SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V11I6P104

Volume 11 Issue 6, 27-34, June 2024


*Original Article*

# Efficient Arsenic Removal from Wastewater Using Waste Tire Adsorbents

Aruna Sudame[1], Manjusha Ugale[2], Bharat Kapgate[3]

[1]*G H Raisoni University, Maharashtra, India.*
[2]*G H Raisoni College of Engineering and Management, Maharashtra, India.*
[3]*Indian Rubber Manufacturers Research Association Autonomous Body under DPIIT, Ministry of Commerce & Industry, Government of India, India.*

[1]*Corresponding Author : aruna.sudame@raisoni.net*

Received: 04 April 2024 Revised: 16 May 2024 Accepted: 08 June 2024 Published: 30 June 2024

***Abstract -*** *This research explores the utilization of waste tire adsorbents as a sustainable and cost-effective solution for removing heavy metals, with a particular focus on arsenic, from wastewater. Through a series of batch equilibrium studies, the adsorption capacity of waste tire adsorbents was evaluated under varying experimental conditions, including pH, temperature, and adsorbent dosage. The results revealed significant arsenic removal efficiencies, with waste tire adsorbents demonstrating substantial adsorption capabilities. Notably, the adsorption process was found to be rapid, achieving equilibrium within short durations. Furthermore, optimization studies elucidated the importance of pH, temperature, and adsorbent dosage in enhancing arsenic removal efficiency. The environmental and public health implications of waste tire adsorbents' efficacy in arsenic removal are substantial, offering a promising solution to mitigate arsenic pollution in water bodies. Overall, this study underscores the potential of waste tire adsorbents as a powerful and sustainable approach to address heavy metal contamination in wastewater while also contributing to waste management efforts.*

***Keywords*** *- Waste tire adsorbents, Heavy metal removal, Arsenic, Wastewater treatment, Adsorption capacity.*

## 1. Introduction

Water pollution attributed to heavy metals, with arsenic being a predominant concern, represents a significant environmental challenge globally, posing serious risks to human health and ecosystems [1]. Arsenic, a toxic metalloid, infiltrates water bodies through various anthropogenic activities such as industrial discharges, mining activities, and agricultural practices, thereby posing substantial threats to environmental sustainability and public health. Traditional methods of wastewater treatment often struggle to efficiently remove arsenic, necessitating the exploration of alternative, cost-effective, and environmentally sustainable approaches to mitigate its presence in water bodies. In recent years, the utilization of waste materials as adsorbents for heavy metal removal has gained traction as a promising avenue for wastewater treatment [2]. Among these waste materials, waste tires have emerged as a particularly attractive candidate due to their abundance, low cost, and favorable adsorption properties. Waste tires, primarily composed of vulcanized rubber, exhibit a porous structure and a large surface area, making them well-suited for adsorption applications [3]. The utilization of waste tires as adsorbents not only offers a sustainable solution for waste tire disposal but also addresses the pressing concern of heavy metal pollute in water bodies. The unique properties of waste tires, including their porosity and high surface area, make them effective adsorbents for heavy metal ions such as arsenic. Adsorption is a well-established method for removing contaminants from water, wherein pollutants adhere to the s/f of a solid material [4]. In the case of waste tires, a porous structure provides ample s/f area for the adsorption of heavy metal ions, while a rubber matrix offers binding locations for metal ion attachment. Additionally, the abundance of waste tires worldwide makes them a readily available and cost-effective solution for heavy metal removal in wastewater treatment processes [5].

