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Adsorption-Based Removal of Dyes from Textile Wastewater Using Sustainable Materials

[1]Dr. Manisha Kumari, [2]Dr.N. Hari Babu , [3]Surendra Kishore, [4]Rani Kumari, [5]Muneshwar Munda
1.Assistant Professor, Department of Science & Humanities(Chemistry)
RTC Institute of Technology, Ormanjhi,Ranchi
2. Principal, RTC Institute of Technology, Ormanjhi,Ranchi
3.Assistant Professor, Department of Civil Engineering
RTC Institute of Technology, Ormanjhi,Ranchi
4.Student, Department of Civil Engineering
RTC Institute of Technology, Ormanjhi,Ranchi
5.Student, Department of Civil Engineering
RTC Institute of Technology, Ormanjhi,Ranchi

Abstract

This paper presents an investigation into the efficacy of adsorption method for the removal of dyes from textile industry wastewater. The persistent environmental challenges posed by dye-laden effluents necessitate the development of more efficient and sustainable treatment technologies. This study outlines the principles and application of adsorption techniques, detailing their operational parameters and reported removal efficiencies. Quantitative results from experimental applications of these methods are presented, demonstrating their capacity to significantly reduce dye concentrations. The findings indicate that these advanced physical processes offer robust alternatives to conventional treatment strategies, providing high removal rates and contributing to improved wastewater quality. The implications for industrial application and future research directions are discussed, emphasizing the potential for enhanced environmental protection.

Keywords: Textile industries, dyes, sustainable, adsorption, wastewater treatment.

1.Introduction

Dyes are chemical compounds used to impart color to surfaces and fabrics. The majority of dyes are complex organic molecules designed to be resistant to degradation from things like detergents. Synthetic dyes are used extensively across many industries, including textiles, paper, leather, food processing, plastics, cosmetics, and printing. They are also used for environmental purposes like tracing groundwater and evaluating activated sludge in wastewater treatment.

Unfortunately, the discharge of these dyes into waterways is a significant source of pollution. Dyes are often resistant to biological and photochemical breakdown, giving water an undesirable color that blocks sunlight and harms aquatic life. The total global production of commercial dyes is over 700,000 tonnes per year. The textile industry alone consumes more than 10,000 tonnes annually, with approximately 100 tonnes of dye being discharged into water streams. The release of these synthetic dyes poses a major challenge for environmental scientists.

Various methods are used to remove dyes from wastewater, including adsorption, coagulation, advanced oxidation, and membrane separation. **Adsorption** is considered one of the most effective and widely used processes for removing hazardous organic and inorganic pollutants. While commercial activated carbon is often used, its high cost has led researchers to seek more affordable alternatives. Recent studies have explored the use of low-cost adsorbents derived from natural materials, industrial solid wastes, agricultural by-products, and biosorbents. Lignin-cellulosic biomass, in particular, has shown promise as an effective adsorbent. Researchers have also explored physical and chemical treatments to improve the adsorption capacity of these raw biomass materials.

This paper provides a comprehensive review of the current state of adsorption technology for removing dyes from aqueous solutions. Our primary goal is to present an up-to-date overview of commercial activated carbon and various sustainable, low-cost alternatives. These alternatives include agricultural waste, industrial solid waste, and biomass-based activated carbons. We will also critically analyze the effectiveness of different adsorbents under various physical and chemical conditions and compare their adsorption capacities. The paper compiles recent published data on adsorption kinetics and key findings.

This review aims to be more comprehensive and critical, analyzing two decades of scattered information on dye adsorption by a wide range of adsorbents. A key aspect of this review is to cover the latest research, identify effective operational conditions, and determine maximum adsorption capacities.

Dyes can be classified by their chemical structure, color, or application method. The application-based classification is often preferred due to the complexity of chemical nomenclature. Dyes are also categorized based on the charge of their particles in aqueous solution: **cationic** (basic dyes), **anionic** (direct, acid, and reactive dyes), and **non-ionic** (dispersed dyes).

