BAB V
KESIMPULAN & SARAN

V.1 Kesimpulan

Penelitian ini berhasil mengembangkan adsorben berbasis bahan alam dari pemanfaatan total buah lerak (*Sapindus rarak*) melalui sintesis komposit residu-MPN dengan variasi rasio Fe:Ekstrak (1:1 dan 1:2). Karakterisasi menggunakan FTIR, XRD, dan SEM-EDS berhasil mengonfirmasi terbentuknya fasa α-Fe_2O_3 dalam struktur organik residu. Material RM_{11} dengan (rasio 1 Fe:1 ekstrak lerak) menunjukkan kapasitas adsorpsi (Q_m) sebesar 52,46 mg/g pada suhu 30°C, sedangkan RM_{12} dengan (rasio 1 Fe:2 ekstrak lerak) memiliki kapasitas adsorpsi yang lebih tinggi, yaitu 65,49 mg/g pada suhu yang sama. Peningkatan performa adsorpsi ini disebabkan oleh penambahan ligan dari ekstrak lerak yang mampu mengoptimalkan struktur material. Selain itu, proses adsorpsi yang terjadi bersifat endotermik, sebagaimana ditunjukkan oleh peningkatan kapasitas adsorpsi seiring naiknya suhu. Hal ini didukung oleh distribusi nanopartikel Fe_2O_3 yang homogen serta ketersediaan situs aktif dari gugus hidroksil dan karboksil terprotonasi pada permukaan material, sehingga interaksi dengan zat teradsorpsi menjadi lebih efektif.

Proses adsorpsi optimal terjadi pada pH 2, dimana protonasi permukaan menghasilkan interaksi elektrostatik kuat dengan anion $HCrO_4^-$ melalui mekanisme pertukaran ion. Analisis kinetika mengikuti model *Pseudo Second Order* (R^2>0,99) yang menunjukkan dominasi *chemisorption*, sedangkan isoterm mengikuti model Langmuir ($R^2 > 0,975$) mengindikasikan terjadinya adsorpsi monolayer pada situs homogen. Kajian termodinamika mengungkap bahwa proses berlangsung secara endotermik ($\Delta H°$ = 36,342 kJ/mol, $\Delta S°$ = 0,0503 untuk RM_{11} dan $\Delta H°$ = 46,793 kJ/mol, $\Delta S°$ = 0,0856 untuk RM_{12}), serta semua kondisi spontan ($\Delta G°$ negatif), dengan peningkatan entropi sistem akibat pelepasan molekul air terikat selama adsorpsi. Temuan ini membuktikan potensi residu lerak termodifikasi sebagai adsorben ramah lingkungan untuk remediasi air tercemar Cr(VI), serta menawarkan solusi berbasis *circular economy* melalui pemanfaatan limbah pertanian. Optimasi rasio Fe:Ekstrak dan suhu sintesis dapat menjadi aspek penting dalam pengembangan material adsorpsi skala industri di masa mendatang.

V.2 Saran

Berdasarkan hasil penelitian yang dilakukan, direkomendasikan agar pemanfaatan residu buah lerak yang telah dimodifikasi dengan *coating* MPN berbasis besi (Fe) terus dikembangkan dan dioptimalkan sebagai bahan baku adsorben ramah lingkungan untuk penanganan limbah logam berat, khususnya ion kromium Cr(VI) dari air limbah industri. Penggunaan residu buah lerak yang dimodifikasi MPN terbukti dapat meningkatkan kapasitas adsorpsi serta menawarkan solusi yang ekonomis dan berkelanjutan dalam mengatasi pencemaran lingkungan. Keunggulan lain dari material ini adalah penggunaan bahan alami yang dapat mengurangi risiko pencemaran dan mendukung prinsip *circular economy*. Untuk penelitian selanjutnya, disarankan diperlukan uji aplikasi adsorben ini dalam skala yang lebih besar dan pada kondisi air limbah nyata, serta evaluasi aspek keberlanjutan dan potensi dampak lingkungan dari penggunaan dan regenerasi adsorben. Hambatan yang perlu dihindari oleh peneliti lain antara lain adalah ekstrak buah lerak sebagai prekursor memiliki kandungan fitokimia beragam, yang masing-masing berpotensi sebagai senyawa organik yang berikatan dengan Fe^{3+} dalam pembentukan MPN, seluruh residu dimanfaatkan tanpa memisahkan pengotor. Larutan sampel adsorpsi yang digunakan adalah larutan sampel yang dibuat, bukan limbah. Selain itu, studi lanjutan terhadap potensi ekstrak buah lerak sebagai ligan MOF, mengingat kandungan saponin dengan banyak gugus –OH dapat menyediakan banyak situs koordinasi logam. Penggunaan ligan ekstrak buah lerak dengan pengaturan rasio dan pelarut yang sesuai. Diharapkan adsorben berbasis residu buah lerak yang dimodifikasi MPN dapat menjadi solusi efektif dan ramah lingkungan untuk remediasi limbah industri di masa mendatang.

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