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REMOVAL OF REACTIVE RED DYE BY BLUE-GREEN ALGAE: A SUSTAINABLE WASTEWATER TREATMENT APPROACH

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ABSTRACT- This research focuses on the removal of Reactive Red dye from aqueous solutions utilizing blue-green algae as a low-cost and eco-sustainable biosorbent. Batch adsorption experiments were systematically performed to explore the influence of operational factors such as adsorbent dosage, Contact time, Temperature, Rpm, and pH on dye removal efficiency. The optimum adsorption conditions were identified as an adsorbent dose of 1g, contact time of 80 mins, temperature of 30°C, agitation speed of 60 rpm, and pH 6. Under these conditions, nearly 90% removal was obtained. The biosorbent also exhibited significant reusability, retaining above 75% efficiency after four successive cycles. These findings confirm that algal biomass can serve as a sustainable, renewable, and efficient adsorbent for treating dye wastewater.

Keywords- Blue-green algae, Reactive Red dye, Adsorption, Waste water Treatment.

I. INTRODUCTION

The release of synthetic dyes from textile and allied industries has become one of the major sources of water pollution worldwide. Dyes are extensively used in sectors such as textiles, leather, plastics and paper, however, nearly 10-15% of the total dyes produced each year are discharged into the environment through wastewater.[1] These effluents contain intense coloration that restricts light penetration, disturbing aquatic photosynthesis and the ecological balance of water bodies [2]. Moreover, most synthetic dyes possess complex aromatic structures that make them non-biodegradable, toxic, and sometimes carcinogenic, posing significant health

hazards to both aquatic life and humans [3],[4].

Among various synthetic dyes, Reactive Red dyes are widely employed in textile processing because of their brightness, stability and strong affinity toward fabrics. However, these properties also make them highly resistant to degradation through conventional wastewater treatment methods [5],[6]. Common techniques such as coagulation-flocculation, oxidation, filtration, and adsorption on activated carbon are widely used but are often constrained by high operating costs, energy demands, and the production of secondary sludge [7],[8]. Therefore, it is necessary to develop cost-effective, sustainable, and efficient alternatives for removing such dyes from wastewater. Biosorption has emerged as one of the most promising eco-friendly approaches for dye removal. This process uses biological materials of their derivatives to capture pollutants through various physiochemical interactions including ion exchange, and electrostatic attraction [9]. Several natural biosorbents such as bacteria [10], fungi [11], agricultural waste [12], and algae [13]- have been successfully explored in recent years. Among these, algae-based biosorbents have received special attention due to their wide availability, large surface area, and abundance of active functional groups like hydroxyl, carboxyl, and amino acids, which provide efficient binding sites for dye molecules [14],[15]. Additionally, their renewable nature and adaptability to diverse environments make algae a sustainable biosorbent source [16],[17].

Both macroalgae (seaweeds) and microalgae have been efficiently used for the adsorption of reactive and acidic dyes from wastewater [18]. Algal biomass can also be cultivated using nutrient-rich effluents, supporting a circular economy by reducing both pollution and biomass production costs [19]. Among different algal types, blue-green algae have shown exceptional biosorption ability because of their unique cell wall composition and photosynthetic properties [20],[21]. Their cell surface contains proteins, lipids and polysaccharides that enable multiple interactions with dye molecules, such as hydrogen bonding, ion exchange, and electrostatic attraction. Previous studies have demonstrated that Spirulina platensis and related cyanobacteria can achieve dye removal efficiencies exceeding 85-90% under optimized conditions [22]-[24]. The adsorption performance of algae largely depends on operational parameters such as adsorbent dosage, contact time, temperature and agitation speed [25],[26].and optimizing these factors

helps to understand the mechanism and improve process efficiency. Furthermore, reusability is a vital aspect of biosorbent applicability. Algal adsorbents have shown excellent regeneration potential, retaining high adsorption capacity even after several cycles, with only minor reductions due to surface site exhaustion [27]-[29]. Hence algal biomass provides an eco-friendly and economical alternative to conventional adsorbents like activated carbon [30].

In the present study work, blue-green algae were employed as a natural biosorbent for removing Reactive Red dye from aqueous solutions. Batch adsorption experiments were carried out to evaluate the effects of adsorbent dose, contact time, temperature, Rpm, pH on dye removal. Adsorption kinetics were studied using pseudo second order and intra particle diffusion models to understand the mechanism and reusability studies were conducted to assess long term performance. This study aims to establish an efficient low-cost, and sustainable treatment method for dye-contaminated wastewater using algal biosorbents.