Industrial discharge of dyes into water bodies is a significant problem. Basic dyes, for example, have high color intensity and are visible even in low concentrations. Many dyes, particularly complex chromium-based ones, are carcinogenic. Dyes can also be toxic to aquatic life by reducing light penetration and introducing metals and aromatic compounds. In humans, dyes can cause severe damage to organs and systems, including the kidneys, liver, brain, and central nervous system. Azo dyes and anthraquinone-based dyes are particularly toxic and resistant to degradation. Reactive dyes are also a major concern, as they are chemically stable and often pass through conventional treatment plants untreated. Due to these toxic effects, it is crucial to develop effective methods and technologies to remove dyes from wastewater. This paper aims to investigate the performance of adsorption method in dye removal, providing quantitative data on their effectiveness and contributing to the advancement of sustainable wastewater treatment practices.

2.Literature review

In recent years, numerous studies have explored the effectiveness of various adsorbents for removing dyes from wastewater. Several researchers have focused on review articles to synthesize the current state of knowledge. For example, MustafaT.Yagub*etal*.:(AdvancesinColloidandInterfaceScience)Volume209,July2014,Pages 172-184 " provided a comprehensive review on the application of adsorption for dye removal, covering topics like dye classification, treatment methods, and the characteristics of different adsorbents, including low-cost alternatives like agricultural by-products and biomass-based activated carbon.

Similarly, S.Mondal**:**(EnvironmentalEngineeringScience)Vol.25,PageNo.3,PublishedOnline:31March2008 reviewed various methods for treating dye house effluent, including oxidation, reduction, and adsorption using activated carbon and biomaterials.

K.Y.FooandB.H.Hameed:(DesalinationandWaterTreatment)Volume19,2010 specifically reviewed dye removal using activated carbon adsorption, discussing its environmental implications and key factors influencing the process.

Additionally, Anastopoulos et al. (2018) summarized important work on using nanoparticles as adsorbents for dye removal, detailing various kinetic and isotherm models.

Other studies have focused on specific adsorbents and dyes. For instance, Rehmanetal.:(CarbohydratePolymers)Volume90, Issue3,15 October 2012,Pages1314-1322 investigated the use of sugar-extracted spent rice biomass to remove methylene blue dye, finding the process to be spontaneous and endothermic.

G.McKay,J.F.Porter&G.R.Prasad:(Water,Air,andSoilPollution)Volume114,pages423–438, (1999)studied five low-cost adsorbents—rice husk, cotton, bark, hair, and coal—for the removal of Safranine and Methylene Blue dyes.

SourjaChakrabortyetal.:(Chemosphere)Volume58,Issue8,February2005,PagesNo.1079-1086 developed an effective adsorbent from sawdust to remove crystal violet dye, while El Boujaady et al. (2011) investigated synthetic calcium phosphates for removing Reactive Yellow 4 dye.

Researchers have also explored advanced and modified materials for dye removal Sankar Chakmaand Vijayan and S.Moholkar:(Journal of Industrial and Engineering Chemistry) Volume37, 25 May 2016, Pages 84-89 reported on the synthesis of bi-metallic oxides nanotubes for the fast removal of dyes using a combined adsorption and sonocatalysis process.

Q.H.Huetal.:(*Industrial&EngineeringChemistryResearch*)Vol45/Issue2,November19,2005) investigated bentonite as an adsorbent for removing Basic Red 2 dye, noting its high adsorption capacity due to cation exchange.

V.Gómez,M.S.Larrechi and M.P.Callao:(Chemosphere) Volume69, Issue7, October2007, Pages1151- 1158 studied the removal of three acid dyes from aqueous solutions using activated carbon, and found the adsorption rates conformed to pseudo-second-order kinetics. These studies collectively demonstrate the breadth of research in this field, highlighting the potential of various materials—from low-cost natural products to synthetic nanoparticles—for effective dye removal from wastewater.

