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ZINC AND LEAD IONS ADSORPTION PRELIMINARY SCREENING: COMPREHENSIVE ANALYSIS OF COMMERCIAL SORBENTS FOR WATER TREATMENT

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Abstract

The annual increase in global water pollution has raised serious health and environmental concerns. Commercially available and well-known sorbents, such as activated carbon, chitosan, and Dowex resin, were utilized for wastewater treatment by sorbing Zn^{2+} and Pb^{2+} ions. The aim of this study was to evaluate and summarize the potential of these three materials as sorbents for wastewater treatment, with an emphasis on their sorption capacities and techno-economic analysis. The sorption capacities were determined in batch experimental conditions in one-component solutions. Concentrations of Zn^{2+} and Pb^{2+} ions before and after the sorption were measured using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). The overall sorption results indicate the effective removal of Zn^{2+} and Pb^{2+} ions, demonstrating the applicability of activated carbon, chitosan, and Dowex resin for the water purification process, with a comprehensive cost-benefit analysis of each sorbent by comparing the qualities and efficacy of each sorbent.

Key words: *Wastewater, heavy metals, water treatment, sorption.*

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Introduction

Industrial progress has provided modern society with innovative technology but has also led to the depletion of energy and water resources, limiting their availability for future generations. One of the prominent ecological issues has been securing clean water sources and developing sustainable purification treatments. The greatest contributors to wastewater production are domestic use, agricultural runoff, industrial and commercial activities which have gradually resulted in water scarcity [1,2]. Additional concern arises with high heavy metal content in wastewater, which has proven to leave detrimental effects on the living organisms and human health. Industries such as mining [3], battery manufacturing, electroplating [4], wood processing [5], petroleum refining, textile and tannery industries [6] are largely responsible for discharging heavy metal contaminated effluents. Heavy metals include: zinc, lead, copper, cobalt, cadmium, nickel, bismuth, tin, etc. These metals are not harmful in low concentrations; however, excessive concentrations can negatively impact humans and animals via the food chain [7].

Prolonged consumption of zinc-contaminated water can result in digestive, respiratory, and nervous system failure. It may also be the cause of cancer in some cases. Elevated zinc concentrations disrupt enzyme function and impair the absorption of other vital metals such as copper and iron. Adverse health conditions such as anemia, weakened immune response, and growth retardation may occur during chronic exposure to this metal. Additionally, excessive zinc levels leave negative consequences on aquatic organisms, hindering the ecosystem balance and biodiversity [8]. Lead toxicity has been widely studied among health professionals, who have revealed numerous negative effects of lead poisoning on most organs of the human body. Adults with long-term exposure to lead have demonstrated inferior cognitive abilities, an increase in blood pressure, anemia, and damage in the renal and neurological systems. An extremely high dose of lead could potentially have a deadly outcome. The biggest risk group is children and infants since they experience severe brain damage and are affected by even small dosages of lead in their bloodstream [9].

The importance of clean water for health, agriculture, medicine, scientific research, and the majority of industry sectors has prompted researchers to develop treatments capable of purifying water from heavy metals. Nowadays, numerous water treatment mechanisms successfully remove toxins from wastewater. The most common are membrane technologies, chemical precipitation, coagulation-flocculation, ion exchange, and adsorption. Adsorption has become a particularly attractive method for water decontamination due to its easy applicability and effective results [10].

The adsorbent plays a crucial role in capturing heavy metals in aqueous media, which in turn determines the overall cost of the adsorption process. Hence, the choice of an adequate adsorbent dictates not only the effectiveness of the process but also its techno-economic standpoint. Some of the most investigated adsorbents include nanomaterials and nanocomposites [11], biochar [12], zeolites [13], nanocellulose-based materials [14], and activated carbon [15].

The aim of this study was to provide a comparative analysis on the adsorption abilities of commercial-grade adsorbents on zinc and lead ions.

