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Removal of anionic and cationic dyes from aqueous solutions using drinking water treatment plant sludge (DWTS): Equilibrium and kinetic evaluation*

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Abstract

The present research investigates the removal of Brilliant Green (BG) and Remazol Brilliant Blue R (RBBR) dyes by an adsorption system utilizing drinking water treatment sludge (DWTS) as an adsorbent for the first time in the literature. It aims to contribute to sustainable treatment methods by evaluating waste sludge as a low-cost and environmentally friendly adsorbent. In the study, the significant parameters affecting the adsorption process were systematically investigated. During the experiments, the effects of factors such as initial pH of the solution, equilibrium time, adsorbent amount, and initial dye concentration on the adsorption efficiency were evaluated. The obtained data were tested with Langmuir and Freundlich isotherm models, and it was determined that adsorption occurred on both homogeneous and heterogeneous surfaces. The maximum adsorption capacity of DWTS was calculated as 100.0 mg/g and 38.9 mg/g for BG and RBBR, respectively. Kinetic analyses were performed to understand the dynamics of the adsorption process. Pseudo-first order and Pseudo-second order kinetic models were evaluated and it was noticed that the pseudo-second order model explained the adsorption data better. As a result, DWTS has been proven to be an effective adsorbent in the removal of BG and RBBR. The findings indicated that DWTS has significant potential for evaluation in advanced treatment processes in terms of environmental sustainability.

Keywords: Adsorption, brilliant green, drinking water treatment sludge, dye, Remazol Brilliant Blue R

1. Introduction

With the industrial revolution, rapidly increasing human activities have brought about various types of environmental pollution, and among these, water pollution has posed major threats to the ecosystem and human health [1]. Since water resources are indispensable for human survival, water pollution constitutes the most critical factor among environmental problems. Water pollutants can be divided into two main categories: organic and inorganic pollutants. Inorganic pollutants include toxic metals and metalloids; organic pollutants include surfactants, phenolic compounds, and anionic and cationic dyes, especially those originating from the textile, chemical, or food industries. These pollutants, which reach the environment, especially water resources, as a result of industrial activities, cause irreversible damage to the ecosystem and threaten the health of living beings [2,3]. In this context, it is necessary to develop economical and efficient treatment processes in order to effectively treat polluted water.

Dyes are considered to be among the most dangerous pollutants due to their chemically stable structure, resistance to degradation and potential carcinogenic properties [4–6]. In addition to these harmful effects, the contamination of natural waters with dyes reduces the rate of light penetration and affects the ecosystem by degrading the overall water quality. In addition, bacteria in the water consume dissolved oxygen to break down the dyes, further degrading the quality of the water [7]. Dyes that pass into human metabolism through the food chain can have serious adverse effects on human health. These include acute health problems such as allergic

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reactions, skin rashes, dermatitis, digestive system disorders, headaches, nausea, vomiting, as well as serious disorders such as reproductive problems, developmental disorders and liver failure [8,9]. Therefore, it is of great importance that dyes in industrial wastewater are effectively treated before they are released into the natural environment. For this purpose, methods such as liquid-liquid extraction [10], ion exchange [11], advanced oxidation [12], coagulation [13], flocculation [14] and adsorption [15] have been developed. The adsorption technique offers high efficiency in removing pollutants from water, air and soil. It has important advantages such as being applicable to different pollutant types and concentrations, providing a wide range of applications, generally not being operationally complex and consuming less energy compared to some other treatment methods. In addition, by selecting the appropriate adsorbent, it can focus on specific pollutants and offers an effective solution for the separation of certain substances in industrial applications [16,17]. Adsorption, which is an environmentally friendly method with low chemical use, also stands out in terms of sustainability with the fact that some adsorbents can be recycled in an environmentally friendly way. However, the high cost of adsorbents to be used in the adsorption process can reduce the interest of wastewater producing factories in the treatment process [18]. For this reason, it is of great importance to develop low-cost, easily available and high adsorption capacity adsorbents for use in wastewater treatment. For this purpose, adsorbents such as acid and base activated *Symplocos racemosa* agro-waste [19], H_3PO_4-functionalized bagasse [20], okara [21], used-tea powder [22], *Ficus benghalensis* tree leaves [23], fava bean peels [24], and watermelon and corn peels [25] have previously been tested by various researchers for the removal of dyes from water. Such adsorbents will both contribute to environmental sustainability and help industrial applications become more widespread [26,27]. In recent years, the usage of drinking water treatment sludge (DWTS) as an adsorbent has also attracted the interest of researchers [28,29].

DWTS is the solid waste generated during processes such as coagulation, flocculation, sedimentation, and filtration, which are used to treat water and make it suitable for drinking water standards. Some chemicals added during water treatment cause the sedimentation of suspended solids and these sediments accumulate as waste sludge over time. The disposal of this waste sludge is challenging and is primarily carried out through storage. Alternatively, under specific conditions, it can be used as a soil improver in agriculture and as a road filler or cement additive in the construction sector. As a result, the proper management of DWTS is very important in terms of both environmental sustainability and economic benefit. Today, various studies are being conducted on the recycling of this sludge and its use in alternative areas [30]. In this context, in the present research, a cheap and effective adsorption method was developed by using DWTS as an adsorbent for the removal of cationic Brilliant Green (BG) and anionic Remozal Brilliant Blue R (RBBR) dyes from aqueous solutions.

2. Materials and methods

2.1. Preparation and characterization of adsorbent

In this study, drinking water treatment sludge (DWTS) used as adsorbent was supplied from a water treatment plant in Trabzon. The samples were homogeneously collected from a mixed sludge reservoir using sterile 500 mL containers. After the DWTS was collected, it was dried without any chemical or physical activation process, then ground to <180 μm and stored in petri dishes.

Scanning Electron Microscope (ZIESS EvoLs10) and Fourier Transform Infrared Spectrometer (Perkin Elmer Spectrum One) were used to elucidate the morphological structure of DWTS and to obtain information about the surface functional groups. The crystal structure of DWTS was investigated by X-Ray Diffraction (XRD) measurements (Rigaku TTR III) with Cu Kα radiation (λ = 1.5406 Å) in the 2θ range of 5-80°.

