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Adsorption of Heavy Ions from Water Using Chitosan

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Adsorption, chitosan, clean water, eco-friendly, heavy metals, purification, waste water managment

ABSTRACT

In this study, the processes of treating water contaminated with heavy metals using chitosan were examined. Chitosan, a natural polysaccharide, stands out as an environmentally friendly adsorbent with the potential to remove various pollutants, particularly heavy metals, from water. The study investigated whether chitosan could effectively remove heavy metal ions such as iron (Fe) and cadmium (Cd) through adsorption processes. Experimental results revealed that chitosan exhibits a higher adsorption capacity compared to activated carbon in removing these metals from solutions. This finding highlights the potential of chitosan for environmental applications, particularly in the treatment of industrial wastewater containing heavy metals. The combination of chitosan's properties—such as low cost, biodegradability, and environmental compatibility—suggests that it could serve as a significant alternative in water treatment technologies. Additionally, chitosan-based adsorbents are considered to offer more efficient and sustainable solutions compared to conventional treatment methods. This study underscores the potential of chitosan in water purification and contributes to the development of environmentally friendly alternatives.

Objective

Heavy metals present in drinking water pose significant health risks to humans and can lead to various diseases. Additionally, heavy metals released from industrial processes into water sources contribute to environmental pollution if not properly treated. Therefore, removing heavy metals from water is crucial for both human and environmental health. Several methods exist for the removal of heavy metals from water, with activated carbon adsorption being one of the most commonly used and cost-effective techniques. The objective of this study is to develop a more effective alternative method compared to activated carbon.

Chitosan, a substance derived from the shells of shrimp and other crustaceans through drying, grinding, and simple chemical processes, can be utilized for water purification. Since chitosan is obtained from waste materials, it presents a more sustainable option compared to other methods. Moreover, it has the potential to be a more efficient adsorbent than activated carbon. For these reasons, a series of experiments were designed and conducted to evaluate the adsorption capability of chitosan.

Introduction

1. What is Chitosan?

Chitosan is derived from industrial waste produced during the processing of crustaceans such as shrimp. It is obtained through the following method:

1. The raw material is washed, dried, ground into a homogeneous powder, and sieved.
2. Organic proteins are removed using 3.5% NaOH.
3. Remaining minerals are eliminated using HCl, at which stage the material is referred to as chitin.
4. The chitin is decolorized using acetone and sodium hypochlorite (NaOCl).
5. To enhance solubility, amino groups are freed by treating the material with 50% NaOH.

At the end of this process, chitosan is obtained as a fine, colorless powder.

Chitin, is the second most abundant renewable biopolymer in nature after cellulose. Chitosan, derived from chitin, has gained significant attention in research due to its effectiveness in heavy metal adsorption. It is widely used in various industries, including textiles, food, cosmetics, medicine, paper, and agriculture. One of the key reasons for its preference is its eco-friendly nature (Kuzgun & İnanlı, 2013; Synowiecki, Al-Khatteb, & Nadia, 2003; Shahidi & Abuzaytoun, 2005).

Properties of Chitosan:

1. Appears as a white, tasteless, odorless powder or particulate substance.
2. Resistant to digestive enzymes.
3. Insoluble in water but dissolves in acidic solutions with a pH below 6.
4. Prolonged exposure to room temperature in solution form affects its stability.
5. Its most significant feature in heavy metal removal is its ability to interact with metal ions such as magnesium, copper, and iron, making it effective in separating toxic heavy metals.

(Yıldız & Yangılar, 2014)

Chitosan is the primary derivative of chitin and is obtained through deacetylation. Unlike chitin, chitosan is soluble in acidic solutions. Although its molecular structure is similar to that of cellulose, chitosan is considered more valuable due to its higher applicability. As a highly effective heavy metal adsorbent, chitosan has become increasingly popular in scientific research. Its greatest advantage is being a renewable resource and a natural, environmentally friendly biopolymer (Yuan & Hu, 2016). Due to these properties, chitosan has found applications in various industries in recent years. Particularly over the last 50 years, it has remained a subject of interest among researchers. Compared to chitin, chitosan offers several advantages and is widely used in fields such as food, cosmetics, agriculture, medicine, paper, and textiles (Rinaudo, 2006).