Materials and methods

The batch adsorption experiments were performed by using commercially available activated carbon (Kemika), chitosan (Aldrich), and DOWEX 1X8 (Serva), which are shown in Figure 1, respectively. Solutions were prepared by dissolving adequate amounts of $Zn(NO_3)_2$ (extra pure, Acros Organics) and $Pb(NO_3)_2$ (analytical reagent grade, Fisher Chemical), in deionized (mili-Q) water. For investigating the sorption affinities of selected adsorbents toward Zn^{2+} and Pb^{2+} ions, single-metal Zn^{2+} and Pb^{2+} solutions with increasing initial metal concentration (from 10^{-4} to $2 \cdot 10^{-3}$) were used. The adsorption experiments were conducted by adding 0,1 g of adsorbent to 20mL of each initial solution in plastic test tubes, on a rotary shaker (10 rpm), at room temperature (22°C) for 48 hours. After the specified contact time, suspensions were filtered through quantitative filter paper (blue ribbon), and Zn and Pb concentrations in solutions were measured using inductively coupled plasma mass spectrometry ICP-OES (PerkinElmer AVIO 200, Shelton, Connecticut, USA). Sorption isotherms were constructed to determine the sorption capacities of selected materials towards Zn and Pb ions. Dependency graph for adsorbed equilibrium quantities Q_e of residual concentrations of metal ions in the solution (C_e) represents the sorption isotherm.

Figure 1: Samples of selected adsorbents a) activated carbon, b) chitosan. c) DOWEX 1X8

Results and discussion

The sorption efficiencies of activated carbon, chitosan, and DOWEX 1X8 were tested for Zn(II) and Pb(II) ions. Each sorbent represents a different class of materials commonly utilized for water treatment, including carbon-based, biopolymeric, and synthetic polymeric ion exchangers. Activated carbon is predominantly a physical adsorbent, with a porous structure and large specific surface area, able to retain a wide range of contaminants through Van der Waals interactions and pore filling [16]. Chitosan is a biopolymer obtained from chitin that contains amino and hydroxyl functional groups, enabling specific coordination with metal cations through chelation and electrostatic interactions [17]. DOWEX 1X8 is a strongly basic anion exchange resin, primarily developed for the removal of anions such as chlorides, sulfates, and nitrates commonly found in industrial wastewaters. Although DOWEX 1X8 has an affinity towards an anion exchange, it was included in this study as a part of a broader investigation of water treatment processes involving different classes of sorbents. Moreover, its sorption capacity for Zn(II) and Pb(II) ions was also investigated to estimate the possibility of this resin in the overall removal of cationic contaminants in real complex systems – multicomponent systems such as industrial effluents. In such systems, due to the simultaneous presence of numerous anionic and cationic species, the overall sorption behavior was heavily influenced by competitive interactions for active sites [18].

The equilibrium sorption capacities (*Qe*) of Zn(II) and Pb(II) ions on activated carbon, chitosan, and DOWEX 1X8 resin are presented in Fig. 2-7, respectively.

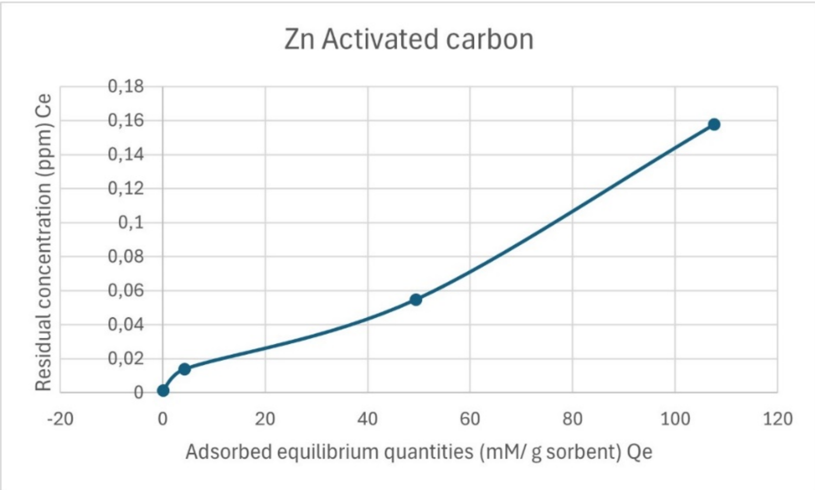

Figure 2: Sorption isotherm of activated carbon for Zn (II)

