Adsorption of reactive dyes onto thermally treated waste from aluminum lamination

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Abstract

The lamination process of aluminum sheets generates a flammable oil-soaked waste, which had been thermally treated (TTW) and used as adsorbent of reactive Remazol Black B (RB) and Remazol Red RB133 (RR), two of the most used dyes in the printing processes on textile industries, with reported carcinogenic and toxic properties. The adsorbent was characterized by Brunauer–Emmett–Teller (BET)-specific surface area, scanning electron microscopy and X-ray diffraction analysis. Kinetic and equilibrium studies were performed to evaluate the TTW adsorption parameters and the isotherm model which best represented the process. It was observed that the system reached the equilibrium state after 5 min for both dyes and obtained their maximum adsorption capacity \( q_m \) at pH 4: 0.69 mg·g\(^{-1}\) and 2.89 mg·g\(^{-1}\), for RB and RR respectively; moreover, the pseudo-second-order model better fitted the adsorption kinetics. The equilibrium data were better fitted to Langmuir isotherm compared to Freundlich’s for the RB and RR adsorption. The maximum removal efficiency obtained in the experiments was 80.2% for RB and 80% for RR; moreover, after the acid activation of TTW, the RB removal efficiency increased from 84.9% to 93.7%.

Key words: adsorption, aluminum lamination waste, reactive dyes, remazol, textile, wastewater

INTRODUCTION

The textile industry has long been known to have a significant environmental impact, due to its discharges of huge volumes of industrial wastewater with a high content of organic compounds and strongly colored effluents (Santos & Boaventura 2016). Besides the water consumption of the textile industry, the use of dyes has been a major concern as they degrade into toxic and carcinogenic products (Tahir et al. 2016). Moreover, dye consumption has continually increased over the years, not just in the textile industry, but also in rubber, plastic, leather, paper, cosmetic, pharmaceutical and food industries (Rani et al. 2017). Total dye consumption in the textile industry worldwide is more than 10,000 tons per year and about 10–15% of this amount is discharged as wastewater during the dyeing processes (Gupta et al. 2013; Sen & Dawood 2014). Dyes can be classified as a function of the charge in reactive, anionic, cationic and non-ionic compounds; among them, the reactive azo dyes are those most commonly used by the textile industry, which is a major concern due to their anaerobic degradation process, which releases toxic aromatic amines (Aguiar et al. 2017).

Adsorption techniques are widely used to remove several classes of pollutants from waters, especially those which are not easily biodegradable, remaining in the water bodies even after conventional treatments. Therefore, a combination of biological treatment and adsorption on activated
carbon became more common for the removal of dyes from wastewater. Activated carbon, a porous material, has been widely applied as an adsorbent in the treatment of textile wastewater; however, the high cost of activated carbon has made it difficult for companies with limited resources to utilise in their treatment processes (Moreira et al. 2017). Waste products from different industrial and agricultural processes have also been studied for their toxic dye adsorbent properties by many authors, such as eucalyptus bark (Tahir et al. 2016), cupuassu shell (Cardoso et al. 2011), coconut activated carbon (Cazetta et al. 2016), coconut shell fibers (Rani et al. 2017), modified flax shives (Wang et al. 2017), electroplating industry waste (Santos & Boaventura 2015), Victorian brown coal (Yuliani et al. 2017), tire waste activated carbon (Brahim et al. 2014), and many others.

Recycling a waste to treat another waste is a philosophy inside the concept of an industrial Circular Economy (CE), which has been pursued by many researchers, and can bring many benefits to those who adopt it, such as financial savings from conventional waste treatments and reduction of the cost of traditional methods to remove toxic substances from liquid effluents. The recycling, reuse and the reduction of materials consumed emphasizes nowadays the need to add value to materials through their application in high value operations (Hu et al. 2011; Clark et al. 2016; Korhonen et al. 2018). The objective of this work is to propose a new application for aluminum industry waste as an adsorbent of two reactive dyes widely used in the textile industry: Remazol Black B and Remazol Red RB133, denominated in this work as RB and RR, respectively.