Chitosan is a white, odorless, tasteless, and semi-transparent substance available in powder or particulate form. It is resistant to digestive enzymes but can be broken down by certain bacteria. Chitosan is insoluble in water and dissolves only in acidic solvents (pH < 6.0). Organic acids such as acetic, formic, and lactic acid are commonly used for dissolution, whereas its solubility in inorganic acids is limited (it dissolves in 1% hydrochloric acid but is insoluble in sulfuric and phosphoric acids) (Rinaudo, 2006). Chitosan solutions lose stability at pH levels above 7.0. Additionally, prolonged storage at room temperature negatively affects their stability. In acidic environments, chitosan exhibits polycationic properties (pK = 6.2–6.8) and can interact with negatively charged ions due to the presence of positively charged NH_3^+ groups (Muzzarelli, 2009). This property enables chitosan to interact with metal ions such as iron, copper, and magnesium, making it highly effective for the removal of toxic heavy metals from water.

2.1. Activated Carbon

Activated carbon is a highly porous adsorbent with an extensive surface area and unique pore structure. It lacks a distinct structural formula or chemical composition but is primarily composed of carbon (Hassler, 1974).

The high surface area, microporous structure, and strong adsorption capacity of activated carbon make it a widely used sorbent. The pore volume of activated carbon is generally greater than 0.2 mL/g, and its internal surface area exceeds 400 m^2 (McDougall, 1991). The surface area of 1 g of activated carbon can range from 300 to 2000 m^2 (Gülensoy & Şengil, 1981), while pore diameters vary from 3 Å to several thousand Ångströms. Organic-based activated carbon consists of 87–97% carbon, with the remaining composition including hydrogen, oxygen, sulfur, and nitrogen (Küçükgül, 2004). Additionally, depending on the raw materials and chemical additives used in the production process, activated carbon may contain various other elements.

2.2. Physical Properties

2.2.1. Molecular and Crystal Structure

The fundamental structural unit of activated carbon resembles that of pure graphite. Graphite crystals consist of hexagonal layers held together by weak Van der Waals forces at an interlayer distance of 3.354 Å. However, the structure of activated carbon is more disordered compared to graphite (Rodríguez-Reinoso & Molina-Sabio, 2004). During the activation process, the orderly arrangement of carbon bonds on the crystal surfaces is disrupted. Due to the preparation method and the presence of impurities, certain voids appear in the microcrystalline structure (Klosgen & Lamm, 1995). The high degree of structural disorder in activated carbon results in numerous reactive possibilities for the carbon atoms located at the edges of the planar layers. As a consequence, oxygen-containing organic functional groups are commonly found on the surface of activated carbon, often positioned along the edges of broken graphitic ring systems (Jiang & Wang, 2006).

2.2.2. Surface Area

One of the most critical physical properties of activated carbon is its surface area. Typical commercial activated carbon products have a surface area ranging from 500 to 2000 m^2/g. However, synthetic activated carbons with a surface area of 3500–5000 m^2/g are used for specialized applications due to their high adsorption capacity (Kroschwitz, 1992; Gündoğdu, 2010). For water treatment applications, the internal surface area of activated carbon particles should be at least 1000 m^2/g. Since contaminants are adsorbed onto the surface of activated carbon, surface area plays a crucial role in pollutant removal. In principle, the larger the surface area, the greater the number of adsorption sites available. Below are some numerical values related to the surface area and pore system of activated carbon, as reported in the literature (Müller & Mehnert, 1997).

