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# Removal of $Pb^{2+}$ from Aqueous Solution Using Recycled Textile Waste as an Adsorbent

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**ABSTRACT**

The growing demand for textile fibers has caused a rapid increase in textile waste, posing serious environmental and health challenges. This study investigates the potential of recovered cotton waste as a low-cost, eco-friendly adsorbent for removing heavy metals—lead (Pb) from contaminated water. Cotton was chosen for its natural, biodegradable nature and inherent adsorption capacity. Post-consumer cotton textiles were collected, shredded, and chemically modified with sulfuric and citric acids to enhance surface area and efficiency. Batch adsorption experiments were conducted under varying pH levels, contact times, and cotton dosages to determine optimal removal conditions. The performance of recycled cotton was compared with conventional water treatment methods, alongside a cost-benefit analysis to assess economic feasibility for large-scale applications. Results showed citric acid–treated cotton achieved up to 71.29% lead removal (2 g dosage, pH 5, 2 h contact time) with a maximum adsorption capacity of 10.15 mg/g. This approach addresses two pressing issues—textile waste and heavy metal pollution—while offering a scalable, sustainable, and cost-effective biosorbent for water purification.

Keywords: Textile waste, Biosorbents, Heavy metal, Adsorption Capacity and Citric acid treatment



## 1. Introduction

The manufacturing of textile fibers is growing exponentially, and this is releasing textile waste-based effluents into the environment at a rate that is negatively affecting both human health and the overall health of the planet [1]. The United Nations estimates that 92 million tons of textile waste are thrown away annually, adding to pollution, overpopulation in landfills, and the loss of natural resources. The world's top cotton producing nations—India, China, the United States, Brazil, Pakistan, Australia, Turkey, Uzbekistan, Turkmenistan, and Burkina Faso—produced about 23.6 million ton of cotton in 2017–2018; the textile and apparel industries used the majority of these natural fibers [2]. Chemicals used in textile production, including as finishing agents and dyes, have the potential to contaminate land and water systems [3].This emphasizes how urgently sustainable approaches to the management and recycling of textile waste—especially cotton waste—are needed. The proper disposal of textile waste is one of the main issues. Only 15% of textile waste is recycled, according to the Environmental Protection Agency (EPA), the remaining 85% is burned or dumped in landfills, releasing toxic greenhouse gases into the atmosphere (EPA, 2022) [4]. In landfills, textile materials can take decades to decompose, releasing harmful chemicals, dyes, and microfibers into nearby soil and water sources. This contributes to soil erosion and water pollution, posing long-term environmental risks [5]. Furthermore, the worldwide plastic pollution catastrophe is exacerbated by petroleum-based synthetic fibers like polyester. These fibers release microplastics into the oceans and are not biodegradable, taking hundreds of years to break down [6]. Many developing nations, lacking proper recycling infrastructure, have become dumping grounds for used clothing from developed countries, harming local ecosystems and communities [7].The production of textiles uses a lot of energy, water, and chemicals, recycling helps reduce the environmental cost of using virgin materials [8]. Textiles are frequently treated during manufacture with dyes, flame retardants, and other chemicals that, if illegally disposed of, can leak into soils and water bodies, endangering both human health and animals [9]. The market for recycled textiles is expanding in tandem with the increased demand for sustainable products. Consumer awareness and regulatory pressures are predicted to propel the worldwide textile recycling market's significant growth in the next years [10].

Rich in cellulose and readily adjustable for improved adsorption, cotton waste is a more environmentally friendly option than traditional adsorbents since it provides a low-cost, sustainable method of removing heavy metals from wastewater while recycling textile waste and lessening its impact on the environment. Recycling textiles reduces landfill use and synthetic incinerator emissions, facilitating waste management, however surface alterations to boost heavy metal uptake may raise costs, complexity, and secondary pollution [11]. Reusing textiles, particularly cotton, encourages sustainable manufacturing and consumption, and regulations like as EPR hold producers responsible for the full life cycle of their goods [12].

