International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Cr(VI) Remediation with Economical Adsorbents: A Path to Environmental Sustainability

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ABSTRACT

Hexavalent chromium Cr(VI) is a highly toxic heavy metal frequently found in Electroplating, Tanneries, Textile & paint industrial wastewater. This study explores the use of waste foundry sand (WFS), Bael fruit shell (BFS), and copper benzene-1,3,5-tricarboxylate (Cu-BTC) metal-organic frameworks (MOFs) for Cr(VI) adsorption. Batch adsorption experiments were conducted under varying pH, Cr(VI) concentrations, contact time, and adsorbent dosages. Characterization of the adsorbents was performed using SEM analysis. The results showed that the Cu-BTC MOF had the highest adsorption capacity, with significant synergies observed when combined with WFS and BFS. These findings indicate that integrating waste materials with MOFs can provide a cost-effective and efficient method for environmental remediation.

INTRODUCTION

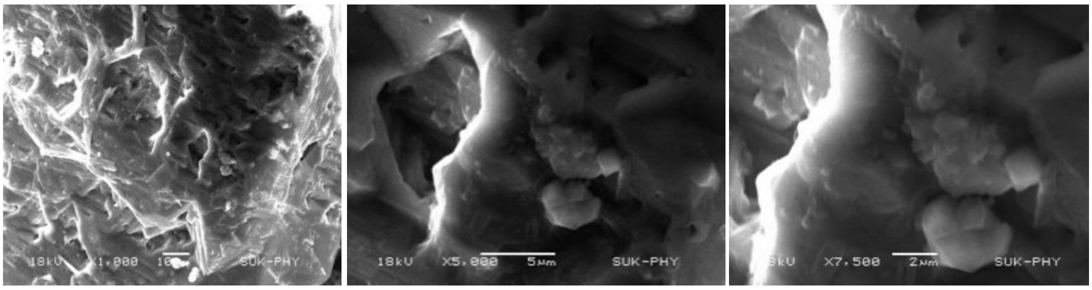
Heavy metals such as chromium (Cr) and nickel (Ni) are toxic pollutants often found in industrial wastewater. They can have detrimental effects on the environment and human health, making their removal from wastewater critical. One of the most effective methods for removing these heavy metals is adsorption, a process where contaminants in a liquid adhere to the surface of a solid adsorbent material. The removal of toxic heavy metalsfrom industrial wastewater is crucial due to their hazardous impacts on the environment and human health. Various innovative methods have been explored to achieve efficient and cost-effective removal of these pollutants. Adsorption using unconventional, low-cost, and environmentally friendly materials such as waste foundry sand, bael fruit shell, and metal-organic frameworks (MOFs) is gaining significant attention due to their potential to provide sustainable solutions for wastewater treatment.

MATERIALS AND METHODS

Waste Foundry Sand as an Adsorbent:

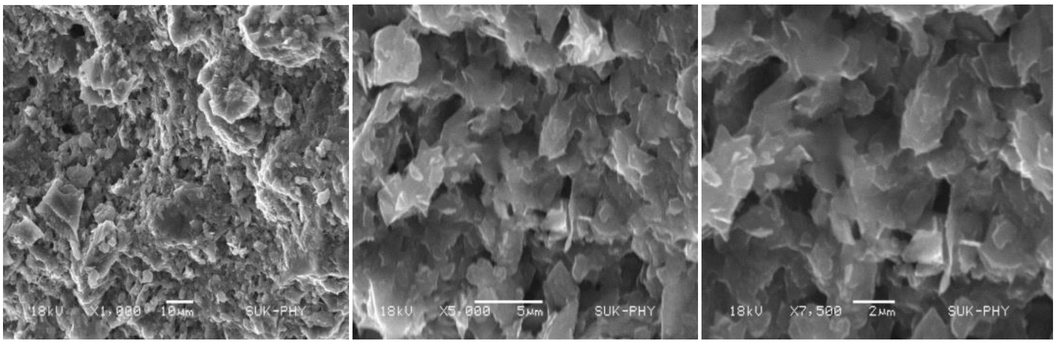
Waste foundry sand is an industrial byproduct generated during metal casting. It consists mainly of silica, with a porous structure that makes it suitable for adsorption processes. The recycling of this sand for Cr(VI) removal helps in addressing two environmental problems, waste disposal and water pollution.Waste foundry sand is abundant, inexpensive, and has a high surface area that enhances its adsorption potential for heavy metals. Heavy metals bind to the surface of the sand particles through ion

exchange, physical adsorption, or surface complexation. The Characterization of Sand has been done using SEM
Analysis.