Surface Area and Pore Characteristics of Activated Carbon (Kirk O, 1971):

- **Surface area:** 400–1600 m^2/g (BET N_2 method)
- **Pore volume:** >30 $m^3/100$ g
- **Pore width:** 0.3 nm – 1000 nm

2.3. Chemical Properties

The mineral content of activated carbons can range from 1% to 20%, depending on the raw material used in their production. The mineral content includes silicates, aluminates, and trace amounts of inorganic compounds such as calcium, magnesium, iron, potassium, sodium, zinc, lead, copper, and vanadium. These inorganic materials influence the adsorption of electrolytes and non-electrolytes from gases and solutions. Iron, calcium, and other alkaline compounds in the structure act as catalysts during the steam activation process. Sodium and potassium hydroxides and carbonates promote the formation of narrow and elongated micropores. Additionally, these alkaline earth compounds enhance mesopore formation by facilitating the channeling of metallic particles (Güngör, 2013).

Activated carbons, with their high pore volumes (0.5–1.5 cm^3/g) and extensive surface areas (500–2000 m^2/g), are excellent adsorbent materials both physically and chemically.

2.3. Aplication Areas

They are widely used in separation, purification, removal, and recovery processes across various industries, including medicine, environmental science, chemistry, energy, metallurgy, textiles, and food processing. The ability of activated carbon to be produced from high-carbon, low-inorganic-content biomass waste and to be regenerated for reuse provides a significant advantage.

Applications in the Food Industry:

Activated carbon is utilized for color, odor, and taste correction in beverages, decolorization in sugar-syrup production, shelf-life control of climacteric fruits and vegetables, removal of organic or toxic non-nutritional compounds, purification of frying oils, and drinking water treatment.

Recent applications of activated carbon in the food industry:

- Aerobic digestion processes
- Modified atmosphere applications
- Purification and next-generation antimicrobial agent production
- Volatile organic compound removal, and aroma recovery
- Electrochemical food sensors and electromagnetically

Active carbons are developed for high-efficiency separation and purification processes (Ülkeryıldız Balçık, Torun & Şahin Nadeem, 2020).

3. Heavy Metals and Their Effects on Health

Heavy metals enter the body through ingestion, inhalation, and skin absorption. Most heavy metals cannot be excreted efficiently through natural detoxification pathways (kidneys, liver, intestines, lungs, skin) without additional biological support. As a result, they accumulate in biological organisms. When these metals reach critical concentrations in living tissues, they can cause severe health conditions such as thyroid disorders, neurological diseases, autism, infertility, and even death.

All metals with toxic properties in medicine are classified as heavy metals. Some of the most common ones include:

- Mercury (Hg), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Cadmium (Cd), Arsenic (As), Chromium (Sn), Lead (Pb), Silver (Ag), Selenium (Se).

The impact of heavy metals on the body depends not only on their concentration but also on:

- The structure of the metal ion,
- Its solubility,

- Chemical properties,
- Redox potential and complex formation ability,
- Route of entry into the body,
- Frequency of exposure in the environment.

The primary toxic effect of heavy metals is their disruption of intracellular metabolic processes. These disruptions lead to:

- DNA damage,
- Increased oxidative stress and oxidative protein degradation,
- Mitochondrial damage and induction of apoptosis (programmed cell death),
- Autoimmune diseases (ulcerative colitis, Crohn's disease, rheumatism, etc.),
- Chronic organic diseases (kidney disease, allergies, eczema, asthma, etc.),
- Neurological disorders (depression, migraines, Alzheimer's disease, Parkinson’s disease).

Most health issues caused by heavy metals are chronic diseases and cancers that require advanced diagnostic and treatment options. Many of these conditions have limited treatment possibilities and can often result in fatal outcomes. Among heavy metals, mercury, lead, cadmium, and copper are considered the most toxic.

3.1. Copper (Cu)

Copper is widely used in electrical and paint industries, as well as in the production of plumbing pipes. Copper salts are also utilized as anthelmintics in veterinary medicine and as fungicides in agriculture. Copper enters the human body through inhaled air, drinking water, food consumption, and skin contact with copper-containing objects such as paintings.

