**Table S1.** Adsorption kinetics of Zirconium hydro (oxide) adsorbents.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Adsorbent | Adsorbate | Maximum adsorption (mg/g) | Optimal pH | Kinetics  model | Equipment  Time (h) | Ref. |
| Hydrous zirconium oxide | fluoride | 124 | 4.0 | Pseudo-second-order model | 10 | (Dou et al., 2012) |
| Zirconium oxide | fluoride | 19 | 4.75 | -- | 25 | (Blackwell and Carr, 1991) |
| Hydrated zirconium oxide | fluoride | 66 | 4.0 | Pseudo-second-order model | 1.67 | (Biswas et al., 2007) |
| Mesoporous zirconium oxide | phosphate | 29.71 | 3.0 | -- | 24 | (Liu et al., 2008) |
| Hydrous zirconium oxide | phosphate | 53 | 2.0 | Pseudo-second-order model | 8.33 | (Rodrigues et al., 2012) |
| Amorphous zirconium hydroxide | phosphate | 30 | 5.0 | -- | 72 | (Chitrakar et al., 2006) |
| Zirconium mesostructured immobilized calcium alginate | phosphate | 67.99 | 2.1-7.2 | Pseudo-second-order model | 25 | (Yeon et al., 2008) |
| Zirconia-functionalized graphite oxide | phosphate | 131.6 | 2.0 | Pseudo-second-order model | 20 | (Zong et al., 2013) |
| Lanthanum carbonate modified microfibrous composite | phosphate | 38.5 | -- | Yoon-Nelson model | -- | (Yang, 2023) |
| Goethite | phosphate | 8.55 | -- | -- | -- | (Zhong et al., 2007) |
| Hydrous zirconium oxide | chromium | 66 | 2.0 | Pseudo-second-order model | 1 | (Rodrigues et al., 2010) |
| Zirconium oxide | mercury | 0.69 | 7.0 | -- | 1 | (Rauf et al., 1989) |
| Hydrous zirconium oxide | mercury | 16.11 | 5.62 | Lagergren first order | 0.33 | (Mishra et al., 1996) |
| carbon nanosheets coated zirconium oxide nanoplate | zinc | 606.06 | 8.0 | Pseudo-second-order model | -- | (Fouda-Mbanga et al., 2023) |
| Vermiculite-based nanoscale hydrated zirconium oxides | nickel | 90.21 | 8.0 | Pseudo-second-order model | 2 | (Liu et al., 2018) |
| Zirconium oxide intercalated sodium montmorillonite scaffold | chromium | 64.57 | 3.0 | Pseudo-second-order model | 1 | (Rathinam et al., 2021) |
| phosphate | 52.46 | 6.0 | Pseudo-second-order model | 1 |
| Zirconium titanium oxides | vanadate | 24.96 | pH=10.5 | Pseudo-second-order model | 50 | (Sizgek et al., 2008; Drisko et al., 2009) |
| Mesoporous Zirconium Titanium Oxides | vanadate | 13.2 | pH>9 | Pseudo-second-order model | 50 | (Griffith et al., 2008) |
| Mesoporous Zirconium Titanium Oxides | uranium | 35.7 | 3.8 | Pseudo-second-order model | 50 | (Sizgek et al., 2009) |
| Zirconium-iron oxide | fluoride | 26.54 | 3.5 |  |  | (Dou et al., 2011) |
| Iron(III)- zirconium(IV)  Hybrid oxide | fluoride | 7.454 | 4.0-7.0 | Intraparticle diffusion model | 11 | (Biswas et al., 2007) |
| Granular zirconium-iron oxide | fluoride | 26.54 | 3.5 | -- | -- | (Awual et al., 2011) |
| Magnetic Fe-Zr binary oxide | phosphate | 17.87 | 3.0 | Intraparticle diffusion model | 24 | (Long et al., 2011) |
| Zirconium iron binary oxide | phosphate | 33.4 | 5.5 | Intraparticle diffusion model | 24 | (Ren et al., 2012) |
