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Removal of Cr(III) from water by polyurethane foam incorporated with green liquor dregs waste

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Abstract: Water bodies contaminated by heavy metals cause a series of severe environmental and health issues. Chromium compounds stand out as one of the main contaminants since they are widely used by several industries. The low efficiency of effluent treatment facilities and the expensive sanitation procedures needed to remove metals from the water lead to serious concerns about the water quality in Brazil. In this study, a rigid polyurethane foam incorporated with green liquor dregs waste was prepared by the free expansion method. The foam composite and its isolated phases were evaluated for removing Cr(III) from water. The isolated dregs removed 81.93% of the Cr(III), which yielded a removal capacity of 135.45 mg·g⁻¹. Whereas, the foam composite displayed Cr(III) removal percentage and capacity of 36.15% and 58.50 mg·g⁻¹, respectively. Results suggests that the hybrid material may be considered for selective removal and extraction of Cr(III) from contaminated water.

Keywords: polyurethane; heavy metal; water contamination; pulp and paper waste; chromium; adsorption; precipitation.

The discharge of heavy metals laden effluents to the environment is hazardous for living organisms and reduce overall water quality due to negative toxicological characteristics ascribed to these inorganic compounds, including high solubility and mobility, high reactivity with biological systems, inhibition of enzymes, and bioaccumulation (Klaasen and Watkins, 2012; Leong & Chang, 2020; Rocha and Azevedo, 2015). Even so, high heavy metals concentrations in sediments and water bodies have been reported in the literature (Andrade et al., 2018; Carvalho et al., 2017; Demarco et al., 2019; Jeong et al., 2021; Ma et al., 2016; Oliveira et al., 2018). Besides of the environmental pollution, these impurities are closely associated with many diseases, including kidney and tumor infections, the efficiency of hemoglobin synthesis and reproductive system, dizziness, fatigue, heart problems, and respiratory disorders (Khan et al., 2013; Tepanosyan et al., 2017; Wu et al., 2018; Zhao et al., 2012).

Contaminations by chromium (Cr) compounds arise from their several industrial applications, such as dyes, paint, ink, pigments manufacturing, production of steel, chrome plating, production of vats, leather tanning, and alloys for wood preservation (ATSDR, 2011; Montoya et al., 2010; Souza et al., 2018). In Brazil, the low rates of sewage and effluent treatment are associated with the low efficiency of biological methods to remove heavy metals (ANA, 2019). Therefore, close attention should be paid to the rapid population growth and the huge social inequality, which increase the demand for water resources and consequent harmful effects of contaminated water vulnerable populations.

Commercial activated carbon is a widespread material for removing contaminants from water (Reck et al., 2018). This expensive adsorbent has limited reuse, which restricts a large-scale application for water decontamination (Ahmaruzzaman, 2008; Coelho, 2014; Crini, 2006; Lima et al., 2018; Linhares et al., 2016). Alternative adsorbents were reported in the literature for the removal of metals (Gonçalves Junior et al., 2013; Rodrigues et al., 2006), oils (Santos et al., 2017), and dyes (Cardoso et al., 2011).

Brazil is the world's second-largest cellulosic pulp producer (IBÁ, 2019) and, for each ton of produced pulp, 800 kg of wastes are generated (Guerra, 2007), including those solid wastes chemically recovered from the black liquor, which are not reused in the process, such as paper sludge, grits, and dregs (Borges et al., 2016). These wastes from the pulp and paper industry could be used to develop alternative technologies to mitigate the water contamination due to their high availability and the high absorption capacity through ion exchange and electrostatic attraction of some of their compounds (Cardoso et al., 2011; Meneghel et al., 2013). The waste recovery chain aims at minimizing the amounts of wastes forwarded for disposal in landfills and the sustainable development of other sectors (Cardoso et al., 2011; Soares, 2018).