Pollution in water is poses such serious health hazards, has emerged as a major environmental concern. The majority of these pollutants include petroleum products, dyes, medicines, pesticides, heavy metals (HMs), and other organic and inorganic substances that dissolve in water [13-

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15]. HMs are the most common pollutant present in environmental waters in different parts of the world [16]. The primary means by which they enter the environment are industrial processes related to the metallurgical, nuclear, battery, leather, fertilizer, pesticide, petroleum, and textile industries [17]. HMs are a group of metals and metalloids with an atomic density of more than 4000 kg/m3, atomic weights between 63.5 and 200.6 and gravity is greater than 5.0 [18]. Lead (Pb) exposure, particularly in children, can result in kidney failure, anemia, neurological problems, and developmental delays [19-20]. Cadmium (Cd) is associated with kidney impairment, bone demineralization, respiratory difficulties, and cancer [20]. Mercury (Hg), particularly methylmercury from fish, is neurotoxic and impairs memory and development [20-21]. Arsenic (As) in drinking water increases the risk of cancer and cardiovascular disease [20-21]. Thus, effective heavy metal removal from waste water is required. Heavy metals are usually extracted from contaminated water through a number of standard techniques, such as flotation, ion exchange, electrochemical treatment, precipitation, solvent exchange, sedimentation, filtration, coagulation, ozonation, flocculation, evaporation and adsorption, etc [2,22-23].The cost-effectiveness, availability, renewability, and environmental sustainability of cotton-based adsorption make it stand out as a better heavy metal removal technique than traditional adsorbents. The aim of this research is to develop and evaluate a novel water treatment method using recycled cotton waste as a low-cost, eco-friendly adsorbent for the removal of lead from contaminated water, contributing to both sustainable waste management and environmental protection.

## 2. Literature Review

The ability of textile waste, especially cotton, to adsorb heavy metals from wastewater has been the subject of numerous investigations. The pH of the solution, the adsorbent dose, the temperature, and the duration of contact all affect how well metals like Pb adsorb. Various methods of modifying cotton fibers have been explored to enhance their adsorption capacity for removing heavy metals from contaminated water. One such method involves citric acid treated cotton fiber (CACF), which has been shown to effectively remove cadmium (Cd). When treated cotton fibers are used at a pH of 5.0 and a concentration of 0.1 mmol/L at a temperature of 25±1°C, the fibers exhibit an adsorption capacity (Qe) of 8.22 mg/g within just one hour[2]. In addition to citric acid treatment, sodium hydroxide treated cotton biochar (SHB) has been studied for its ability to remove several heavy metals, including lead (Pb), nickel (Ni), and cadmium (Cd). For lead (Pb), SHB shows high adsorption capacities, reaching 8 up to 44.64 mg/g after 4 hours with concentrations ranging from 10 to 80 mg/L[24]. For nickel (Ni), SHB can adsorb 6.20 mg/g within 4 hours at concentrations between 1 to 10 mg/L [24], while for cadmium (Cd), the adsorption capacity is lower at 0.648 mg/g within the same time frame. Another modification technique involves sulphuric acid treated cotton biochar (SAB), which has also been tested for cadmium and nickel removal. In the case of cadmium, SAB exhibits an adsorption capacity of 0.5 mg/g at concentrations between 0.1 and 1.0 mg/L [24], while for nickel, the capacity is 2.05 mg/g within 1 [24]. This demonstrates that sulphuric acid treatment also enhances the cotton biochar's ability to adsorb heavy metals, albeit with varying effectiveness depending on the metal being targeted .The citric acid treated cotton fiber (CACF) was further tested for lead (Pb(II)) removal. Under similar conditions as for cadmium (pH 5.0, concentration of 0.1 mmol/L, and temperature of 25±1°C), CACF adsorbed 21.62 mg/g of lead within 1 hour [2]. This highlights the versatility of citric acid treatment for improving cotton fibers' ability to adsorb different heavy metals. These results indicate that modifying cotton fibers using different chemical treatments such as citric acid can significantly enhance their adsorption capacities for removing heavy metals like lead, cadmium from water, providing a promising low-cost, sustainable solution for water decontamination.

## 3. Methodology

The first step in preparing recycled cotton for lead adsorption research is gathering and classifying textile waste; 100% cotton is preferred because blended materials might not work well in adsorption tests. At this point, any non-cotton elements like buttons, zippers, or blended fibers ought to be taken out. The cotton is mechanically shred into smaller pieces using a fabric cutter or shredder. After that, the cotton is washed to remove any dirt, oils, or colors that can affect its ability to adsorb substances. To guarantee that the cotton fibers are completely dried, the cotton is either air-dried or dried using a low-temperature dryer after washing.to increase the adsorption ability a chemical pretreatment was done. 1L 0.5M of the citric acid solution is used to soak 20 g of the dried recycled cotton in order to treat it. A magnetic stirrer is used to continually swirl the liquid for two hours at room temperature. After the treatment, the cotton is taken out of the solution and given a good rinse with distilled water to get rid of any last traces of citric acid. The cotton is then prepared for use in lead adsorption tests by drying it by air. Synthetic lead-contaminated water with known Pb2+ concentrations is used in batch studies to evaluate the regenerated cotton's adsorption capacity. To find the ideal adsorption parameters, the experiments are conducted under a variety of circumstances, such as changing the temperature, pH levels, contact time, and cotton dose. Each combination of pH and contact time was tested for both 1g and 2g cotton samples. The process is shown in Fig.1.