3. Adsorption as a Primary Strategy for Dye Effluent Treatment

3.1. Principles of Adsorption Method for Dye Removal

Adsorption is a widely used method for treating textile wastewater due to its simplicity, effectiveness, and low cost. The process involves using an adsorbent material to attract and bind dye molecules from the water.

How it Works:

- **Adsorbent:** The dye-contaminated water is mixed with an adsorbent material.
- **Binding:** The adsorbent's surface binds to the dye molecules, effectively removing them from the solution.
- **Separation:** The treated water is then separated from the adsorbent material, which now contains the captured dye.

3.2. Benefits of Adsorption:

- **Cost-Effective:** Compared to many other wastewater treatment methods, adsorption is relatively inexpensive, especially when using low-cost alternative adsorbents.
- **High Efficiency:** It is particularly effective at removing certain types of pollutants, especially those that are difficult to break down biologically or chemically.
- **Eco-Friendly and Renewable:** Using adsorbents derived from agricultural or food waste promotes a circular economy and utilizes renewable resources.

3.3. Key Factors Affecting Adsorption:

The efficiency of the adsorption process is influenced by several factors:

- **pH of the water:** The acidity or alkalinity of the water affects the surface charge of the adsorbent and the dye molecules, which in turn impacts their interaction.
- **Adsorbent Dose:** The amount of adsorbent used directly correlates with the number of available binding sites for the dye molecules.
- **Contact Time:** A sufficient amount of time is needed for the dye molecules to diffuse and bind to the adsorbent's surface.

Common Adsorbents: Activated Carbon: A highly effective, but often more expensive, commercial option.

4. Sustainable Low-Cost Adsorbents: An Emerging Solution

The pursuit of cost-effective alternatives to commercial activated carbon has led to an innovative shift towards utilizing readily available, often waste-derived materials

4.1 Low-Cost Alternatives: Researchers are increasingly exploring inexpensive and eco-friendly adsorbents made from waste materials such as: Orange peels, Coffee grounds, various types of agricultural waste

4.2 Discussion on Lignin Cellulosic Biomass as an Effective Adsorbent

Among the diverse range of alternative precursors, lignin cellulosic biomass has been specifically identified as behaving as a good and effective adsorbent . This class of natural materials, abundant as agricultural residues (e.g., rice husks, corn cobs) or forestry by-products (e.g., wood chips, sawdust), possesses inherent properties that make it suitable for adsorption. Lignin and cellulose, the primary components of plant biomass, feature complex structures rich in functional groups such as hydroxyl, carboxyl, and phenolic groups. These groups can serve as active sites for chemical interactions with dye molecules, while the natural porous structure of biomass provides a substantial surface area for physical adsorption.

5. Materials and Methods

5.1Groundnut Shell and Chalk Powder as Adsorbents for Dye Removal

Groundnut shells and chalk powder are commonly used, cost-effective, and environmentally friendly materials for the removal of dyes from textile wastewater. They act as adsorbents, each with unique properties and mechanisms for attracting and binding dye molecules.

5.1.1. Groundnut Shell

- **Composition:** Primarily consists of lignin, cellulose, and hemicellulose, which create a porous structure.
- **Adsorption Mechanism:** The porous nature and functional groups on the material facilitate dye adsorption through a combination of physical and chemical interactions.
- **Key Characteristics:**
  - High surface area, enhancing adsorption capacity.
  - Cellulose and lignin content effectively bind dye molecules.
  - Porous structure allows for efficient dye removal.
  - Non-toxic, biodegradable, and cost-effective.
- **Advantages:**
  - High removal efficiency (up to 95%).
  - Fast adsorption rate.
  - Effective over a wide pH range (2-8).
  - Can be regenerated and reused.
  - Produces minimal sludge.
- **Optimization Parameters:**
  - Contact Time: 30-60 minutes
  - pH: 2-8
  - Temperature: 25-40°C
  - Dose: 0.5-2 g/L
  - Agitation Speed: 100-200 rpm