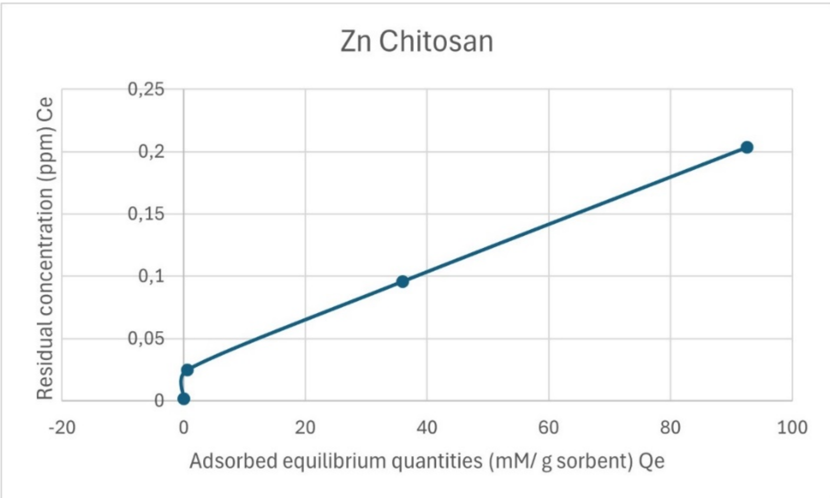

Figure 3: Sorption isotherm of chitosan for Zn (II)

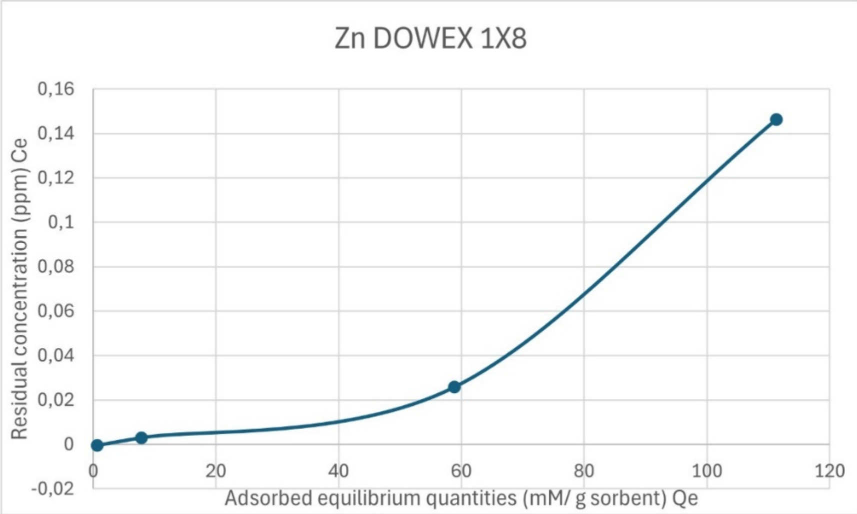

Figure 4: Sorption isotherm of DOWEX 1X8 for Zn (II)