II. MATERIALS AND METHODS-

The materials used in this study included Corafix Reactive Red dye as the target pollutant and Blue-green algae as the adsorbent. Analytical grade HCL and NaOH were used to adjust the solution pH. The experimental setup consisted of a Horizontal Shaker, UV-visible spectrophotometer for analysis and a pH meter.

III. EXPERIMENTAL

Batch adsorption experiments were performed by a fixed amount of algal biomass with 100ml of dye solution at varying initial concentrations. The dye stock solution of 1000ml was prepared using distilled water and diluted to desired concentrations The influence of different process parameters such as adsorbent dose, contact time, temperature, agitation speed and pH was evaluated to determine the optimal conditions for maximum dye removal. The residual dye concentration was analyzed using a UV Spectrophotometer at the maximum adsorption wavelength of 580nm, determined by Beer-Lamberts law. The adsorption capacity t (qt) and equilibrium (qe) were calculated using the following equations.

$$q_t = \frac{(C_0 - C_t)V}{m}$$

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (2)$$

Where Co, Ct and Ce represent the initial, time-dependent and equilibrium concentrations respectively. V is the volume of solution and m is the adsorbent mass.

The equilibrium data were further analyzed using kinetic models such as pseudo second order and intraparticle diffusion model to interpret the adsorption mechanism.

IV. RESULT AND DISCUSSION-

4.1 Effect of Adsorbent dose

The adsorbent dosage is one of the most critical parameters influencing adsorption efficiency, as it determines the availability of surface-active sites for the dye molecule. In this study, the adsorbent dose was varied from 0.5-3g to evaluate its effect on the removal of Reactive Red dye. The results revealed that dye removal efficiency increased sharply from 65% at 0.5g to 90% at 1 g. The initial rise in removal efficiency can be due to increased surface area and number of active sites for adsorption. Therefore, optimized dose of 1g was selected for the experiments to ensure maximum removal efficiency.

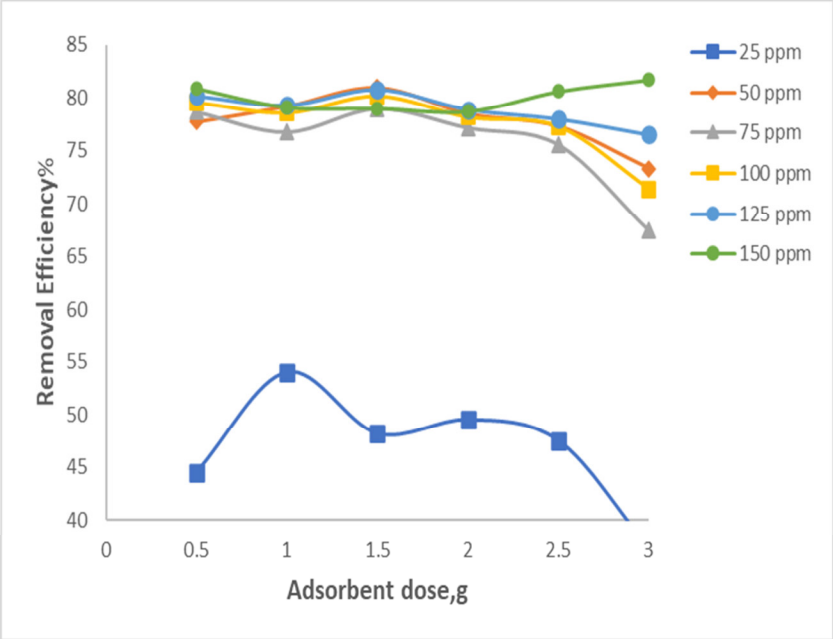

Fig no 1. Effect of Dosage

4.2 Effect of Contact time

The rate of adsorption is initially rapid, as adsorption sites are available for dye molecule. As shown in fig 2 the removal of Reactive Red dye increased steadily with time, reaching equilibrium at 80 minutes, where maximum adsorption of 90% was observed. During the first 40-60 minutes, a high rate of dye uptake occurred due to the abundant availability of active binding sites. The adsorption rate slowed down and eventually reached equilibrium because of site saturation and intra-particle diffusion

resistance. This behavior indicates that the adsorption process is controlled by both surface adsorption and inner pores of the algal biomass. The optimized time observed is 80 minutes.