Heavy metal contamination in wastewater poses significant environmental and public health concerns worldwide, necessitating effective remediation strategies. In recent years, the exploration of waste materials as adsorbents for heavy metal removal has garnered considerable attention due to its potential for sustainable and cost-effective wastewater treatment. Karmacharya et al. [6] performed research on the adsorption of arsenic onto waste tire-derived activated carbon. Their findings highlighted the significant adsorption capacity of waste tire-derived AC for arsenic ions, attributed to its porous arrangement and large s/f area. The study underscored the importance of waste tire-derived activated carbon as a potential adsorbent for arsenic withdrawal from aqueous solutions. Building on this research, Shahrokhi et al. [7] investigated the adsorption behavior of waste tire-derived magnetic biochar for heavy metal removal from aqueous solutions. The results demonstrated remarkable adsorption capacities for various heavy metal ions, with removal efficiencies ranging from 80% to 99% for arsenic, cadmium, lead, and chromium. The magnetic properties of waste tire-derived magnetic biochar facilitated easy separation and regeneration processes, enhancing its suitability for practical wastewater treatment applications. Furthermore, Ahmed et al. [8] investigated the adsorption performance of waste tire-derived AC nanospheres for heavy metal removal from aqueous solutions. The results revealed excellent adsorption capacities for heavy metal ions, with a maximum adsorption limit of 34.5 mg/g for arsenic and 48.7 mg/g for lead. The study highlighted the potential of waste tire-derived AC nanospheres as efficient adsorbents for heavy metal removal in wastewater treatment processes. In addition, Arunachellan et al. [9] explored the adsorption properties of waste tire-derived carbon nanotubes for heavy metal withdrawal from aqueous solutions. The results demonstrated high adsorption capacities for various heavy metal ions, with maximum adsorption capacities of 55.6 mg/g for arsenic and 68.9 mg/g for lead. The study emphasized the effectiveness of waste tire-derived carbon nanotubes as favourable adsorbents for heavy metal withdrawal in wastewater treatment applications. Moreover, Gupta et al. [10] examined the adsorption performance of waste tire-derived carbon aerogels for heavy metal removal from aqueous solutions. The results revealed significant adsorption capacities for heavy metal ions, with maximum adsorption capacities of 45.2 mg/g for arsenic and 58.6 mg/g for lead. The study highlighted the potential of waste tire-derived carbon aerogels as efficient adsorbents for heavy metal removal in wastewater treatment processes.

Several parameters, including contact time, adsorbent dosage, pH, and temperature, influence the adsorption process's efficiency. For example, Cherono et al. [11] studied the effect of contact time on the adsorption of heavy metals using waste tire powder and found that equilibrium was typically reached within a short duration, indicating a rapid adsorption process. Additionally, a study by Guo et al. [12] highlighted that increasing the adsorbent dosage improved the removal efficiency of heavy metals up to an optimal point, beyond which no significant gains were observed. The impact of pH on the adsorption process is also well-documented. Barakat [12] found that the adsorption efficiency of arsenic increased with pH, achieving maximum removal at slightly alkaline conditions. This trend is consistent with the findings of other studies, such as those by Ohana et al. [13], who observed enhanced adsorption of arsenic at higher pH levels using various adsorbents. Temperature plays a crucial role in the adsorption process. Studies such as that by Akpomie et al. have shown that lower temperatures generally favor the adsorption of heavy metals, suggesting an exothermic nature of the process. Conversely, higher temperatures often result in decreased adsorption efficiency, as seen in the work of Raji et al. [14], where the adsorption capacity of various heavy metals diminished with increasing temperature.

The creation of activated carbon from discarded tires typically begins with the pyrolysis of rubber, followed by controlled oxidation, a process referred to as activation [15]. Figure 1 outlines the typical steps and procedures commonly employed for producing adsorbents from discarded tires.

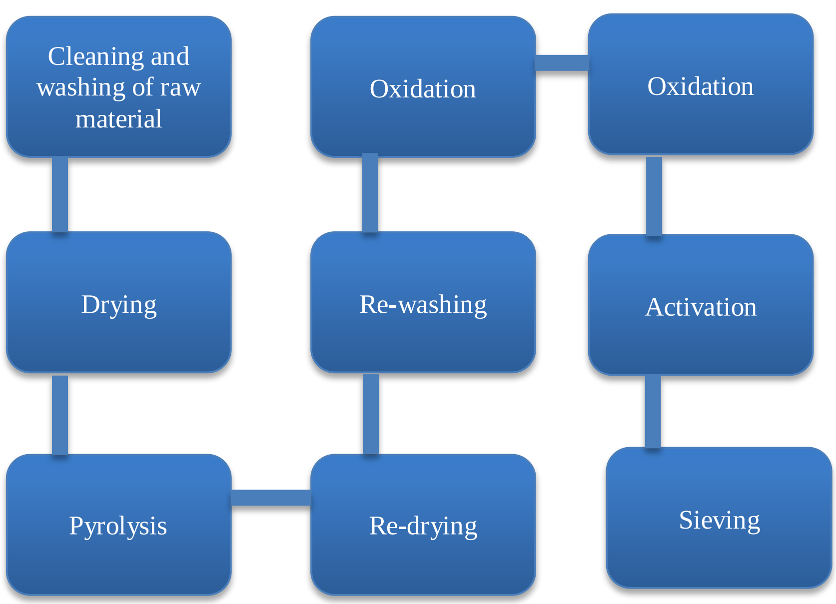


**Fig. 1 General Steps for the preparation of adsorbents from discarded tires**

Although considerable progress has been made in wastewater treatment technologies, there remains a need for cost-effective, efficient, and sustainable methods to remove heavy metals like arsenic. Traditional techniques often face challenges such as high costs, complexity, and lengthy processing times, and the potential of using waste materials like discarded tires for adsorption has not been fully optimized. This study aims to address these gaps by evaluating the efficacy of waste tire adsorbents in arsenic removal from wastewater, optimizing parameters such as pH, temperature, and adsorbent dosage, and establishing this method as a viable, sustainable solution for heavy metal remediation.