Copper is naturally present in all human organs and tissues, with concentrations ranging from a few parts per million (ppm) to 100 ppm. The liver is the primary organ with the highest copper concentration, but significant amounts are also found in the brain, heart, stomach, and intestines.

However, excessive copper intake can be toxic. Ingestion of more than 15 mg of elemental copper can cause:

- Fatigue,
- Vomiting,
- Diarrhea,
- Abdominal pain,
- Widespread muscle pain.

In severe cases, excessive copper exposure can lead to neurological disorders, coma, and even death.

3.2. Iron (Fe)

Acute iron poisoning can cause gastrointestinal bleeding, cardiovascular collapse, mental confusion, liver and kidney failure. The severity of iron toxicity is dose-dependent:

- >20 mg/kg: Mild iron poisoning,
- >40 mg/kg: Severe iron poisoning,
- >60 mg/kg: Potentially fatal iron poisoning.

A chronic condition known as hemochromatosis occurs when the body absorbs excessive iron from food. This results in iron accumulation in the liver, heart, and pancreas, leading to severe complications such as liver disease, heart problems, and diabetes, all of which can be life-threatening.

3.3. Cadmium (Cd)

Cadmium is one of the most harmful heavy metals in the ecosystem and is highly toxic to living organisms. Due to the prolonged use of phosphorous fertilizers and sewage sludge, many agricultural areas worldwide have been exposed to cadmium contamination.

The high mobility of cadmium in soil allows it to easily enter the food chain, posing significant risks to plants, animals, and human health. When absorbed by plants, cadmium negatively affects several biochemical processes, including:

- Protein synthesis,
- Nitrogen metabolism,
- Enzyme activation,
- Photosynthesis and chlorophyll synthesis.

In modern agriculture, intensive fertilization practices make the contamination of food with cadmium almost unavoidable. Cadmium and its compounds accumulate particularly in the kidneys and heart, leading to severe health issues such as:

- Hypertension,
- Lung cancer,
- Osteoporosis,
- Anemia.

A significant portion of cadmium pollution originates from human activities. The estimated sources of cadmium in the soil are:

- 54-58% from phosphorous fertilizers,
- 39-41% from atmospheric deposition,
- 2-5% from sewage sludge and farmyard manure.

Adding more than 3 mg/kg of cadmium to the soil can pose a serious toxicity risk for plants and animals. Even at low concentrations, cadmium exposure can cause significant harm to aquatic ecosystems (Öktüren, Sönmez & Çıtak, 2007).

Treatment of Heavy Metals

The effective removal of metal ions from wastewater is a significant issue in modern environmental science. Various treatment technologies have been developed to regulate the uncontrolled presence of hazardous substances in wastewater, which pose risks to environmental and biological health. These technologies include chemical precipitation, ion exchange, membrane separation, ultrafiltration, electrocoagulation, solvent extraction, sedimentation, electrochemical degradation, reduction, reverse osmosis, dialysis, electrodialysis, adsorption, filtration, and evaporation. Determining the most suitable method for pollutant removal depends on several critical factors, including permissible chemicals, adsorbents, initial concentration, pH value, and other operational conditions.

The Heavy Metal Limits in Freshwater Sources

Water Quality Parameters	Upper Limits (mg/L)
Mercury (Hg)	0.01
Cadmium (Cd)	0.05
Lead (Pb)	0.5
Zinc (Zn)	2.0
Arsenic (As)	0.5
Chromium (Cr)	0.5
Copper (Cu)	0.5
Nickel (Ni)	0.5