Polyurethane foams (PU) are a well-known technology in engineering for many different applications, including low-cost adsorbents and supports for retaining chemical substances in aqueous media, such as dyes (Baldez et al., 2008; Kong et al., 2016; Moawad et al., 2015; Schio et al., 2019), oils (Li et al., 2012; Nikkhah et al., 2015; Oribayo et al., 2017) and metals (Hussein and Abu-Zahra, 2017; Ossman and Addelfattah, 2018; Soriano and Cassella, 2013).

The incorporation of industrial waste fillers in PU foams normally aims to improve technological properties of the polymer matrix and/or reduce its cost (Brito et al., 2011; Tan et al., 2011). Nonetheless, filled PU foams can also be alternative adsorbents to decontaminate certain areas due to their high durability, reusability, and flotation. When these foams contain polyols derived from plants instead of oil-

based polyols, they can be called as biofoams. The objective of this work is to evaluate the use of polyurethane biofoams filled with a cellulose industrial waste for the adsorption of Cr(III) from contaminated synthetic aqueous solutions.

Methods

Foams and filler preparation

Green liquor dregs wastes were supplied by CMPC located in Guaiba/Brazil. This residue was dried at 50°C and sieved (100-mesh screen; aperture of 150 μm). Neat PU and dregs/PU foams were prepared by the free expansion method using two mixture components (A and B) at a 1:1 NCO/OH ratio and 5% filler content (Delucis et al., 2018). Component A consisted of castor oil (hydroxyl content of 160mg of KOH·g⁻¹), glycerin P.A., dregs, chain extender (polyethylene glycol), surfactant (Tegostab B804), and distilled water. These compounds were homogenized for 60 s under mechanical stirring (1000 rpm) and was then left to degas for 120 s. Component B is a catalyst (Tegoamin DMEA) and a polymeric MDI (Diphenylmethane Diisocyanate), which were added to Component A and then stirred for 20 s under mechanical stirring (1000 rpm). The final mixture was poured into an open mold and was left to rise for 24 h. The solid foam was cured at 60°C for 2 h in an oven and post-cured at 65% relative humidity and 20°C for two weeks, as recommended by Delucis et al. (2018).

Characterization steps

Scanning electron microscopy (SEM)

Surface morphology of the different materials was analyzed by scanning electron microscopy (SEM) using a JSM 6610LV equipment (Jeol, Japan). The microscope was adjusted for a working voltage of 15 kV and magnifications of 500 $\times$ and 40 $\times$.

X-ray diffraction (XRD)

X-ray diffraction (XRD) patterns were obtained using a D-8 diffractometer (Bruker, Germany) coupled with a diffracted beam monochromator and employing a Ni filtered CuK α radiation ($\lambda = 1.5406$ Å) at 40 kV and 40 mA. The 2 θ angle was scanned from 10° to 60° and the counting time was 1.0 s at each angle step (0.02°).

Fourier-transform infrared spectroscopy (FT-IR)

Chemical groups were qualitatively evaluated by Fourier-transform infrared spectroscopy (FT-IR) using IRPrestige-21 equipment (Shimadzu, Japan) adjusted for 32 scans in the 400-4000 cm⁻¹ range, transmittance mode, and a resolution of 4 cm⁻¹.

Point of Zero Charge (PZC)

Point of zero charge (PZC) was obtained by adding 0.1 g of solid material to 20 mL of a KNO₃ solution (0.01M) into a 50 mL plastic flask, which was stirred at 50 rpm for 24 h in initial pH solutions that varied from 1 to 12. The pH values were measured using a pH meter and the PZC was obtained after

plotting ΔpH ($\text{pH}_{\text{final}} - \text{pH}_{\text{initial}}$) against the initial pH. This methodology was adapted from that described by Farage et al. (2020).

Water uptake

The methodology described by Schulz et al., (2020) was adapted. Percentage mass gain (Equation 1) was determined for cubic samples (side equal to 2 mm), which were immersed in distilled water at room temperature and their weights were measured eight times from 5 min to 6 h.

$$\text{wateruptake} = \frac{m_f - m_i}{m_i} * 100\% \quad (1)$$

Where m_i and m_f are initial mass and final mass, respectively.

