A REVIEW ON TEXTILE DYE WASTEWATER TREATMENT USING SUSTAINABLE MATERIALS

Abstract

Dyes constitute prominent pollutants within our environment. The unregulated discharge of textile effluents into surroundings poses grave threats to both water bodies and ecosystems. Consequently, there is a growing need for cost-effective and efficient dye treatment methodologies. For this concept an effective approach is utilizing the sustainable materials. Natural materials, industrial by-products, or synthetically modified substances, which offer economical options as adsorbents, are generally referred to as low-cost adsorbents (LCAs). LCAs have demonstrated remarkable efficacy in removing textile dyes.

In many developing countries, the exploration of natural adsorbents such as rice husk, saw dust, fruit peels, clay, fly ash etc. has been extensively as it a sustainable material. This chapter focuses on two affordable natural materials: clay (including Safiot clay, bentonite clay, and natural clay) and fly ash (in forms such as mixtures with sandy clay loam soil, raw fly ash, and bottom ash) as potential adsorbents. Through batch experiments, parameters such as initial dye concentration, solution pH, adsorbent dosage, and contact time were calculated to establish optimal operating conditions. Among various clay types, natural Sofiot Clay exhibited a dye removal efficiency of approximately 97.03% for Methylene Blue dye. Among different fly ash proportions, mixtures with sandy clay loam soil demonstrated remarkable dye removal, achieving up to 99.2% for direct yellow 28.

Keywords: Sustainable, Clay, Fly ash, Low-cost adsorbents, Methylene Blue dye, Direct yellow 28

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I. INTRODUCTION

Addressing the imperative of preventing water pollution and safeguarding it for the future holds paramount significance. Despite remarkable advancements in society, science, and technology, these accomplishments often come at the expense of natural resource depletion. An outcome of this rapid progress is environmental imbalance coupled with a substantial pollution challenge. Human-driven activities have significantly compromised the quality of our essential resource – water. The rapid exhaustion of freshwater reservoirs has led to an imminent crisis. The global scale of water pollution necessitates immediate recognition of its severity.

It is now crucial to acknowledge the pressing need to eliminate pollutants from water sources. Developing a cost-efficient and ecologically sound approach to achieve this objective presents a formidable task. Sustainable Development Goal (SDG) 6 specifically focuses on the clean water and sanitation. In this chapter the study helps to achieve the SDG Target 6.3 (i.e. improve water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals and materials).

Dyes, characterized as colored substances with an affinity for the materials they adhere to, exhibit their hue due to preferential absorption of certain light wavelengths. The historical utilization of dyes spans millennia, with evidence of their use dating back to Neanderthal communities around 180,000 years ago. Notably, in 1856, Perkin's discovery of the first synthetic dye, Mauvine, marked a pivotal moment. Subsequently, these synthetic dyes gained widespread popularity and underwent large-scale production. Presently, the annual global production exceeds 7.0x105 units, encompassing nearly a thousand distinct dye variations[1].

Dyes are categorized based on their solubility and chemical characteristics. Acid dyes, which are anionic and soluble in water, find application on fibers like silk, wool, nylon, and modified acrylic fibers through dye baths with neutral to acidic conditions. On the other hand, direct dyes are utilized for coloring cotton, paper, leather, wool, silk, and nylon. These dyes saturate the textile when applied, resulting in complete and vibrant coloring. Colors are commonly classified into two main types: natural colors and engineered colors, based on their origin. Additionally, colors can be organized according to fundamental or functional groups, as well as their ionic charge upon dissolution in liquid solutions.

The primary classifications of dyes are natural dyes and synthetic dyes. Natural dyes are derived from sources such as plants, invertebrates, and minerals. Plant sources like roots, berries, bark, leaves, and wood, along with other biological sources like fungi, contribute to the majority of natural dyes. In contrast, synthetic dyes can be defined as benzene derivatives to which chromophores and auxochromes have been introduced[2].

Typically, wastewater containing color is managed through various methods including coagulation, flocculation, anaerobic treatment, electrochemical treatment, membrane filtration, and adsorption techniques. Among these approaches, adsorption stands out as the most widely employed due to its effectiveness and straightforward nature. Industries that generate colored wastewater often resort to using commercial activated carbon to remove color, owing to its exceptional porosity and large surface area (ranging from 500 to 2000 m^2/g) [3].