2.2. Chemicals and instruments

All chemicals used in the study were of analytical grade and were supplied by Fluka (Buch, Switzerland) or Merck (Darmstadt, Germany). To prepare stock BG and RBBR solutions at a concentration of 5000 mg/L, 1.250 g of solid dyes were weighed and dissolved, and the final volume was completed to 250 mL with distilled water. Calibration and working solutions were obtained by diluting these stock solutions. Na_2CO_3 and Na_3PO_4 were used to evaluate the effects of salts on dye adsorption. Perkin Elmer Lambda 25 model UV-Vis spectrophotometer was used to determine the dye concentration in the solution medium before and after adsorption, Hanna pH-2221 model desktop pH meter was used to prepare solutions at desired pHs and to determine the pH values of the solutions, BOECO PSU-15i model mechanical shaker was used for adsorption experiments, BOECO S-8 model centrifuge was used to separate the adsorbent from the solution, Sartorius BP1106 model analytical balance was used for weighing the adsorbent and other chemicals.

2.3. Batch adsorption experiments

Adsorption experiments were carried out by batch method. For this purpose, certain amounts of DWTS (1.0-

20.0 g/L for BG and 1.0-15.0 g/L for RBBR) were weighed into 15 mL polypropylene centrifuge tubes. Then 10 mL each of BG solutions with an initial concentration range of 10-750 mg/L (at its natural pH) and a series of RBBR solutions with a concentration range of 10-600 mg/L (adjusted to an initial pH of 2.0) were added to the tubes and the resulting mixtures were shaken at 300 rpm on a mechanical shaker for 1-120 min. At the end of the determined periods, the adsorbate solutions were separated from the adsorbent by centrifuging at 3500 rpm for 5 min. The concentration of the dye remaining unadsorbed in the solution was determined by analyzing with a UV-Vis Spectrophotometer at 625 and 592 nm wavelengths for BG and RBBR, respectively. The amount of dye adsorbed by 1 g of DWTS was calculated as mg g^{-1} using Eq. 1.

$$q_e = \frac{(C_o - C_e) \times V}{m} \quad (1)$$

Here, q_e (mg g^{-1}) represents the amount of BG or RBBR retained by 1 g of DWTS, C_0 (mg/L) is the initial concentration of BG or RBBR, C_e (mg/L) is the concentration of each dye remaining in the aqueous solution at equilibrium because of not being adsorbed by the DWTS, V (L) is the volume of dye solution added on the DWTS, and m (g) is the mass of DWTS.

3. Results and discussion

3.1. Characterization of DWTS

To identify the functional groups responsible for the adsorption of dyes on the surface of DWTS, the FTIR spectrum of DWTS was analyzed. According to the spectrum shown in Fig. 1, the peaks at 990 cm^{-1} and 694 cm^{-1} are attributed to Si–O groups, the peak at 3385 cm^{-1} is associated with O–H, and the peak at 1635 cm^{-1} is attributed to C=C stretching vibrations [30].

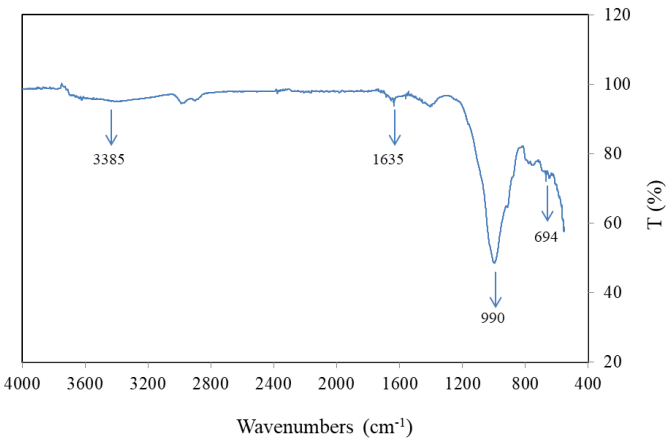

Figure 1. FTIR Spectrum of DWTS

SEM images, obtained at different magnifications (5000x and 10000x), were used to investigate the surface morphology of the DWTS (Fig. 2). These images reveal that the DWTS surface is relatively rough with indentations and lacks significant porous structures or channels. There are agglomerated particles of varying sizes observed in the structure suggesting a non-uniform texture. This structure of the surface may affect the adsorption capacity of dyestuffs. In addition, according to EDX data, it is noticed that there is a significant amount of Si (52%) and Al (18%) in the DWTS structure.

XRD spectrum was obtained to get an idea about the crystal structure of DWTS (Fig. 3). In spectrum, characteristic peaks of kaolinite, quartz, muscovite and calcite minerals were observed at specific 2θ angles. As a result of the analysis, intense diffraction peaks were determined at 24.9° for kaolinite (JCPDS No: 01-078-1996), 26.6° for quartz (JCPDS No: 01-085-0795), 29.5° for muscovite (JCPDS No: 01-076-0663) and 23° for calcite (JCPDS No: 01-072-1652). These peaks were verified by comparing them with standard patterns registered in the JCPDS (ICDD) database. Based on these comparisons, it can be stated that DWTS is primarily composed of kaolinite, quartz, muscovite and calcite minerals [30].

3.2. Influences of initial pH

In the adsorption of anionic and cationic dyes, pH is a critical parameter to optimize as it influences both the chemical structure of the dye and the surface properties of the adsorbent [31]. The effect of pH on the adsorption of BG and RBBR was tested in the range of pH 2.0-8.0 using 5.0 g/L DWTS at an initial dye concentration of 100 mg/L. The adsorption efficiency of BG, a cationic dye, is low at low pH values but increases with rising pH, reaching an optimum at pH 5.0, beyond which no significant changes are observed. While the adsorption efficiency of RBBR, which is an anionic dye, is 6.49 mg/g at pH 2.0, it decreases to 0.30 mg/g at pH 8.0. The effect of pH on the adsorption of dyes can be explained by considering the pH_{pzc} value of DWTS. The pH_{pzc} value for DWTS is calculated as 8.4. At low pH values ($pH<pH_{pzc}$), the surface of the adsorbent is generally protonated and carries a positive charge, while at high pH values, the protons on the surface are separated and the adsorbent surface becomes negatively charged ($pH>pH_{pzc}$). Since BG is positively charged in aqueous solution, it creates a stronger electrostatic attraction with the negatively charged adsorbent surface at high pH values and the adsorption efficiency increases. However, since RBBR is negatively charged in aqueous solution, it shows a weak adsorption efficiency due to the repulsive forces with the negatively charged adsorbent surface at low pH values. However, at low pH values, when the surface is positively charged, electrostatic attractive forces increase RBBR adsorption [32]. The pH of the aqueous solution affects not only electrostatic interactions but also van der Waals forces, hydrogen bonds and hydrophobic interactions.