Analysis of Cr (III) Removal by Atomic Absorption Spectrophotometry (AAS)

The pH of synthetic Cr(III) stock solutions of $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ (Dynamic, PM: 266.45) with a concentration of $1000\text{mg} \cdot \text{L}^{-1}$ was adjusted using 0.1M NaOH and H_2SO_4 solutions. These assays were performed under a fixed stirring of 200 rpm using a Jartest JTM 6036 (Milan). Aliquots were taken at 1, 5, 10, 15, 30, 60, 120, 180, 240, 300, 360, 420, 480, 540, 600, 660, and 720 min. The dregs was previously centrifuged using a NT800 equipment (Nova Técnica) at 10000 rpm for 10 min. The samples were then diluted (1:10) and acidified before being analyzed by atomic absorption spectrophotometry using an AAnalyst 200 equipment (PerkinElmer) and the final pH was measured in a mPa-210 bench pH meter (MS Tecnopon Instrumentation). These results were analyzed according to both pH and adsorbent dosage in order to determine both the adsorption capacity (q) in relation to the mass of adsorbent per mass adsorbed ($\text{mg} \cdot \text{g}^{-1}$) (Equation 2) and percentage of removed Cr(III) (Equation 3).

$$q = \frac{(C_0 - C_e)V}{W} \quad (2)$$

$$\%R = \frac{(C_0 - C_e)}{C_0} 100 \quad (3)$$

Where: q = adsorption capacity ($\text{mg} \cdot \text{g}^{-1}$); $\%R$ = percentage of removal (%); C_0 = initial solute concentration ($\text{mg} \cdot \text{L}^{-1}$); C_e = equilibrium solute concentration ($\text{mg} \cdot \text{L}^{-1}$); V = volume of the solution (L); W = mass of solid adsorbent (g).

The adsorptions kinetic parameters were obtained by applying the kinetic equations for the pseudo-first-order model (Equation 4), the pseudo-second-order model (Equation 5) and Elovich (Equation 6) in the Statistic 7.0 software (Statsoft, 2004) by the non-linear method.

$$q_t = q_1 (1 - \exp(-k_1 t)) \quad (3)$$

$$q_t = \frac{t}{\left(\frac{1}{k_2 q_2^2}\right) + \left(\frac{t}{q_2}\right)} \quad (4)$$

$$q_t = \frac{1}{a} \ln(1 + abt) \quad (5)$$

Where: q_t = adsorption capacity on time ($\text{mg} \cdot \text{g}^{-1}$); q_1 and q_2 = theoretical values for the adsorption capacity ($\text{mg} \cdot \text{g}^{-1}$); k_1 = constant of pseudo-first-order model (min^{-1}); k_2 = constant of pseudo-second-order model ($\text{g} \cdot \text{mg}^{-1} \text{min}^{-1}$); a = initial adsorption rate ($\text{mg} \cdot \text{g}^{-1} \text{min}^{-1}$); b = Elovich constant ($\text{g} \cdot \text{mg}^{-1}$); t = time (min).

Results

Scanning electron microscopy (SEM)

Fig. 1 shows SEM images of all the studied materials. The dregs showed rough, rugged, and homogenous particles. Both neat PU and dregs/PU foam composite are mostly composed of closed cells. Compared to the neat polyurethane foam, the filled one shows more irregular shaped cells.

X-ray diffraction (XRD)

The degree of crystallinity of each compound is related to the three-dimensional shape of its respective molecules. In an XRD diffractogram, amorphous structures are represented by either absence or minor peaks, whereas crystalline domains are associated with prominent peaks (Almeida et al., 2018). Fig. 2 displays XRD diffractograms for the studied materials. Regarding the dregs, the found peaks are probably related to calcium carbonate (CaCO_3) in the form of calcite, which is known as the only crystalline phase from dregs. That peak at a 2θ angle of 28° for the filled foam confirms the presence of the filler into the foam cell structure. The neat PU showed two prominent peaks at 2θ angles of 19° and 43° , which indicates a certain crystallinity degree.