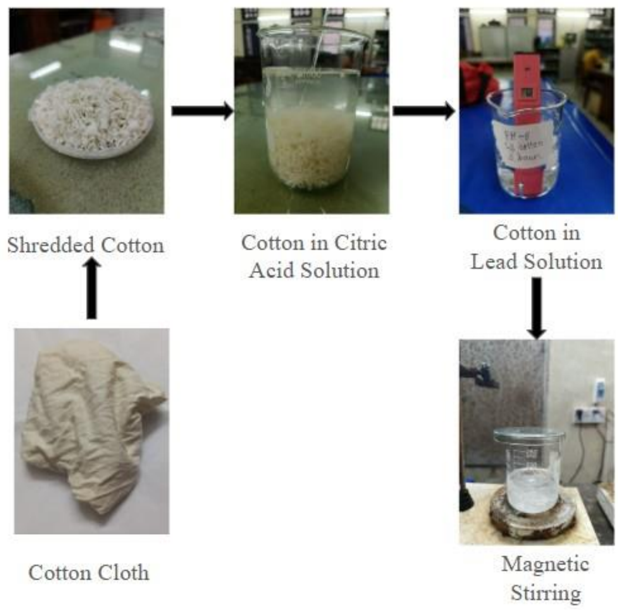


Fig.1: Lead Removal Process

The experimental setup can be summarized as Table 1.

Table 1: Experimental Conditions for Batch Adsorption

| Sample No | Cotton Dosage (g) | pH Level | Contact Time (s) |
|---|---|---|---|
| 1 | 1 | 5 | 1 |
| 2 | 1 | 5 | 2 |
| 3 | 1 | 6 | 1 |
| 4 | 1 | 6 | 2 |
| 5 | 2 | 5 | 1 |
| 6 | 2 | 5 | 2 |
| 7 | 2 | 6 | 1 |
| 8 | 2 | 6 | 2 |

After the corresponding stirring times were up, the cotton was filtered out of the lead solution. Two to three drops of concentrated nitric acid (HNO) were added to each
100 ml filtrate to stabilize the lead ions and prevent them from precipitating or adhering to the walls of the container .The preserved samples were kept in a dark, cool place. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was used to measure the residual concentration of lead ($Pb^{2}$) in each sample following the completion of the batch adsorption studies and the appropriate preservation of the filtered samples. The percentage removal for each sample under various experimental circumstances was then determined using the measured lead concentrations.
By adding more functional groups to the cellulose surface, sulfuric and citric acid treatments improved the regenerated cotton's capacity for adsorption. While citric acid adds carboxyl groups by esterifying with surface hydroxyls, sulfuric acid modification can produce sulfate and hydroxyl groups by partially hydrolyzing cellulose. In this study, only citric acid modification was carried out to enhance the adsorption capacity of recycled cotton. It is known from the literature that these chemical alterations enhance metal ion binding and increase the number of active sites. Due to equipment restrictions, surface characterization techniques like FTIR or SEM were not used in this investigation; as a result, the chemical alterations were comprehended using proven pathways documented in earlier research rather than direct experimental verification.

## 4. Data collection and analysis

The performance of the recycled cotton was evaluated by calculating removal efficiencies and adsorption capacities under various testing settings.

Table 2: Percentage Removal and Adsorption Capacity (Initial Concentration =220 ppm)

| Sample No | Final Pb (mg/L) | % Removal | Adsorption Capacity (mg/g) |
|---|---|---|---|
| 1 | 168.000 | 23.64 | 5.20 |
| 2 | 118.500 | 46.14 | 10.15 |
| 3 | 164.690 | 25.14 | 5.53 |
| 4 | 135.174 | 38.56 | 8.48 |
| 5 | 134.018 | 39.08 | 4.30 |
| 6 | 63.168 | 71.29 | 7.84 |
| 7 | 187.038 | 14.07 | 1.65 |
| 8 | 184.277 | 16.24 | 1.79 |

