Journal of Chemical Health Risks

www.jchr.org

JCHR (2024) 14(2), 3332-3341 | ISSN:2251-6727

Unveiling the Ecological and Health Ramifications of Heavy Metal Dyes in Textile Industries: A Critical Analysis

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(Received: 07 January 2024 Revised: 12 February 2024 Accepted: 06 March 2024)

KEYWORDS

Textile wastewater, Heavy metals, Adsorption, Environmental impact, Agricultural waste.

ABSTRACT:

Introduction: Water, the quintessential natural resource, is critical for the survival of all living entities. In the wake of escalating urbanization and industrialization, water demand has surged, exacerbating environmental challenges. Particularly, the textile industry, a significant consumer and polluter of water, generates wastewater containing dyes and heavy metals like lead (Pb(II)), cadmium (Cd(II)), chromium (Cr(VI)), and zinc (Zn(II)). These contaminants pose severe environmental and toxicological risks, impacting both ecosystems and human health.

Objectives: This study aims to conduct a comprehensive review of the environmental impact of textile wastewater, focusing on the presence of heavy metals and their implications. It endeavors to assess the effectiveness of adsorption as a remediation technique, using agricultural wastes as adsorbents, to mitigate these impacts economically and efficiently.

Methods: We delve into an extensive analysis of the types of dyes and heavy metals prevalent in textile effluents, examining their environmental and health hazards. The study evaluates various adsorption methods, emphasizing the use of low-cost agricultural wastes as superior adsorbents for removing heavy metals from wastewater. Comparative analyses with traditional methods are provided to underline the advantages of adsorption techniques.

Results: The findings reveal that adsorption, particularly using agricultural wastes as adsorbents, offers a highly effective, cost-efficient solution for detoxifying textile wastewater of heavy metals. This approach not only surpasses traditional methods in efficacy but also contributes to the sustainable use of agricultural by-products.

Conclusions: The review underscores the urgent need for sustainable wastewater management practices in the textile industry to address the critical environmental challenge posed by heavy metal contamination. It highlights the promising potential of using agricultural wastes as adsorbents in adsorption processes, offering an economically viable and environmentally friendly alternative to conventional methods. This strategy not only aids in purifying water resources but also in promoting the circular economy by valorizing agricultural residues.

1. Introduction

Rapid industrialization, urbanization, and population in the country have generated enormous pressure on water use and significantly increased global pollution, which has increased the need for clean water for daily use. The ability of water to dissolve a wide range of chemicals, unlike any other liquid on Earth, has been associated with water contamination [26]. In the current scenario, the clothing and textile industries contribute approximately 6% to the world export goods manufacturing process [8]. The percentage share of the world goods manufacturing process is shown in Figure 1.

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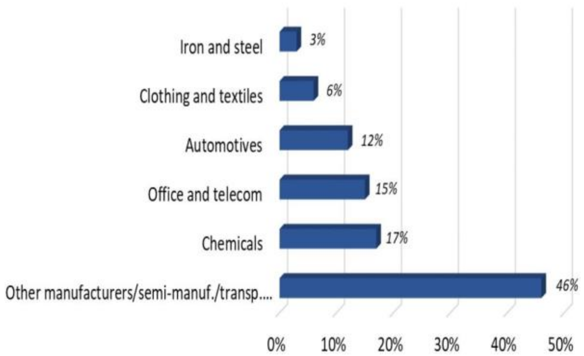

Figure 1 shows the Percentage share of the world goods manufacturing process.

Discharge from various industries, including those from the paper, textile, pulp, dye, tannery, paint, pharmaceutical and kraft bleaching sectors, is regarded as a major source of industry that contributes to the environment. "Among all sectors, the textile industry has the most adverse environmental impacts (Figure 2).

Global difficulties in the textile industry manufacturing process include environmental contamination and the discharge of harmful compounds. The textile industry uses many synthetic and chemical dyes for various processes. The preprocessing of raw materials, dyeing, and printing of fabrics largely rely on water.

Figure 2 shows the Comparison of dye discharge from different industries.