Sustainable materials play a crucial role in modern construction and manufacturing, with options like fly ash and clay gaining significant attention. Fly ash, a byproduct of coal combustion, has found its place as a valuable resource in various industries. Its incorporation into concrete not only enhances its durability and strength but also reduces the need for traditional cement production, which has a high environmental impact. This repurposing of fly ash diverts a potential waste product from landfills, contributing to a more circular economy. On the other hand, clay, a naturally abundant material, is being increasingly utilized for sustainable design. Clay-based materials offer energy-efficient solutions due to their low embodied energy and efficient thermal regulation properties. By using clay in construction and manufacturing, we can lower the demand for energy-intensive materials while capitalizing on a renewable and locally available resource. As the focus on sustainability grows, materials like fly ash and clay exemplify how innovative choices can lead to more environmentally friendly practices across various industries [4][5].

In the field of wastewater treatment, a range of sustainable materials has emerged as effective solutions to address environmental challenges. Among these innovations, constructed wetlands stand out as a noteworthy approach. Leveraging natural processes, constructed wetlands integrate vegetation along with layers of gravel and sand to create a filtration system that purifies water by means of biological and physical interactions, effectively removing contaminants. Another promising option is biochar, a form of charcoal derived from organic waste. Biochar's exceptional pollutant-absorbing properties and ability to boost microbial activity in wastewater treatment systems contribute not only to water purification but also to the repurposing of organic waste that might otherwise contribute to landfill buildup. Algae also hold significant potential as a sustainable material for wastewater treatment. Algae-based systems capitalize on the innate capacity of algae to uptake nutrients and pollutants from water. These systems offer both water purification benefits and the possibility of generating biofuels and capturing carbon. By integrating these sustainable materials into wastewater treatment processes, we can attain enhanced efficiency, cost-effectiveness, and environmentally conscious solutions for the purification and management of our vital water resources[6][7]. For this research, it was opted to study about the performance of two sustainable materials: clay (including sofia clay, bentonite clay, and natural clay) and fly ash (comprising mixtures of fly ash with sandy clay loam soil, as well as raw fly ash and bottom ash) as adsorbents for dye removal process.

II. MATERIALS AND METHODS

The aim of this research is to study the characteristics of two sustainable materials: clay (including sofia clay, bentonite clay, and natural clay) and fly ash (comprising mixtures of fly ash with sandy clay loam soil, as well as raw fly ash and bottom ash) as an adsorbent. The following properties were obtained from the collected literatures[8][9][10][11][12].

1. **Clay:** Clay materials possess distinct properties due to their fine particle size and unique crystal structures. These characteristics encompass cation exchange capacity, plasticity when wet, catalytic potential, swelling behavior, and low permeability. While clay minerals exhibit considerable diversity, they all share a common feature of having crystal

or grain sizes below 2 μm. The chemical identity of clays is determined by their crystal structure and chemical composition. Their spectroscopic signatures manifest Si–O stretching and bending, along with OH bending absorptions, primarily within the 1300–400 cm^{-1} range. Consequently, dioctahedral minerals exhibit absorptions within the 950–800 cm^{-1} region, while the OH absorption of trioctahedral minerals shifts to lower frequencies, specifically within the 700–600 cm^{-1} range[13].

2. **Bentonite Clay:** Bentonite boasts exceptional properties such as hydration, swelling, water absorption, viscosity, and thixotropy, rendering it invaluable across a diverse array of applications. X-ray diffraction (XRD) analysis indicates that the Bentonite from the Jambi region is composed of minerals including kaolinite, monmorrilonite, quartz, and cristobalite. The Fourier-transform infrared (FTIR) spectrum of bentonite reveals distinctive bands in the lower region, marked at 1385, 1104, 1032, 1009, 913, 797, 695, 538, 470, and 433 cm^{-1}, corresponding to the vibrational modes of SiO_4 tetrahedra. These outcomes align with reported values for bentonites sourced from other origins [14].

3. **Fly Ash:** Generated during the combustion process of coal in power stations, fly ash is a heterogeneous by-product characterized by fine, grey, spherical glassy particles carried by flue gases. Owing to its pozzolanic components, fly ash can react with lime to form cementitious materials. Qualitative XRD analysis reveals that low-calcium/Class F fly ash (typically derived from bituminous coal) generally comprises quartz, mullite, hematite, and magnetite crystalline phases within an aluminosilicate glass matrix. Fourier transform infrared (FTIR) spectroscopy has been employed to study the Al–O and Si–O bond environments in fly ash[11][9].

4. **Bottom Fly Ash:** Bottom ash finds application in various sectors, including construction and railroad fill, asphalt roofing shingle granules, concrete aggregate, traction substitute on icy roads, and enhancing soil permeability. XRD analysis of both original and ground bottom ash demonstrates the presence of quartz and mullite crystalline phases. This power plant waste, known as bottom ash, was harnessed to effectively remove organic pollutants from coking wastewater and papermaking wastewater[8].

