Dye removal from textile industrial effluents by adsorption on exfoliated graphite nanoplatelets: kinetic and equilibrium studies

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ABSTRACT

The concept of physical adsorption was applied for the removal of direct and reactive blue textile dyes from industrial effluents. Commercial graphite nanoplatelets were used as substrate, and the quality of the material was characterized by atomic force and transmission electron microscopies. Dye/graphite nanoplatelets water solutions were prepared varying their pH and initial dye concentration. Exceptionally high values (beyond 100 mg/L) for adsorptive capacity of graphite nanoplatelets could be achieved without complicated chemical modifications, and equilibrium and kinetic experiments were performed. Our findings were compared with the state of the art, and compared with theoretical models. Agreement between them was satisfactory, and allowed us to propose novel considerations describing the interactions of the dyes and the graphene planar structure. The work highlights the important role of these interactions, which can govern the mobility of the dye molecules and the amount of layers that can be stacked on the graphite nanoplatelets surface.

Key words | adsorption, blue textile dyes, graphite nanoplatelets, π-π interactions

INTRODUCTION

The textile industry uses various types of dyes, pigments and chemical auxiliaries that, when processed, produce a liquid effluent with unique characteristics that requires specific treatment to meet environmental legislation. The composition of this wastewater varies according to the different characteristics of the production process: dyeing and printing are key generators of effluents, with high concentrations of organic load depending on raw materials or chemicals (Forgacs et al. 2004).

The discharge of effluents contaminated with dyes is highly undesirable, since, even at low concentrations, they are easily visible to the naked eye. Commonly, these materials exhibit complex chemical structures, which hamper the identification of the contaminants. With a high solubility in the aqueous medium, dyes promote harmful impacts on rivers and lakes, poisoning aquatic animals and plants. Water colored by dyes can, for example, block the transmission of sunlight, reducing natural processes of plant photosynthesis and oxygenation of water (Alves de Lima et al. 2007).

Several physical, chemical and biological methods have been used to remove organic dyes from industrial effluents. The current available techniques include chemical coagulation/flocculation, ozonation, oxidation, chemical precipitation, ion exchange, reverse osmosis and ultrafiltration methods. Most of these technologies, however, present significant constraints associated with high cost, formation of hazardous waste and intensive energy consumption (Calvete et al. 2010).

The implementation of stringent laws and regulations as well as the development of more competitive markets is demanding more efficiency from companies with respect to productive and environmental issues. The increase in industrial production should be linked to sustainable development, with lower cost of inputs and the generation of non-environmental impacts. The use of new adsorbent materials has been investigated with the purpose of minimizing costs and maximizing the quality of the wastewater treatment process (Crini 2006).
Recently, the interest in the use of nanomaterials as adsorbents has steadily increased, related to a number of associated advantages (Sitko et al. 2013). Graphene, a two-dimensional carbon layer in which the carbon atoms are arranged on a hexagonal lattice, resembling a honeycomb, has attracted great interest since it was first reported in 2004 (Novoselov et al. 2004). Properties, such as large surface areas, chemical stability, durability, strength and conductivity (Geim & Novoselov 2007), reveal graphene or oxidized/functionalyzed graphene as potential material to be used in adsorption processes (Ramesha et al. 2011; Wang et al. 2011; Liu et al. 2012; Li et al. 2013; Xu et al. 2013; Wu et al. 2014; Moradi et al. 2013).

Commercial graphene, or more precisely exfoliated graphite nanoplatelets, were used in this work as adsorbent for the removal of commercial dyes, widely used by the textile industry in Brazil, from contaminated effluents. Studies of the kinetics and adsorption equilibrium were performed and compared with theoretical models.

MATERIALS AND METHODS

Exfoliated graphite nanoplatelets

The exfoliated graphite nanoplatelets (graphene xGnP®, Grade M ~ 25 microns) used in this work are commercialized by XG Sciences (USA), with the trend name of graphene sheets. We prefer to use the designation graphite nanoplatelets as the product consists of a certain amount of graphene sheets stacked together (Xiang & Drzal 2011). According to the datasheet, the exfoliated graphite nanoplatelets are produced via microwave expansion at high temperatures (Drzal & Fukushima 2004) and contain less than 1wt.% of oxygen, retained as functional groups (carboxylic acid, ether, and hydroxyl) attached to the sheet surface. The platelets have an average thickness from 6 to 8 nm and an average diameter of 25 μm.