The textile sector causes a number of ecological issues due to the considerable volume of wastewater discharged with pollutants and hazardous heavy metals. Industrial textile wastewater contains persistent coloring pollutants, synthetic dyes, formaldehyde, phenols, phthalates, aromatic compounds, surfactants, chlorophenol, and various heavy metals, such as cadmium (Cd), zinc (Zn), arsenic (As), lead (Pb), chromium (Cr), and nickel (Ni), along with sulfates and chlorides as contaminants [10] (Figure 3). According to Bhatia et al. (2017) [1], the environmental pollution attributed to the textile industry is predominantly a result of its discharge of untreated effluents containing dyes and heavy metals into water bodies, which accounts for 80% of all emissions produced by this sector [24]. Due to the increase in pollution, it is necessary to develop practical materials that are highly effective, affordable, and simple to use to treat industrial wastewater. Moreover, suitable techniques must be developed to remove heavy metals from textile effluents. A developing economy is threatened by aquatic resource deficits due to the discharge of wastewater into waterbodies by the textile industry. According to an Indian study, only 60% of the 38354 MLD of sewage produced each day is treated for large-scale enterprises [22].

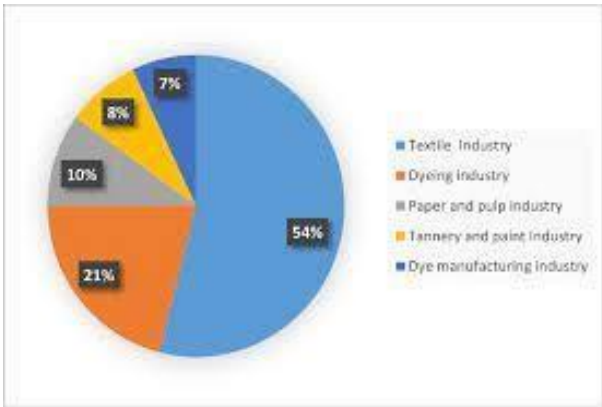

Figure 3 comprises an illustration of the textile industry's contribution to water contamination.

The removal of heavy metals from textile wastewater requires reliable, practical, and affordable techniques [6]. To achieve this goal, researchers are currently investigating the removal of heavy metals from wastewater using affordable byproducts via waste from agriculture, including wood shavings, rice husks, coconut hulls, neem growl, oil palm exterior, bagasse from sugarcane, etc. The cost-effectiveness of these agricultural waste materials, along with chemical and physical features, make them suitable adsorbents for the removal of heavy metals (Table 1).

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Table 1 shows the Low-cost adsorbents for agricultural waste.

Low cost adsorbents	Main consistent	Primary source	Physical structure	Chemical characterization (%)		Primary use
Rice husk	Is collected from one of the rice processing factories	Rice	Granular structure insolubility in water, chemical stability, high mechanical strength and its local availability at almost no cost	Cellulose	32.2	Wastewater treatment
				Hemicellulose	21.3	
				Lignin	21.4	
				Extractives	1.82	
				Water	8.11	
Fly ash	A particulate material produced from the combustion of coal in power plants	Bituminous coal-burning power plant	Spherical shape and pozzolanic properties	SiO_2	57.82	Building materials, soil amendment and fillers
				Al_2O_3	22.10	
				Fe_2O_3	8.33	

In the textile industry, heavy metals, including chromium (Cr), cadmium (Cd), lead (Pb), and copper (Cu), are notably employed for the creation of color pigments. These heavy metals can be found naturally in textile compositions, or they can seep into the fibers during the manufacturing process, during the process of dyeing or through chemicals used for storage. These dangerous dyes, which contain heavy metals that have seeped into the environment, can bioaccumulate in aquatic organisms, natural lakes and rivers, and the earth [12]. Azo dyes are frequently used in dyeing processes within the textile industry and other sectors owing to their economic stability, which surpasses that of both synthetic and natural dyes [27]. The majority of synthetic dyes are azo dyes, which have distinct azo groups (-N=N-) in their structure [23]. These dangerous hues from fabric waste remain in the environment for an extended period and pose health risks when released without adequate water treatment. There are numerous primary, secondary, and tertiary treatment options for textile effluents. The three primary categories of textile effluent treatments are chemical (filtration, reverse osmosis, ion exchange, adsorption, precipitation and coagulation/flocculation), physical (ozonation, oxidation and electrolysis), and biological (microorganisms and enzymes) approaches.