Fourier-transform infrared spectroscopy (FT-IR)

The dregs showed prominent bands at 1743 cm^{-1} , 1389 cm^{-1} , 869 cm^{-1} , and 711 cm^{-1} (Fig 3), whereas neat and filled foams presented similar shaped spectra with remarkable bands at 3313 cm^{-1} , 2924 cm^{-1} , 2852 cm^{-1} , 1701 cm^{-1} , 1595 cm^{-1} , 1510 cm^{-1} , 1411 cm^{-1} , 1311 cm^{-1} , 1209 cm^{-1} , 1056 cm^{-1} , 808 cm^{-1} and 761 cm^{-1} , which indicate that none band attributed to the dregs were detected for the filled foam.

Point of Zero Charge (PZC)

Based on Fig. 4, which displays ΔpH versus initial pH charts, the dregs presented a pzc of 8.40, whereas, for the same property, neat and filled foams presented 6.46 and 7.14, respectively.

Water Uptake

The water uptake was also influenced by the insertion of dregs into the PU foam, as observed in Fig. 5. The filled foam presented a higher mass gain rate if compared to the neat PU, especially after 5 min. This is probably related to the hydrophilic character of the filler and the morphological changes induced by the filler into the foam cell structure, as discussed above on the SEM images. Both foams reached a gradual stability, especially after 30 min. The neat PU reached a final water uptake around 1.82 ± 0.18 , whereas the filled PU was about 1.21 ± 0.09 .

Cr (III) Removal

High Cr(III) removal potentials were exhibited by all of the studied materials (Table 1). The highest efficiency was at pH 6 for all adsorbents. The dregs showed the highest removal efficiency and, when compared to neat PU and dregs/PU foam, the highest removal was 81.93% with $135.45\text{ mg}\cdot\text{g}^{-1}$ of material. Incorporating the dregs in the PU foam reduced its removal efficiency when compared to its isolated phase. At pH 6, neat PU and dregs/PU foam showed removal potentials of 36.15% and 36.02% and absorptive capacities of $57.56\text{ mg}\cdot\text{g}^{-1}$ and $58.50\text{ mg}\cdot\text{g}^{-1}$, respectively.

The parameter of the dosages in Table 2 showed that the increase in the dosage of the absorbent decreased both their percentage of removal and q . The experiment with the highest dosage ($1.2\text{ mg}\cdot\text{L}^{-1}$)

was the one that presented the lowest efficiency. The PU presented 4.13% and 1.7 mg g⁻¹, the dregs achieved 70.62% and 29.34 mg·g⁻¹, and the dregs/PU reached 3.09%, and 1.26 mg·g⁻¹ for R(%) and q, respectively. As with the effect of pH, both neat PU and dregs/PU foam showed similar behavior.

The maximum adsorption of the dregs occurred in the first 5 min, yielding removal percentage and capacity of 96.21% and 159 mg·g⁻¹, respectively. It is possible to observe the equilibrium of the kinetics at 135.45 mg·g⁻¹ after 420 min. The behaviors of PU and dregs/PU foam were similar throughout the kinetics and both materials reached equilibrium after 660 min (Fig. 6).

The kinetic parameters were applied in the best experimental condition and dregs/PU and neat PU did not fit in any kinetic adsorption model. For dregs, pseudo-first-order and pseudo-second-order models were better adjusted to demonstrate its adsorption kinetics (Table 3).

Discussion

The morphology of polyurethane foams is a honey comb-like structure, in which the gas bubbles are surrounded by polymeric cells and the addition of a solid filler may change overall the cell wall structure (Gu et al., 2013; Macedo et al., 2017). The high number of elliptical closed cells elongated in the expansion direction indicates a proper polymerization process of the neat PU (Delucis et al., 2018).