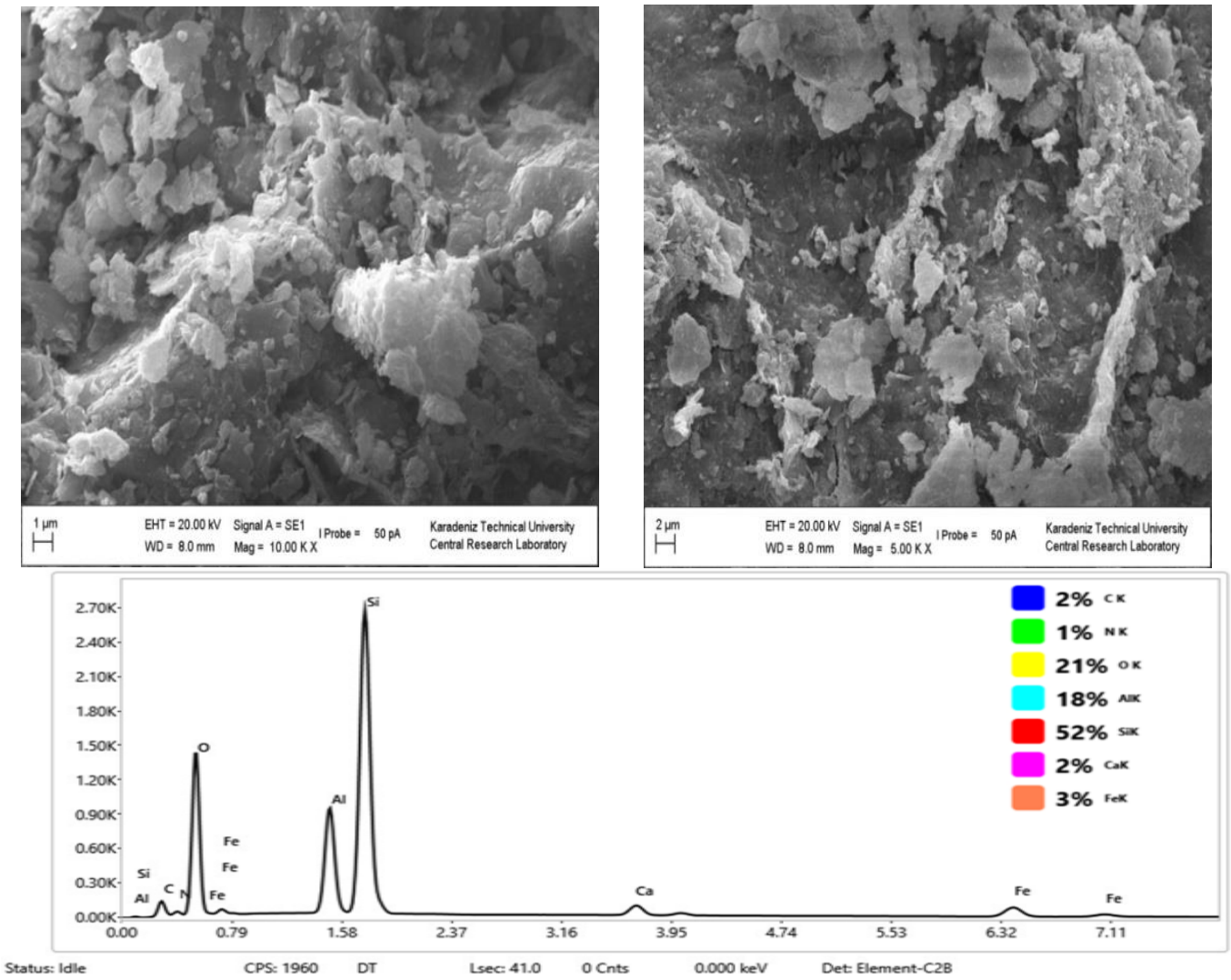

Figure 2. SEM-EDX images of DWTS

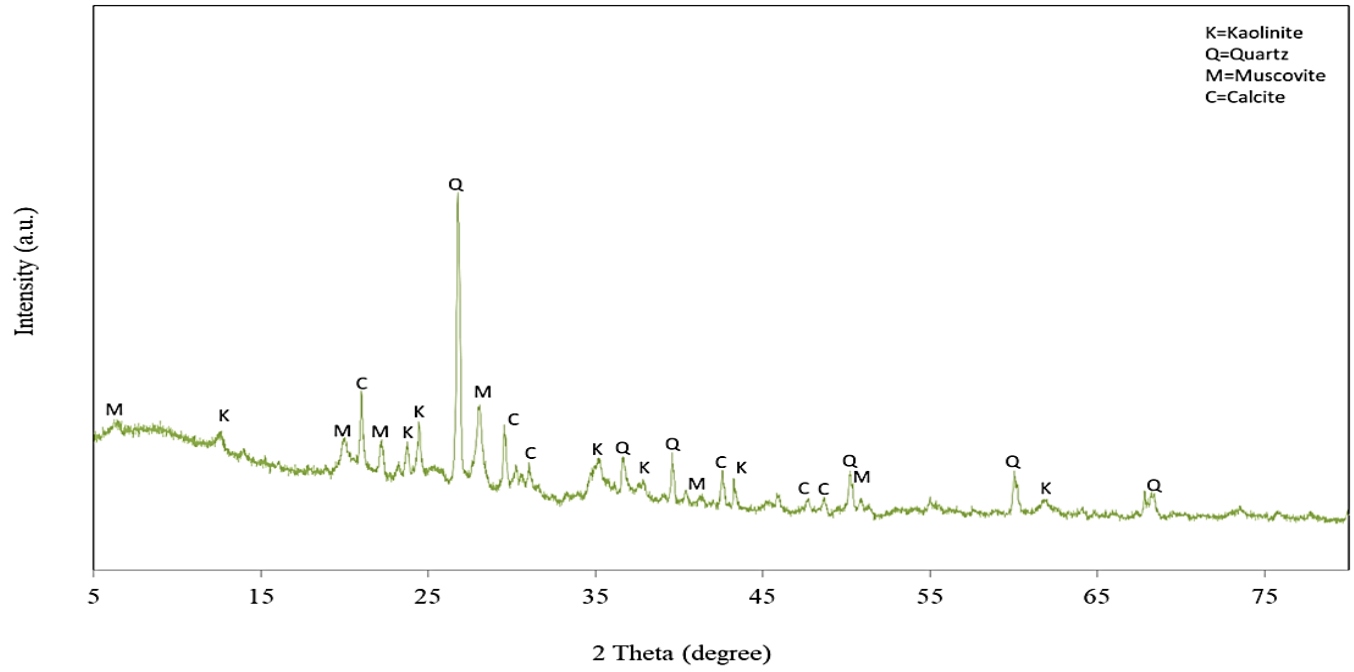

Figure 3. XRD Spectrum of DWTS

Therefore, the optimal pH range in each system must be determined experimentally. In general, lower pH values enhance the adsorption efficiency of anionic dyes ($pH<pH_{pzc}$), while higher pH values ($pH>pH_{pzc}$) improve the adsorption efficiency of cationic dyes. As a result, further studies on the adsorption of BG onto DWTS were carried out at the natural pH value of the dye, while the optimum pH for RBBR was determined as 2.0.

3.3. Influences of contact time and the kinetic studies

The equilibrium time plays a crucial role in ensuring the effective completion of the developed adsorption process. Data obtained from the equilibrium time study help to interpret the rate control mechanism of adsorption such as film diffusion, intraparticle diffusion or chemical bonding. In industrial applications, systems with short equilibrium times are preferred both to save time and to be more economical. However, the equilibrium time of the adsorption system is significantly affected by the surface area and pore structure of the adsorbent, the molecular size and concentration of the adsorbate, and the properties of the medium such as temperature and pH. In this study, the effect of equilibrium time for BG and RBBR adsorption on DWTS was investigated in detail. For this purpose, 10 mg of DWTS for BG and 50 mg of DWTS for RBBR were weighed separately and then 10 mL of BG (100 mg/L) at natural pH value and RBBR (100 mg/L) solution adjusted to pH 2.0 were added to them. After shaking at different time intervals, the adsorbate and adsorbent mixtures were separated from each other by centrifugation and the dye concentrations remaining unadsorbed in the solution were determined by UV-Vis Spectrophotometer and then the amount of dye (q_t) adsorbed by 1 g DWTS at different time intervals were calculated. In the initial stages of both BG and RBBR adsorption (1-5 min time interval), the adsorption rate is high due to the presence of many active binding sites on DWTS. In