A threat to the environment from textile discharge is its color and the presence of poisonous, carcinogenic, and nonbiodegradable content [16]. Cutting-edge techniques for eliminating heavy metals include the use of magnetic fields, enhanced oxidation procedures, membrane filtration, adsorption with both natural and synthetic adsorbents, and electrocoagulation (EC). Heavy metals can be eliminated from inorganic effluent using conventional treatment techniques such as chemical precipitation, electrochemical treatment, adsorption, coagulation-flocculation, membrane separation, ion exchange, reverse osmosis, and biological treatments. These techniques are effective at removing heavy metals, which are expensive, energy intensive, and present as toxic sewage [4]. Adsorption is a highly effective technique for eliminating heavy metals from streams of waste, and the removal process commonly uses activated carbon as an adsorption medium [2]. According to adsorption studies, activated carbon is a costly substance that is used to treat water.

In recent years, several researchers have investigated the use of low-cost agricultural waste leftovers for the removal of heavy metals from wastewater, such as bagasse from sugarcane, oil palm shell, wood shavings, coconut husk, rice husk, and neem growl. Due to the affordability and safety of these materials, this topic has received increased attention in recent years [15].

Heavy metals are used in various processes involved in the textile industry. In the textile industry, fibers are reshaped into fabric and yarn and then subjected to numerous steps of textile processing. The textile industry uses two methods to classify its processing activities: wet process and dry process. The following steps constitute the dry method, which uses water: opening, blending, and mixing are among the first steps, followed by carding, combing, spinning, weaving, and knitting. Figure 4 [7] illustrates how the wet method uses more water than does the dry process for the following steps: (i) sizing, (ii) desizing, (iii) scouring, (iv), bleaching, (v), mercerizing, (vi), dyeing, and (vii) printing and finishing. The following is a summary of the various stages involved in wet processing [22].

1. The first step is sizing (the size of the fibers strengthens them and prevents breakage).

2. Desizing is the process of removing size components before weaving.

3. Scouring helps to remove impurities from fibers by emulsifying and suspending pollutants in the scouring bath while also breaking down natural oils, waxes, and surfactants. Sodium hydroxide is typically used in scouring.

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4. Bleaching is the process of removing undesirable fiber colors using hydrogen peroxide and sodium hypochlorite.

5. Mercerizing is a chemical procedure that is used to intensify the appearance of fibers.

6. The process of dyeing involves adding color to the fabric. To promote dye absorption onto fibers, numerous chemicals, including heavy metals, are used.

7. The final phase in this procedure is printing and finishing.

Several chemicals and solvents are used in the textile industry to meet the standards of finished fabric products. The production of textile fabrics uses byproducts such as textile effluent, which contains oxygenated solvent, waste fabrics that have soaked up oil and grease, chlorinated solvents, etc. The substances found in textile wastewater discharge are highly toxic to humans and the aquatic environment. Furthermore, these substances pose a threat to the environment as they resist natural decomposition processes, becoming nonbiodegradable. The four main sectors that contribute to textile wastewater are pretreatment, dyeing, printing, and finishing. Table 2 provides a list of various salts and heavy metals used in the manufacturing of textiles [11].

Table 2 shows the Metal-containing chemicals used in the textile processing stages.

STAGE OF TEXTILE PROCESSING	USENABLE CHEMICALS	THE POLLUTANT'S ORIGIN	DERIVATIVE OF HEAVY METAL
Production of fiber	Lead and Lead Acetate	Additional mordant/dying agent	Pb (II)
	Cadmium	Stage of pigmentation	Cd (II)
	Zinc Salt	Catalyst	Zn (II)
	Chromium Compound	Oxidizing agent	Cr (VI)
The printing process, dyeing and coloring	Lead Acetate	Diminishing/oxidizing substance	Pb (II)
	Compounds of Zinc	The process of fixation	Zn (II)
	Zinc	Biocide substances and stabilization	Zn (II)
	Zinc sulphoxylate formaldehyde	Fixation	Zn (II)
	Chromium-containing substance	Fixation (color)	Cr (VI)
Water treatment, softening, and finishing	Zinc chloride	Treatment for wrinkles and a catalyst	Zn (II)
	Chromium and fatty acid complex	Agent that impregnates	Cr (VI)
	Zinc salts	Impregnating agent	Zn (II)
Care easy treatments and Finishing	Zinc nitrate	Treatment for wrinkle resistance and catalyst	Zn (II)
	Zinc fluoroborate	Treatment for wrinkle resistance	Zn (II)
Printing purposes Coloration, and Finishing	Compounds of Chromium	Dye Fixation	Cr (VI)
	Chromium (III)	Acid dye	Cr (III)
	Chromium (VI)	Acid dye	Cr (VI)
Finishing	Chrome (III) oxide	Agent for cross-linking	Cr (III)
	Cadmium selenide	Antimicrobial coating (avoidance of deterioration)	Cd (II)
	Zinc salts	Antimicrobial coating (avoidance of deterioration)	Zn (II)
Treatments for softening, easy-care, and water	Zinc fluoroborate	Treatment for wrinkle resistance	Zn (II)
	Zinc nitrate	Treatment for wrinkle resistance and catalyst	Zn (II)
	Fatty acid/chromiu	Impregnating agent	Cr(VI)