These morphological changes may also be associated with the particle size of the dregs. The use of rice husk as filler in PU foams yielded distorted cells and less uniformity when compared to neat ones (Silva et al., 2013). In other previous study, the addition of cellulose fillers also promoted a more irregular PU structure, which was worse for high filler contents (Macedo et al., 2017). A similar behavior was reported for PU foams filled with lignin particles, which presented a more heterogeneous cellular structure ascribed to the lignin insertion, although the particle size distribution did not influence in this case (Dražić et al., 2016; Santos et al., 2017). This influence of the dregs in the PU cell structure may be attributed to a poor dregs/PU chemical interaction, which probably hindered the foam nucleation in this case (Delucis et al. 2018).

Regarding the XRD patterns, the presence of amorphous structures in the PU are also reported in the literature (Almeida et al., 2018; Almeida et al., 2020; Schio et al., 2019; Sadeghi et al., 2011). According to Trovati et al. (2010), the peaks at 2θ angles of 19° and 43° are assigned to the scattering from PU chains with regular interplanar spacing.

In relation to the infrared spectra, the bands at 3310 cm⁻¹ and 1513 cm⁻¹ are related to the presence of the N-H bonds from urethane groups ((-NH-(C=O)-O-) belonging to the PU macromolecule (Kumari et al., 2016; Schio et al., 2019; Delucis et al., 2018). The band at 2837 cm⁻¹ is associated with -CH stretching of aliphatic groups (Santos et al., 2017; Kumari et al., 2016), whereas the signal at 2274 cm⁻¹ is related to the vibration of N=C=O bonds from isocyanates (Santos et al., 2017; Kumari et al., 2016), which can also be related to unreacted NCO groups (Schio et al., 2019). The attenuation of this band for the dregs/foam in relation to the neat PU indicates that the filler probably chemically reacted with NCO groups from the isocyanate. The bands at 1708 cm⁻¹ (C=O), 1209 cm⁻¹ (C-N) and 1042 cm⁻¹ (C-O) are typically ascribed to the polyol (Delucis et al., 2018; Kumari et al., 2016).

Increases in water uptake ascribed to fillers inserted in PU foams were also reported by Delucis et al. (2018). According to them, rigid foams incorporated with vegetable particles were quickly filled by

water and the weight gains only stabilized after 5 h, which was also attributed to the hydrophilic character of the fillers. A filled foam can have unreacted polar groups in the filler surface, like hydroxyls, which are free to react with any absorbed moisture (Mosiewicki et al., 2015).

Irregularly shaped particles, lacking either order or agglomeration, and presence of visible pores were reported for dregs by Mymrin et al., (2016). The peaks at 2θ angles between 25 and 30° refer to the crystalline fraction of calcite (CaCO_3). Besides of that, there were small amounts of other minerals, such as perovskite ($\text{Ca}_4\text{Ti}_4\text{O}_{12}$), dolomite ($\text{CaMg}(\text{CO}_3)_2$), quartz (SiO_2), and manganite ($\text{Mn}_4\text{O}_8\text{H}_4$) (Mymrin et al, 2016; Jia et al., 2019; Wolff, 2008; Quina and Pinheiro, 2020). Nevertheless, as any industrial leftover, the particle size and composition of a dregs waste may vary depending on the applied process, environmental and, storage conditions.

The high pzc of the dregs is also due to the presence of Ca compounds. Farage et al. (2020) reported a pzc of 9.75 for another dregs waste. Most of the wastes leftover from pulp and paper industry have an alkaline character with pH values up to 13.0 (Quina and Pinheiro, 2020). Regarding the pzc of 8.40 obtained for the dregs, the high efficiency of this residue at pH 6 is probably related to the presence of carbonates and hydroxides, which suggests a potential for adsorption of anionic ions (Farage et al., 2020). The foam surface is positively charged at pH 6, although electrostatic repulsions may occur below the pcz, yielding a reduced adsorption (Kumari et al., 2016). Cui et al. (2013) also reported that, the lower the pH value, the lesser the complexation between Pb (II) and PU foams with microorganisms. These authors also reported a Pu (II) percentage removal of 20% in 8 h and concentration of $10 \text{ mg}\cdot\text{L}^{-1}$ in 0.12 g of adsorbent. Zhou et al. (2009) also affirmed that their highest removal of Cu(II) by PU foam with immobilized microorganisms occurred at a pH level of 6.