Water Treatment Methods

Method	Advantage	Disadvantage
Chemical Precipitation and Filtration	Easy to use, Low cost	Difficulty in separation at high concentrations, Insufficient performance efficiency, Toxic sludge production
Electrochemical Methods	High metal removal efficiency	High cost of materials (electrodes), Efficiency only at high concentrations
Reverse Osmosis	Easy to use, Low cost	High-pressure systems
Ion Exchange	High metal removal efficiency, Pure waste recovery	Sensitivity to particles, High cost of resin
Evaporation	Pure waste recovery	High energy demand, High cost requirements, Toxic sludge production
Membrane	Pure waste recovery	High-pressure systems, High costs for applicability due to membrane size
Adsorption	Cheap, Effective availability, Applicability in pollutant removal, Applicability for all metals	Effective at low concentrations

5. Comparison of Chitosan and Activated Carbon

Heavy metals, chemical reagents, dyes, and other water pollutants pose a serious threat to human health and present significant challenges for environmental protection efforts. Currently, adsorption is the most effective and widely used method for wastewater pollutant removal. Chitosan (CS) is a natural adsorbent capable of reducing water turbidity, color, and small particles. More importantly, CS can also remove heavy metal ions, microbial contaminants, and harmful substances such as dyes, pesticides, and herbicides from water. Approved by the U.S. Environmental Protection Agency for drinking water treatment, CS is widely used in water treatment facilities worldwide to eliminate oil, grease, heavy metals, and fine particles from water. The amino groups in CS act as excellent chelating ligands with a strong affinity for metal cations, playing an effective role in wastewater treatment by forming chelates with metal ions such as cadmium, copper, lead, and mercury.

Currently, CS is predominantly used for heavy metal removal in wastewater treatment. Its adsorption capacity for heavy metals is influenced by factors such as the degree of deacetylation, wastewater conditions, and the type of heavy metal present. However, the adsorption capacity of CS alone is not sufficiently strong. To enhance its adsorption rate for heavy metals, CS derivatives can be synthesized through reactions with specific substituents. Additionally, chemically modified CS derivatives enable selective adsorption of heavy metals in wastewater. For instance, Zhang et al. synthesized novel CS derivatives by grafting acrylic acid onto CS and subsequently developing a composite adsorbent material (PAA/CTS/BC) using biochar. Their study demonstrated that PAA/CTS/BC effectively and rapidly adsorbs heavy metal ions, including Cu^{2+}, Zn^{2+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Mn^{2+}, Co^{2+}, and Cr^{3+}. The primary adsorption mechanism involves the formation of inner-sphere complexes between the carboxyl, hydroxyl, or amino groups of the composite adsorbent material and surface heavy metals, exhibiting strong selective adsorption. Among the tested metals, PAA/CTS/BC showed the highest selectivity for Cr^{3+}, supporting metal recovery from industrial wastewater (Zhang, Y., Wang, J., & Liu, Z., 2021).

In recent years, significant research advancements have been made in the use of chitosan and its derivative adsorbents for environmental applications. However, the selective adsorption capacity, preparation cost, and reusability of these materials still require further improvement.

Carbon-based nanoporous adsorbents, particularly activated carbons (ACs), carbon nanotubes (CNTs), and graphene (GN), are widely used in heavy metal removal applications due to their large surface areas (500–1500 m^2/g). The surface charges of carbon materials can be enhanced with functional groups (e.g., carboxyl, phenyl, and lactone groups, as shown in Figure 1b) to improve heavy metal retention capacity. Among various modification methods, nitrogenation, oxidation, and sulfurization are the most commonly employed techniques to enhance specific surface area, pore structure, adsorption capacity, thermal stability, and mechanical strength. However, these methods often rely heavily on adsorbent materials that are relatively expensive. Therefore, cost considerations should be taken into account when selecting the most suitable adsorbents (Karagöz, S., Uçar, S., Ertaş, M., & Tay, T., 2008).