| Mixed hydrous oxides (Zr, Fe, Al) | phosphate | 22.9 | 4.0 | Pseudo-second-order model | 25 | (Chubar et al., 2005) |
| Zirconium-aluminum hybrid adsorbent | fluoride | 65.07 | 5.0-9.0 | Pseudo-second-order model | 48 | (Wu et al., 2018) |
| Nickel-aluminum-zirconium complex hydroxide | phosphate | 157.2 | / | -- | -- | (Ogata et al., 2020) |
| Iron-zirconium bimetal oxide | hexavalent chromium | 59.88 | 2.0 | Pseudo-second-order model | 1 | (Huang et al., 2015) |
| Zirconium-iron oxide nanoparticle | phosphate | 63.9 | 1.5 | Pseudo-second-order model | 16.67 | (Zhang et al., 2017) |
| Zirconium impregnated cashew nut shell carbon | fluoride | 162 | 3.0 | Pseudo-second-order model | 15 | (Alagumuthu and Rajan, 2010) |
| Zirconium impregnated collagen fiber | fluoride | 41 | 5.5 | Pseudo-first-order model | 9.17 | (Liao and Shi, 2005) |
| Zirconium carbon hybrid sorbent | fluoride | 7.4 | - | -- | 0.83 | (Velazquez-Jimenez et al., 2014) |
| Zirconium-modified-Na-attapulgite | fluoride | 24.55 | 4.13 | Pseudo-second-order model | 2 | (Zhang et al., 2012) |
| Zirconium complexes of chelating resins | fluoride | 109 | 2.0-4.0 | -- | -- | (Tanaka et al., 2002) |
| Zircnoium  impregnated coconut shell carbon | fluoride | 9.11 | 8.0 | Pseudo-second-order model | -- | (Sathish et al., 2007) |
| hybrid sorbent of Zr(IV) ethylenediamine | fluoride | 68.25 | 7.0 | Pseudo-second-order model | 0.5 | (Swain et al., 2012) |
| Zirconium Ion Modified MgAl-layered Double Hydroxides | phosphate | 17.7 | - | -- | 48 | (Miyauchi et al., 2009) |
| Zirconium loaded orange waste gel | phosphate | 57 | 3.0 | Pseudo-second-order model | 24 | (Biswas et al., 2008) |
| Zirconium-modiﬁed bentonite | phosphate | 40.2 | 4.0 | Elovich kinetic model | 48 | (Lin et al., 2018) |
| Surfactant modiﬁed zeolite/hydrous zirconium oxide | phosphate | 18.14 | 7.5-9.8 | -- | -- | (Xie et al., 2017) |
| Zirconium-pillared montmorillonite | Trivalent chromium | 129.63 | 8.0 | Pseudo-second-order model | 2 | (Ma et al., 2016) |
| Zirconium-loaded Ca-montmorillonite | phosphate | 22.37 | 4.0-8.5 | Elovich model | 72 | (Zou et al., 2020) |
| Zirconium alginate beads | ﬂuoride | 32.797 | 2.0 | -- | 20 | (Zhou et al., 2014) |
| Sodium alginate/zirconium hydrogel | phosphate | 256.79 | 3.0 | Intraparticle diffusion model | 48 | (Qing et al., 2022) |
| Zirconium-Modified Activated Sludge | phosphate | 82.65 | 2.0 | Pseudo-second-order model | 4.5 | (Wang et al., 2018) |
| Zirconium‑modified biochar | phosphate | 58.93 | 2.0 | Elovich model | 9.2 | (Huang et al., 2022) |
| Amorphous zirconium oxide | Arsenate | 32.4 | 7.0 | Pseudo-second-order model | 8 | （Cui et al., 2012）） |
| Arsenite | 83 | 7.0 | Pseudo-second-order model | 8 |
| Zirconium metal-organic framework UiO-66 | Arsenate | 303.34 | 2.0 | -- | -- | (Wang et al., 2015) |
