

Article

Eggshell-Activated Carbon from Water Hyacinths for Heavy Metal Removal from Wastewater: Isotherm and Kinetic Studies

Claire Atumanye ¹, Simon Bbumba ^{2,3} , Hakim Nsubuga ⁴ , Ivan Kiganda ^{2,*} , Timothy Omara ^{2,*} 
and Justus Kwetegyeka ^{1,*}

¹ Department of Chemistry, Faculty of Science, Kyambogo University, Kyambogo P.O. Box 1, Uganda; claireatumanye01@gmail.com

² Department of Chemistry, College of Natural Sciences, Makerere University, Kampala P.O. Box 7062, Uganda; sbbumba762@gmail.com

³ Department of Science, Faculty of Science and Computing, Ndejje University, Kampala P.O. Box 7088, Uganda

⁴ Department of Chemistry, Faculty of Science, Muni University, Arua P.O. Box 725, Uganda; h.nsubuga@muni.ac.ug

* Correspondence: ivan.kiganda@mak.ac.ug (I.K.); timothy.omara@mak.ac.ug (T.O.); jkwetegyeka@kyu.ac.ug (J.K.)

Abstract

Heavy metals (HMs) such as copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr) and zinc (Zn) from industrial activities are discharged into nearby water resources after treatment. In the present study, the potential of utilizing chemically activated carbon derived from water hyacinths as a sustainable and low-cost adsorbent for heavy metal removal from industrial wastewater from the Nakawa industrial area, Uganda was investigated. The measured physicochemical parameters of wastewater (temperature, pH, electrical conductivity, total dissolved solids, turbidity, dissolved oxygen, chlorides and total hardness) varied significantly among the three sampled sites ($p < 0.05$), except for pH. Similarly, the concentration of the HMs in the samples ($0.54 \pm 0.04 \text{ mg L}^{-1}$ for Cr to $93.54 \pm 0.07 \text{ mg L}^{-1}$ for Pb) varied significantly between sites ($p < 0.05$), exceeding the maximum permissible limits of Cd, Pb, Cr, Cu and Zn specified in the National Environment Standards for Discharge of Effluent into Water or Land. The water hyacinth biomass was activated using eggshell powder and phosphoric acid, followed by thermal treatment. Characterization using Fourier-transform infrared spectroscopy and scanning electron microscopy confirmed that there was improvement in its surface functionality and porosity post activation. Batch adsorption experiments indicated that optimal removal of the HMs was achieved at pH 4–5, contact time of 90 min, and 1.0 g of adsorbent. Maximum adsorption capacities of Pb, Cd, Cu, Cr and Zn were in the range of $1.04\text{--}8.36 \text{ mg g}^{-1}$. Under the optimized conditions, the eggshell-activated carbon derived from water hyacinths had removal efficiencies of $91.2 \pm 9.1\%$ (range: 71.3–100%). Adsorption occurred through both monolayer and multilayer coverage, as indicated by the experimental data which fitted well to the Freundlich isotherm (Cd^{2+} , Pb^{2+} , Zn^{2+} and Cu^{2+} ions) and Langmuir isotherm model (Cr^{3+} ions). These results support the potential of water hyacinth-derived activated carbon as an ecofriendly alternative for treating low concentrations of these HMs in industrial wastewater.

Keywords: adsorption; *Eichhornia crassipes*; kinetics; optimization



Received: 22 May 2026

Revised: 6 July 2026

Accepted: 6 July 2026

Published: 8 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Heavy metals (HMs), toxic metals or potentially toxic elements as they are interchangeably called refer to a group of metals and metalloids that have relatively high densities and are toxic even at parts per billion concentrations [1]. Most HMs occur naturally in the