The percentage removal of lead from the aqueous solution was calculated using the following equation:

$$\% \; of \; Removal = \left(\frac{C_i - C_f}{C_f}\right) \times 100 \qquad (1)$$

where $C_i$ is the initial concentration of lead (220 mg/L), and $C_f$ is the final concentration of lead measured by ICP-OES. It was observed that lead removal efficiency was generally higher at pH 5 compared to pH 6. For both dosages, samples stirred for 2 hours showed higher lead removal than those stirred for only 1 hour. Increasing the cotton dosage from 1g to 2g led to improved removal efficiency. As shown in Table 2, the removal percentage at pH 5 with 2g cotton and 2-hour contact time reached the highest value of 71.29%, indicating optimal conditions for lead adsorption. Meanwhile, the lowest removal, about 14.07%, was observed at pH 6 with 2g cotton and 1-hour contact time (see Table 2).
One important factor that gives a numerical indication of the amount of pollutant eliminated per unit mass of the adsorbent is the adsorption capacity (Eq 2).

$$q_e = \frac{(C_0 - C_e) \times V}{m} \qquad (2)$$

where :
$q_e$ = adsorption capacity (mg/g)
$C_0$ = initial concentration of metal ions (mg/L)
$C_e$ = equilibrium (final) concentration (mg/L)
V = volume of the solution (L)
m = mass of adsorbent used (g)

Higher adsorption capabilities, for instance, were noted at lower pH levels and with longer contact times, suggesting improved active site availability and surface.
The percentage removal of lead (Pb2+) under various experimental conditions, including changes in pH, cotton dosage, and contact time, is depicted in the bar chart (Fig.2).

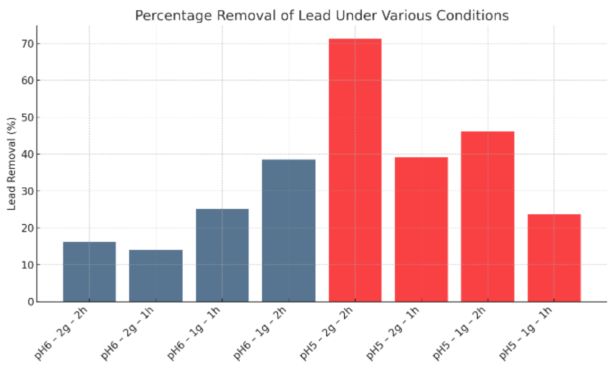


Fig.2: Percentage removal of lead under various conditions

The greatest elimination (71.29%) of all samples was recorded at pH 5 after two hours of contact time and two grams of cotton. This suggests that adsorption efficacy is increased by lower pH and longer contact duration.
The graph in Fig.3 illustrates how adsorption is affected by pH at a fixed cotton dosage of 2g and contact period of 2 hours. The final lead concentration declined sharply to 63.168 mg/L at pH 5, but it stayed high at pH 6 (184.277 mg/L).

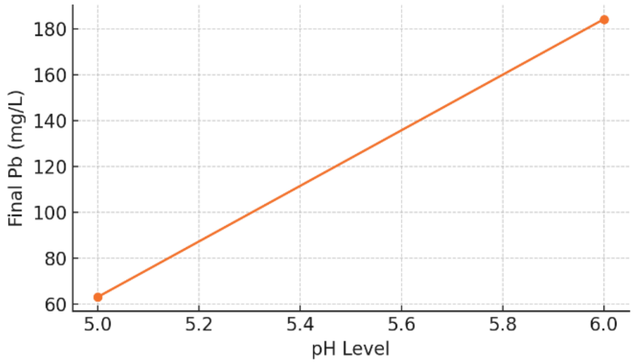


Fig.3: Effect of pH on lead Adsorption

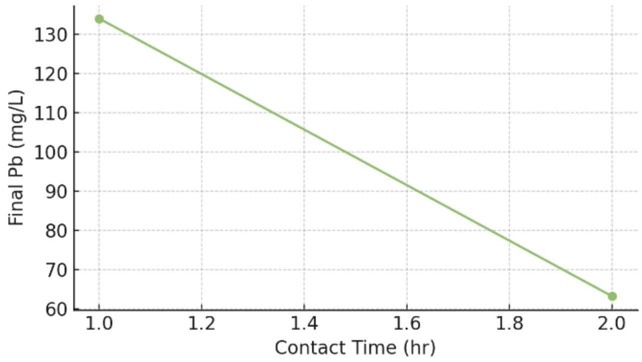


Fig.4: Effect of Contact Timeon lead Adsorption

In Fig.4 the line graph illustrates how contact time affects lead adsorption at a fixed pH of 5 and a dosage of 2g cotton. The final Pb content was 134.018 mg/L after an hour of stirring, but it drastically dropped to 63.168 mg/L after two hours. The system needs enough time to approach equilibrium, as evidenced by the adsorption capacity almost doubling. This lends credence to the theory that more Pb2+ ions can bond with the cotton surface's accessible active sites when the interaction period is longer.

