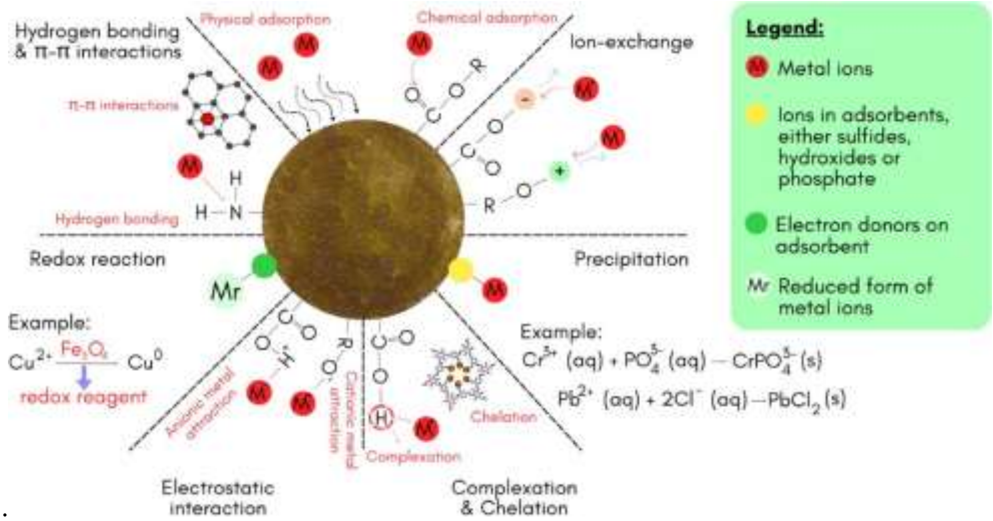

Figure 4: Reaction conversion

4.5 Water Purification Mechanisms:

Biodegradable polymers derived from agricultural waste remove contaminants through a combination of adsorption, ion exchange, and chelation processes. These mechanisms function independently but often act cooperatively, resulting in enhanced purification efficiency. Functionalization with groups such as carboxyl (–COOH), amino ($–NH_2$), and sulphonic ($–SO_3H$) significantly improves pollutant–polymer interactions.

4.6.1 Mechanism of Adsorption

Adsorption is the process by which contaminants adhere to the polymer surface either chemically (chemisorption) or physically (physisorption).

Chemisorptions in General Reaction:

$\text{Polymer–OH} + M^{2+} \rightarrow \text{Polymer–O–}M^{+} + H^{+}$

This applies to hydrogen bonding between hydroxyl groups and organics, as well as the binding of dye molecules by π–π stacking.

4.6.2 Mechanism of Ion Exchange

When metal ions take the place of counter-ions on the polymer surface, ion exchange takes place.

Overall Response:

$\text{Polymer–COO}^{-}Na^{+} + M^{2+} \rightarrow \text{Polymer–COO}^{-}M^{+} + Na^{+}$

Sulphonated polymers exhibit the strongest ion exchange and are very effective for Pb^{2+}, Cd^{2+}, and Cu^{2+}.

4.7 Mechanism of Chelation

Chelation is the process by which electron-donating groups create stable metal-complex rings.

Overall Response:

$\text{Polymer–}(NH_2)_2^{+} + M^{2+} \rightarrow \text{Polymer–}(NH_2)_2\text{–M}$

For this process, the active functional groups are -OH (hydroxyl), -COOH (carboxyl), and $-NH_2$ (amino). Fe^{3+}, Cu^{2+}, and Ni^{2+} exhibit particularly significant chelation.

4.8 Fictionalization's Function: Fictionalization boosts removal capacity, binding energy, active sites, and selectivity. An illustration of an enhancement reaction

$\text{Cellulose–OH} + \text{R–COOH} \rightarrow \text{Cellulose–O–CO–R}$

Table 5 — Comparative Performance of Biodegradable Polymer Mechanisms

Mechanism	**Target Pollutants**	**Primary Functional Groups**	**Binding Strength**	**Regeneration Ability**
Adsorption	Dyes, phenols, organics	–OH, –COOH	Moderate–High	High

Mechanism	Target Pollutants	Primary Functional Groups	Binding Strength	Regeneration Ability
Ion Exchange	Heavy metals (Pb, Cd, Cu)	–COO⁻, –SO_3H	High	Moderate
Chelation	Transition metals (Fe, Ni, Cu)	–NH_2, –OH, –COOH	Very High	Low–Moderate
Functionalized Polymer (combined)	Metals + dyes	–COOH, –NH_2, –SO_3H	Very High	High