About the kinetics models, there is a reduction in the adsorptive capacity of dregs over time, is probably a better fit to the beginning of the process since it is characterized as physical adsorption. The adsorption of metals at alkaline conditions is generally low since certain chemical groups only deprotonate at low pH values, allowing the binding of metals on the adsorbent surface (Boas et al., 2012). Geremias et al. (2010) also cited a positive effect on the adsorption of Cu (II), Zn (II), and Mn (II) at pH values of 5.6, 7.8, and 8.3, respectively.

Decreases in removal percentage at high adsorbent dosages may be related to the saturation of adsorption sites (Alshameri et al., 2014), which was also reported by Fidelis (2015). In these cases, the reduction in removal capacity may be associated with the formation of adsorbent aggregates, which reduces their surface area, as well as demands changes in operational parameters (like speed) in order to ensure a suitable adsorbate/adsorbent contact. The floating capacity of the foams probably also impaired the adsorption, even for high weights of adsorbent, since this material may be only partly in contact with the solution. Furthermore, the porosity of the PU also probably prevented the binding of the contaminant on active sites (Shashirekha et al., 2008). Considering the percentage removal obtained for the studied PU foams and that these cellular polymers can float on water, their use as buoys for the decontamination of water bodies seems plausible.

The water absorption of the studied foams starting at 60 min explains the q peak. Besides of that, the weight stabilization at 360 min may also be related to a new peak of adsorptive capacity. This moment

is related to the complete filling of the foam cells and adsorption of the contaminant. There was another water absorption cycle near to the end of the process and then another adsorption stabilization.

A hybrid removal mechanism of absorption and precipitation may be attributed to the dregs due to the presence of carbonates and hydroxyls on its chemical structure, which indicates a high potential of neutralization of acidic media (Matias, 2012; Almeida et al., 2007). The use of CaCO_3 for removing Cu yielded a high efficiency and generated a final neutral pH without applying any subsequent step (Hu et al., 2017).

Ma et al. (2012) studied a hybrid material composed of CaCO_3 and pepsin, as structural protein, for the removal of Pb^{2+} and Cu^{2+} from contaminated water. The adsorption capacity of this adsorbent was ascribed to its high surface area, transformation by precipitation, and the high solubility of the CaCO_3 . Ma et al. (2018) used of a Ca_2SiO_4 -based powder by-product for the removal of Ni (II), Cu (II), Zn (II), and Co (II) with maximum adsorption capacities of 420.17, 680.93, 251.89, and 235.29 $\text{mg}\cdot\text{g}^{-1}$, respectively. The efficiency of the residue for the removal of metals is due to the ion exchange of calcium ions with the contaminants (Ma et al., 2018). Farage et al. (2020) studied a dregs waste with a porosity of 66% and reported Cu and SO_4 removal capacities of 189 $\text{mg}\cdot\text{g}^{-1}$ (c.a. 63%) and 1,699 $\text{mg}\cdot\text{g}^{-1}$ (79%), respectively. Besides of that, as reported in this study, the dregs showed a maximum removal of 99.5% (299 $\text{mg}\cdot\text{g}^{-1}$) in the first minutes of the assay, suggesting removal of the contaminants by precipitation and absorption by mechanisms.

The use of pulp and paper industry wastes for acidic wastewater neutralization provides savings for mills and cost reduction in waste transportation and disposal (Pöykiö et al., 2006; Quina and Pinheiro, 2020). The retention of heavy metal contamination in soils due to the presence of carbonate and buffering capacity was also suggested (Ouhadi et al., 2010).

Conclusions

PU foams incorporated with green liquor dregs waste were successfully produced and characterized. The foam composite and its isolated phases reached highest Cr(III) removals at pH 6, which is ascribed to their point of zero charge. The filler content of 5wt% into the PU foam did not interfere in the Cr(III) removal. The dregs themselves reached the highest Cr(III) removal capacity, which can be attributed to its hybrid mechanism of adsorption and precipitation.