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	m complex		
	Salts of zinc	Agent that impregnates	Zn(II)
Finishing and printing	Titanium dioxide	Titanium white Agent for cross-linking,	Ti (IV)
Antimicrobial treatment	Mercury-containing substances	Biocide	Hg (II)
	Copper compounds	Biocide	Cu (II)
	Cadmium selenide	Biocide	Cd (II)
	Tin compounds	Biocide	Sn (II)
	Zinc compounds	Biocide	Zn (II)
	Copper naphthenate	Biocide	Cu (II)
	Copper quinolone	Biocide	Cu (II)

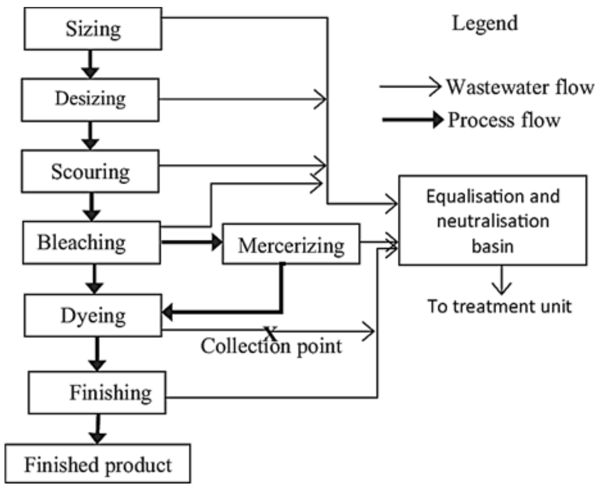

Figure 4 shows the various Wet processing techniques.

2. Classification of Textile Dyes and Their Pollutants

The classifications of dyes are based on their solubility, affinity, and fixation rate. Because of their capacity to generate anionic and cationic dyes to dissolve their components in a water-based solution, dyes are used in the textile industry [13]. The contaminants caused by the dyes are listed in Table 3.

Table 3 shows the Pollutants and types of dyes.

Dye class	Characteristics	Pollutants
Acidic	Anionic substances soluble in water	Color, organic acids, and unfixed dyes
Basic	Brilliant, water-soluble dyes used in dye baths with a slight acidity	NA
Dispersive	Water insoluble	Transporters, phosphates, leveling agents, colorants, dispersing agents, acids of organic origin, defoamers, and diluents.
Direct	Water-soluble ionic compounds that can be applied without a mordant	Salts, Hue, and unresolved dye
Reactive	The most significant class of dyes, water-soluble anionic compounds	alkaline substances, color, brine, finish, defoamer, dilution agents, and surfactants
Vat	Water-insoluble colorants, complex chemical substances, and outdated coloring	chemicals that are coloring, deteriorating, reducing, as well as alkaline
Sulphur	Organic substances comprising sulfur or sodium	An alkaline solution, hue, oxidation, reducing, and unred dye.

Dyes are categorized into water-soluble and water-insoluble types, depending on the solubility of heavy metals. Vat azoic and indigo sulfur are water-insoluble dyes. Basic, direct, reactive, and acidic dyes are water soluble (Fig. 5). Textile industry dyes exhibit toxicity even at low concentrations in the environment. Because the majority of dyes utilized by multiple sectors are not recyclable, they have greater adverse impacts on the ecosystem. In addition to contaminating the water, it also results in severe health issues, such as migraines, lack of focus, vomiting, tiredness, exhaustion, muscle soreness, discomfort in the joints, dizziness, breathing difficulties,

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heartbeats that are erratic, epileptic fits, allergic reactions to the skin, diarrhea, and, in the worst-case scenario, tumors [13].