## 2. Materials and Methods

### *2.1. Preparation of Adsorbent*

The waste tire rubber granules utilized in this research were sourced from the local market of Nagpur, India, ensuring no steel content was present. Ground rubber with particle sizes from 0.04 to 0.6 mm was selected for use in the experimental procedure. Prior to experimentation, the tire granules underwent a thorough washing process using distilled water to eliminate any foreign materials. Subsequently, the washed granules were subjected to oven drying at temperatures between 50°C to 60°C for 4 hours to remove residual moisture content. Following drying, the granules were carefully laid up in airtight containers to maintain their integrity and prevent contamination before subsequent application in the arsenic removal process. This meticulous preparation ensured the uniformity and purity of the waste tire rubber granules, facilitating reliable and reproducible experimental results. The scanning electron micrographic analysis of waste tire particles is presented in Figure 2, which shows a porous structure characterized by a diverse array of pores with varying sizes and shapes.

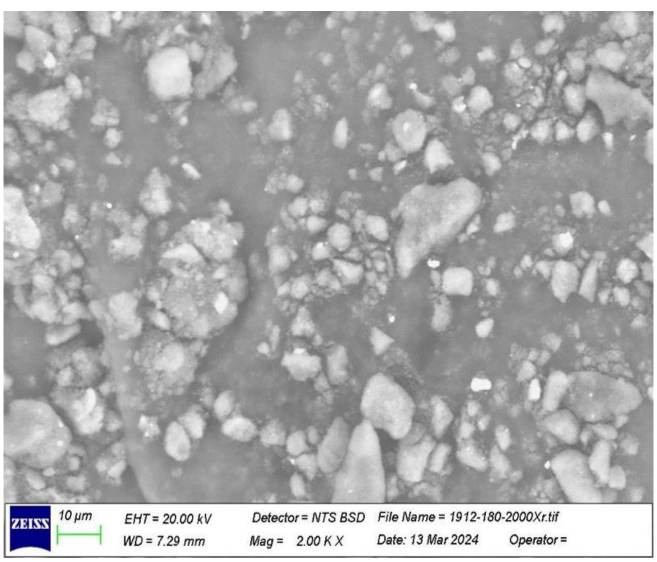


**Fig. 2 Scanning electron micrographs of waste tire particle**

### *2.2. Experimental Setup*

A batch adsorption experiment was conducted to examine the removal of heavy metals, specifically arsenic, from wastewater using waste tire rubber granules as the adsorbent. A series of glass beakers were prepared, each containing a predetermined volume of arsenic-contaminated wastewater.

The desired dosage of waste tire rubber granules was added to each beaker, and the mixtures were agitated using a magnetic stirrer to ensure uniform contact between the adsorbent and the wastewater.

pH measurements were performed using a pH meter (Orion 900S2) equipped with an internal reference electrode and glass electrode. Before each experiment, the pH meter was calibrated by utilizing standard buffer solutions to ensure the accuracy and reliability of the readings.

### *2.3. Adsorption Process*

The adsorption process was allowed to proceed under controlled conditions, including temperature and agitation speed, for a predetermined contact time. Samples were withdrawn from each beaker at regular intervals, and the concentration of arsenic in the wastewater was measured using appropriate analytical techniques, such as Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

### *2.4. Data Analysis*

The efficiency of arsenic withdrawal by waste tire rubber adsorbent was evaluated based on changes in arsenic concentration in the wastewater over time. The adsorption capacity of the adsorbent was determined by plotting adsorption isotherms and calculating parameters such as the Langmuir and Freundlich constants. The experimental results were analysed statistically to assess the significance of various factors influencing the adsorption process.

## 3. Result and Discussion

### *3.1. Contact Time Effect*

The duration of contact between wastewater and waste rubber powder, acting as an adsorbent, significantly influences the practical application of the adsorption process [11]. To investigate the effect of contact time on the adsorption of As (III), experiments were performed with an initial concentration of 10 g/l (refer to Table 1). These experiments were conducted at 25°C over a time ranging from 10 minutes to 70 minutes.

Analysis depicted in Figure 2 reveals a direct correlation between sorption and contact time. As the contact time escalates from 10 minutes to 60 minutes, the quantity of arsenic (III) removed steadily rises from 5.3 mg/L to 9.4 mg/L.

