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Adsorptive removal of Zinc (II) from aqueous solution by using sugarcane bagasse as non-conventional adsorbent

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ABSTRACT

The Heavy metal which are present as metal cations in the water/wastewater, one of them a common metal such as Zn (II), which is toxic to human health create a series problem with their poisoning cases in their presence in the environment. The removal of metal from aqueous solution is one of the most important environmental and economic issue today. This research paper presented the Zn (II) removal/ adsorption of metal by using adsorption technique for better removal/ adsorption by using sugarcane bagasse which is non-conventional, low-cost agricultural adsorbents. The removal/ adsorption by using sugarcane bagasse at different metal concentration at temp. 30.0±0.1C°, particle size <53µm and at pH=7.2. The removal of Zn (II) on chemically modified sugarcane bagasse (MSB) was nearly 19% higher against unmodified sugarcane bagasse (USB). So, the rate of Zn (II) removal on the sugarcane bagasse (MSB) adsorbent gave good fit for better removal/adsorption.

KEY WORDS: - Heavy metals, sugarcane bagasse, non-conventional

Introduction: - While industries are often regarded as the lifeblood of a nation's development and a primary measure of economic progress, they also generate wastewater that poses a significant environmental hazard. If left untreated, these effluents threaten the health of humans, animals, and plant ecosystems. To address these challenges, recent advancements in sustainable materials and nanotechnology have emerged as crucial tools. These innovative technologies provide sophisticated solutions for water purification and environmental conservation, offering a pathway to balance industrial growth with the urgent need for ecological protection. Ghayda Yasen et.al. (2025). These effluents are particularly hazardous because they contain heavy metals that are toxic and resistant to biological decomposition. Their environmental persistence leads to accumulation in aquatic and terrestrial ecosystems, posing a severe threat to water and soil quality. Consequently, these non-biodegradable pollutants represent a major long-term risk to the health of both humans and the broader environment.

The rapid pace of industrialization and tremendous increase of human population growth have led to increasing sewage pollution, because most of the public living in the bank of big cities in India. Then the sewage/wastewater pollution particularly heavy metals such as Zn (II) metal which pose serve environmental and health risk in human and other living beings. Because Zn is very widely used metal in the environment. The main source of aquatic contamination of metal production units and other industries like pharmaceuticals, electroplating paints and pigment manufacturing textiles and all dye industries, which causes series problem when Zn metal enters in water/wastewater. It leads to dehydration and electrolyte imbalances, often accompanied by abdominal pain, nausea, vertigo, and impaired muscular coordination (NRC, 1997).

The accumulation of metal cations such as Zn, Fe, Cu, Cd, and Cr in aquatic ecosystems represents a significant environmental challenge due to their non-biodegradable nature and indefinite persistence. Once discharged into waste streams, these mobile ions transition easily through the liquid phase, facilitating their entry into the food chain where they bioaccumulate and reach toxic levels even at low concentrations. Consequently, the remediation of Zn (II) is of particular importance given its high toxicity and widespread industrial utility in batteries, construction, pigments, and rubber vulcanization. By removing these persistent contaminants, we mitigate a severe threat to aquatic life and prevent the long-term adverse health effects associated with heavy metal exposure in human populations. (WHO, 1984) and dye industries, which causes serious problem to human health.

The remediation of toxic metal ions from water and wastewater has necessitated the development of diverse physio-chemical methodologies. While biological treatment systems—such as those utilizing activated sludge—are primarily engineered for the degradation of organic matter, they often provide the secondary benefit of heavy metal reduction through microbial interaction. However, contemporary research has pivoted toward more sustainable and cost-effective alternatives, specifically focusing on the efficacy of agricultural byproducts and natural biosorbents. Materials including sugarcane bagasse, coconut shell, rice husk, maize cobs, and fruit peels (such as orange and banana) have demonstrated significant potential as adsorbents. These low-cost materials offer a promising "green" chemistry approach to heavy metal removal, aligning modern wastewater management with circular (Patil kishor et al. 2012; Bernard et al. 2013; Santos, et al., 2019; Briffa, et al., 2020; Putra et al., 2014, Zulfareen et.al. 2018).