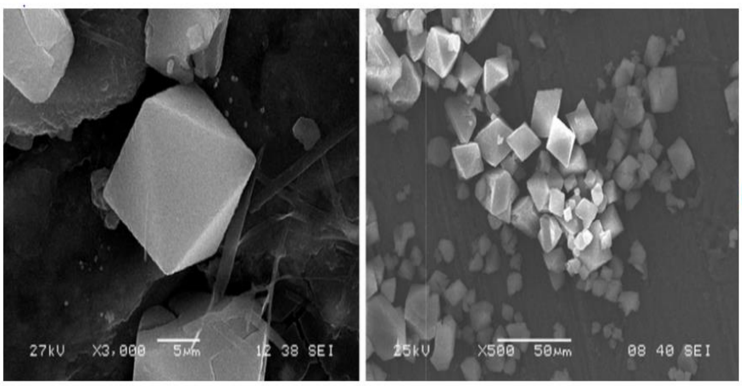
Bael Fruit Shell as an Adsorbent:

Bael fruit shell is a natural biomass that can be converted into an effective adsorbent for removing Cr(VI) from aqueous solutions. Its porous structure and high surface area, along with functional groups like hydroxyl and carboxyl, make it highly effective for metal ion capture.Bael fruit shell is biodegradable, renewable, and an inexpensive material that can be used in the adsorption process. The removal of Cr (VI) occurs through both physical and chemical adsorption, as the metal ions interact with functional groups on the shell surface



Metal-Organic Frameworks (MOFs):

Cu-BTC MOF (Copper-Benzene-1,3,5-tricarboxylate): Prepared through solvothermal synthesis. This MOF has a high surface area and tunable pore structure, making it ideal for Cr(VI) ion adsorption.Metal-organic frameworks (MOFs) are highly porous materials composed of metal ions coordinated to organic ligands, forming a crystalline structure. MOFs have emerged as a highly efficient adsorbent due to their large surface area, tunable pore size, and functionalized surfaces, which can be engineered to selectively capture heavy metals.MOFs offer exceptionally high adsorption capacities .They can also be regenerated and reused, making them attractive for sustainable applications. Adsorption in MOFs occurs via physical entrapment of metal ions in the pores and chemical interaction between the functional groups of MOFs and metal ions



EXPERIMENTAL SETUP:

Batch Adsorption Studies: Adsorption experiments were conducted by using following Experimental set-up. Synthetic Solution i.eknown concentration of Cr(VI) solution Mixed with each adsorbent. Parameters like initial Cr(VI) concentration (10–100 ppm), pH (2–10) & contact time (10–200 minutes) were varied. After adsorption, the remaining concentration of Cr(VI) was measured using UV-Visible spectrophotometer at 540 nm. Adsorption efficiency was calculated using the following formulaAdsorption efficiency (%)=((C0−Ce) /C0) ×100

Fig. Experimental Setup for adsorption

EFFECTS OF PARAMETERS ON ADSORPTION EFFICIENCY

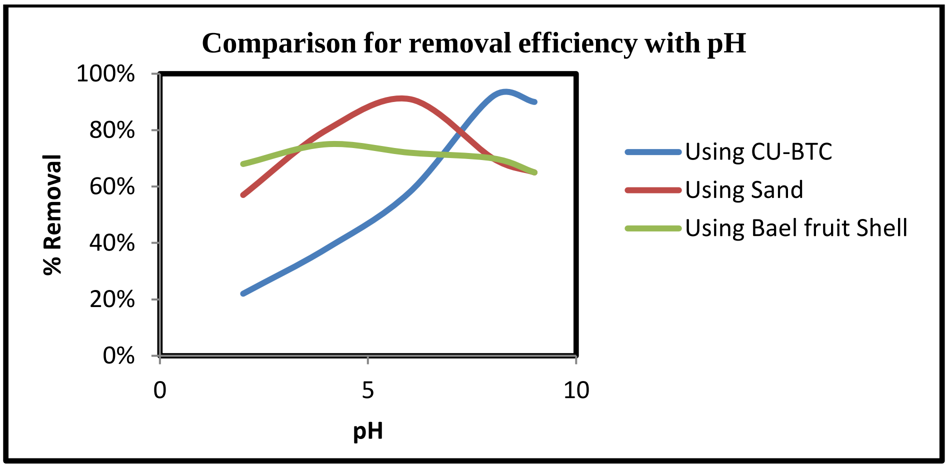
Effect of pH:

The pH of the solution significantly influenced the adsorption of Cr(VI). Maximum adsorption occurred between pH 4-8 , likely due to the protonation of functional groups on the adsorbents, which enhanced electrostatic attraction between the adsorbent surface and Cr(VI) anions. As the pH increased, the adsorption efficiency increases upto certain limit then decreases ,hence that neutral or basic conditions are less favorable for Cr(VI) removal. Following are the results of various adsorbents,

Sand Adsorption Shows an increase in adsorption with pH Increases up to pH 6 due to its surface properties but decreases beyond that as surface deprotonation becomes less effective.