Surface modification typically reduces surface area while increasing the content of surface functional groups. As a result, more metal ions can be adsorbed. Adsorption capacity increases when factors such as the surface area of the adsorbent, adsorbent dosage, initial concentration of metal ions, and contact time are enhanced. Although multi-walled carbon nanotubes (MWCNTs) have garnered particular interest for heavy metal removal, they are highly hydrophobic and tend to aggregate rapidly in aqueous solutions due to strong van der Waals forces, which reduces their adsorption potential (Yavuz, H., & Kara, A., 2016).

There is a lack of quantitative evaluation in the literature regarding the role of functional groups in heavy metal ion retention. Additionally, existing surface modification techniques require high temperature/pressure, strong acid/base treatments, or intense oxidation/reduction reactions. This complex preparation process makes carbon-based adsorbents expensive, limiting their widespread use in industrial applications. Therefore, researchers should propose innovative, cost-effective, and environmentally friendly surface modification techniques.

Laboratory and Industrial Applications

6.1. Causes and Types of Water Pollution

The discharge of wastewater containing one or more heavy metals or other toxic substances into receiving waters exerts a toxic effect on aquatic organisms and endangers life in the ecosystem. Heavy metals not only prevent the self-purification of polluted waters but also impose certain limitations on their use in agriculture for irrigation purposes.

Key sources of water pollution include:

- Soil transported by erosion
- Industrial waste from factories
- Sewage and wastewater discharge
- Diesel, tar, and burned oil from marine vessels
- Harmful chemicals released from pharmaceutical and paper industries

- Household waste, pesticides, and fertilizers
- Insoluble detergents polluting streams and eventually seas
- Thermal pollution from power plants, where heated water is discharged into rivers or seas

6.2. Industrial Pollution

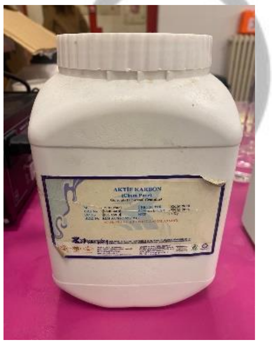
Advancements in metal production technologies have also introduced significant environmental challenges. The metal processing industry is one of the key sectors in national economic development. In addition to cast materials, sheet metal, rods, and wire-shaped materials are also processed in this industry. Various metal processing techniques are employed for manufacturing metal goods, machinery, and related products. Industrial waste encompasses all unused materials generated by factories, workplaces, and large-scale production facilities, and its release into the environment contributes to industrial pollution.

Power plants and factories are the primary sources of industrial pollution. Acidic compounds, toxic metals, and detergents from industrial activities contaminate rivers, lakes, seas, and groundwater. When industrial waste exceeds nature's capacity to assimilate it, it leads to environmental degradation and poses risks to human health. Industrial activities release acidic compounds, as well as toxic fumes and vapors of metals such as lead, zinc, copper, and arsenic. These airborne industrial pollutants, in the form of gases, vapors, and fine dust, eventually settle as atmospheric deposition or acid rain, contaminating soil and water resources (Arslan, H., & Demirbaş, A., 2013).

Method

Solution Preparation

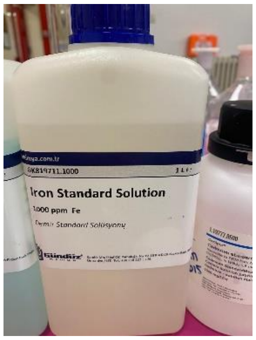
Stock solutions of iron (Fe), copper (Cu), and cadmium (Cd) metal ions were used. Each stock solution was diluted in 1 liter of deionized water, and a standard dilution process was applied to achieve the required metal ion concentrations. The stock solution concentration was determined based on laboratory measurements, and a reference photograph of the solution was taken.