MATERIALS AND METHODS

Reactive dyes

In order to evaluate the efficiency of thermally treated waste (TTW) as a dye adsorbent, two dyes were used: the reactive RB and RR, due to their widespread use in the dyeing processes of the textile industry. All the dyes were supplied by Dystar do Brasil S/A. Figure 1 presents the molecular structures for RB (a) and RR (b), with a molecular weight 991.79 g·mol⁻¹ and 984.18 g·mol⁻¹, respectively. Prior to the sorption experiments, a complete scan of a 100 mg·L⁻¹ solution of each dye was undertaken to detect their wavelength of maximum absorbance ($\lambda_{\text{max}}$) in order to calibrate the UV-vis spectrophotometer. The $\lambda_{\text{max}}$ obtained for RB and RR were 597 nm and 514 nm, respectively. These data were

![Figure 1](http://iwaponline.com/wpt/article-pdf/13/3/629/479387/wpt0130629.pdf)
used to build the calibration curve for each dye concentration, using the range of 0.11 mg·L⁻¹ to 11.0 mg·L⁻¹.

Waste thermic treatment

Fresh aluminum lamination waste was provided by Arconic Alumínio S/A, Itapissuma, Brazil. It is composed of a mixture of two types of earth: Celite 503, a diatomite clay usually found in Mexico, and Tonsil Optimimum, an acidified bleaching earth derived from raw bentonite clay. After its use in the oil filtration and recycling process in the aluminum industry, the mix of filtering earth becomes steeped in oil, soaps and aluminum filings. The waste samples were submitted to direct combustion to eliminate the oil content. The waste was then calcined in a muffle model Quimis Q518M (Brazil) at 500°C for 4 h until the organic matter impregnating the filtering earth was completely removed.

TTW cost analysis

Arconic’s aluminium plant generates 45 tons of filtration earth waste per month and pays on average USD 212.21/ton for transport and treatment of the waste. The power cost in Pernambuco State is BRL 0.45 per kWh (USD 0.14 per kWh). The muffle potency is 1.72 kW and the average load of waste is 80–100 g per cycle. The cost of the thermic treatment is USD 2.54 per kilogram of waste, mostly due to the energy consumption of calcination; however, it is considerably cheaper than activated carbon in the local market (USD 29.93 per kilogram). However, the thermic treatment cost can be eliminated if calcination could be performed through the energy generated by the direct burning, in which the residue itself should provide the fuel for the calcination oven. A short comparative overview of some reported adsorbents of azo-reactive dyes is provided at the end of this work. Furthermore, a preliminary economic evaluation of production and operational costs for each sorbent is given based on the costs of raw materials, reactants, additives, transport and energy consumption according to their reported methodology (Supplementary Material 1).

Acid activation of the adsorbent

The acid activation was performed using the method proposed by Hai et al. (2015) to enhance the RB removal by TTW and its adsorption capacity. 50 g of TTW was separated and put in contact with 900 mL of HCl 6.0 mol·L⁻¹ in a flask, under agitation of 500 rpm for 4 h. After the activation process, the sample was washed with distilled water to eliminate excess HCl and then dried in an oven at 100°C for 24 h (Tsai et al. 2004). The acidified TTW was used to remove RB from an aqueous solution kept at its natural pH (6.0), with a stirring speed of 300 rpm. The adsorbent dosages used were 2.0, 4.0 and 6.0 g and the RB removal efficiencies were compared for each condition.

Adsorbent characterization methods

The characterization of the adsorbent after the direct burning and the calcination process was made through the analysis of specific superficial area through the Brunauer, Emmet and Teller (BET) Method, undertaken at the Catalytic Processes Lab of the Chemical Engineering Department of UFPE. Scanning electron microscopy (SEM) with dispersive energy spectroscopy (DES) and X-ray diffraction (XRD) were undertaken in the Pernambuco Institute of Technology – ITEP. SEM analysis of the virgin earths and the TTW before and after the thermic process was performed to evaluate the textural properties, such as the surface morphology, and possible changes that may have occurred during
the thermic treatment; the analyses were performed using a scanning electron microscope with DES SS-550 (Shimadzu, Kyoto, Japan). The mineralogical compositions of the raw materials and TTW samples were determined using an X-ray diffractometer from Rigaku Ultima (Tokyo, Japan). The specific surface area (S_{BET}) and total pore volume (V_p) of TTW samples were performed through a specific superficial area analyzer (BET) (Nova 100e, Quantachrome Instruments, Boynton Beach, FL, USA) and the data was obtained using the BET technique through N_2 physisorption by assuming the section area of nitrogen molecule to be 0.098 nm^2.