the initial stages, the active binding sites that are empty on DWTS promote rapid diffusion. After the 5 min, the adsorption rate decreases as the active sites on the DWTS surface begin to be filled with BG and RBBR molecules. Intraparticle diffusion is effective at this stage. After the 90 min for BG and the 60 min for RBBR, an equilibrium occurs between the dye concentration in the solution and the adsorbed amount on DWTS, and after this stage, no significant change occurs in the adsorption amount [33]. Therefore, in subsequent studies for BG and RBBR, the equilibrium time of 90 and 60 min was accepted as optimum, respectively (Fig. 4).

Kinetic models are essential for understanding the adsorption rate, mechanism, and controlling steps of BG and RBBR on DWTS. The experimental data obtained from kinetic studies were analyzed using the pseudo-first order (PFO) and pseudo-second order (PSO) models.

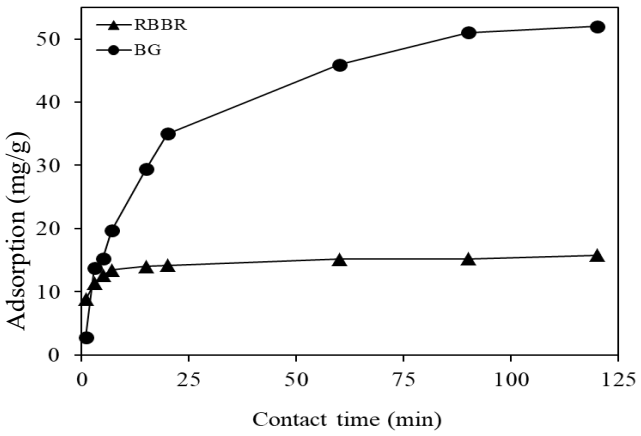

Figure 4. Effect of contact time on the adsorption of RBBR and BG onto DWTS

The PFO model is used to describe cases where adsorption is controlled by physical processes, while the PSO model is more appropriate for situations where chemical adsorption dominates.

The linear equations for the PFO [34] and PSO [35] models are given in Eq. 2 and Eq. 3, respectively.

$$ln(q_e - q_t) = ln\, q_e - k_1 t \quad (2)$$

$$\frac{t}{q_t} = \frac{1}{k_2 {q_e}^2} + \frac{t}{q_e} \quad (3)$$

In the equations, q_e (mg g^{-1}) and q_t (mg g^{-1}) are the amounts of BG and RBBR adsorbed on the DWTS at equilibrium and at any time t (min), respectively. k_1 (min^{-1}) and k_2 (g mg^{-1}min^{-1}) are the rate constants of the PFO and PSO models, respectively. According to the PFO kinetic model, k_1 and q_e values are obtained from the slope and intercept of the ln (q_e–q_t) graph against t, respectively. Considering the PSO kinetic model, q_e and k_2 values are calculated from the slope and intercept of the figure plotted between t/q_t–t, respectively. The constants obtained for each kinetic model, together with the relevant correlation coefficients (R^2), are shown in Table 1.