Transmission electron microscopy (TEM) images of the platelets were acquired using the equipment Morgagni (Fei Co.). The microscope was operated at 100 kV. A carbon-coated grid was used for the deposition of the samples. Atomic force microscopy (AFM) characterization of the graphite nanoplatelets was performed with a PicoPlus instrument (Molecular Imaging) operated in normal tapping mode, using silicon tips NSG11 (NT-MDT). We deposited our nanoplatelets/chloroform dispersions onto freshly cleaved mica substrates by spraying a pipette-held droplet (~10 μL) with a burst of compressed air.

A LABRAM confocal Raman spectroscope equipped with an optical microscope was utilized. Samples were irradiated with a red laser (652.8 nm) supplied by Melles Griot. Nitrogen adsorption analysis (Micromeritics ASAP 2420) was used to further characterize the surface area of the graphite nanoplatelets. The samples were degassed for 12 hours at 195 °C, under vacuum. The surface area was calculated following the Brunauer–Emmett–Teller (BET) method (Brunauer et al. 1938).

Dye solution

Indosol SFGL and Drimaren HFRL blue, commercial anionic textiles dyes used for coloring cotton fibers (jeans), were donated by Archroma/Clariant® industries. Indosol SFGL blue (Figure 1(a)) is characterized as a direct dye, containing water-soluble compounds through van der Waals interactions, with more than one azo group (diazo, triazo, etc.). Drimaren HFRL blue (Figure 1(b)) is characterized as a reactive dye, characterized as water-soluble compounds through covalent interactions, where the chromophore contains a substituent (mainly sulfonic groups) that reacts with the substrate. The exact structures of these Chrom.-NR groups are hidden, following the policy of the company.

Standard distilled water solutions, with dye concentrations ranging from 5 to 100 mg/L, were used to build the calibration curves. UV–visible (UV-Vis) absorption spectra were recorded using a spectrophotometer (Spectroquant® Pharo 300, Merck) operating at 593 and 610 nm, values which were determined through preliminary scanning.

Effect of pH

The influence of pH on the adsorption capabilities of graphite nanoplatelets for the dyes Indosol SFGL blue and
Drimaren HFRL blue was evaluated via batch experiments using an orbital shaker (MA-420, Marconi). We applied a pH range from 1.0 to 12.0; solutions were adjusted with 0.1 M HCl and 0.1 M NaOH (Kim et al. 1997). Dye/water solutions (50 mL) were prepared at a concentration of 50 mg/L, and placed in contact with 0.05 g of graphene using round-bottom flasks (250 mL). The dispersion was then agitated for 120 min under 150 rpm. Subsequently, the samples were filtered through a hydrophilic syringe filter (PTFE, 0.22 μm pore size). The remaining concentrations \((C_e)\) of dye in solution were measured via UV-Vis. Preliminary spectrum scans indicated wavelengths of 593 nm and 610 nm for Indosol SFGL blue and Drimaren reactive blue, respectively. Quantification of dye removal by graphene, \(q\) (Equation (1)), could then be calculated for the pH resulting in higher removal efficiency, \(X\) (Equation (2)). The obtained pH was then held constant for the subsequent experiments.

\[
q = \frac{(C_0 - C_e)}{m} \cdot V \left(\frac{\text{mg}}{g}\right) \tag{1}
\]

\[
X = \frac{(C_0 - C_e)}{C_0} \cdot 100 \text{(%)} \tag{2}
\]

Based on the literature (Li et al. 2013), the overall dye removal was evaluated at initial dye concentrations \((C_0)\) of 5.0, 50.0 and 100.0 mg/L, using a sealed Erlenmeyer flask containing 50 mL of each solution and a constant mass of 0.05 g of graphite nanoplatelets (1 mg/L graphite nanoplatelets/water concentration). The dispersions were then agitated (orbital shaker) for a period of 6 h at 150 rpm, at room temperature (25 °C).