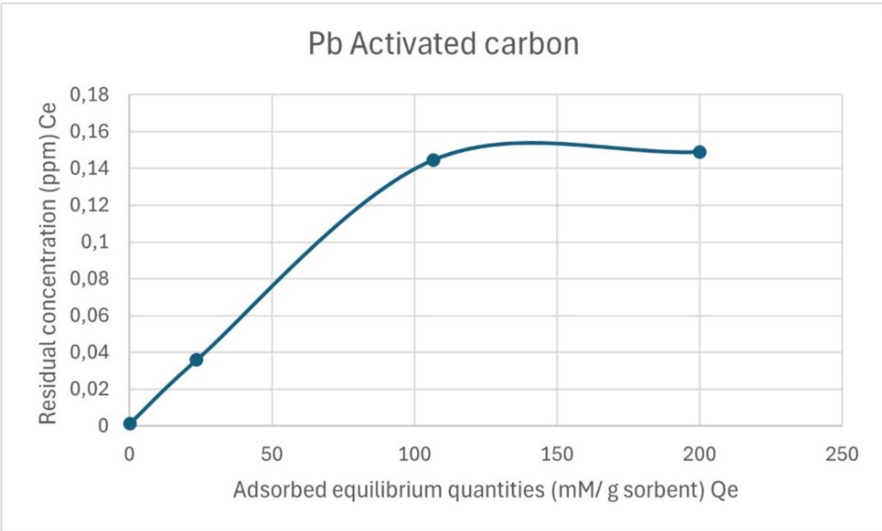

Figure 5: Sorption isotherm of activated carbon for Pb (II)

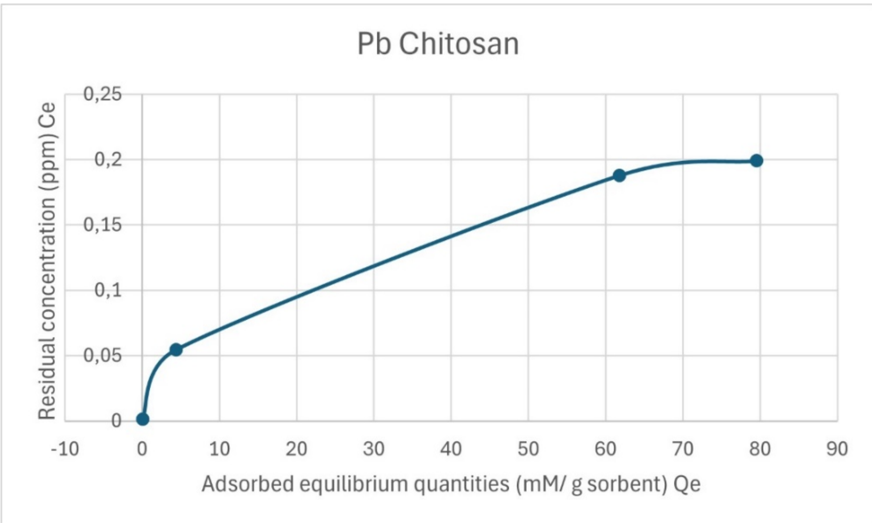

Figure 6: Sorption isotherm of chitosan for Pb (II)

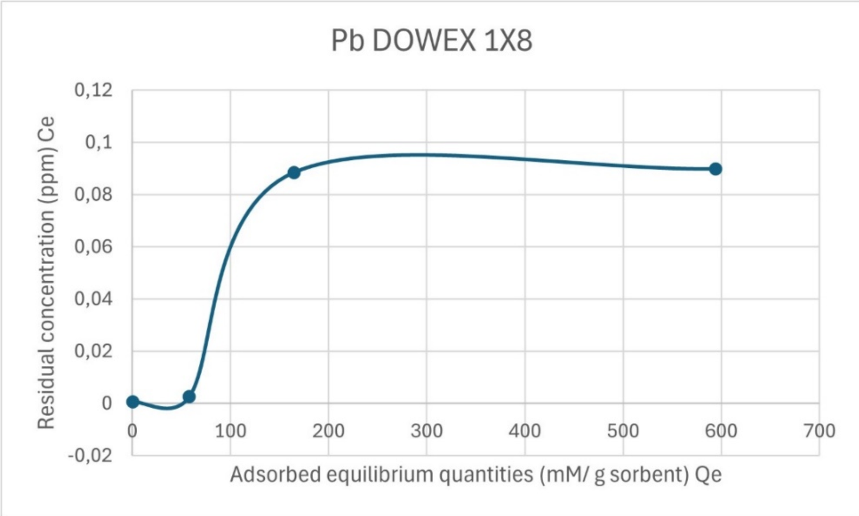

Figure 7: Sorption isotherm of DOWEX 1X8 for Pb (II)