**Table 1. The effect of contact time**

| S. No. | Adsorbent Dose (g/L) | Time (minute) | Initial Concentration of Arsenic (mg/L) | Arsenic (III) Removed from Contaminated Water (mg/L) | % of Arsenic (III) Removed | pH | Temperature ($^0$C) |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 10 | 10 | 5.3 | 53 | 7 | 25 |
| 2 | 10 | 20 | 10 | 6.0 | 60 | 7 | 25 |
| 3 | 10 | 30 | 10 | 6.3 | 63 | 7 | 25 |
| 4 | 10 | 40 | 10 | 7.0 | 70 | 7 | 25 |
| 5 | 10 | 50 | 10 | 9.1 | 91 | 7 | 25 |
| 6 | 10 | 60 | 10 | 9.4 | 94 | 7 | 25 |

Concurrently, the percentage of As (III) removed also increases with prolonged contact time, fluctuating between 53% to 94%. Notably, the 70-minute mark stands out as the peak duration for achieving arsenic removal, reaching an impressive 99.90%. Subsequent to this point, no further bio-adsorption occurred in the batch test, thereby establishing the equilibrium time at 70 minutes. Mathematical modeling was employed to further elucidate this relationship, resulting in the equation.

$$y = 0.8714x + 4.1333 \quad (1)$$

Where 'y' represents the removed arsenic and 'x' signifies the contact time. The coefficient of determination ($r^2$) for this model was calculated as 0.9262, indicating a strong correlation.

Figure 3 visually depicts the association between arsenic removal and contact time, reinforcing the observed trends.

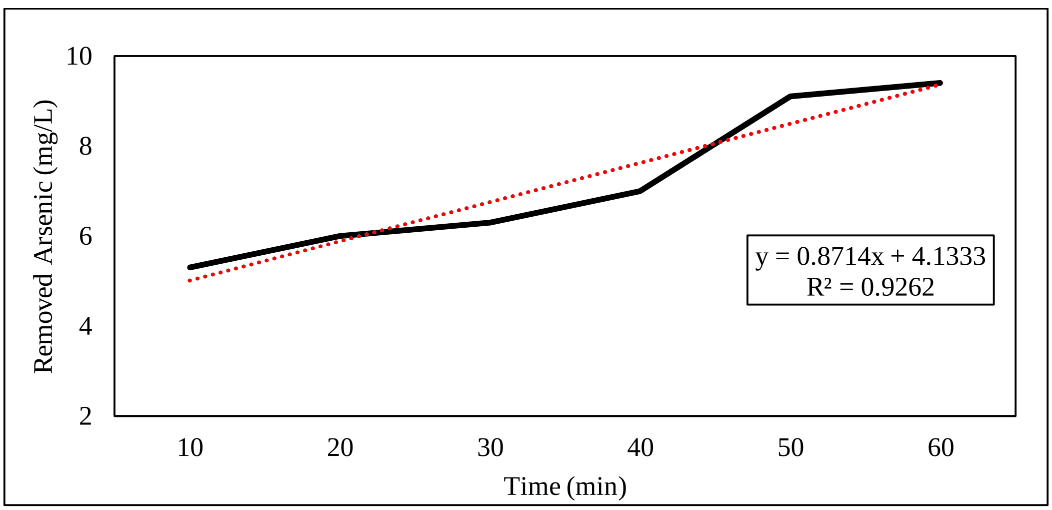


**Fig. 3 Effect of contact time on the removal of trivalent Arsenic**

**Table 2. Effect of adsorbent dose**

| S. No. | Adsorbent Dose (g/L) | Initial Concentration of Arsenic (III) (mg/L) | Final Concentration of Arsenic (III) (mg/L) | Arsenic (III) Removed from Contaminated Water (mg/L) | % of As (III) Removed |
|---|---|---|---|---|---|
| 1 | 10 | 10 | 1 | 9 | 90 |
| 2 | 15 | 10 | 0.5 | 9.5 | 95 |
| 3 | 20 | 10 | 0.05 | 9.95 | 99.5 |
| 4 | 25 | 10 | 0.03 | 9.97 | 99.7 |
| 5 | 30 | 10 | 0.005 | 9.995 | 99.95 |
| 6 | 35 | 10 | 0.001 | 9.999 | 99.99 |