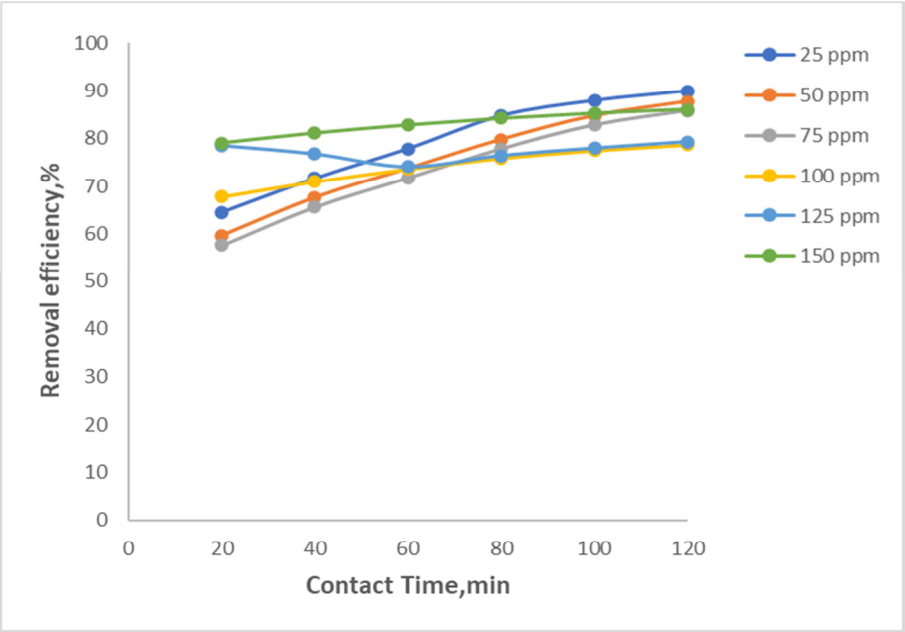

Fig. 2. Effect of Contact time.

4.3 Effect of Temperature

Temperature significantly affects the adsorption process by influencing the dye-adsorbent interaction, diffusion rate, and solubility of the dye molecules. Experiments were conducted at 30-50 °C. The maximum removal efficiency of 90% was obtained at 30°C, while a gradual decline was observed beyond this temperature. The decrease in adsorption efficiency of temperature shows that the process is exothermic in nature. Higher temperatures tend to weaken the van der Waals and electrostatic interactions between dye molecules and the algal surface. Hence the optimized temperature was 30°C.

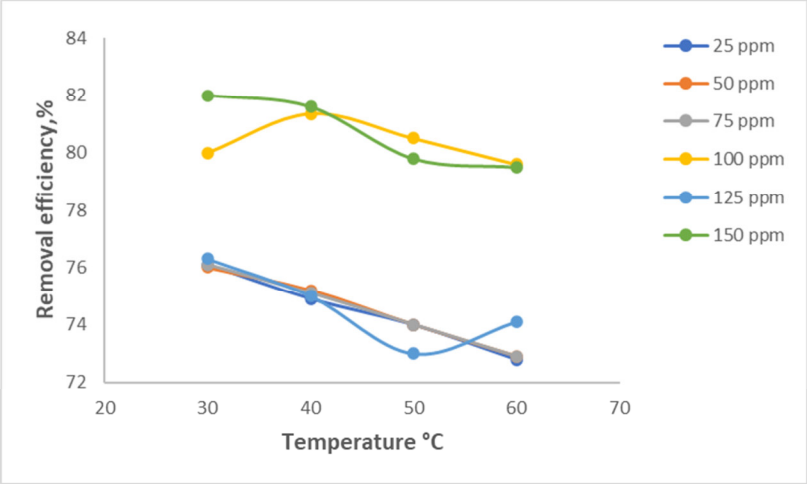

Fig. 3. Effect of Temperature

4.4 Effect of Agitation speed

Agitation speed plays a major role in enhancing the mass transfer rate of dye molecules from the bulk solution to the surface of the adsorbent. Experiments were performed at agitation speeds ranging from 60-120 rpm. The adsorption efficiency increased with increasing agitation speed up to 60 rpm, achieving 90% removal, beyond which it showed slight decrease. At low agitation speeds (below 60 rpm), the diffusion of dye molecules toward the algal surface is relatively slow, leading to lower adsorption rates.Excessively high agitation speeds may disrupt the adsorbent-adsorbate equilibirum causing partial desorption of previously attached dye molecules.Thus 60 rpm was the optimum agitation speed for maximum dye uptake.