Activated Carbon

Copper Standart Solution

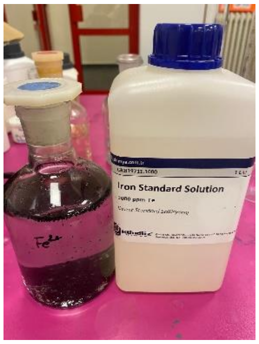
Standart Cadmium



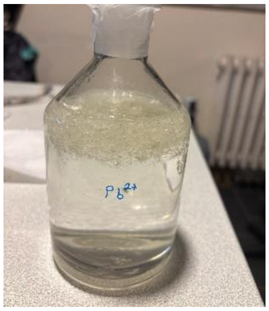
Iron Standart Solution

Active Carbon Copper Solution

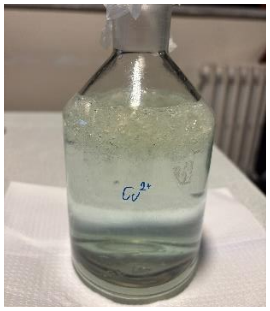
Active Carbon Cadmium Solution



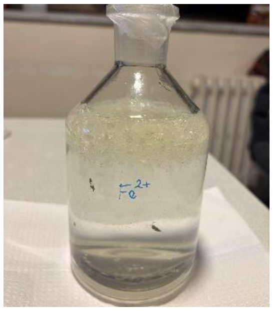
Active Carbon Iron Solution



Lead Solution Containing Chitosan



Copper Solution Containing Chitosan



Iron Solution Containing Chitosan

All solutions were further diluted with deionized water to a final volume of 1 liter and thoroughly mixed.

Addition of Activated Carbon

For each prepared metal ion solution, 0.5 g of activated carbon was added. The activated carbon was continuously stirred to ensure interaction with the metal ions in the solution. During the addition process, constant mixing was maintained. The stirring time and activated carbon dosage were adjusted according to predetermined experimental parameters. The solutions were periodically stirred over a two-week period and subsequently sent for analysis at the end of the experiment.

Addition of Chitosan Solution

A solution was prepared by dissolving 0.5 g of chitosan in 1% acetic acid. This chitosan solution was then added to each metal ion solution in specific proportions while ensuring continuous stirring. Chitosan was used to enhance the adsorption process by binding metal ions. The stirring process was maintained for a specific duration to increase the interaction between chitosan and the metal ions. After two weeks, the final solutions were sent for analysis.

Project Work-Time Schedule

Months					
Task Description	**September**	**October**	**November**	**December**	**January**
Literature Review	x	x	x	x	
Field Study			x	x	
Data Collection and Analysis			x		
Project Report Writing				x	x

Findings

In this study, the efficiency of chitosan and activated carbon in the treatment of aqueous solutions containing copper, cadmium, and iron was investigated. The findings compare the effectiveness of the control group with the treatment processes using chitosan and activated carbon for each metal:

1. Copper (Cu) Removal

- **Control Group:** The initial copper concentration was measured as **19.312 mg/L**.
- **Chitosan Treatment:** After the application of chitosan, the copper concentration decreased to **12.622 mg/L**, indicating a **34.6% reduction**.
- **Activated Carbon Treatment:** The treatment with activated carbon reduced the copper concentration to **4.182 mg/L**, achieving a **78.3% reduction**.
- **Evaluation:** Activated carbon demonstrated significantly higher efficiency in copper removal compared to chitosan.

2. Cadmium (Cd) Removal

- **Control Group:** The initial cadmium concentration was recorded as **19,220.66 µg/L**.
- **Chitosan Treatment:** After chitosan application, the concentration decreased to **11,833.49 µg/L**, corresponding to a **38.4% reduction**.
- **Activated Carbon Treatment:** The use of activated carbon lowered the cadmium concentration to **15,436.64 µg/L**, resulting in a **19.7% reduction**.
- **Evaluation:** Chitosan proved to be a more effective adsorbent for cadmium removal compared to activated carbon.