Various researchers have highlighted the viability of agricultural byproducts as effective substrates for the sequestering of metal ions from aqueous environments and industrial wastewater. While these raw materials possess inherent adsorptive properties, recent advancements emphasize By applying chemical modifications to agricultural adsorbents can significantly enhance their sorption capacity. By introducing specific functional groups or altering the surface area through chemical pretreatment, the overall efficiency of these biosorbents is markedly improved. Consequently, these modified materials represent a high-performance, sustainable alternative for remediating heavy metal contamination, bridging the gap between waste management and advanced water purification technologies. (Ajmal et al., 2000, Bhattacharya 2006, Thakur & Parmar; 2013; Singh N.B. and Pandey Shivani (2011), Kong, W, et.al. (2014), Balaji et al., 2014; Priyanka Kumari 2017, Razi et al., 2018; Rao, et al., 2020, Melkamu B G et.al. (2022), Gemechu L et.al. (2023), Ghayda et.al. 2025).

EXPERIMENTAL METHOD:

The experimental procedure utilized analytical-grade chemicals to ensure high precision throughout the study. A stock solution of Zn was prepared by dissolution in diluted HNO_3, with subsequent working concentrations achieved through serial dilution using distilled water. To maintain experimental consistency, parameters such as temperature, particle size, and the pH of the adsorbent were kept constant. The pH of the medium was precisely adjusted using 0.1 N NaOH or HCl, required. Following the adsorption process, the final concentration of Zn was quantified via spectrophotometry, adhering strictly to the standardized APHA methodology.

Preparation of adsorbents:

The non-conventional, low-cost adsorbent, sugarcane bagasse, was sourced from local farmers and subjected to a rigorous cleaning process. The raw material was initially soaked in hot deionized water and detergent for 24 hours to eliminate impurities. Following this, the bagasse was rinsed thoroughly with hot deionized water to remove residual sugars, impurities, and soluble extractives. any remaining debris and then air-dried. The resulting dried fibers were ground and processed through a standardized set of sieves to isolate the specific particle size required for optimal heavy metal removal.

Activation of adsorbents:

To prepare the adsorbents, the sugarcane bagasse fibre was initially acid-washed by soaking in a 0.3 M HNO_3 solution for 24 hours to remove existing mineral impurities. The resulting mixture was filtered through a Whatman No. 41 filter paper, rinsed thoroughly with deionized water, and air-dried for 24 hours. This cleaned material was then divided into two equal portions: one remained untreated and was designated as Unmodified Sugarcane Bagasse (USB). The second portion was subjected to chemical functionalization by treatment with a 1M mercaptan acetic acid

($HS.CH_2COOH$) solution and stirred for 30 minutes to form Modified Sugarcane Bagasse (MSB). Following filtration, the residues were further treated with 1M hydroxyl amine (NH_2OH) and re-filtered. Finally, the processed adsorbents were rinsed with distilled deionized water and stored in airtight plastic containers for use in the metal sequestration experiments.

Table 1: Chemical Composition of Sugarcane Bagasse

S. No.	Component	% w/w (Dry Matter)
(i)	Total Reducing Sugars (TRS)	70.9%
(ii)	Xylose	25.2%
(iii)	Glucose	41.0%
(iv)	Fermentable Reducing Sugars (FRS)	44.6%
(v)	Non-fermentable Reducing Sugars (NRS)	26.3%
(vi)	Lignin	23.0%
(vii)	Ash	1.1%
(viii)	Moisture (% w/w of wet matter)	47.8%

Adsorption Kinetics of Metal Cations:

The adsorption kinetics of Zn (II) removal were investigated for each selected adsorbent at a controlled of pH=7.2 and at temperature 30.0±0.1ºC. For these studies, an initial metal ion concentration $1.82\times10{-}4$M was utilized, with a consistent adsorbent particle size of <53**μ**m. Experimental trials were conducted by introducing of the adsorbent into (100ml) was taken in 250ml Erlenmeyer flask. Adsorbent (0.5 gm each) Erlenmeyer flask, followed by agitation in a shaker at a constant speed of (90 rpm). Upon reaching the predetermined equilibrium period, the supernatant was filtered through Whatman No. 41 filter paper. The residual Zn (II) concentration in the filtrate was subsequently quantified via spectrophotometric analysis to determine the metal uptake. To evaluate the adsorption dynamics and calculate the rate constants, the data were modelled using first-order reversible reaction kinetics. (Bhattacharya et.al. 2006, Arias and Sen 2009, Singh and Pandey 2011, Putra et al., 2014, Kong et.al. 2014, Priyanka kumari 2017, Sarker et.al. 2017 Melkamu et. al. 2022, Gemechu et.al. 2023).