The obtained isotherms show that the amount of ions retained on the sorbent's specific surface increased with rising equilibrium concentration. In the case of Pb(II), a distinct plateau was observed, indicating monolayer coverage of available active sites and attainment of equilibrium. In contrast, Zn(II) sorption shows a trend of increase within the investigated concentration range, suggesting that equilibrium had not yet been reached and that the maximum sorption capacity could be higher at elevated concentrations. Among the investigated sorbents, the sorption capacities increased in a series chitosan > activated carbon > DOWEX 1X8 as expected. Chitosan exhibited the highest sorption capacities for both Zn(II) and Pb(II) ions, with values of 0.203 mmol/g and 0.199 mmol/g, respectively. This high performance can be attributed to its multiple chelation sites, along with amino ($-NH_2$) and hydroxyl (-OH) groups, which attract metal ions through coordination bonds or ion-exchange interactions [19]. These findings align with those published by Benettayeb et al [17], where were observed similar trends in the adsorption of heavy metals using chitosan-based materials.

Activated carbon and DOWEX 1X8 resin demonstrated lower sorption efficiencies for both Zn(II) and Pb(II) ions. This can be attributed to their lower ion-exchange capacities and the absence of functional groups capable of forming coordination bonds with metal cations. Specifically, activated carbon's adsorption efficiency is influenced by factors such as surface area, pore structure, and the presence of surface functional groups like carboxyl and lactone groups. However, the ion-exchange capacity of activated carbon is generally lower compared to materials with dedicated ion-exchange functionalities [16].

As expected, DOWEX 1X8 resin exhibited lower sorption efficiencies for Zn(II) and Pb(II) ions, which can be attributed to its structural composition and functionalization – based on a polystyrene–divinylbenzene (PS–DVB) matrix functionalized with quaternary ammonium groups [18]. The absence of chelating functional groups, such as amino or hydroxyl groups, limits the formation of coordination bonds with metal cations (ref). However, DOWEX 1X8 showed modest sorption capacities toward the tested ions, reaching 0.08988 mmol/g for Pb(II) and even 0.146 mmol/g for Zn(II).

In general, Pb(II) ions showed higher sorption efficiency compared to Zn(II) across all sorbents, likely due to their larger ionic radius and stronger affinity toward the sorbent's active sites. The obtained results indicate that both the sorbent type and the physicochemical characteristics of the ions significantly influence the overall sorption performance. For instance, a study by Maslova et al. [20] demonstrated that Pb^{2+} ions have a higher adsorption rate compared to Zn^{2+} ions due to differences in their effective radii and hydration energies. Specifically, Pb^{2+} has a smaller hydrated radius and lower hydration energy, facilitating its easier release of water molecules and stronger interaction with sorbent active sites.

Additionally, a study by Ekop et al. [21] found that the adsorption efficiency of Pb^{2+} was higher than that of Zn^{2+} on Helix aspera shell biomass. This was attributed to the ionic character of Pb^{2+}, which has a larger charge-to-mass ratio and smaller ionic radius compared to Zn^{2+}, leading to stronger electrostatic interactions with the sorbent surface. Furthermore, research by Long et al. [22] on MMB (modified magnetic biosorbent) indicated that in a binary system of Pb^{2+} and Zn^{2+}, MMB preferentially adsorbed Pb^{2+} over Zn^{2+}. The study attributed this preference to the larger ionic radius and stronger affinity of Pb^{2+} for the sorbent's active sites.

Conclusion

Sorption isotherms were derived based on the results of ICP analysis for three different groups of adsorbents. Based on the results, it can be concluded that the type of adsorbent greatly influences the sorption capacity. Sorption capacities of DOWEX 1X8 were 0.08988 mmol/g for Pb(II) and 0.146 mmol/g for Zn(II), and 0.1487 mmol/g for Pb (II), and 0.1577 mmol/g for Zn (II) for activated carbon. Namely, DOWEX 1x8 resin and activated carbon showed lower sorption capacity values for Zn (II) and Pb (II) compared to chitosan, whose sorption capacities were 0.199 mmol/g for Pb (II), and 0.203 mmol/g for Zn (II). In terms of overall sorption efficiency, Pb (II) ions have a superior affinity towards selected sorbents compared to Zn (II) due to their larger ionic radius. In addition to the type of adsorbent, the physicochemical properties of the ions also have a significant influence on the adsorption efficiency.

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