Bael fruit Adsorption Contains functional groups like carboxyl and hydroxyl that facilitate Cr(VI) adsorption at intermediate pH levels but lose efficacy at higher pH.Optimum ph is in the range of 4 to 6.

Cu-BTC MOFs: Exhibit a sharp increase in adsorption at optimal pH, leveraging their high surface area and tunable chemistry.The adsorption of Cr(VI) onto Cu-BTC MOFs increases with up to pH 8, after which it decreases due to competition from OH^- ions and changes in the speciation of Cr(VI). Optimal adsorption typically occurs in moderately acidic to neutral pH conditions, where the balance between surface charge and Cr(VI) speciation favors adsorption."



Effect of Contact Time:

The adsorption rate was rapid during the initial phase, with equilibrium reached within 120 minutes for Cu-BTC and 150 minutes for WFS and BFS. Cu-BTC demonstrated the highest adsorption rate due to its large surface area and availability of active sites

In all three cases, the percentage removal of Cr(VI) increases rapidly during the initial phase due to the availability of abundant adsorption sites. Over time, the rate of removal slows as the adsorption sites become occupied, and equilibrium is eventually reached. The time to reach equilibrium and the overall removal efficiency vary depending on the adsorbent's surface area, pore structure, and the availability of functional groups.

Cu-BTC MOFs exhibit the fastest Cr(VI) removal and reach equilibrium sooner due to their high surface area and porosity.

Bael fruit shell shows moderate removal efficiency, benefiting from functional groups but limited by lower surface area.

Foundry sandhas fastest removal rate of Cr(VI) due to the availability of abundant adsorption sites on the surface of the foundry sand. During this period, a large portion of Cr(VI) is adsorbed onto the surface, and the percentage removal increases rapidly

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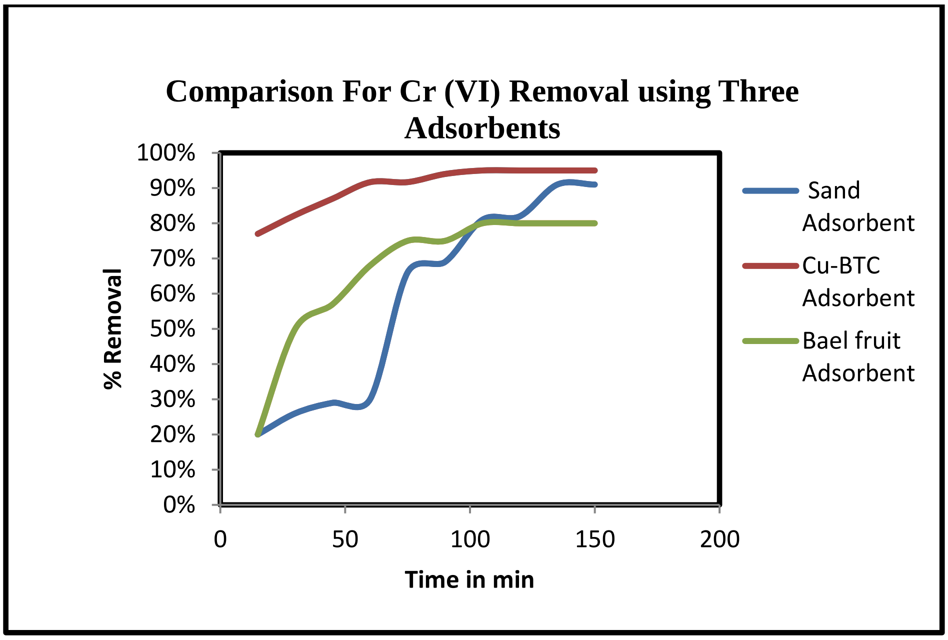

Conclusion:

The use of waste foundry sand, bael fruit shell, and MOFs for the removal of Cr(VI) from wastewater represents a sustainable and cost-effective approach. These materials, derived from industrial waste, natural resources, and advanced frameworks, offer diverse adsorption mechanisms and high efficiency in reducing heavy metal pollution. This approach not only aids in the detoxification of water sources but also contributes to the circular economy by reusing waste materials.

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