### Adsorption isotherm

The experiments of equilibrium and adsorption kinetics were performed in triplicate, using batch systems. The amount of graphite nanoplatelets was fixed at 0.01 g and the samples (100 mL) were placed in an Erlenmeyer flask and then brought to the orbital shaker at temperature of 25 °C, constant stirring speed of 150 rpm and pH of 3.5, a value which was adjusted with 0.1 M HCl. Experiments described in the section ‘Effect of pH’ indicated the pH of 3.5 as the most favorable for the adsorption of the dye. For the equilibrium study, the dye concentrations ranged from 5 to 100 mg/L, with total stirring time of 360 min. For the adsorption kinetics study, the dye concentration was fixed at 100 mg/L, and the stirring time ranged from 2 to 360 min. Subsequently, for both studies, the samples were filtered through a hydrophilic syringe filter (PTFE, 0.22 μm pore size). The residual concentrations of the dyes in solution were then analyzed via UV-Vis spectrophotometry (Spectroquant® Pharo 300, Merck).

### RESULTS AND DISCUSSION

#### Morphology and structure of the graphite nanoplatelets

Figure 2 shows the morphology of the material. TEM images indicate that the graphene platelets are, mostly, stacked or folded together. The surface dimensions (mean diameter) of the analyzed samples (~20) were on average 1 to 2 μm (see Figure 2(a)). Stacked thicker platelets, as shown in Figure 2(b), were found constantly. These values are well below 25 μm, as specified in the datasheet.
AFM analysis shows the average thickness of the graphite nanoplatelets. It is important to mention that many samples were discarded, because they presented external surface residues or were agglomerated, preventing proper AFM topographic analysis. Most of the samples presented an average thickness higher than 10 nm, as shown in Figure 3(b) and the profile in Figure 3(d). However, the few samples of exfoliated platelets that could be found had an average thickness of less than 5 nm, as shown in the profile analysis of Figure 3(a). It was also possible to see that the samples exhibited no surface area greater than 5 μm², confirming the information obtained by TEM.

Raman spectroscopy is often used as a characterization tool to identify carbon materials. The Raman spectra of all carbon systems have a rather simple set of peaks. The main features of such spectra are two distinctive peaks called the D peak (~1,360 cm⁻¹) and the G peak (~1,560 cm⁻¹) and a few other second order harmonics (Ferrari et al. 2006). The G peak is due to the stretching motion of sp² bonds between carbon atoms, which reflects the crystalline graphite structure of graphite/graphene materials. The D peak is due to the Raman scattering induced by zone-boundary phonons, which reflects disordered structures. Such disordered structures include defects, edges, crystal boundaries and symmetry breaking. The most prominent second order harmonic at around 2,700 cm⁻¹ is called the G' peak, or 2D. This peak reflects the stacking structure of graphite along the c-axis. Such structure includes the number of layers and crystallinity degrees. It is known that single-layer graphene has a single, symmetric 2D peak, since there is only one possible scattering process. When the number of layers increases further, typically 10 layers or more, the 2D peak curves converge and show only two peaks, which is virtually the same as the 2D peak of bulk graphite (Ferrari 2007). This is what can be seen from the spectrum of Figure 4 and confirmed from the literature (Xiang & Drzal 2011) and the images of AFM and TEM. A more detailed and recent comparison of graphite/graphene Raman spectra depending on the graphene synthesis route is described elsewhere (Ghislandi et al. 2015).

According to BET analysis, the graphite nanoplatelets sample had an averaged specific surface area of 90.08 ± 12.36 m²/g. This value is lower than that specified by the supplier (120–150 m²/g). A high specific surface area is extremely important in this context because it allows a larger surface available for direct adsorption of dye molecules.

**Effect of pH and dye concentration**

Figure 5 shows the absorbance spectra of the two dyes as the pH value is varied. The scans indicated highest absorbance at wavelengths of 593 nm and 610 nm for Indosol SFGL blue and Drimaren reactive blue, respectively. As shown, there is no variation in the peak position of absorbance as the pH is varied, for both, SFGL and HFGL, dyes.