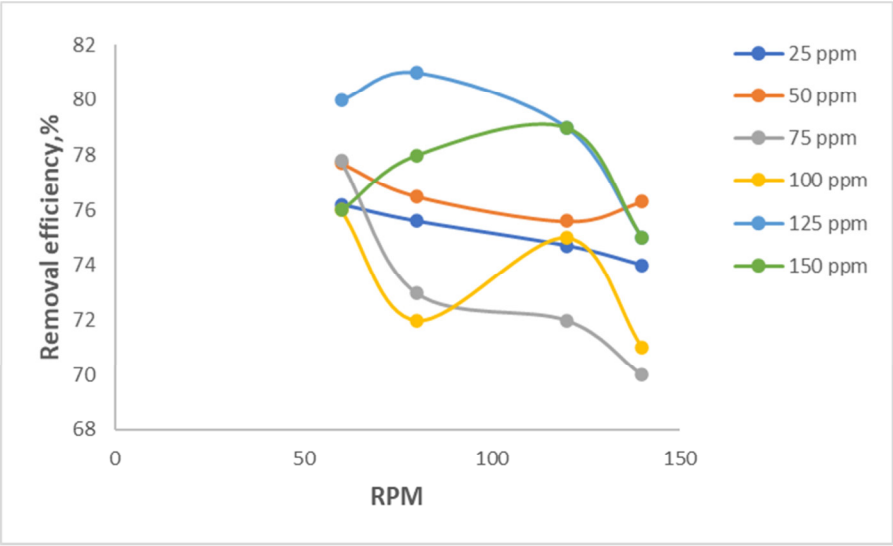

Fig. 4. Effect of agitation speed

4.5 Effect of pH

The pH of the solution is a key parameter influencing both the surface charge of the biosorbent and the degree of ionization of dye molecules. Experiments were conducted at pH values ranging from 2-10. The adsorption efficiency increased with pH up to pH 6, after which a decline was noted. At low pH values, the high concentration of hydrogen ions (H^+) competes with cationic sites on the dye molecules for active adsorption sites, resulting in lower adsorption. At neutral pH 6, the blue green algal surface carries negatively charged functional groups such as carboxyl (-COO-) and phosphate (-PO_4^{3-}), which strongly attract the charged reactive dye molecules through electrostatic attraction and hydrogen bonding. Beyond pH 7, adsorption decreases again due to increased electrostatic repulsion between negatively charged dye ions and algal surfaces. The optimum pH for adsorption was determined as 6.

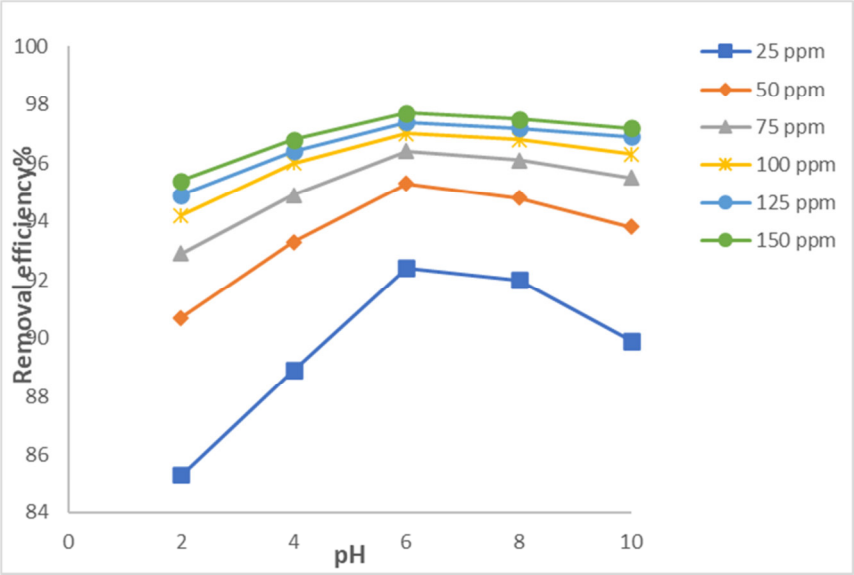

Fig. 5. Effect of pH

V. ADSORPTION KINETICS

5.1 Intraparticle Diffusion model

Intraparticle diffusion model was proposed by Weber and Morris. According to this model, adsorption occurs in multiple stages involving boundary layer diffusion and intraparticle diffusion. The linear form of the model is represented by equation(1).