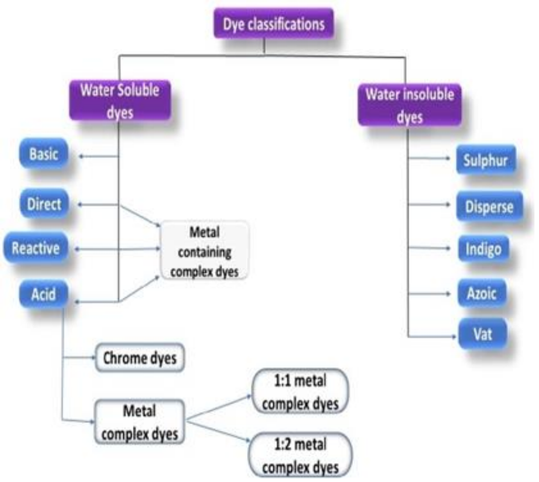

Figure 5 shows Categorization of dyes.

3. Heavy metals used in the textile industry

The major role of metals is for washing fastness with directly dyed fabrics, which is achieved by treating the fabrics with metal ion salts. The major heavy metal ions in textile industry wastewater effluents are mentioned below.

3.1 Chromium (Cr)

Heavy metal contamination is an ecological drawback. Textile discharge has become a severe environmental threat and has adverse impacts on human health. In the textile sector, chromium (VI) is used as a dyeing catalyst as well as a wool dye (chrome dye). Many sectors, such as electroplating, metallurgy, steel production, atomic power plants, metal deep processing, polishing, tanning, printing, pigments, fungicides, and the dye industry, extensively use chromium. Its oxidation states range from +2 to +6 [5 & 25]. The heavy metal chromium enters the body through three main routes: the oral cavity, the epidermis, and the respiratory system. Because Cr(III) is less readily absorbed than Cr(VI), their methods of delivery to cells differ [19]. A wide range of adsorbents, such as ion-exchange resins, activated carbon from natural wastes, and inorganic nanomaterials, have been investigated for the removal of chromium ions from textile effluents. There is a demand for inexpensive adsorbents with high chromium removal efficiencies [3].

3.2 Pb: lead

Many textile industries generate heavy metal toxicity during various stages. Leads (Pb) are discharged during the production of fertilizers, hydrometallurgy, tanning, smelting and plating. Toxic metals such as Cr(III, VI), As(III, V), Cd(II), Pb(II), Cu(II), Zn(II), and Hg are released into aquatic environments. Lead discharge has negative effects on the ecosystem and the well-being of humans [7].

3.3 Cadmium (Cd)

Due to the extensive use of cadmium in a variety of industries, such as textiles, ceramics, electronic devices, metal finishing, metal plating, petroleum, pigments, insect repellents, works with solders, televisions, stainless steel, imaging, polymers, metalworking, and chemical manufacturing, cadmium is the heavy metal with the highest level of toxicity found in industrial effluents [20]. Anthropogenic cadmium (Cd) activities, primarily from metal smelting, mineral extraction, smoking, factory expulsion, and airborne fine particles, cause Cd(II) contamination of water [18]. The amount of cadmium-containing chemicals used in textiles and other industries should be reduced as much as possible due to the harmful effects of cadmium (Cd) on living organisms and the environment [22].

3.4 Zinc (Zn)

Zinc (Zn) plays a vital role as a textile effluent and enters the food chain via the bioaccumulation process [21]. Zn plays an important role in controlling a variety of biochemical procedures and physiological processes in tissues. The textile, paper, pulping, plating, and metal industries are some of the industrial sources of zinc. Adsorbents such as carbon nanomaterials, active carbon, bentonite, biomass, and resin are more efficient for the removal of Zn(II). According to Zhao et al. (2012) [28], substances that utilize graphene oxide have a greater capacity for adsorption and can thus remove zinc metallic substances from water solutions.