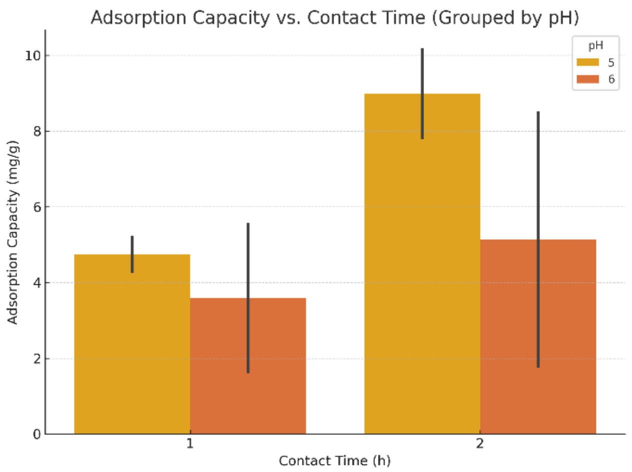


Fig.5: Adsorption Capacity Vs. Contact Time

Comparing contact time with adsorption capacity reveals a clear trend—longer contact enhances heavy metal uptake, with pH 5 consistently outperforming pH 6. After 2 hours, adsorption at pH 5 nearly doubles its 1-hour value while pH 6 shows only a moderate increase (Fig.5). This suggests that optimal adsorption is achieved under mildly acidic conditions, and that sufficient contact time significantly boosts performance.

No direct experimental comparison with conventional methods was performed, but literature was consulted to evaluate how citric acid–modified cotton performs. Activated carbon, for example, is highly effective at removing heavy metals due to its large surface area and porous structure, but it is relatively expensive ($0.50–$2.00 per kg) and requires significant energy for regeneration [25]. In this study, the textile waste was collected for free, as it is usually discarded by industries, and citric acid was used as a low-cost, biodegradable treatment. Reported adsorption capacities of citric acid–treated cotton for lead are comparable to those of many activated carbons, indicating that recycled cotton can serve as a cost-effective and environmentally sustainable alternative for heavy metal removal.

Nevertheless, during the experiment, several restrictions were found. The initial lead solution prepared had an estimated concentration of 38,000 ppm, but samples with concentrations above 1000 ppm could not be tested by the ICP-OES system utilized for analysis. Samples were diluted before to testing in order to remedy this. Dilution was carried out using a standard pipette since a micropipette was not available, which might have resulted in some errors or discrepancies in the final ppm readings. Additionally, throughout the solution preparation process, there may have been minor variations in the measurement of lead salt and pH control. Notwithstanding these difficulties, the data's general patterns were trustworthy, and the findings confirm that modified cotton works well as an adsorbent for lead-contaminated water.

## 4. Conclusion

This study shows that regenerated cotton waste has a promising future as a powerful adsorbent for removing heavy metals from tainted water. The adsorption capability for heavy metals like lead (Pb) was greatly increased by chemically altering cotton waste with citric acids. Optimized circumstances, such as modified pH, contact time, and cotton dosage, improved the cotton adsorbent's capacity to remove heavy metals, according to batch adsorption trials. The findings also demonstrated that recycled cotton, a cheap and accessible resource, offers a sustainable substitute for traditional adsorbents such as activated carbon, which are frequently expensive and less ecologically friendly. This study provides a novel solution to the expanding issue of textile waste in addition to addressing water contamination. Reducing trash and enhancing water quality are two environmental advantages that highlight how crucial it is to implement circular economy concepts in environmental restoration projects. The method's economic feasibility is further supported by the study's cost-benefit analysis, particularly for large-scale applications in places with limited water treatment capabilities. Since the primary goal of this study was to assess the cotton adsorbent's initial adsorption capacity, reusability and regeneration were not examined. However, prior research on comparable cellulose-based adsorbents has demonstrated that, with the use of mild desorbing agents, these materials can retain between 70 and 80 percent of their adsorption efficacy after multiple regeneration cycles [26]. This study promotes further research and development of recycled cotton-based adsorbents as a practical heavy metal decontamination solution, taking into account their scalability, environmental impact and long-term usability. This will pave the way for sustainable waste management and water treatment in both industrial and community settings.

## 3. Acknowledgement

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