The removal efficiency of the dye Indosol SFGL direct blue and Drimaren HFRL reactive blue by the graphite nanoplatelets XGnP® was evaluated in terms of pH and...
initial dye concentration in the solution. The variation of pH had a significant effect on the removal efficiency of the dyes; the results clearly indicate reduction in removal efficiency to a minimum value by increasing the pH to approximately 8–10 of both dyes, above which dye removal started to increase again (see Figure 6). At lower pH values the removal efficiency was significantly increased for both dyes, especially for Drimaren HFRL reactive blue (Figure 6(b)), which reached more than 60% efficiency at pH 1.0. We believe this behavior is associated with reactive dyes that typically have a functional group containing from one to three sulfonic acid groups (-SO3H) in their structure, plus the highly electronegative fluorine (F) elements, which are present in the structure of HFRL. It is assumed that in acid pH solution, the dye (anionic) exhibits repulsion to the liquid medium and consequently a higher affinity to the inert sheets of graphite nanoplatelets, enabling a better fixation of the dye (Ramesha et al. 2014). A pH of 3.5 was then fixed for assessing the influence of initial dye concentration and the following equilibrium studies, as it also represents a value similar to that observed in real textile industrial effluents (Kositzi et al. 2004).

In Figure 7, the values of adsorption capacity of graphite nanoplatelets for the dyes are shown according to their initial concentration in solution. In both cases, it was observed that the adsorbed amount was greater at higher $C_0$. At concentrations of 50 mg/L and 100 mg/L of the dye Indosol SFGL blue, this dye could be removed at 54.8 mg/g and 104.3 mg/g, respectively, while, for Drimaren HFRL blue, the removal capabilities for the same concentrations were 115.60 mg/g and 151.2 mg/g.

**Study of adsorption equilibrium**

The adsorption equilibrium of the dyes Indosol SFGL direct blue and Drimaren HFRL reactive blue on graphite nanoplatelets XGnP® is shown in Figure 8. The results show that the value of $q$ increases as the concentration of the dye (adsorbate) in solution also increases. The adsorption of Drimaren HFRL was higher than that of Indosol SFGL for all tested concentrations. However, it was observed that at
low concentrations the adsorbed amounts were closer. We believe that this effect, as observed in the pH study, is again related to the major role of protonation controlling the absorption process, which in the case of HFRL is associated with the highly electronegative fluorine elements plus the sulfonic groups that are present in the chromophore of reactive dyes.

Adsorption isotherm models are usually used to indicate the interaction between the absorbent and the adsorbate when the adsorption process reaches equilibrium. The BET adsorption model is based on the assumption that the adsorbate could be adsorbed onto the adsorbent surface forming multilayers in a random distribution of adsorbed particles and this has already been reported for the removal of methylene blue by modified graphene oxide (Wu et al. 2014). Adsorption equilibria are often classified according to the shape of the equilibrium isotherm (types I to V).

The profile behavior (trend curves in Figure 8(a)) indicates an adsorption isotherm of type II (Brunauer et al. 1940), established by a multilayer coating. The multilayer behavior can be represented by the BET model, Equation (3) (Rice & Do 2012), where \( q_e \) (mg/g) is the equilibrium amount adsorbed, \( q_m \) (mg/g) is the maximum adsorption in the monolayer, \( d \) is the number of layers, \( K \) is the adsorption equilibrium constant and \( x = C_e/C_0 \) is the ratio between the equilibrium concentration and the maximum initial concentration (100.0 mg/L),

\[
q_e = \frac{q_m \cdot K \cdot x}{1 - (d + 1) \cdot x^d + d \cdot x^{d+1}} \cdot \frac{1}{1 + (K - 1) \cdot x - K \cdot x^{d+1}}
\]

The experimental equilibrium data were fitted to the proposed model by minimizing the objective function \( fob(q_m, K, d) \) of type HYBRID (Foo & Hameed 2000), according to Equation (4),

\[
fob(q_m, K, n) = \frac{100}{n - p} \sum_{i=1}^{n} \left( \frac{q_{exp} - q_{calc}}{q_{exp}} \right)^2
\]

where \( n \) is the number of experimental data, \( p \) is the number of parameters \( (q_m, K, n) \), \( q_{exp} \) (mg/g) is the adsorbed amount obtained experimentally and \( q_{calc} \) (mg/g) is the adsorbed amount calculated by the model equation.