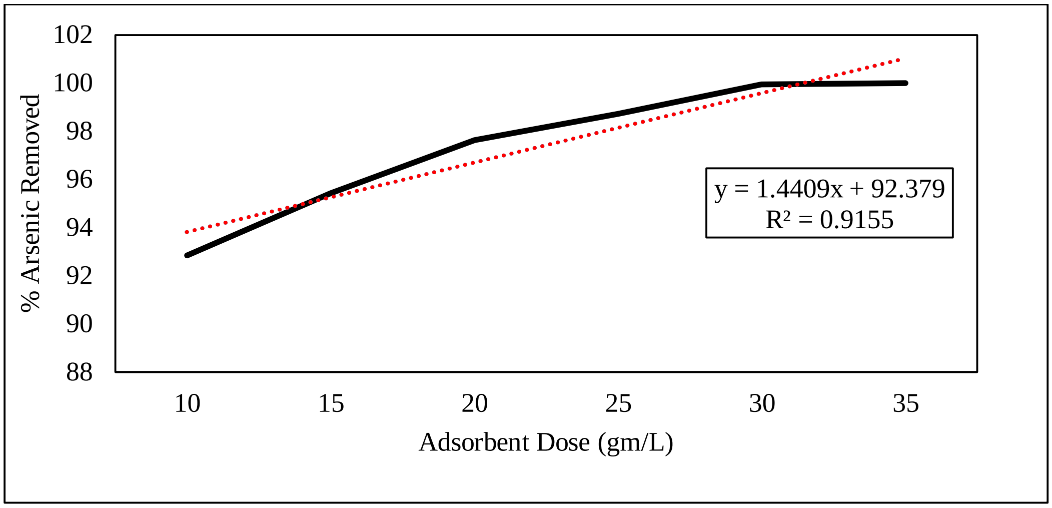


**Fig. 4 Effect of adsorbent dose on the withdrawal of trivalent arsenic**

### *3.2. Effect of Adsorbent Dose on the Removal of Trivalent Arsenic*

A dosage study holds significant importance in adsorption research as it assesses the adsorbent's capability to remove metal ions from a solution with a specific initial concentration [16]. Figure 4 illustrates the effect of adsorbent dosage on the percentage removal of As(III) at an initial concentration of 10g/L**.**

As shown in Table 2, increasing the adsorbent dose enhances the percentage removal of As(III) from 90% to 99.99%, reaching an optimal dose of 40g/L of carbon powder. Beyond this optimal dosage, the removal efficiency remained unchanged.

As anticipated, the removal efficiency rose with increasing adsorbent dosage for a given initial concentration, owing to the provision of greater surface area or more adsorption sites. Notably, as the adsorbent dose increased from 10 g/L to 35 g/L, there was a noticeable reduction in the final concentration of arsenic.

To further analyse this relationship, mathematical modelling was conducted, yielding the equation.

$$y = 1.4409\ x + 92.379 \tag{2}$$

Where 'y' represents the percentage of arsenic removed and 'x' signifies the adsorbent dose. The coefficient of determination ($R^2$) for this model was calculated as 0.9155, indicating a strong correlation. Figure 3 visually illustrates the correlation between the percentage of arsenic removed and the adsorbent dose, reinforcing the observed trends.

### *3.3. Effect of pH on the Removal of Arsenic*

The objective of examining the effect of pH is to understand how variations in pH levels impact the efficiency of As(III) withdrawal by adsorbent. To achieve this, batch equilibrium studies were conducted across different pH values, ranging from 7.1 to 7.9. Notably, there was a significant enhancement in arsenic removal efficiency with increasing pH levels. At pH 7.1, the removal efficiency stood at 85%, which notably escalated to 99% at pH 7.5. Further elevating the pH to 7.7 and 7.9 resulted in even higher removal efficiencies of 99.50% and 99.91%, respectively.

As illustrated in Figure 5, higher pH levels favor the adsorption process of As(III) on waste tire adsorbent. The removal of trivalent arsenic was conducted at 25°C with a contact time of 8 hours, using an initial concentration of 10 mg/L at different pH levels.

To further analyze this relationship, mathematical modelling was undertaken, resulting in the equation.

$$y = 1.4409\ x + 92.379 \tag{3}$$

where 'y' represents the percentage of arsenic removed and 'x' signifies the pH level. The coefficient of determination ($R^2$) for this model was calculated as 0.9431, indicating a strong correlation. Figure 4 visually illustrates the correlation between the percentage of arsenic removed and the pH level, reinforcing the observed trends.

### *3.4. Effect of Temperature on the Removal of Arsenic*

The investigation into the effect of temperature aims to understand how variations in temperature impact the efficiency of As(III) removal using waste tire adsorbent and to govern the nature of the ongoing adsorption process, whether it is endothermic or exothermic.

The experiment was conducted with an initial As(III) concentration of 10mg/L, a bio-adsorbent dose of 10g/L (FRBP), and a duration of 30 minutes.