**Batch sorption experiments**

The initial concentration for each dye was 10 mg·L^{-1}, which represents the average dye concentration after conventional treatment of textile wastewaters, such as bioremediation, according to the data reported in the literature (Chakraborty et al. 2003; Wang et al. 2011; Fazal et al. 2018). Volumes of 1,000 mL of 10 mg·L^{-1} dye solution were prepared for RB and RR dyes and 50 mL of each dye solution was transferred to flasks of 125 mL. The varying amounts of adsorbent were added to the dye solution for 10 min. After the contact time, the samples were then centrifuged to separate the adsorbent from the solution. The solution concentrations were measured in a UV-Vis spectrophotometer (Genesys™ 10-S, Thermo Fisher Scientific, Waltham, MA, USA).

Afterwards, the dye removal efficiency (η in %), or adsorption degree (Rani et al. 2017), and the adsorption capacity (q in mg·g^{-1}) were calculated using data analysis software, using the following equations:

\[
\text{Removal efficiency: } \eta(\%) = \frac{C_0 - C}{C_0} \times 100
\]

\[
\text{Adsorption capacity: } q = \frac{(C_0 - C)V}{m}
\]

where \(C_0\) is the initial concentration (mg·L^{-1}), \(C\) is the equilibrium state or final concentration (mg·L^{-1}), \(V\) is the volume of the solution (L) and \(m\) is the mass of the adsorbent (g).

**Influence of pH and the zero point of charge**

The point of zero charge (pHzPC) for the TTW was obtained in order to estimate the ranges where the surface charge is positive – below PZC – and negative – above PZC (Santos & Boaventura 2016). The pHzPC of the adsorbent was determined by adding 2.5 g of the adsorbent to several Erlenmeyer flasks. The total volume of solution with the adsorbent in each flask was 50 mL. A range of initial pH values (pH_initial) of the solutions were adjusted from 2.0 to 12.0 by adding solutions of 0.1 mol·L^{-1} of HCl and 0.1 mol·L^{-1} of NaOH. The influence of the pH changes on the adsorption rate was evaluated in further equilibrium studies, where equilibrium curves q vs C were obtained for each initial solution’s pH value as well as the maximum adsorption capacity (q_m) and its variation according to the changes in solution pH.

**Adsorption kinetics**

The adsorption kinetics were analysed to discover the moment which the system reached equilibrium. To discover this point, solutions of 50 mL of adsorbate were separated into flasks of 125 mL. TTW samples of an equal weight were then added to the flasks containing the adsorbate. The time of contact between adsorbent and adsorbate varied from 1 to 30 min. All the experiments were conducted at environmental temperature (25°C), in duplicate, and using the dye solutions at their
natural pH value of 6.0. The influence of varying adsorbent amount was observed by performing different experiments with the adsorbent weight changing between 1.0 g and 0.5 g.

Equilibrium studies and adsorption isotherms

The equilibrium studies were undertaken using a range of concentration values: 2, 5, 10, 15, 20, 30, 40 and 50 mg·L⁻¹, through which it was possible to determine the adsorption isotherm models which better described the adsorption mechanisms. The classical adsorption isotherms that are most often applied are the Langmuir's and the Freundlich's. After the experiments, all data were treated and the curves were plotted, then the experimental data were linearized to obtain the isotherm which best represented the adsorption process; the process parameters, such as the equilibrium constant ($K_L$) and the maximum adsorption capacity ($q_m$) were obtained. The saturation values were affected by the initial dye concentration, and at identical values of $C_0$ the dye uptake was lower for the coarsest particles, according to reported results obtained with silica. For finer particles, on the other hand, the values did not differ much.

Two models were tested to describe the adsorption process studied in this paper: the Langmuir’s and the combined Langmuir-Freundlich’s. The Langmuir adsorption isotherm has been applied to many other real sorption processes and it has used to explain the sorption of dyes by various adsorbents. The experimental results have been fitted to the Langmuir and Langmuir-Freundlich models (Ruthven 1984). The Langmuir adsorption isotherm follows the expression in Equation (3):

$$\frac{q}{q_m} = \frac{K_L C}{1 + K_L C}$$  \hspace{1cm} (3)

where $q_m$ is the maximum adsorption capacity or the adsorption capacity when the system achieves equilibrium (mg·g⁻¹); $K_L$ is the equilibrium constant (L·mg⁻¹); $C$ the adsorbate concentration at equilibrium state (mg·L⁻¹); $q$ the adsorption capacity for each concentration.