4. Environmental and health impacts of heavy metal toxicity

- Heavy metals from textile industry effluent wastewater, such as copper (Cu), zinc (Zn), lead (Pb), mercury (Hg), chromium (Cr), and cadmium (Cd), may be hazardous to human

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JCHR (2024) 14(2), 3332-3341 | ISSN:2251-6727

health. Heavy metals can impair energy levels and affect the liver, kidneys, brain, lungs, kidney function, blood composition, and other vital organs.

- Excessive exposure to heavy metals can lead to serious health consequences. In addition to liver damage, the kidneys, lungs, blood components, and other essential organs are affected, and heavy metal toxicity can negatively affect or impair the functions of the brain and central nervous system. Alzheimer's disease, malignancies, multiple sclerosis and muscular dystrophy can be caused by heavy metal toxicity.
- The three main pathways by which heavy metals from the environment enter a healthy system are through food consumption, inhalation, and skin exposure. These heavy metal exposure routes affect the oral tract, causing cancer and many health disorders.
- Because heavy metals affect plant growth in both severe and long-term ways and are extensively distributed in the environment, heavy metals have a significant impact on agriculture and aquatic life. Aquatic life and plant habitat slowly disappear, having long-term effects. Heavy metal pollution harms both ecology and human health. Heavy metal traces and the microorganisms present in textile wastewater pose a threat to human health [14].
- According to Kadirvelu et al. (2001) [9], heavy metals such as zinc, arsenic, lead, nickel, copper, mercury, cadmium, and chromium are regarded as hazardous pollutants because of their high solubility in aquatic environments. The release of textile effluents containing heavy metals can disturb environmental processes when discharged into soil and water bodies. This causes absorption by plants through contaminated soil, which ultimately finds its way into the food chain and into other organisms.
- Heavy metals are harmful even at very low quantities when they are discharged into the environment and when taken up by aquatic animals. Heavy metals can accumulate in living beings through the web chain and cause serious health issues because they are persistent, poisonous, and carcinogenic.

Table 4 shows various detrimental impact of heavy metals on human health.

POLLUTANTS	SOURCES	HEALTH HAZARDS	PERMISSIBLE LEVELS (mg/L)
As	Metal smelters, Fungicides, Pesticides	Bronchitis, Poisoning, Dermatitis	0.02
Cd	Insecticides, Electroplating, fertilizers,and welding	Lung cancer, bone abnormalities, Lung disease, kidney damage and renal dysfunction	0.06
Pb	Paint, insecticides, tobacco use, vehicle emissions, burning coal, and the mining process	Neonatal death, newborn development delay, encephalopathy, chronic nervous system damage, liver and kidney damage	0.1
Mn	Adding fuel, producing, ferromanganese and welding	Central nervous system injury from touch or inhalation	0.26
Hg	Paper industry, batteries, Pesticides	Protoplasm Poisoning ,Gingivitis, Tremors, Nervous System Impairment and Spontaneous Abortion	0.01
Zn	Refineries, the production of brass, and metal plating	Dermatitis, Harm to the nerve System	15
Cr	Mine, mineral source	Irritation and nervous system damage	0.05
Cu	Mining, making pesticides,and the chemical industry	Anemia, kidney and liverdamage, and stomach discomfort	0.1

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5. Discussion

Current challenges in environmental studies include the removal of toxic dyes from industrial discharge. Most of our country is in the textile industry, and care must be taken in treating the waste generated from this industry. The processes occurring in the textile industry must be streamlined to discharge no or few pollutants into the environment. The purification of textile wastewater containing toxic and nonbiodegradable heavy metals through modern technology is costly. There is an urgent need to discover innovative methods that use biodegradable agricultural waste to purify such wastewater at a more affordable cost, thereby significantly reducing its environmental impact. Although various conventional methods are available for treating industrial wastewater, because we are continuously exploring cost-effective and biological adsorbents, identifying such methods will help researchers provide alternative remedies. In ongoing research, inexpensive agricultural wastes are being examined, and initial investigations indicate their potential as effective adsorbent materials. This review focuses on the crucial role played by agricultural and low-cost absorbents, as well as their functionalized composites, in removing heavy metals such as Cr, Zn, Pb, and Cd from textile effluents.

Acknowledgment

Thanks to the Department of Biotechnology, Rajalakshmi Engineering college, Thandalam, India for providing the facility to carry out my review paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors reported there is no funding associated with the work featured in this article.

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