III. RESULTS AND DISCUSSION

1. **Natural Sofiat Clay:** The impact of Natural Sofiat Clay (NSC) adsorbent dose, ranging from 5 to 35 mg, was studied in relation to the removal of Methylene Blue (MB) and Safranin (SAF) dyes. The removal percentage exhibited a range of 49.16% to 97.03% for the MB-NSC system and 13.14% to 94.35% for the SAF-NSC system. As pH increased from 2 to 12, the dye removal percentage from the aqueous solution rose from 92% to 96% for MB and 83% to 91% for SAF. This phenomenon was attributed to the prevalence of negative charges on the adsorbent's surface in basic conditions, leading to an electrostatic attraction between the negative charges of OH- on the clay surface and the positive charges of the dyes[15].

2. **Bentonite Clay on Dye Removal:** Bentonite clay, with its distinctive characteristics including hydration, swelling, water absorption, viscosity, and thixotropy, holds diverse applications. Analysis revealed that Jambi region's Bentonite consists of minerals such as kaolinite, montmorillonite, quartz, and cristobalite. The FTIR spectrum displayed specific

bands at various wavenumbers, corresponding to the vibrational modes of SiO4 tetrahedra. Removal efficiency for Basic Red 46 (BR 46) dye ranged from 80% to 100% at different pH levels, within the first 10 minutes. Optimal removal percentages were achieved up to an initial concentration of 60 mg L^{-1}. However, at 80 mg L^{-1}, only 75% was attained at pH 7 and 25 °C, demonstrating a decrease in removal efficiency at higher initial concentrations[16].

3. **Fly Ash and Bottom Fly Ash:** Utilized for its pozzolanic properties, fly ash, produced during coal combustion in power stations, holds promise. A wide range of dye removal efficiencies were observed in batch and column experiments with soil-fly ash mixtures, where the process demonstrated sensitivity to solution concentration. Albanis et al. (2000) conducted batch and column experiments under equilibrium conditions, covering dye concentrations ranging from 5 to 60 mg/L. In the context of a soil mixture containing 20% fly ash content, the average removal percentages from adsorption batch experiments were observed to be up to 53.0% for acid yellow 7, 44.9% for acid yellow 23, 99.2% for direct yellow 28, 96.8% for basic yellow 28, and 88.5% for disperse blue 79. However, the removal of dyes in column experiments showed a decline as the solution concentration increased from 10 to 50 mg/L at a temperature of 20°C. This highlights the significant influence of solution concentration on the removal process[17].

Moreover, coal-based bottom ash exhibited low surface area, affecting its micro-porosity. Changes in pH were found to influence dye adsorption behavior, with higher pH levels enhancing adsorption due to electrostatic interactions. In particular, CBBA (coal-based bottom ash) showed lower BET surface area and adsorption capacity compared to GAC (granular activated carbon). Dye removal efficiency was higher at lower dye concentrations due to unoccupied binding sites on the adsorbents. Higher dye concentrations led to reduced removal efficiency due to coverage of binding sites. Equilibrium adsorption for CBBA took longer than GAC[8].

IV. CONCLUSION

Increasing initial dye concentration decreased adsorption process due to increased interactions and lesser availability of active sites. The dominance of negative charges on the adsorbent's surface in basic conditions led to electrostatic attraction with positive charges of dyes. Natural Sofit Clay demonstrated significant dye removal, outperforming other clay types. Fly ash mixtures exhibited high removal percentages, with natural zeolite displaying greater surface area and pore volume than fly ash. This study underscores the effectiveness of both NSC and fly ash mixtures in dye removal.

REFERENCES

[1] Y. Zhang, K. Shaad, D. Vollmer, and C. Ma, “Treatment of textile wastewater using advanced oxidation processes—a critical review,” Water (Switzerland), vol. 13, no. 24, pp. 1–22, 2021, doi: 10.3390/w13243515.
[2] M. Islam and M. Mostafa, “Textile Dyeing Effluents and Environment Concerns - A Review,” J. Environ. Sci. Nat. Resour., vol. 11, no. 1–2, pp. 131–144, 2019, doi: 10.3329/jesnr.v11i1-2.43380.
[3] K. Shahul Hameed, P. Muthirulan, and M. Meenakshi Sundaram, “Adsorption of chromotrope dye onto activated carbons obtained from the seeds of various plants: Equilibrium and kinetics studies,” Arab. J. Chem., vol. 10, pp. S2225–S2233, 2017, doi: 10.1016/j.arabjc.2013.07.058.