| Oxygen-rich poly-bisvanillonitrile embedded amorphous zirconium oxide | Arsenite | 115 | 3.0-5.0 | Pseudo-second-order model | -- | Seynnaeve et al., 2021) |
| Arsenate | 245 | 3.0-5.0 | Pseudo-second-order model | -- |
| Zirconium modified pomegranate peel | Arsenate | 83.33 | 4.0 | Pseudo-second-order model | 12 | (Poudel et al., 2021) |
| Zirconium based nanoparticle | Arsenate | 256.4 | 2.5-3.5 | Intraparticle diffusion model | 12 | (Ma et al., 2011) |
| UiO-66(Zr)-derived t-zirconia | Arsenate | 352.1 | 3.0 | Pseudo-second-order model | 8 | （Qu et al., 2022） |
| Arsenite | 147.5 | 11.0 | Pseudo-second-order model | 8 |
| Zirconium oxide immobilized alginate beads | Arsenate | 28.5 | 2.0 | Pseudo-second-order model | 240 | (Kwon et al., 2016) |
| Arsenite | 32.3 | 7.0 | Pseudo-second-order model | 240 |
| Zirconium-chitosan modified spherical sodium alginate composite | Arsenate | 76.78 | 3.0 | Pseudo-second-order model | 150 | (Lou et al., 2021) |
| Arsenite | 43.19 | 3.0 | Intraparticle diffusion model | 150 |
| Calcium-alginate hydrogel-sphere encapsulated with Fe–Mn–Zr ternary metal composite | Arsenite | 83 | 7.0 | Pore/surface diffusion model | 35 | (Yuan et al., 2023) |
| Fe–Mn–Zr ternary magnetic sorbent | Arsenic | 81.3 | 2.0 | Pseudo-second-order model | 24 | (Zou et al., 2022) |
| Activated charcoal coated zirconium-manganese nanocomposite | Arsenate | 95.6 | 6.0 | Pseudo-second-order model | 9 | (Yin et al., 2019) |
| Arsenic | 132.28 | 10.0 | Pseudo-second-order model | 9 |
| Iron and zirconium modified luffa fibre | Arsenate | 2.89 | 7.0 | Intraparticle diffusion model | 24 | (Nguyen et al., 2020) |
| Iron-zirconium microwave-assisted modification of small-pore zeolite | Arsenate | 42.31 | 3.0-9.0 | Pseudo-second-order model | 24 | (Abdellaoui et al., 2021) |
| La-Zr bimetallic MOFs | Arsenic | 83.4 | 2.0 | -- | 12 | (Han et al., 2022) |
| Bowknot-like Zr/La bimetallic organic frameworks | Arsenate | 102 | 5.0 | Pseudo-second-order model | 12 | (Kong et al., 2022) |
| Amorphous zirconium phosphate | lead  cadmium  zinc | 621  190.6  91.5 | 5.5  5.5  5.5 | -- | 1.5 | (Pan et al., 2007) |
| Polymer-based zirconium phosphate | lead | 410 | 3.5 | Pseudo-first-order model | 4.5 | (Pan et al., 2007) |
| Amorphous zirconium phosphate | lead | 155 | 5.5 | -- | 1 | (Jiang et al., 2008) |
| Crystalline zirconium phosphates | lead | 21 | 6.0 | -- | 1 | (Jiang et al., 2008) |
| Polysulfone capsules containing zirconium phosphate | lead | 149.7 | 5.75 | Intraparticle diffusion model | 7 | (Ma et al., 2011) |
| Polymer-supported zirconium phosphate | lead | 556 | 6.0 | -- | 0.2 | (Pan et al., 2006) |
| Zirconium phosphate nanoparticles | lead | 672.5 | - | -- | -- | (Zhang et al., 2011) |
| Silicon-based zirconium phosphate | strontium | 100.77 | 6.0 | Pseudo-second-order model | 1.5 | (Jiao et al., 2021) |
| Polypyrrole modified zirconium (IV) phosphate nanocomposite | hexavalent chromium | 62.5 | 2.0 | Pseudo-second-order model | 1.33 | (Behera et al., 2022) |