Freundlich's model is derivated assuming a non-uniform distribution of the adsorption energy over the adsorbent's heterogeneous surface. The Freundlich's mathematical model is given by Equation (4):

$$q = K_F C^{1/n}$$  \hspace{1cm} (4)

where $C$ is the solution concentration; $q$ the adsorption capacity; $K_F$ is the Freundlich constant (mg⁻¹·L¹/n·g⁻¹); $1/n$ is the factor of heterogeneity; and $K_F$ and $1/n$ are indicative of adsorption capacity and adsorption intensity, respectively (Ncibi et al. 2008).

The combined Langmuir-Freundlich isotherm (L-F) considers adsorption to occur across multiple layers, therefore being useful to describe adsorption on heterogeneous surfaces, and can be applied to species of the same molecular size and nature and focuses on the steps of adsorption on the sorbent surface (Carvalho et al. 2012; Soares et al. 2016). The L-F model is given by Equation (5). This model was used to fit the experimental data by a linear model and consequently to achieve the adsorption parameters ($q_m$, $K_L$, and $n$).

$$\frac{q}{q_m} = \frac{K_L^n C^n}{1 + K_L^n C^n}$$  \hspace{1cm} (5)

where $q_m$ is the maximum adsorption capacity (mg·g⁻¹), $C$ is the concentration of the adsorbate in the equilibrium state (mg·L⁻¹), $K_L$ is the affinity constant for adsorption and $n$ is the heterogeneity factor.
RESULTS AND DISCUSSION

BET analysis

The calcined waste presented a high specific surface area in comparison to the burned waste, due to the elimination of the excess organic material impregnated on its surface. The morphological parameters of the TTW were: specific surface area ($S_{\text{BET}}$) = 55.39 m$^2\cdot$g$^{-1}$ and total pore volume ($V_p$) = 2.54 $\times$ 10$^{-2}$ cm$^3\cdot$g$^{-1}$. The surface area is considerably lower compared to classical adsorbents, such as activated carbon, which presents an elevated surface area of $S_{\text{BET}}$ = 1,250 m$^2\cdot$g$^{-1}$–2,400 m$^2\cdot$g$^{-1}$.

The total volume of pores is also considerably lower in comparison to the activated carbon: $V_p$ = 0.57 cm$^3\cdot$g$^{-1}$. The BET specific surface area results obtained for the Spanish virgin diatomaceous clay and the acid treated Taiwan's spent diatomaceous earth, respectively, showed $S_{\text{BET}}$ = 3.07 m$^2\cdot$g$^{-1}$ and 2.85 m$^2\cdot$g$^{-1}$, very close to the Celite result, which forms one of the raw materials of the waste (Tsai et al. 2004; Tlili et al. 2012).

Scanning electron microscopy with DES

Figures 2(d) and 2(e) show the microphotographs of the waste after direct burning and after calcination at 500°C, respectively. The right images show the material at a higher magnification. Through these photographs, is possible observe the presence of a small amount of diatomaceous grains mixed with the bleaching earth and oxides aggregated with the material.

The dispersive energy spectrometry (electron microscopy with DES) technique was applied to analyse the material's overall chemical composition, combined with the images obtained through the electronic microphotography (EM). The elements which make up the diatomaceous clay Celite 503 presented in the waste are: O (70.07%); Si (29.53%), basically due to the presence of silicon dioxide (SiO$_2$), which is the main component in the diatomaceous earth (Tsai et al. 2004; Al-Ghouti et al. 2009); Na (0.36%) and K (0.05%). The chemical composition of the Tonsil was mostly O (68.66%), Si (21.32%), and in smaller amounts, Al (4.46%), C (3.23%) and Fe (1.17%).

DES analysis also showed that the fresh bleaching earth is mostly made up of SiO$_2$ (71.27%), followed by Al$_2$O$_3$ (12.56%) and Fe$_2$O$_3$ (5.40%), all data given in atomic wt. %. These results point to an increase in the oxygen content in the diatomaceous clay from 36.12% to 70.07%, due to the oxides formed in the direct burning process and during calcination at 500°C. The metallic elements (Si, Al, Ca, K) in the raw materials remain practically unchanged after the direct burning and calcination. There was a reduction, but only slightly, of the Ca presented in the Celite clay due to the burning process – it was eliminated in the form of oxides. Similar behavior was seen for Fe – there was a minimal decrease from 1.36% to 1.17%. It is also possible to verify the removal of magnesium after the calcination of the acidified bleaching earth Tonsil.