5.1.2. Chalk Powder (Calcium Carbonate - $CaCO_3$)

- **Composition:** Composed mainly of calcium carbonate, which serves as the active adsorbent.
- **Adsorption Mechanism:** Removes dyes through precipitation, surface adsorption, and ion exchange.
- **Advantages:**

- Readily available and low-cost.
- Helps neutralize acidic wastewater.

- **Future Directions:**
  - Modification of chalk powder to improve performance.
  - Integration with other wastewater treatment technologies.
  - Application in pilot-scale and industrial settings.
  - Exploration of other calcium-based adsorbents.
- **Optimization Parameters:**
  - Contact Time: 30-60 minutes
  - pH: 2-8
  - Temperature: 25-40°C
  - Dose: 0.5-2 g/L
  - Agitation Speed: 100-200 rpm

5.2 Procedure for Absorbance Test

This procedure outlines the steps for a study on the effectiveness of chalk powder in removing methyl blue dye from a water solution, measured by a digital photo colorimeter.

Step 1: Prepare the Stock Solution

- Dissolve 0.25 grams of methyl blue dye in 250 ml of water to create a stock solution.

Step 2: Prepare the Test Samples

- Create a series of water samples with different concentrations of the methyl blue stock solution. These will be used to establish a baseline for absorbance measurements.

Step 3: Determine Initial Absorbance

- Using a digital photo colorimeter, measure and record the absorbance of each of the prepared dye solutions. This provides the initial absorbance value before treatment.

Step 4: Treat the Samples with Adsorbent

- Add a specific amount of Adsorbent to each test sample.
- Allow the samples to sit for 1 hour to ensure the Adsorbent fully interacts with and adsorbs the dye molecules.
- After the interaction period, filter the solutions to separate the Adsorbent and any adsorbed dye from the treated water.

Step 5: Determine Final Absorbance

- Using the same digital photo colorimeter, measure and record the absorbance of the filtered solutions. This final absorbance value will demonstrate the amount of dye remaining in the water after treatment with Adsorbent

The experiment measures the absorbance of a methyl blue dye solution before and after treatment with Adsorbents. By comparing the initial and final absorbance values, one can determine the efficiency of Adsorbents in removing the dye.