[4] S. H. Javed, A. Zahir, A. Khan, S. Afzal, and M. Mansha, “Adsorption of Mordant Red 73 dye on acid activated bentonite: Kinetics and thermodynamic study,” J. Mol. Liq., vol. 254, pp. 398–405, 2018, doi: 10.1016/j.molliq.2018.01.100.

[5] M. Ayisha Sidiqua and V. S. Priya, “Removal of yellow dye using composite binded adsorbent developed using natural clay and activated carbon from sapindus seed,” Biocatal. Agric. Biotechnol., vol. 33, no. March, 2021, doi: 10.1016/j.bcab.2021.101965.

[6] N. Y. Donkadokula, A. K. Kola, I. Naz, and D. Saroj, “A review on advanced physico-chemical and biological textile dye wastewater treatment techniques,” Rev. Environ. Sci. Biotechnol., vol. 19, no. 3, pp. 543–560, 2020, doi: 10.1007/s11157-020-09543-z.

[7] V. Katheresan, J. Kansedo, and S. Y. Lau, “Efficiency of various recent wastewater dye removal methods: A review,” J. Environ. Chem. Eng., vol. 6, no. 4, pp. 4676–4697, 2018, doi: 10.1016/j.jece.2018.06.060.

[8] A. R. Dinçer, Y. Güneş, N. Karakaya, and E. Güneş, “Comparison of activated carbon and bottom ash for removal of reactive dye from aqueous solution,” Bioresour. Technol., vol. 98, no. 4, pp. 834–839, 2007, doi: 10.1016/j.biortech.2006.03.009.

[9] V. V. Basava Rao and S. Ram Mohan Rao, “Adsorption studies on treatment of textile dyeing industrial effluent by flyash,” Chem. Eng. J., vol. 116, no. 1, pp. 77–84, 2006, doi: 10.1016/j.cej.2005.09.029.

[10] A. A. Peláez-Cid, V. Romero-Hernández, A. M. Herrera-González, A. Bautista-Hernández, and O. Coreño-Alonso, “Synthesis of activated carbons from black sapote seeds, characterization and application in the elimination of heavy metals and textile dyes,” Chinese J. Chem. Eng., vol. 28, no. 2, pp. 613–623, 2020, doi: 10.1016/j.cjche.2019.04.021.

[11] P. Pengthamkeerati, T. Satapanajaru, N. Chatsatapattayakul, P. Chairattanamanokorn, and N. Sananwai, “Alkaline treatment of biomass fly ash for reactive dye removal from aqueous solution,” Desalination, vol. 261, no. 1–2, pp. 34–40, 2010, doi: 10.1016/j.desal.2010.05.050.

[12] P. Sharma, H. Kaur, M. Sharma, and V. Sahore, “A review on applicability of naturally available adsorbents for the removal of hazardous dyes from aqueous waste,” Environ. Monit. Assess., vol. 183, no. 1–4, pp. 151–195, 2011, doi: 10.1007/s10661-011-1914-0.

[13] Z. Bencheqroun, I. El Mrabet, M. Kachabi, M. Nawdali, I. Neves, and H. Zaitan, “Removal of basic dyes from aqueous solutions by adsorption onto Moroccan clay (Fez city),” Mediterr. J. Chem., vol. 8, no. 3, pp. 158–167, 2019, doi: 10.13171/10.13171/MJC8319050803HZ.

[14] S. A. Hamid, M. Shahadat, and S. Ismail, “Development of cost effective bentonite adsorbent coating for the removal of organic pollutant,” Appl. Clay Sci., vol. 149, no. July, pp. 79–86, 2017, doi: 10.1016/j.clay.2017.07.022.

[15] A. El Kassimi, Y. Achour, M. El Himri, M. R. Laamari, and M. El Haddad, “High efficiency of natural Safiot Clay to remove industrial dyes from aqueous media: Kinetic, isotherm adsorption and thermodynamic studies,” Biointerface Res. Appl. Chem., vol. 11, no. 5, pp. 12717–12731, 2021, doi: 10.33263/BRIAC115.1271712731.

[16] L. C. Paredes-Quevedo, C. González-Caicedo, J. A. Torres-Luna, and J. G. Carriazo, “Removal of a Textile Azo-Dye (Basic Red 46) in Water by Efficient Adsorption on a Natural Clay,” Water. Air. Soil Pollut., vol. 232, no. 1, 2021, doi: 10.1007/s11270-020-04968-2.

[17] T. A. Albanis, D. G. Hela, T. M. Sakellarides, and T. G. Danis, “Removal of dyes from aqueous solutions by adsortion on mixtures of fly ash in batch and column techniques,” Glob. NEST J., vol. 2, no. 3, pp. 237–244, 2018, doi: 10.30955/gnj.000174.