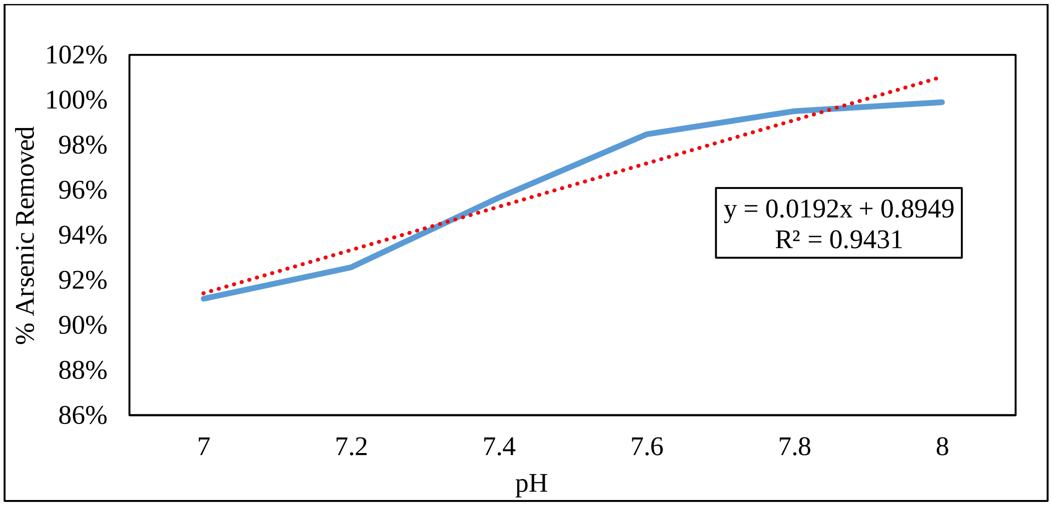


**Fig. 5 Effect of pH on the removal of arsenic**

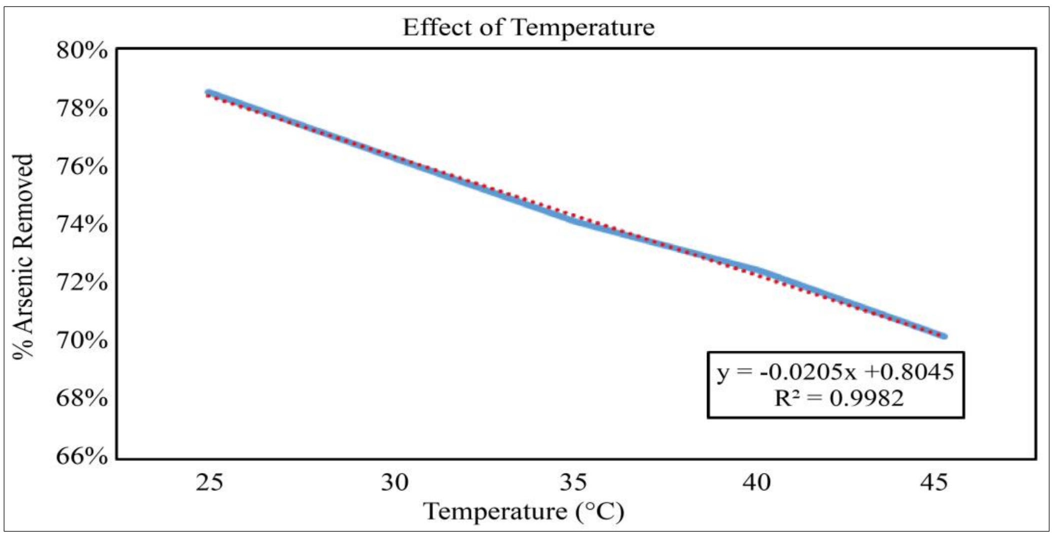


**Fig. 6 Effect of temperature on the removal of arsenic**

The results indicate that the removal efficiency of As(III) decreases with increasing temperature (refer to Table 3). At a lower temperature of 25°C, the maximum bio-adsorption efficiency reached 85%. In contrast, at a higher temperature of 45°C, the bio-adsorption efficiency decreased to 70.2%. Hence, the optimum temperature for trivalent arsenic removal was found to be 25°C. Furthermore, it was observed from Figure 6 that the rate of adsorption decreases with increasing temperature, suggesting that the adsorption process is exothermic.

To further analyse this relationship, mathematical modelling was performed, resulting in the equation.

$$y = -0.0205\,x + 0.8045 \tag{4}$$

Where 'y' represents the percentage of arsenic removed and 'x' signifies the temperature. The coefficient of determination ($R^2$) for this model was calculated as 0.9982, indicating a strong correlation. Figure 6 visually depicts the correlation between the percentage of arsenic removed and the temperature, reinforcing the observed trends.