3. Iron (Fe) Removal

- **Control Group:** The initial iron concentration in the control sample was measured at **18,056.98 µg/L**.
- **Chitosan Treatment:** Following chitosan application, the iron concentration decreased to **10,936.98 µg/L**, showing a **39.4% reduction**.
- **Activated Carbon Treatment:** The treatment with activated carbon reduced the iron concentration to **16,207.32 µg/L**, achieving a **10.2% reduction**.
- **Evaluation:** Chitosan exhibited superior performance in iron removal compared to activated carbon.

Conclusion

The overall findings of the study indicate that both chitosan and activated carbon exhibit varying degrees of effectiveness depending on the metal being treated:

- **Chitosan** has proven to be particularly effective in removing iron and cadmium.
- **Activated carbon** has shown superior performance in removing copper.

These differences in performance stem from the surface chemistry, pore structure, and the chemical characteristics of the metal ions being adsorbed. Activated carbon, with its large surface area and high porosity, is more efficient in physical adsorption processes, while chitosan's amino and hydroxyl groups enhance its capacity for chemical binding with metal ions.

Moreover, the results from this study support the use of environmentally friendly and sustainable materials in wastewater treatment. Chitosan's biodegradability and non-toxic nature make it a promising material for developing sustainable solutions to reduce environmental pollution

Recommendations

1. Potential Use of Chitosan:
Chitosan can be considered an effective and environmentally friendly alternative for the treatment of wastewater containing iron and cadmium. This study supports its high performance in removing these metal ions. However, for copper removal, activated carbon should be preferred due to its superior efficiency in this context.

2. Development of Hybrid Adsorbents:
Combining the properties of chitosan and activated carbon to create a hybrid adsorbent material could enable the simultaneous and efficient removal of multiple metal ions. Such hybrid systems can provide more comprehensive solutions by combining chitosan's chemical binding capacity with activated carbon's large surface area.

3. Modification of Chitosan:
Chemical modification of chitosan's surface could enhance its efficiency, particularly in copper ion removal. For instance, adding sulfur or phosphate groups to the chitosan surface could provide stronger binding with copper ions, improving adsorption performance.

4. Improvment Of Activated Carbon's Pore Structure:
Optimizing the pore sizes during the production of activated carbon could increase its adsorption capacity, especially for larger ions like cadmium and iron. Additionally, enriching the surface with functional groups could enhance the selectivity of activated carbon for specific

metal ions, making it a more versatile adsorbent.

5. Economic and Environmental Analyses:
Detailed analyses of the production costs, reusability options, and environmental impacts of chitosan and activated carbon should be conducted. Specifically, obtaining chitosan from waste shells (e.g., shrimp shells) can offer an economically viable and sustainable source management approach, contributing to both cost reduction and waste minimization.

6. Expansion of Application Areas:
The combination of chitosan and activated carbon should not only be investigated for wastewater treatment but also for potential applications in industrial processes, agricultural irrigation, and drinking water purification. Researching the versatility of this combination across various sectors could lead to broader environmental and economic benefits.

7. Kinetic and Thermodynamic Analyses:
Kinetic and thermodynamic models should be applied to analyze the adsorption processes, allowing a deeper understanding of the adsorption mechanisms of these materials towards metal ions. This will provide crucial information for optimizing the adsorption process in real-world applications.

8. Reusability and Regeneration:
The reusability of chitosan and activated carbon adsorbents should be investigated, focusing on their regeneration processes. For example, cleaning the used materials with acid or base solutions to restore their activity could reduce costs and decrease waste generation, making the process more sustainable.

9. Pilot-Scale Applications:
The results obtained in laboratory-scale studies should be validated through pilot-scale applications in real wastewater systems. Such studies are essential for assessing the commercial and industrial potential of chitosan and activated carbon in large-scale operations.

10. Studies on Multiple Pollutants:
In real wastewater systems, multiple pollutants (e.g., heavy metals, organic contaminants) are typically present. Therefore, the effectiveness of chitosan and activated carbon in removing multiple pollutants simultaneously should be investigated. This will help to determine their broader application potential for more complex waste treatment scenarios.

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