The studied materials showed promising results for water decontamination; and further studies may address higher filler contents up to 20%. Studies suggest potential use of dregs as a neutralizing agent in industrial processes, soil decontamination, removal of heavy metals, and toxicity evaluation.

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Declarations

- Ethics approval and consent to participate
Not applicable.

- Consent for publication
Not applicable.
- Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.
- Competing interests
The authors declare they have no financial interests.
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- Authors' contributions
Guilherme Pereira Schoeler: Conceptualization, Data curation, Investigation, Visualization, Writing – original draft
Thays França Afonso: Conceptualization, Data curation, Investigation
Carolina Faccio Demarco: Conceptualization, Data curation, Investigation
Daisa Hakbart Bonemann: Investigation
Anderson Schwingel Ribeiro: Resources, Supervision
Rafael de Avila Delucis: Conceptualization, Methodology, Resources, Writing – review & editing
Benedict C Okeke: Writing – review & editing
Robson Andreazza: Conceptualization, Methodology, Resources, Writing – review & editing

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Tables

Table1 - pH parameter on removal percentage and adsorption capacity of PU, dregs, and dregs/PU for Cr(III) (T=720 min, 200 rpm, V=2L, m=0.3 g·L⁻¹, Co=50mg·L⁻¹).

Material	pH	R(%)	q (mg·g ⁻¹)	pH _f ·pH _i ⁻¹
PU	4	26.72	41.72	0.93
dregs	4	72.03	118.79	1.48
dregs/PU	4	27.65	44.67	0.93
PU	5	9.93	16.08	1.00
dregs	5	65.77	107.69	1.20
dregs/PU	5	11.79	18.31	1.05
PU	6	36.15	57.56	0.91
dregs	6	81.93	135.45	1.00
dregs/PU	6	36.02	58.50	0.94

Table 2 - Dosage parameter on removal percentage and adsorption capacity of PU, dregs, and dregs/PU for Cr (III) (pH=6.0, T=720 min, 200 rpm, V=2 L, Co=50mg·L⁻¹).

Material	Dosage (g·L ⁻¹)	R(%)	q (mg·g ⁻¹)	pH _f ·pH _i ⁻¹
PU	0.3	37.74	57.56	0.91
dregs	0.3	81.93	135.45	1.00
dregs/PU	0.3	36.02	58.58	0.99
PU	0.6	15.53	12.88	0.88
dregs	0.6	71.1	59.2	1.12
dregs/PU	0.6	14.09	11.85	0.91
PU	1.2	4.13	1.7	0.97
Dregs	1.2	70.62	29.34	1.23
dregs/PU	1.2	3.09	1.26	0.98

Table 3 - Parameters of the kinetic models of dregs for Cr (III) adsorption.

Pseudo-first-order model	
q ₁ (mg g ⁻¹)	145.22
k ₁ (min ⁻¹)	28.6
R ²	0.94
EMR(%)	5.32
Pseudo-second-order model	
q ₂ (mg g ⁻¹)	145.24
k ₂ (mg·g ⁻¹ ·min ⁻¹)	1.75E+09
R ²	0.94
EMR(%)	5.33
Elovich	
a (mg·g ⁻¹ min ⁻¹)	0.181
b (mg g ⁻¹)	1.02E+10
R ²	0.84
EMR(%)	10.7

Figures

Fig. 1 – SEM images for dregs (a/b), dregs/PU foam (c/d), and neat PU foam (e/f).

Fig. 2 –X-ray diffractograms for dregs (a), dregs/PU foam (b), and neat PU foam (c).

Fig. 3 - Infrared spectra for dregs (a), dregs/PU foam (b) and neat PU foam (c).

Fig. 4 - Point of zero change for dregs (a), dregs/PU foam (b), and neat PU foam (c).

Fig. 5 - Water Uptake for dregs/PU foam and neat PU foam.

Fig. 6 - Adsorption kinetics of Cr (III) for dregs, dregs/PU foam, and neat PU foam. (pH=6.00, T=720 min, 200 rpm, V=2L, m=0.3 g·L⁻¹, C₀=50mg·L⁻¹).