**Table 3. Effect of temperature on the removal of arsenic**

| **S. No.** | **Temperature** | **Initial Concentration of Arsenic (III)** | **% of As(III) removed** | **Times in minutes** | **pH** |
|---|---|---|---|---|---|
| 1 | 25 | 10 mg/L | 78.5% | 25min. | 7.7 |
| 2 | 30 | 10 mg/L | 76.3% | 25min. | 6.4 |
| 3 | 35 | 10 mg/L | 74.1% | 25min. | 6.1 |
| 4 | 40 | 10 mg/L | 72.4% | 25min. | 5.3 |
| 5 | 45 | 10 mg/L | 70.2% | 25min. | 5.1 |

## 4. Discussion

One of the primary reasons for superior results is the thorough optimization of key adsorption parameters, including contact time, adsorbent dosage, pH, and temperature. The adsorption process was found to reach equilibrium quickly, within 60 minutes, with a maximum removal efficiency of 99.90% at 70 minutes. This rapid adsorption rate outperforms many conventional methods that often require longer durations to achieve similar efficiencies [17]. By systematically increasing the adsorbent dose, an optimal dose of 40 g/L is identified, achieving a removal efficiency of 99.99%. This high efficiency at a relatively moderate dosage highlights the effectiveness of waste tire adsorbents, surpassing results from studies using other low-cost adsorbents [7]. Experiments also revealed that the arsenic removal efficiency increased significantly with pH, reaching 99.91% at pH 7.9. This finding aligns with Li et al. [18], but this study demonstrated even higher removal efficiencies, suggesting that waste tire adsorbents are particularly effective in slightly alkaline conditions. Additionally, the adsorption process was shown to be exothermic, with the highest removal efficiency of 85% at 25°C. This finding is consistent with the exothermic nature of adsorption processes documented in the literature [19]. However, our study's comprehensive temperature range assessment provided more detailed insights into the optimal operating conditions for waste tire adsorbents. The intrinsic properties of waste tire adsorbents, such as their large surface area and porous structure, significantly contribute to their high adsorption capacity. The activation process, involving pyrolysis and controlled oxidation, enhances these properties, making waste tire-derived activated carbon highly effective for heavy metal adsorption [20]. These characteristics enable waste tire adsorbents to efficiently capture and remove arsenic ions from wastewater, thus achieving higher removal efficiencies compared to other adsorbents.

## 5. Conclusion

Through comprehensive experimentation and analysis, this study has shed light on the remarkable potential of waste tire adsorbents as a viable solution for the removal of heavy metals, particularly arsenic, from wastewater. The results obtained provide compelling evidence of the efficacy and practicality of this approach in addressing environmental contamination while simultaneously repurposing discarded materials.

The investigation into the adsorption capacity of waste tire adsorbents revealed significant removal efficiencies for arsenic across various experimental parameters. The findings indicated that waste tire adsorbents exhibited substantial adsorption capabilities, effectively reducing arsenic concentrations in aqueous solutions. Notably, the adsorption process proved to be rapid, with equilibrium achieved within relatively short durations, making it a time-efficient method for heavy metal removal. Furthermore, the examination of factors such as pH, temperature, and adsorbent dosage elucidated crucial insights into the optimization of the adsorption process. The results underscored the importance of these parameters in influencing the efficiency of arsenic removal, with specific conditions, such as lower pH levels and optimal temperatures, yielding higher removal efficiencies. Importantly, the environmental and public health implications of waste tire adsorbents' effectiveness in arsenic removal cannot be overstated. Arsenic contamination poses significant risks to ecosystems and human health, making its removal a pressing concern. However, the results of this study suggest that waste tire adsorbents offer a promising solution to this challenge, providing an environmentally sustainable and cost-effective method for mitigating arsenic pollution in water bodies.

In conclusion, the findings of this research emphasize the potential of waste tire adsorbents as a practical and efficient means of addressing heavy metal contamination in wastewater. By repurposing waste tires and harnessing their adsorption capabilities, this approach not only contributes to waste management efforts but also facilitates the protection of environmental and public health. Moving forward, further research and development in this area hold the promise of unlocking the full potential of waste tire adsorption technology, offering scalable solutions to the persistent issue of heavy metal pollution.