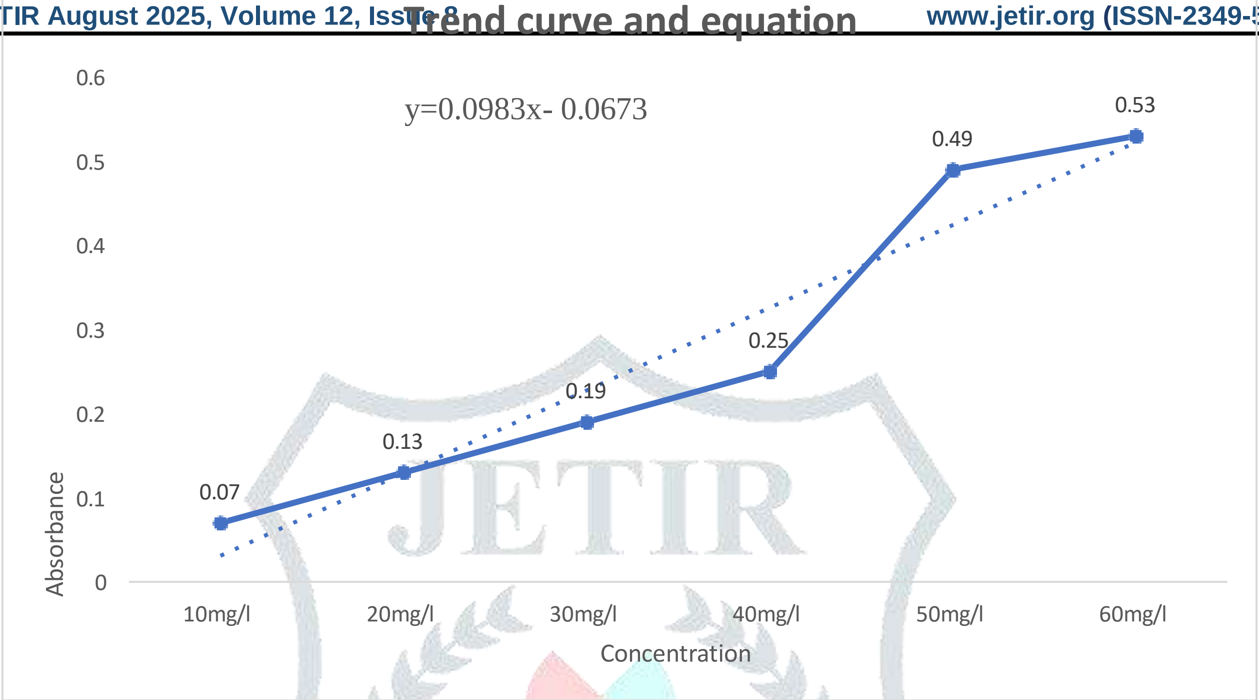
6. Observation and Result

Table No.1 Groundnut Shell Absorbance Table

Concentration(mg/l)	Absorbance(before) filter	Absorbance(after) filter
10	0.05	0.01
20	0.13	0.04
30	0.19	0.09
40	0.20	0.10
50	0.27	0.13
60	0.30	0.16

Table No.2 Chalkpowder Absorbance Table

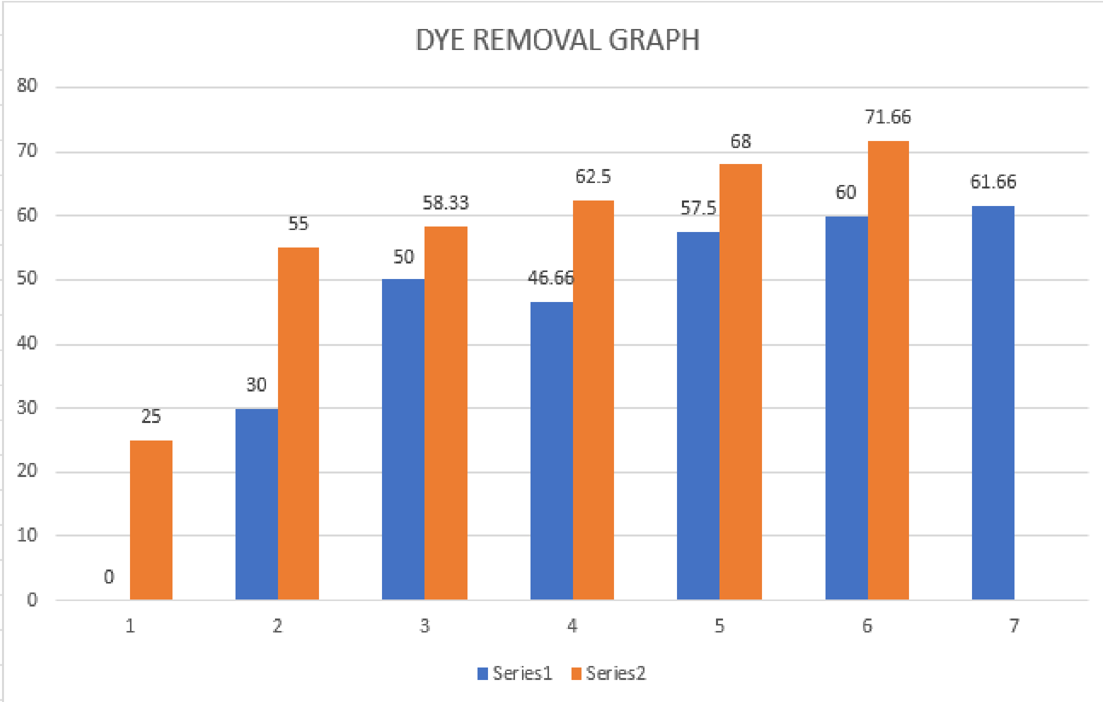
Concentration(mg/l)	Absorbance(before) filter	Absorbance(after) filter
10	0.05	0.02
20	0.13	0.03
30	0.19	0.07
40	0.20	0.08
50	0.27	0.09
60	0.30	0.10