Table 1. Kinetic parameters in the adsorption of RBBR and BG onto DWTS

	Adsorbate	
Kinetic models	**RBBR**	**BG**
$q_{e\ exp}$ (mg/g)	15.8	52.0
PFO		
k_1 (min^{-1})	-0.024	-0.040
$q_{e\ cal}$ (mg/g)	3.64	44.6
R^2	0.7968	0.9780
PSO		
k_2 (g mg^{-1} min^{-1})	0.041	0.012
$q_{e\ cal}$ (mg/g)	15.8	58.5
R^2	0.9994	0.9962

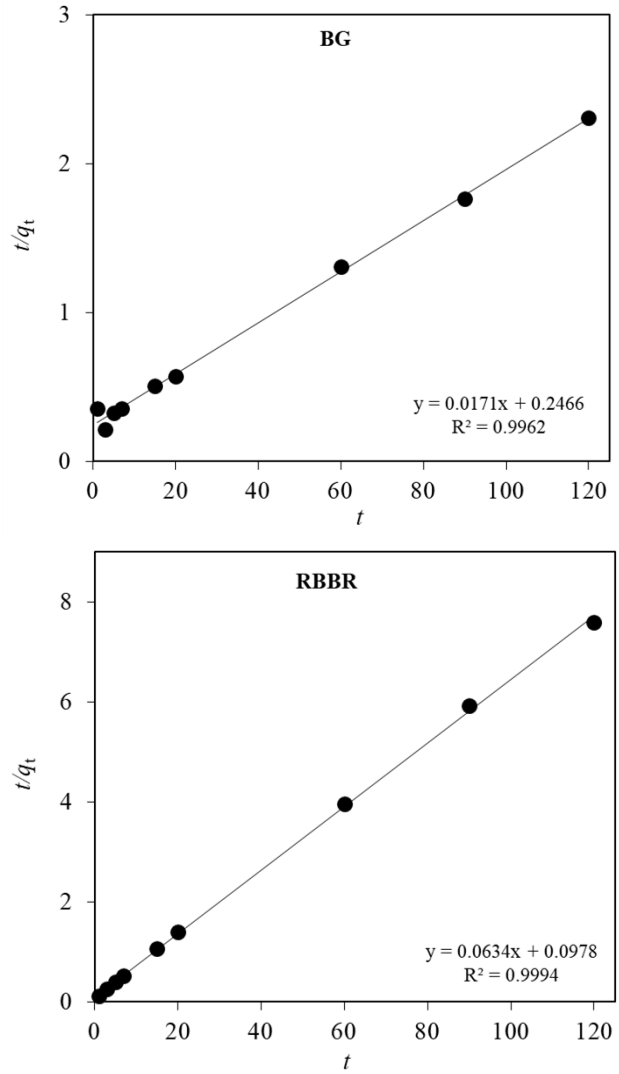

Figure 5. Pseudo-second order kinetics model

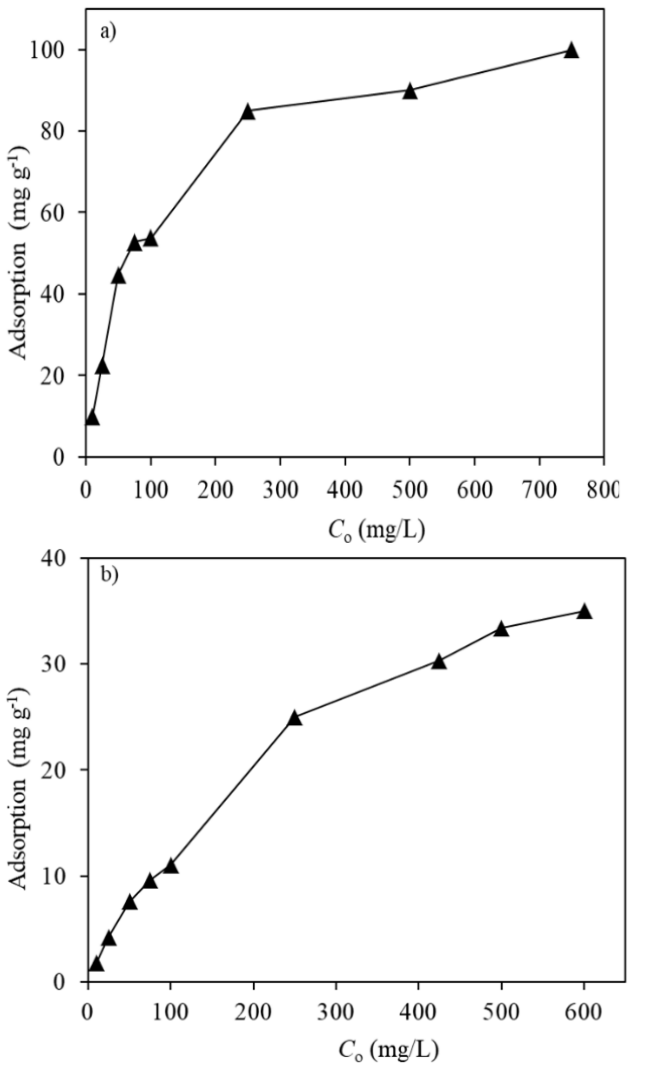

Figure 6. Effect of initial dye concentration on the adsorption efficiency of a) BG b) RBBR

The $q_{e,exp}$ values for BG and RBBR were calculated as 52.0 mg/g and 15.8 mg/g, respectively. After applying the PFO kinetic model to the experimental data, the $q_{e,cal}$ values for BG and RBBR were determined to be 44.6 mg/g and 3.64 mg/g, respectively, with R^2 values of 0.978 and 0.797, respectively. By applying the PSO kinetic model, the $q_{e,cal}$ values for BG and RBBR were found to be 58.5 mg/g and 15.8 mg/g, respectively, with R^2 values exceeding 0.995 for both adsorbates (Fig. 5). Considering these data, it is noticed that the PSO kinetic model is dominant in the adsorption mechanism of both BG and RBBR on DWTS, as the experimentally calculated q_e values are close to the q_e values observed by applying the model. On the other hand, higher R^2 values were also obtained by applying the PSO kinetic model. This result indicates that chemisorption plays a significant role in the adsorption mechanism.

3.4. Influences of initial dye concentration and adsorption isotherms

The efficiency of the adsorption process and the adsorbent capacity are significantly affected by the initial dye concentration. As the initial concentration of dye molecules in solution increases, a concentration gradient is formed between the molecules in the solution and the DWTS surface, which increases the rate of dye molecules moving to the adsorbent surface. However, the active sites on the adsorbent surface are rapidly saturated at high dye concentrations. The initial concentration also influences the amount of dye adsorbed per unit of adsorbent (q_e). Generally, as the initial concentration increases, q_e increases because more dye molecules are adsorbed onto the adsorbent surface; however, after a certain stage, q_e remains constant because the surface reaches saturation [36].