Adsorption equilibrium studies were conducted to evaluate the maximum uptake capacity of the modified bagasse under varying initial concentrations. using the Langmuir, Freundlich, and Temkin isotherm models to evaluate the interaction between Zn (II) ions and the adsorbents. These investigations were performed across a range of initial metal concentrations from 20 to 100 mg/L. To assess the effectiveness of the biosorption process, both the equilibrium adsorption capacity (qe), representing the mass of metal adsorbed per unit mass of the bagasse, and the total removal percentage (% adsorption) were calculated. These parameters serve as essential indicators for determining the surface affinity and the maximum theoretical capacity of the modified and unmodified sugarcane bagasse. Adsorption isotherms were investigated to evaluate the surface properties and affinity of the chemically modified adsorbent following equation-

$$qe = \frac{V(Co - Ce)}{100M}$$

$$\% \text{ Adsorbed} = \frac{(Co-Ce)}{Co} x100$$

"The amount of metal ions sequestered at equilibrium, qe (mg/g), was calculated using the mass balance relationship involving the initial concentration (Co), equilibrium concentration (Ce), solution volume (V), and dry adsorbent mass (M). This approach allowed for a comparative efficiency analysis of the modified and unmodified biosorbents. Furthermore, these values served as the primary input for non-linear regression fitting with the Langmuir, Freundlich, and Temkin isotherm models."

Table 2: Adsorption kinetics of Zinc (II) by modified sugarcane bagasse at different metal concentrations.

(Temperature 30.0±0.1°C; Particle size < 53 □M; pH = 7.2)

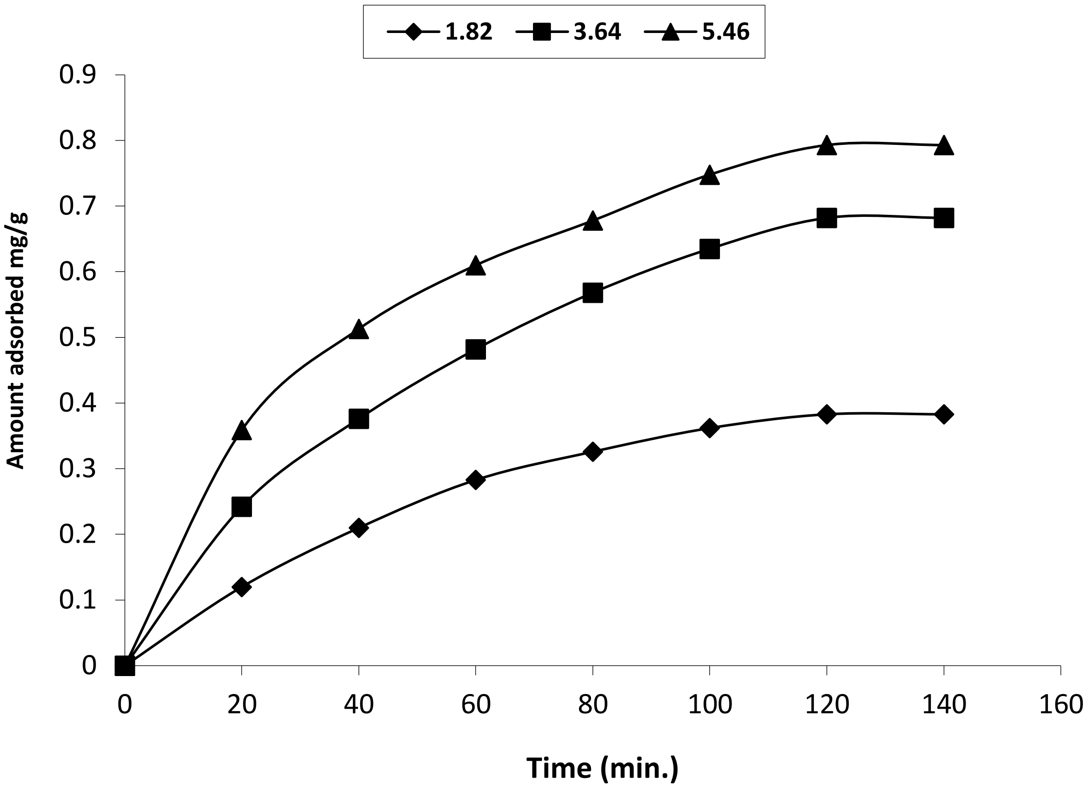
Time (min)	Different Concentration					
	1.82×10^{-4} M		3.64×10^{-4} M		5.46×10^{-4} M	
	Amount adsorbed mg/g	% Adsorption	Amount adsorbed mg/g	% Adsorption	Amount adsorbed mg/g	% Adsorption
20	0.120	25.00	0.242	27.72	0.359	26.21
40	0.210	38.10	0.376	41.83	0.513	34.21
60	0.283	47.12	0.482	52.10	0.610	38.10
80	0.326	59.72	0.568	62.17	0.678	44.23
100	0.362	70.12	0.635	67.22	0.748	48.16
120	0.383	76.10	0.682	72.12	0.793	52.81
140	0.383	76.10	0.682	72.12	0.793	52.81