X-ray diffraction

The XRD analysis of TTW revealed an intense peak on $2\theta$ = 2.17°, which characterizes the Tonsil earth diffraction plane 002 (Figure 2(b)). It can be observed in Figure 2(c) that the TTW has characteristic peaks of Celite 503 and the Tonsil Optimum, confirming the mixing of both virgin earths which form the adsorbent. It's also feasible to verify that the calcination process has not caused great changes to the clay material’s composition, only the increase of peak’s intensity in $2\theta$ from 23°, which is due to the oxides formed during calcination. This aggregated on the material’s surface, giving the material a smooth aspect, as observed on the electronic microscope images. Through the diatomaceous clay analysis was performed before and after thermic treatment, it mostly showed an...
amorphous silica phase, revealed by a large peak between 16° and 26° (2θ), but also presented characteristic peaks of quartz and some carbonates, such calcite and ankerite (Benkancem et al. 2016).

Effect of pH

The equilibrium curves for the three different pH rates are presented in Figure 3(a) and 3(b) for RB and RR, respectively. The maximum adsorption capacities ($q_m$) in each pH range were obtained after adjusting the Langmuir model to the adsorption data. Better values of adsorption capacity ($q$) were obtained at pH 4.0 for both dyes. Furthermore, at pH 8.0, $q_m$ values were not satisfactory, indicating that the adsorption is favorable when pH < pH_{PZC} (Figure 3(c)). According to the literature data, it is rather difficult to determine an absolute PZC for the clays (Errais et al. 2012); however, low pH leads to an increase in H$^+$ ions on the surface of TTW, which results in a strong electrostatic attraction between the negatively charged dye molecules and the positively charged active sites of the adsorbent (Al-Debs et al. 2008). Hydroxyl groups presented on the surface of the diatomite can gain or lose a proton; at low pH, surface
sites are protonated and the surface becomes positively charged and increases the electrostatic interactions with the sulfonate groups present in RB (Al-Ghouti et al. 2009). Figure 3(c) shows the PZC analysis, in which at pH\textsubscript{PZC} 6.3, the residual charge of the TTW is zero.

**Adsorption kinetics**

The kinetics experiments were conducted under the following experimental conditions: initial concentration of 10.0 mg·L\(^{-1}\), volume of solution of 50 mL. Figures 4(a) and 4(b) present the curves of adsorption capacity versus time obtained after the adsorptive process involving both dyes. From Figure 4(a) is possible verify that the RB reached the equilibrium state after 5 min with \(q = 0.10\) mg·g\(^{-1}\). RR also reached the equilibrium after 5 min with \(q = 0.20\) mg·g\(^{-1}\) (Figure 4(b)). The results indicate that the adsorption rate of the two dyes onto the TTW is very fast at the early stages (0–5 min) and then slows down gradually. Sorbent dosage evaluation showed that higher values for the adsorption capacity were achieved with a lower amount of adsorbent – 0.5 g. The removal efficiencies obtained at the equilibrium state per adsorbent weight for RB were: 50.21% (0.5 g) and 85.48% (1.0 g); for RR: 58.86% (0.5 g) and 81.00% (1.0 g). The short time necessary to achieve the equilibrium state (below 5 min) is characteristic of the monolayer physisorption process, in which the adsorbate binds to the adsorbent surface through weak intermolecular interactions such as van der Waals forces, hydrophobicity, hydrogen bonding, polarity, static interactions, dipole-dipole interactions and π–π interactions (Ruthven 1984; Sen & Dawood 2014; Scheufele et al. 2016). The pseudo-second-order model best fit the experimental data, with a good coefficient of determination (R\(^2\)) for both dyes.
Equilibrium studies