Treatment Result

Initial concentration (mg/l)	Removal percentage of Groundnut shell	Removal percentage of Chalk Powder
10	30%	25%
20	50%	55%
30	46.6%	58.33%
40	37.5%	62.5%
50	60%	68%
60	61.6%	71.66%

Percentage removal



Series1-groundnutshell

Series2-chalkpowder

Result-

Maximum dye absorption / remove = 17.07 and 23.19

Maximum dye absorption in % =71.66 and 61.66

7.Conclusion and Future Research Directions

7.1 Key Findings Regarding Effective Dye Removal via Adsorption

The extensive and persistent tendency of industrial dye pollution poses a significant environmental and public health threat, necessitating robust and effective wastewater treatment solutions. Adsorption has been firmly established as a highly effective and industrially viable method for removing these hazardous organic compounds from aqueous solutions. While commercial activated carbon has historically dominated this application due to its high efficacy, its prohibitive cost has driven extensive research into more sustainable and economically viable alternatives.The study highlights the successful emergence of a diverse range of low-cost adsorbents derived from readily available natural materials, industrial solid wastes, and agricultural by-products. These materials offer a dual benefit: effective dye removal and the valorization of waste streams, thereby promoting a more circular economy approach to wastewater treatment. It is evident that while these sustainable adsorbents demonstrate considerable promise, their performance is intricately linked to various physiochemical parameters, including solution pH, temperature, and initial dye concentration. The selection and optimization of an adsorbent must therefore consider the specific characteristics of both the dye and the wastewater matrix. The field is progressively moving towards a more holistic and sustainable approach to wastewater treatment, integrating waste valorization with pollutant removal, driven by both environmental necessity and economic viability. This convergence signifies a mature and promising research direction where wastewater treatment becomes increasingly integrated with resource recovery and waste management, moving towards a more circular industrial ecosystem

7.2 Future Directions for Sustainable Adsorption Technologies

Despite significant progress in sustainable adsorption technologies, several key areas need further development to unlock their full potential. Future research should focus on:

- Optimizing Pre-treatment and Regeneration: Finding better ways to prepare and reuse low-cost adsorbents to increase their effectiveness and reduce environmental impact and cost.
- Ensuring Long-term Stability and Reusability: Studying how well these materials hold up and can be reused, especially in complex, real-world industrial wastewater.
- Developing Novel Adsorbents: Creating new hybrid and nanomaterial adsorbents (like those using graphene or carbon nanotubes) to improve performance, selectivity, and speed.
- Creating Standardized Evaluation Methods: Establishing consistent ways to test and compare different adsorbents to ensure reliable and comparable results across various research teams.
- Scaling Up to Industrial Applications: Conducting more pilot- and full-scale studies to test the economic viability and practical challenges of these systems outside of a lab.
- Managing the Ultimate Fate of Adsorbed Dyes: Investigating safe disposal, degradation, and regeneration methods for used adsorbents to prevent secondary pollution.

These efforts will require an integrated, multidisciplinary approach involving material scientists, engineers, and environmental experts to develop solutions that are effective, economical, and truly sustainable.

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