Figure 8(b) shows that the BET model fits to the experimental data, considering a margin of error of 5%, whose correlation coefficient \( (R^2) \) were 0.82 and 0.98, for the dyes SFGL and HFRL, respectively. In Table 1, we see that the maximum adsorption in the monolayer \( (q_m) \) is higher for HFRL (50.66 mg/g) than that obtained for SFGL (24.95 mg/g). We believe this behavior is related
first to the different protonation systems, as explained before. However, the number of layers \(d\) covered by SFGL (~53) is higher as compared to HFRL (~32). The explanation for this last result might be related to the different molecular structure of the dyes, resulting in distinct \(\pi-\pi\) interaction with the basal plane of the graphite nanoplatelets. Thus, according to results, the SFGL with 53 layers could achieve a maximum capacity \(q_m\) adsorption of 1,325 mg/g, while the HFRL with 32 layers could reach a \(q_m\) above 1,620 mg/g, in the operating conditions studied.

The graphene surface is reported to be able to adsorb nonpolar molecules on its basal plane through \(\pi-\pi\) stacking or hydrophobic interactions (Ghislandi et al. 2013). Generally, the \(p-p\) stacking interactions are realized by a solvent mixing of two components for some time, allowing full contact of these two components (Cao et al. 2011). In our water/dye/graphite nanoplatelets system, interfacial \(\pi-\pi\) stacking interactions between graphite nanoplatelets and the phenyl rings of dyes can occur. \(\pi\) interaction, or \(\pi-\pi\) stacking, refers to attractive, non-covalent interactions between neutral closed-shell systems. Despite intense experimental and theoretical interest, there is no unified description of the exact factors that contribute to \(\pi-\pi\) stacking interactions.

Grimme (2008) recommends using the term with care. For systems with about 10 or fewer carbon atoms or fewer, there is little theoretical evidence for a special role of the \(\pi\) orbitals. This view is supported by experimental phase change data for hydrocarbons, and even extreme cases, such as intramolecular \(\pi-\pi\) stacking in cyclophanes, fit in (Grimme 2008). Thus, the term ‘\(\pi-\pi\) stacking’ should be used as a geometrical descriptor of the interaction mode in unsaturated molecules and to understand \(\pi-\pi\) interactions as a special type of electron correlation (dispersion) effect that can only act in large unsaturated systems when they are spatially close, which is only possible in a stacked orientation. As mentioned in the ‘Introduction’, some studies reported that graphene is able to adsorb nonpolar structures on its basal plane through \(\pi-\pi\) stacking or hydrophobic interactions. We speculate then that, due to a more suitable and larger planar structure for the formation of \(\pi-\pi\) stacking with the aromatic rings of Indosol direct SFGL blue, this dye exhibits a more homogeneous interaction with the graphene plane, and consequently a greater amount of layers can be stacked on its surface. We tried to more easily illustrate the proposed theory in Figure 9.

The analysis of variance (ANOVA) was used to assess the fitting of the BET model to the experimental results (Taguchi et al. 1987). The application of the ANOVA test resulted in \(P\)-values of \(2.0 \times 10^{-5}\) and \(2.0 \times 10^{-6}\) for SFGL and HFRL, respectively. These low values indicate that the average difference between the experimental data and those predicted by the model is not significant. In this sense, the model satisfactorily represents the experimental equilibrium data for both dyes.

### Table 1

<table>
<thead>
<tr>
<th>Dye</th>
<th>(q_m) (mg/g)</th>
<th>(K)</th>
<th>(d)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFGL</td>
<td>24.95</td>
<td>118.9</td>
<td>53.46</td>
<td>0.82</td>
</tr>
<tr>
<td>HFRL</td>
<td>50.66</td>
<td>17.94</td>
<td>32.41</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**Figure 9** Proposed sketch showing the interactions between the planar structure of graphite nanoplatelets and: (a) SFGL direct blue molecules, (b) HFRL reactive blue molecules.
Study of the adsorption kinetics

Adsorption kinetics for the dyes Indosol SFGL and Drimaren HFRL blue are shown in Figure 10. The profiles indicate the increase in the adsorption capacities ($q$) for the dyes onto the graphite nanoplatelets surface until they reach an equilibrium plateau (Step I). The plateau remains unchanged for a longer time ($\sim$100 min) for the dye Indosol SFGL (Figure 10(a)) than for Drimaren HFRL (Figure 10(b)). After this pseudo-equilibrium the adsorptive capacity increases again (Step II) for both dyes.