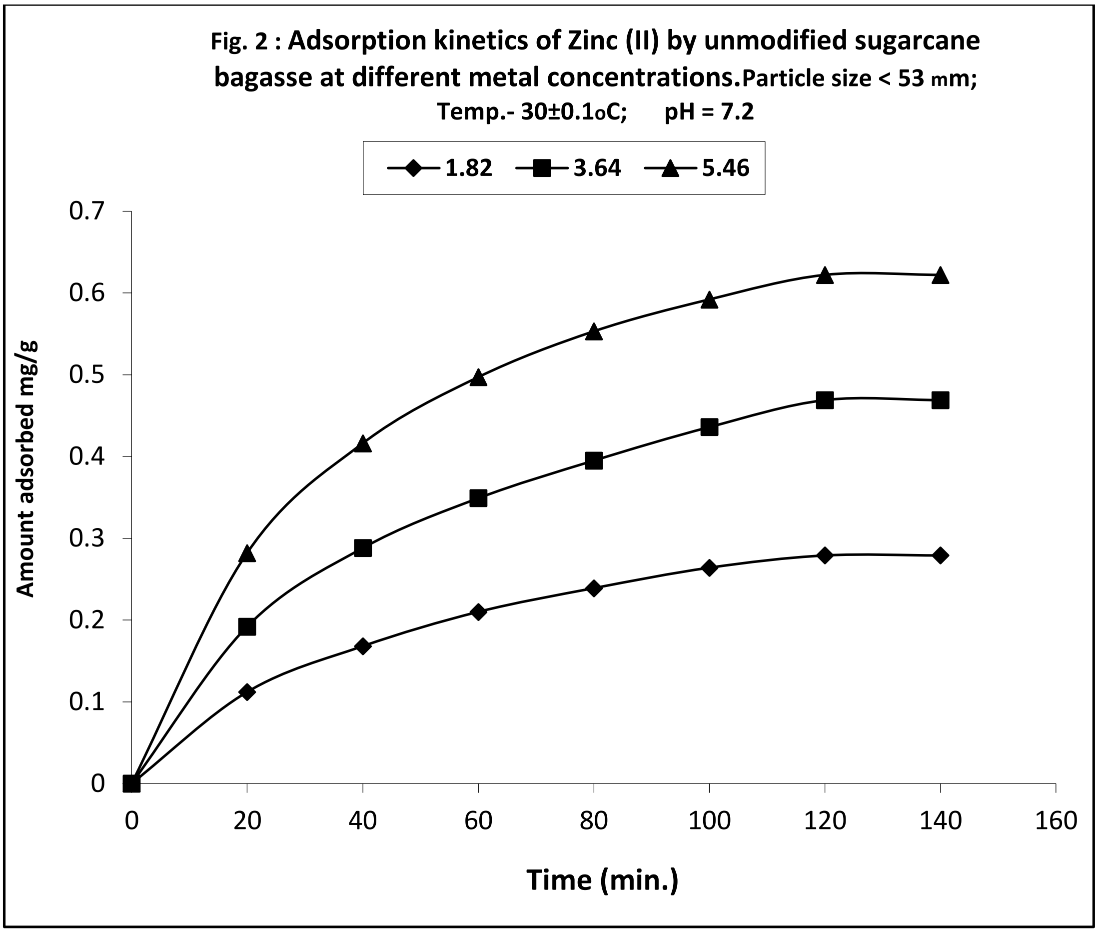
Table 3: Adsorption kinetics of Zinc (II) by unmodified sugarcane bagasse at different metal concentrations.