The equilibrium isotherm $q$ versus $C$ (Figure 5(a) and 5(c)) for both dyes showed a type I isotherm, characteristic of microporous adsorbents, in which the sorbent pore size is not larger than the sorbate molecular diameter (Ruthven 1984). Langmuir isotherm better fitted the adsorption for both dyes with a good coefficient of determination ($R^2 > 0.99$) in comparison to the Langmuir-Freundlich model. Maximum adsorption capacity ($q_m$) was 0.69 mg·g$^{-1}$ and 2.89 mg·g$^{-1}$ for RB and RR, respectively. The better adjustment of the Langmuir model to the experimental data is due to the homogeneous distribution of the active sites on the surface of the adsorbent, since the Langmuir equation assumes the homogeneity of the surface and the equal distribution of energy on each active site (Ncibi et al. 2008). Once the system is working in a sorbate low concentration range, it is assumed that there are no interactions between the molecules adsorbed on the sorbent sites and those still in solution (Ruthven 1984).

The adsorption capacity ($q$) obtained by the experiments with RR was higher than that obtained by the RB, due to a major electrostatic interaction with the sulfonate groups (present in greater amount in the RR structure, and which gives an anionic behavior to both dyes) with the active sites on the surface of the TTW, characterized by the oxides and hydroxyl groups; these groups are distributed across the surface of diatomaceous clay (Al-Ghouti et al. 2009).

Removal of RB by acidified TTW

The evaluation of the influence of TTW acid activation on the adsorption efficiency showed that RB removal increased after chemical treatment with HCl; however, this was not observed when a smaller weight of adsorbent of 2.0 g was used (Figure 6). RB removal increased from 84.9% to 93.7% after...
chemical activation, when 4.0 g of acidified TTW was used. Similar behavior was observed, though at a lower intensity, when 6.0 g of acidified TTW was used – RB removal increased from 80.2% to 82.3%. This suggests that the treatment of diatomite earth with strong acid can reduce mineral impurities, such as Fe₂O₃ and alkali metal oxides (CaO, MgO), and eliminate carbonates; however the original geometry of the pores is preserved, thus enhancing the adsorption of RB (Benkancem et al. 2016). Further studies using different acids or even hydroxides to enhance the adsorbent would be helpful to better understand the charging exchange mechanisms on the TTW surface and their impact on the reactive dyes sorption process.
Table 1 summarizes the sorption results obtained from studies using TTW and classical adsorbent, as well as recently developed low cost adsorbents, reported in the literature. It is easily inferable that, for some adsorbents, the higher the adsorbent specific surface area, the higher its maximum adsorption capacity, as observed in the activated carbon data. The results of TTW maximum adsorption capacity showed relatively low values in comparison with the data presented by other adsorbents; moreover it showed a lower BET specific surface area. However, TTW’s cost of treatment is considerably lower than other reported sorbents, in terms of capital and operational cost. Moreover, TTW’s further use in the masonry industry maintains the material cycle, hence contributing to the industrial CE (detailed information can be found in Supplementary Material 1). Furthermore, RB and RR’s high removal efficiency (%) by TTW suggests that it can be applicable as a post conventional treatment adsorbent, where the effluent concentration is lower than it is at the end of pipe. However, it can be proposed that activating the waste using an acid treatment method increases the TTW’s adsorption capacity to remove this class of dyes, as showed in the previous section.

**CONCLUSIONS**

The removal of reactive dyes from wastewaters is a challenge to small industries due to the cost of conventional treatment and the environmental impact caused by illegal discharges. In this study, a new adsorbent material was suggested which can be used to remove dye from textile wastewater: a flammable residue, which has been submitted to a thermic treatment. This study presents the potential
of TTW as a replacement for traditional, but expensive, adsorbents, such as activated carbon. Preliminary studies determined conditions of adsorbent mass, stirring speed and pH for the two dyes evaluated in this paper. It was observed that good dye removal results were obtained at a low pH. Kinetic and equilibrium studies showed that the adsorption process reached equilibrium quickly (before 5 min), suggesting the monolayer and physical adsorption characteristics; moreover, the Langmuir isotherm better fitted the adsorption process, with an elevated coefficient of determination. Despite the results showing good RB and RR removal efficiency, the adsorbent presented a low maximum adsorption capacity in comparison to activated carbon and other classical adsorbents presented in the literature. However, its adsorption capacity and removal efficiency can be enhanced through an acid activation procedure, already applied for clay sorbents. Moreover, using TTW forms a key step in the process of value aggregation of the clay residue, in accordance with the concepts of the industrial circular economy.

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