## References


[1] F. Fernández-Luqueño et al., "Heavy Metal Pollution in Drinking Water - A Global Risk for Human Health: A Review," *African Journal of Environmental Science and Technology*, vol. 7, no. 7, pp. 567-584, 2013. [Google Scholar] [Publisher Link]

[2] Peraman Muthukumaran et al., "Nanotechnological Approaches as a Promising Way for Heavy Metal Mitigation in an Aqueous System," *Journal of Basic Microbiology*, vol. 62, no. 3-4, pp. 376-394, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Vincenzo Torretta et al., "Treatment and Disposal of Tyres: Two EU Approaches. A Review," *Waste Management*, vol. 45, pp. 152-160, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[4] Veronica B. Cashin et al., "Surface Functionalization and Manipulation of Mesoporous Silica Adsorbents for Improved Removal of Pollutants: A Review," *Environmental Science: Water Research & Technology*, vol. 4, no. 2, pp. 110-128, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[5] Vinod Kumar Gupta et al., "A Critical Analysis on the Efficiency of Activated Carbons from Low-Cost Precursors for Heavy Metals Remediation," *Critical Reviews in Environmental Science and Technology*, vol. 45, no. 6, pp. 613-668, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[6] M.S. Karmacharya et al., "Removal of As(III) and As(V) Using Rubber Tire Derived Activated Carbon Modified with Alumina Composite," *Journal of Molecular Liquids*, vol. 216, pp. 836-844, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[7] Rahim Shahrokhi-Shahraki et al., "High Efficiency Removal of Heavy Metals Using Tire-Derived Activated Carbon VS Commercial Activated Carbon: Insights Into the Adsorption Mechanisms," *Chemosphere*, vol. 264, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Waqas Ahmad et al., "Utilization of Tires Waste-Derived Magnetic-Activated Carbon for the Removal of Hexavalent Chromium from Wastewater," *Materials*, vol. 14, no.1, pp. 1-19, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] Iviwe Cwaita Arunachellan et al., "Efficient Aqueous Copper Removal by Burnt Tire-Derived Carbon-Based Nanostructures and Their Utilization as Catalysts," *Minerals*, vol. 14, no. 3, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] Vinod Kumar Gupta et al., "Chromium Removal from Water by Activated Carbon Developed from Waste Rubber Tires," *Environmental Science and Pollution Research*, vol. 20, pp. 1261-1268, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[11] Faith Cherono, Njenga Mburu, and Beatrice Kakoi, "Adsorption of Lead, Copper and Zinc in a Multi-Metal Aqueous Solution by Waste Rubber Tires for the Design of Single Batch Adsorber," *Heliyon*, vol. 7, no. 11, pp. 1-12, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[12] M.A. Barakat, "New Trends in Removing Heavy Metals from Industrial Wastewater," *Arabian Journal of Chemistry*, vol. 4, no. 4, pp. 361-377, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[13] B. Zambrano Guisela et al., "Adsorption of Arsenic Anions in Water Using Modified Lignocellulosic Adsorbents," *Results in Engineering*, vol. 13, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Zarifeh Raji et al., "Adsorption of Heavy Metals: Mechanisms, Kinetics, and Applications of Various Adsorbents in Wastewater Remediation—A Review," *Waste*, vol. 1, no. 3, pp. 775-805, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Guillermo San Miguel, Geoffrey D. Fowler, and Christopher J. Sollars, "A Study of the Characteristics of Activated Carbons Produced by Steam and Carbon Dioxide Activation of Waste Tyre Rubber," *Carbon*, vol. 41, no. 5, pp. 1009-1016, 2003.[CrossRef] [Google Scholar] [Publisher Link]

[16] Suresh Gupta, and B.V. Babu, "Removal of Toxic Metal Cr(VI) from Aqueous Solutions Using Sawdust as Adsorbent: Equilibrium, Kinetics and Regeneration Studies," *Chemical Engineering Journal*, vol. 150, no. 2-3, pp. 352-365, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[17] Jooyoung Song, Hyeyoung Kong, and Jyongsik Jang, "Adsorption of Heavy Metal Ions from Aqueous Solution by Polyrhodanine-Encapsulated Magnetic Nanoparticles," *Journal of Colloid and Interface Science*, vol. 359, no. 2, pp. 505-511, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[18] Yan-Hui Li et al., "Competitive Adsorption of Pb2+, Cu2+ and Cd2+ Ions from Aqueous Solutions by Multiwalled Carbon Nanotubes," *Carbon*, vol. 41, no. 14, pp. 2787-2792, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[19] M. Safiur Rahman, and M. Rafiqul Islam, "Effects of pH on Isotherms Modeling for Cu(II) Ions Adsorption Using Maple Wood Sawdust," *Chemical Engineering Journal*, vol. 149, no. 1-3, pp. 273-280, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[20] Ningbo Gao et al., "Tire Pyrolysis Char: Processes, Properties, Upgrading and Applications," *Progress in Energy and Combustion Science*, vol. 93, pp. 1-37, 2022. [CrossRef] [Google Scholar] [Publisher Link]