In order to evaluate the effect of initial dye concentration on the adsorption efficiency of BG and RBBR on DWTS and to obtain the adsorption isotherm data, adsorption studies were carried out with dye solutions with initial concentrations ranging from 10 to 750 mg/L for BG and 10 to 600 mg/L for RBBR. The results obtained from the experimental studies showed that with the increase of BG concentration from 10 mg/L to 750 mg/L and RBBR concentration from 10 mg/L to 600 mg/L, the adsorbed dye amount increased from 10.0

mg/g to 100.0 mg/g (Fig. 6a) and from 1.78 mg/g to 35.0 mg/g (Fig. 6b), respectively.

The Langmuir [37] and Freundlich [38] isotherm models, based on different assumptions, were applied to the experimental data to mathematically represent the adsorption process and interpret its mechanism. The Langmuir isotherm model is based on the assumption that adsorption occurs in a single layer on the adsorbent surface, that all active sites on the adsorbent surface have equal energy, and that there is no interaction between molecules adsorbed on the surface. According to the Freundlich isotherm model developed to explain the adsorption processes occurring in multilayers on heterogeneous surfaces, the active sites on the adsorbent surface have different binding energies. The linear equations of these isotherm models are given in Eq. 4 and Eq. 5, respectively.

$$\frac{C_e}{q_e} = \frac{C_e}{q_{maks}} + \frac{1}{bq_{maks}} \quad (4)$$

$$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e \quad (5)$$

In these equations, q_e (mg g^{-1}); is the amount of BG or RBBR adsorbed per unit DWTS mass, C_e (mg L^{-1}); is the dye concentration in the aqueous solution at equilibrium, b (L mg^{-1}); is the free energy of adsorption, q_{max} (mg g^{-1}); is the maximum monolayer adsorption capacity, K_f (mg g^{-1}); is the adsorption capacity, and n is a unitless constant representing the adsorption density.In addition, the applicability of an adsorption process is estimated by evaluating the R_L parameter calculated with the help of Eq. 6. R_L values between 0 and 1 reveal suitable adsorption.

$$R_L = \frac{1}{1 + b.Co} \quad (6)$$

C_e/q_e versus C_e plots (for Langmuir isotherm) and $\ln q_e$ versus $\ln C_e$ plots (for Freundlich isotherm) for BG and RBBR are given in Fig. 7 and Fig. 8, respectively. The constants for both isotherm models were calculated from the slope of the plots and the point where they intersect the ordinate axis, and the values are provided in Table 2. When the data obtained for BG and RBBR adsorption were evaluated, the R^2 values obtained from both the Langmuir and Freundlich isotherm models were higher than 0.95, providing an idea that the DWTS surface exhibits both homogeneous and heterogeneous properties in its adsorption behavior. This indicates that the DWTS surface has a complex structure and contains active sites with different binding energies. It also indicates that DWTS can support both monolayer and multilayer adsorption processes. The DWTS surface exhibiting both homogeneous and heterogeneous properties can be attributed to several factors. DWTS generally contains various inorganic and organic components. The presence of clay minerals, metal oxides (such as Fe and Al oxides), and organic matter can contribute to both homogeneous and heterogeneous characteristics of the surface. On the other hand, the DWTS surface may contain various functional groups responsible for adsorption. The irregular distribution of these groups can lead to homogeneous adsorption in some regions, while causing heterogeneous adsorption in others. Using the Langmuir isotherm model, the maximum adsorption capacities of DWTS for BG and RBBR were calculated as 100.0 mg/g and 38.9 mg/g, respectively. The proposed adsorbent exhibits a higher adsorption capacity than many of the adsorbents listed in Table 3 [19–25]. The R_L values obtained from the Langmuir isotherm model were in the range of 0.645–0.024 for BG concentrations of 10–750 mg/L and in the range of 0.862–0.094 for RBBR concentrations of 10–600 mg/L, supporting that the adsorption process was suitable under the studied conditions [39]. In addition, the n value obtained from the Freundlich isotherm model also gives an idea about the suitability of the adsorption process. The fact that this value is in the range of 1-10 indicates the suitability of the adsorption process [40]. The n values for BG and RBBR were calculated as 4.20 and 2.02, respectively, and this result supports the interpretation made for R_L.

3.5. Influences of adsorbent amount

During the adsorption process, the amount of DWTS directly influences the number of active sites available for binding with BG and RBBR molecules in the solution, making it one of the key parameters that determine the adsorption efficiency. The increase in the amount of adsorbent increases the number of active sites, which can lead to an increase in adsorption capacity. However, this increase continues up to a certain point; after this point, the adsorption process may reach saturation, and further increases in the amount of adsorbent do not provide a significant change in adsorption efficiency [41]. The effects of DWTS amount on the removal efficiency of BG and RBBR from aqueous media were evaluated for DWTS amounts in the range of 1.0-20.0 g/L and 1.0-15.0 g/L, respectively. The equilibrium BG and RBBR amounts and dye removal efficiency percentages are plotted against DWTS amounts in Fig. 9a and Fig. 9b, respectively. The increase in the amount of DWTS caused an increase in the active adsorption sites, and the