(Temperature 30.0±0.1°C; Particle size < 53 □M; pH = 7.2)

Time (min)	Different Concentration					
	1.82×10^{-4} M		3.64×10^{-4} M		5.46×10^{-4} M	
	Amount adsorbed mg/g	% of Adsorption	Amount adsorbed mg/g	% of Adsorption	Amount adsorbed mg/g	% of Adsorption
20	0.112	13.80	0.192	17.82	0.282	25.80
40	0.168	22.92	0.288	26.20	0.416	37.38
60	0.210	27.92	0.349	33.16	0.497	44.87
80	0.239	31.27	0.395	40.12	0.553	51.23
100	0.264	35.97	0.436	44.20	0.592	54.21
120	0.279	40.12	0.469	47.10	0.622	57.93
140	0.279	40.12	0.469	47.10	0.622	57.93

Fig. 1 : Adsorption kinetics of Zinc (II) by modified sugarcane bagasse at different metal concentrations. Particle size < 53 mm; Temp.- 30±0.1oC; pH = 7.2





RESULTS AND DISCUSSION:

Adsorption kinetics of Zinc (II) by modified and unmodified (MSB & USB) sugarcane bagasse is a time-dependent process, exhibiting rapid initial uptake followed by a slower rate as the adsorbent approaches saturation, as illustrated in Figures 1 and 2. This kinetic profile highlights the efficiency of these non-conventional adsorbents in reaching equilibrium while demonstrating the superior capacity of the modified biomass for metal removal. Modified and unmodified (MSB & USB) at different metal concentration at temp. 30.0±0.1C°, particle size <53µm and at pH=7.2 are constant. Adsorption kinetics of Zinc (II) 76.10 % (Fig 1 & Table 2) at metal concentration $1.82x10^{-4}$M by sugarcane bagasse (modified) greater with 57.93 % (Fig 2 & Table 3) at metal concentration 5.46 $x10^{-4}$M by sugarcane bagasse unmodified. It was nearly 19 % greater adsorption by sugarcane bagasse fibers modified adsorbent in comparison to unmodified sugarcane bagasse. The characteristic profile of the time-dependent adsorption curves and saturation periods remained independent of initial metal concentrations. Kinetic studies for both biosorbents revealed a two-stage process: a rapid initial sequestration followed by a slower transition toward equilibrium as available active sites were occupied. The variation in percent adsorption at different metal concentration value shown by both adsorbents, so it is clear that MSB>USB. Thus, the modified sugarcane bagasse fibers were found more efficient adsorbent than unmodified sugarcane bagasse fibers, because modified sugarcane bagasse fibers se was maximum uptake due to increase in surface area as compared unmodified sugarcane bagasse fibers.

The Researchers attribute variations in metal cation adsorption to surface hydroxylation and the occurrence of oxides at the solid-solution interface. The increased uptake at pH 7.2 likely results from the availability of specific active sites, while at the higher pH levels, the synthesis of hydrozincite and zincate ions may further facilitate the removal process. (Singh et al., 1988, Ghayda et.al. 2025). Chemical modification of sugarcane bagasse enhances its surface area, significantly increasing sorption capacity compared to the unmodified form and making it a highly efficient, low-cost adsorbent for metal cation removal. This improved structural framework ensures that modified bagasse serves as a superior, cost-effective sustainable and low-cost alternative for remediating wastewater contaminated with heavy metals such as Zinc (II).

CONCLUSION:

The present study aims to assess the efficacy of sugarcane bagasse both modified (MSB) and unmodified (USB) as a cost-effective agricultural byproduct for adsorption. Chemical kinetics revealed a rapid initial uptake of Zinc (II) followed by a slower rate as equilibrium was approached. The findings indicate that, under optimized experimental parameters, MSB outperforms USB as a superior adsorbent in alkaline media. This high efficiency implies that adjusting metal concentrations and utilizing low-cost, non-conventional MSB can provide a viable technology for designing advanced wastewater treatment systems.

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