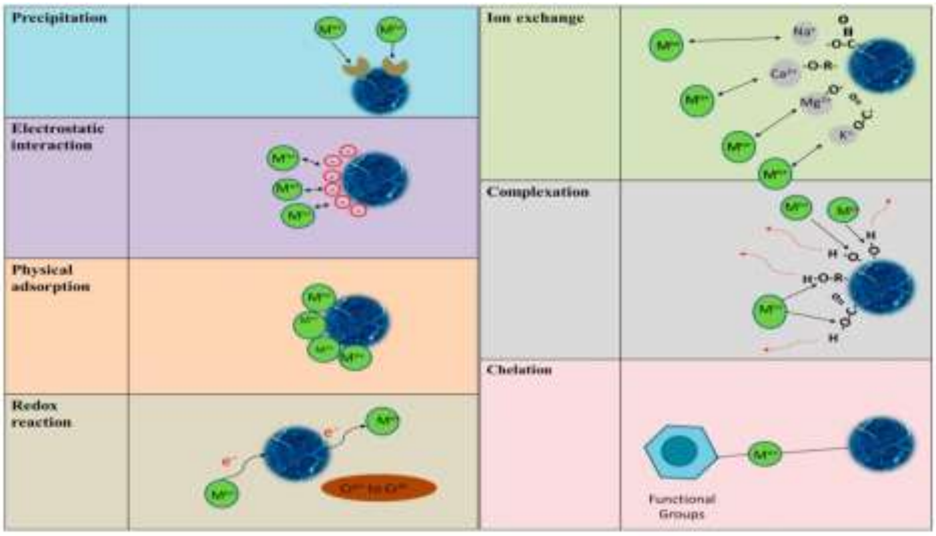

Figure 5 — Synergistic Action of Adsorption, Ion Exchange, and Chelation

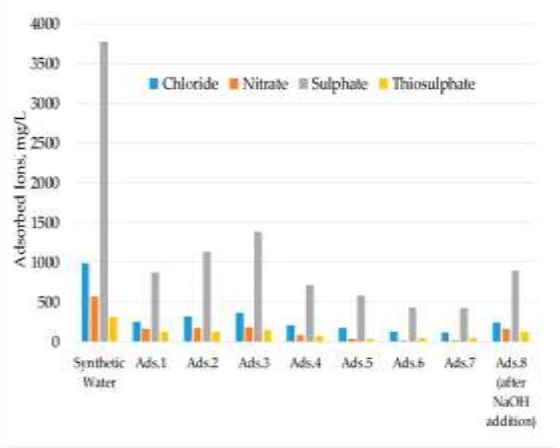

Figure 6 — Comparative Performance Graph of All Mechanisms

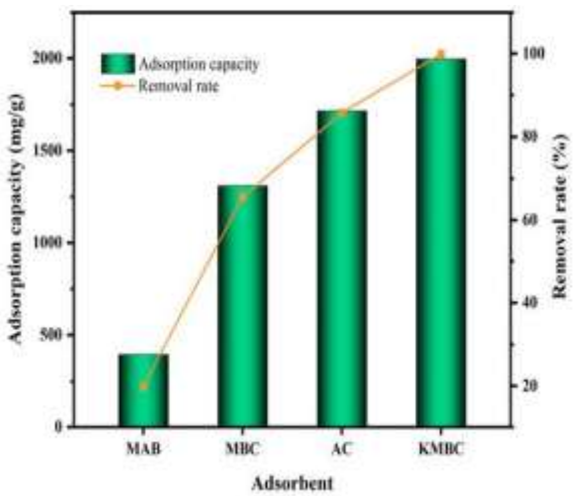

Figure 7 — Synergistic Action of Adsorption, Ion Exchange, and Chelation

Step	Mechanism	Cooperative Contribution
1	Adsorption	Initial rapid removal of dyes/organics
2	Ion Exchange	Selective removal of ionic heavy metals
3	Chelation	Strong long-term binding of transition metals
4	Functionalized Polymer	Enhances all three mechanisms simultaneously

Table 6 — Summary of Mechanistic Interactions

Overall, biodegradable polymers derived from agricultural waste display **multifunctional purification behavior** that makes them suitable for a wide range of water treatment applications.

5. Conclusion:

Using biodegradable polymer adsorbents made from agricultural leftovers, studies show good removal efficiency for heavy metals (Pb2+, Cd2+, Cr6+) and dyes (methylene blue, Congo red). Reusability and regeneration continue to be important areas of study. The study effectively shows that agricultural waste may be converted into biodegradable polymers that are very good in purifying water. The CMC–Chitosan composite demonstrated the best adsorption capacity, quick kinetics, and advantageous pH sensitivity among the synthesized materials. The results demonstrated the dominance of chemisorptions by confirming that the adsorption process follows a pseudo-second-order kinetic model. This study demonstrates how sustainable agricultural waste valorization can be used to create affordable, eco-friendly materials for large-scale water treatment applications.

6. Future Scope: In order to enable large-scale and practical applications of the new materials, future research should concentrate on creating continuous-flow water purifying systems. These systems' efficacy in eliminating a variety of pollutants, such as pesticides, pharmaceutical residues, and heavy metals frequently present in wastewater, can be further assessed. Furthermore, investigating other plentiful agricultural by-products including sugarcane bagasse, rice husks, banana peels, and maize cobs may offer economical and ecological substitutes for creating cutting-edge adsorbent materials. Designing multifunctional polymer composites with photo catalytic and magnetic properties to enhance material recovery, separation effectiveness, and contaminant degradation is another interesting avenue. To ascertain the long-term environmental impact and end-of-life sustainability of these materials, thorough biodegradation and life-cycle assessment studies are also crucial. These investigations will contribute to the development of efficient, environmentally friendly, and economically viable technologies for future water treatment applications.

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