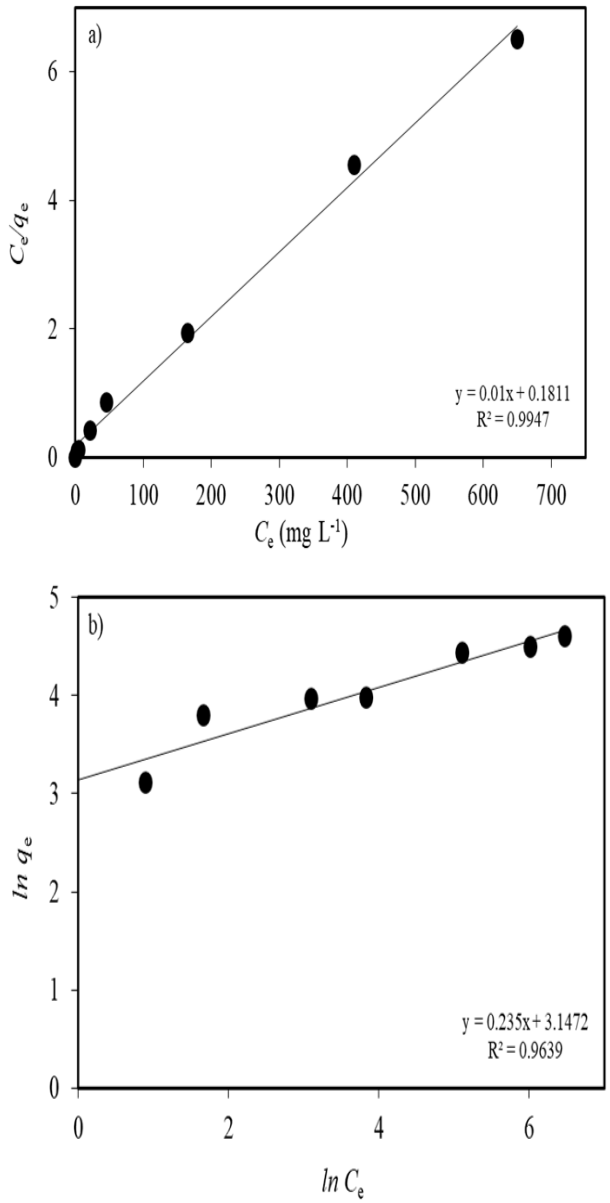

Figure 7. a) Langmuir isotherm model b) Freundlich isotherm model for the adsorption of BG

adsorption percentage increased from 20.1% to 97.4% and from 36.8% to 79.8% for BG and RBBR, respectively. However, since the excess amount of DWTS caused the formation and agglomeration of unsaturated adsorption surfaces, the amount of BG and RBBR adsorbed per gram of adsorbent decreased from 100.6 mg/g to 24.4 mg/g and from 73.5 mg/g to 10.6 mg/g, respectively.

3.6. Influences of foreign ions

During the adsorption process, the salts present in the solution can affect the electrostatic interactions between the adsorbent and the adsorbate, which can increase or decrease the adsorption efficiency. Therefore, the effects of various salts containing ions that can be commonly found in wastewater on the adsorption efficiency of BG and RBBR on DWTS were tested. Na_2CO_3 and Na_3PO_4 were used as model salts.

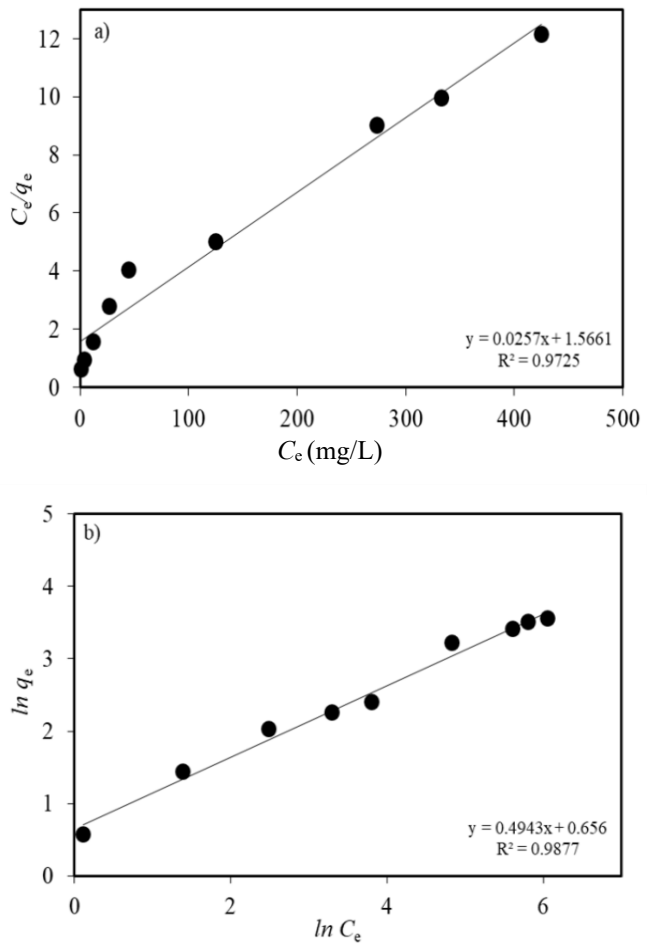

Figure 8. a) Langmuir isotherm model b) Freundlich isotherm model for the adsorption of RBBR

Table 2. Isotherm parameters for the adsorption of RBBR and BG

	RBBR	BG
Langmuir isotherm model		
q_{max} (mg/g)	38.9	100.0
b (L mg^{-1})	0.016	0.055
R^2	0.9725	0.9947
Freundlich isotherm model		
K_f (mg/g)	1.93	23.3
n	2.02	4.2
R^2	0.9877	0.9639

Table 3. Comparison of the maximum dye adsorption capacities of various adsorbents

Adsorbent	Dye	q_{max} (mg/g)	Reference
Acid activated *Symplocos racemosa* agro-waste	BG	62.9	[19]
Base activated *Symplocos racemosa* agro-waste	BG	71.0	[19]
H_3PO_4-functionalized bagasse	BG	139	[20]
Okara	BG	64.33	[21]
Used tea leaves	BG	101.01	[22]
Ficus benghalensis Tree Leaves	BG	19.5	[23]
Fava bean peels	BG	28.14	[24]
Watermelon peel	RBBR	1.046	[25]
Corn peel	RBBR	0.047	[25]
DWTS	BG	100.0	This Study
DWTS	RBBR	38.9	This Study

In order to investigate the effect of salts on BG adsorption, BG solutions containing 10 mg DWTS at a concentration of 150 mg/L and salt solutions with a concentration of 0.01–0.10 M (at natural pH value) were treated separately for 90 min. In order to investigate the effect of salts on RBBR adsorption, RBBR solutions containing 50 mg DWTS at a concentration of 50 mg/L and adjusted to pH 2.0 and salt solutions with a concentration of 0.01–0.10 M were treated separately for 60 min. After determining the concentration of BG and RBBR remaining unadsorbed in the solution, the amount of BG and RBBR adsorbed per gram of DWTS (q_e) was plotted against the concentration of salts with the obtained data (Fig. 10a and Fig. 10b). No significant change was observed in the adsorption efficiency by increasing the concentrations of Na_2CO_3 and Na_3PO_4 from 0.01 M to 0.10 M for both dyes. This shows that the developed adsorption process will be effectively applied to wastewaters containing high concentrations of salt.

