



Cite this: DOI: 10.1039/d6ra05654g

Molecularly imprinted ZSM-5 zeolite for selective creatinine removal from dialysate: toward enhanced uremic toxin clearance

Yanuardi Raharjo,^a Maipha Deapati Arief,^b Novia Amalia Sholeha,^c Triyanda Gunawan,^d Dayang Norfizan Awang Chee,^e Aemi Syazwani Abdul Keyon,^f Hartati,^g Aida Rifdatul Aisy,^h Muhammad Nidzhom Zainol Abidin^g and Nur Fariha Mahmuda^a

Dialysate regeneration *via* uremic toxin removal remains to be studied. In this study, the removal of creatinine, one of the most water-soluble uremic toxins, using ZSM-5 zeolite as an adsorbent was investigated. The zeolite ZSM-5 was successfully synthesized (57%) with a mole ratio of 0.1 Na₂O : 1 SiO₂ : 0.0125 Al₂O₃ : 20H₂O. Modification was performed using an imprinting technique with creatinine as the template to produce creatinine-imprinted ZSM-5 (IZ). Based on X-ray diffraction (XRD) characterization, the crystallinity of IZ was 67%. The successful imprinting of creatinine onto ZSM-5 was confirmed by comparing the FT-IR and surface area analysis characterization results with those of the synthesized ZSM-5. The FT-IR spectra of IZ and synthesized ZSM-5 exhibited similar patterns, indicating that the zeolite framework was preserved during the imprinting process. IZ exhibited shorter contact time and higher adsorption capacity than synthetic ZSM-5. The synthesized IZ was fabricated into a flat-sheet mixed matrix membrane (MMM) with cellulose acetate (CA) and acetone using a glass plate printing method with a composition of 30 CA : 0.1 zeolite : 100 acetone. The efficiency of creatinine adsorption by IZ in the powder form (84%) was greater than that of the MMM/IZ membranes (28.8%).

Received 26th June 2026

Accepted 14th July 2026

DOI: 10.1039/d6ra05654g

rsc.li/rsc-advances

Introduction

Hemodialysis (HD) is widely recognized as the primary renal replacement therapy for patients with end-stage chronic kidney disease (CKD). This procedure involves circulating the patient's blood through a dialyzer or artificial kidney, where metabolic waste products are removed across a semipermeable membrane.¹ The dialysate, which is a solution consisting of water, buffering agents, and electrolytes, plays an essential role

in this process. It is continuously pumped through the dialyzer, facilitating solute exchange with the blood *via* diffusion across a semipermeable membrane.² Each HD session requires up to 300 liters of dialysate and is performed approximately three to four times per week.³ In Indonesia, the number of HD procedures reached 4631 per week in 2012 and showed a consistent upward trend in subsequent years.⁴

Consequently, the increasing prevalence of CKD in patients undergoing HD has elevated the demand for dialysates. In routine practice, spent dialysate is generally discarded without further treatment, thereby contributing to medical waste and posing potential environmental concerns.⁵ To address this issue, dialysate regeneration has emerged as a viable strategy to reduce environmental impact and offers the additional benefit of decreasing water consumption, requiring approximately 6 liters of dialysate per session.⁶ Dialysate regeneration refers to the repeated utilization of dialysate in HD therapy following a purification process to eliminate uremic toxins accumulated during prior dialysis sessions.⁷

Water-soluble uremic toxins (WSUTs) such as creatinine and urea are the primary targets in dialysate purification because they are most readily removed during hemodialysis (HD). The average serum creatinine level in patients with CKD is approximately 8.6 mg dL⁻¹, with reported values ranging from 4.4 to 18.4 mg dL⁻¹.⁸ In contrast, normal creatinine levels in healthy

^aComposite Materials and Applications Research Group, Chemistry Department, Faculty of Science and Technology, Universitas Airlangga, Surabaya, Indonesia. E-mail: yanuardiraharjo@fst.unair.ac.id

^bChemical Analysis Study Program, Bantaeng Industrial Manufacturing Community Academy (AK-Manufaktur Bantaeng), Bantaeng, Indonesia

^cCollege of Vocational Studies, Bogor Agricultural University (IPB University), Jalan Kumbang No. 14, Bogor, 16151, Indonesia

^dDepartment of Chemistry, Faculty of Science and Data Analytics, Institut Teknologi Sepuluh Nopember, Jl. Arif Rahman Hakim, Kampus ITS Keputih-Sukolilo, Surabaya, 60111, Indonesia

^eFaculty of Resource Science and Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

^fDepartment of Chemistry, Faculty of Science and Centre for Sustainable Nanomaterials, Ibnu Sina Institute for Scientific and Industrial Research, Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Johor, Malaysia

^gDepartment of Chemistry, Faculty of Science, Universiti Malaya, Kuala Lumpur 50603, Malaysia