This behavior may be due to the multilayer coating adsorption verified at equilibrium associated with the external diffusion process. After the accommodation of the dye molecules during Step I, a new driving force restarts the adsorptive process in consequence of adsorbate concentration difference between the surface of the adsorbent and the solution (Step II). Thus, the establishment of this equilibrium becomes dynamic until complete saturation of the adsorbent. The same behavior was observed in the literature (Wu et al. 2014), although the modeling was done assuming one single step. We suspect that again the higher and more homogeneous interaction between SFGL and the graphene planar structure hinders the mobility of the adsorbate molecules and consequently a longer agitation time (more energy) is required to start the second adsorption step. The agitation time contributed to the reduction of external resistance to diffusion, allowing more molecules to reach the surface for adsorption.

The representation of the adsorption kinetics for the batch process follows Equation (5),

$$\frac{dC}{dt} = - \frac{m}{V} \cdot \frac{dq}{dt}$$

where $m$ (g) is the mass of adsorbent, $C$ (mg/L) is the residual concentration of dye in solution and $V$ (L) is the volume of the solution. Considering the representation of the adsorption kinetics, two models, one of pseudo-first order and another of pseudo-second order were compared. These models have been applied for the steps I and II independently and results are shown in Table 2. The pseudo-second order model exhibited a more accurate fitting, according to Equation (6),

$$\frac{dq}{dt} = \frac{k}{C_e - q}$$

where $k$ (g/mg.s) is the coefficient of mass transfer of pseudo-second order. The kinetic data were also fitted to

![Figure 10](image)

**Figure 10** | Adsorption kinetics for the dyes (a) Indosol SFGL blue and (b) Drimaren HFRL blue.

**Table 2** | Parameters obtained for SFGL and HFRL using pseudo-second order model: $q_m$ (mg/g) is the maximum adsorption in the monolayer, and $k$ (g/mg.s) is the coefficient of mass transfer of pseudo-second order

<table>
<thead>
<tr>
<th>Dye</th>
<th>$q_m$ (mg/g)</th>
<th>$k$ (g/mg.s)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step I</td>
<td>Step II</td>
<td></td>
</tr>
<tr>
<td>SFGL</td>
<td>84.5 ± 0.6</td>
<td>95.6 ± 10.4</td>
<td>0.87</td>
</tr>
<tr>
<td>HFRL</td>
<td>104.3 ± 1.9</td>
<td>167.8 ± 20.1</td>
<td>0.90</td>
</tr>
</tbody>
</table>
the proposed model by minimizing the objective function $[Fob(\kappa_i)]$ of the type HYBRID (Foo & Hameed 2010).

**CONCLUSIONS**

Direct and reactive blue textile dyes, widely used for coloring jeans worldwide, were systematically studied comparing the removal efficiency from wastewater via adsorption onto commercial xGnP® graphite nanoplatelets. The results were assessed via studies of kinetics and adsorption equilibrium. To the best of our knowledge, for the first time a study is reported comparing these results (removal efficiency) and exploring the different physical/chemical interactions between the basal plane of graphite nanoplatelets and specific blue dyes which contain low and high amount of aromatic rings on their structure. We believe this is a fundamental study for understanding the principles that govern the adsorption behavior of these materials.

It was confirmed that at lower pH values the dye removal efficiency is greatly increased. It is assumed that in acid pH solution, the dye (anionic) exhibits repulsion to the liquid medium and consequently a higher affinity to the inert sheets of graphite nanoplatelets, enabling a better fixation. The removal capabilities at low pH (~3.5) and high initial dye concentration (100 mg/L) reached $q$ values well above 100 mg/g. These values are significantly higher than the maximum adsorption capacities of similar dyes reported for modified organic adsorbents (Fan et al. 2012), reduced graphene/carbon nanotubes (Ai & Jiang 2012) and powdered activated carbons (Yener et al. 2008).

The adsorption equilibrium exhibited an adsorption isotherm of type II for both dyes, with characteristics of multilayer coating. Exceptionally high rates, above 1,300 mg/g, could be reached for both dyes considering the total number of adsorbed layers. The maximum adsorption in the monolayer is higher for the reactive blue HFRL than that obtained for direct blue SFGL. However, direct dyes like SFLG, with oriented aromatic rings along its structure, can interact with the basal carbon plane of graphene via π−π stacking, promoting an increase in the number of adsorbed stacking layers as compared to reactive dyes like HFRL, which exhibits a lower amount of aromatic rings.

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