4. Conclusions

In the present study, drinking water treatment sludge (DWTS) has been utilized as a low-cost and effective adsorbent for the removal of Brilliant Green (BG) and Remozal Brilliant Blue R (RBBR) dyes from waters and wastewaters. This study is an original research in which DWTS is used as an adsorbent for the first time in the removal of BG and RBBR dyes. In this context, DWTS, which has no economic value and is formed as a waste, has been functionalized as an adsorbent in this study and has been created as an alternative to other adsorbents that are generally high cost and require the use of chemicals. This approach not only contributes to the solution of an environmental problem but also offers a sustainable waste management strategy.

In batch adsorption experiments, the adsorption of BG onto DWTS was found to be most efficient at the

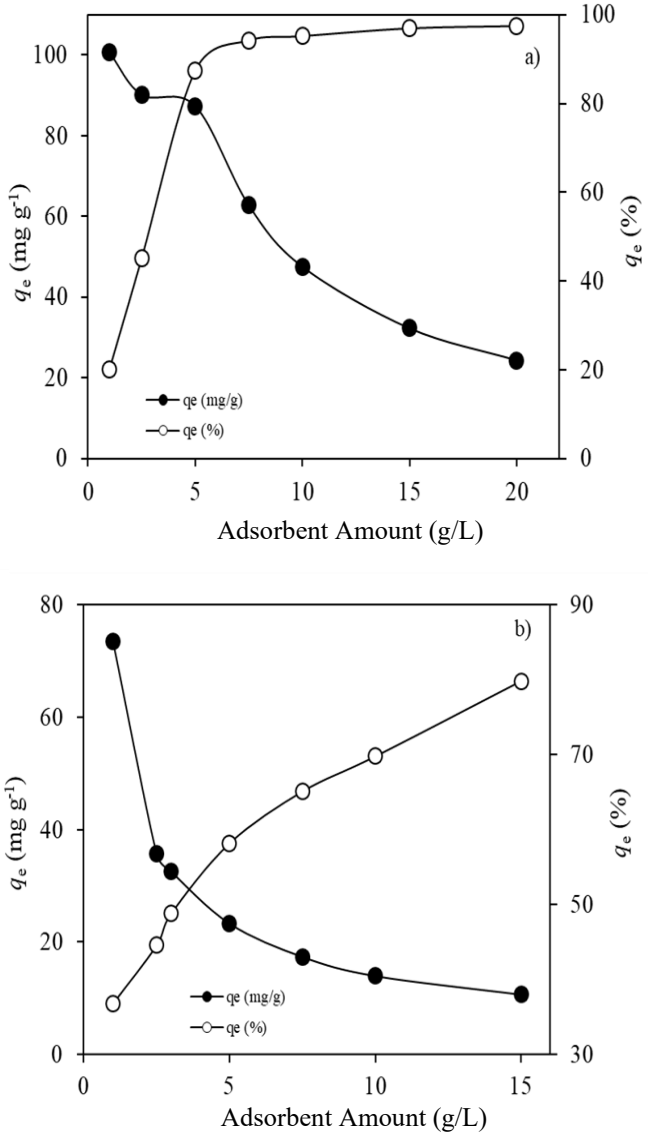

Figure 9. Influences of adsorbent dosage on the adsorption of a) BG b) RBBR

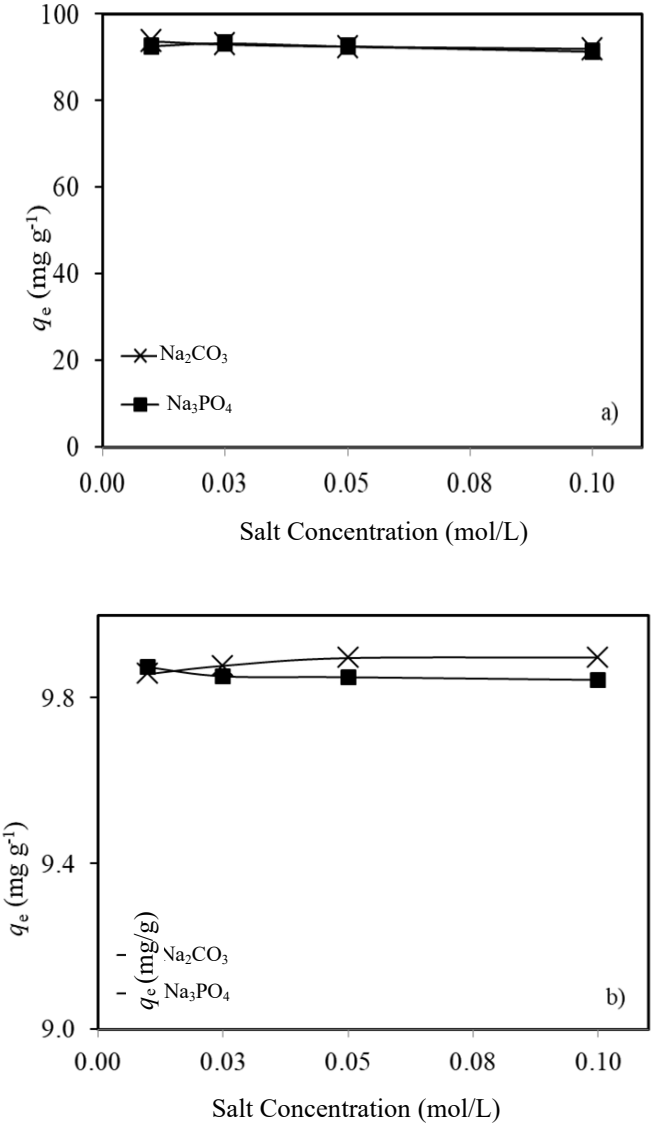

Figure 10. Effect of foreign salts on the adsorption efficiency of DWTS in the adsorption of a) BG b) RBBR

dye's natural pH, whereas the optimum pH for RBBR was determined to be 2.0. The equilibrium time for the most efficient adsorption of BG and RBBR was optimized as 90 min and 60 min, respectively. Using the Langmuir isotherm model, the maximum adsorption capacity of DWTS was obtained as 100 mg/g for BG and 38.9 mg/g for RBBR. This adsorption capacity is observed to be higher than many difficult-to-prepare adsorbents reported in the literature.

In further studies, it is suggested to investigate the potential of DWTS not only for the removal of other dyes but also for the removal of inorganic pollutants. Such studies may offer new opportunities for the development of environmentally friendly and economical adsorbents.

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