$$qt = k_p t^{0.5} + C \text{----------(1)}$$

where k_p is the rate constant of intraparticle diffusion (mg g^{-1} $min^{0.5}$), qt is the amount of dye adsorbed at time t

(mg/g), t is the contact time (min), and C represents the thickness of the boundary layer.

The plots of qt versus t for different dye concentrations(25-150 ppm) are shown in fig 6. The obtained lines were multi-linear and did not pass through the origin, indicating that intraparticle diffusion was not the rate controlling step. The first linear portion represents film diffusion while the second portion corresponds to intraparticle pore diffusion. The increase in C values at higher concentrations signifies a greater boundary layer effect, confirming that both film and intraparticle diffusion govern the overall adsorption rate.

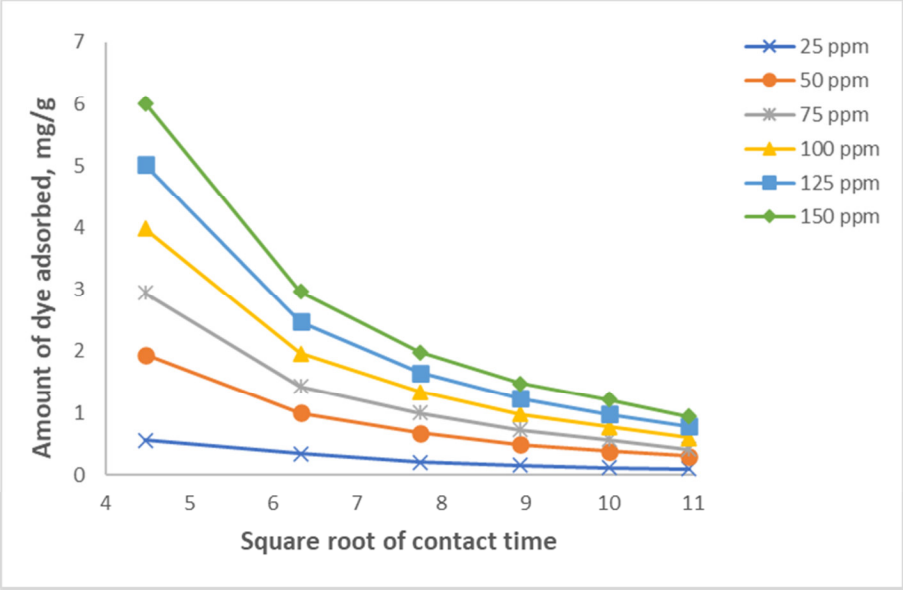

Fig. 6. Intraparticle Diffusion Model

5.2 Pseudo Second Order Model

The pseudo second order kinetic model was applied to describe the adsorption behaviour of Reactive Red dye on blue-green algae. This model assumes that chemisorption is the rate -controlling step and that the rate of adsorption does not depend on the initial dye concentration. The linearized form of the model is expressed by equation(2).

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t$$

Where,

qt = amount of dye adsorbed at time t (mg g^{-1})

qe = amount of dye adsorbed at equilibrium (mg g^{-1})

t= Contact time (min)

k_2 = pseudo second order rate constant (g mg^{-1} min^{-1}).

A linear relationship was obtained between t/qt and t for all initial dye concentrations (25-150 ppm) as shown in fig 7. The high correlation coefficients (R^2) indicate that adsorption of Reactive Red dye onto blue-green algae follows the pseudo second-order kinetic model.

This confirms that chemisorption involving electron exchange between the dye molecules and functional groups such as -OH, -COOH, -NH2 on the algal surface governs the adsorption process.

The calculated values of k^2 and R^2 are presented in table 2.

Table 2. Rate constant and correlation coefficient for pseudo second-order model

Initial concentration, mg/L	Rate constant g/mg min-1	R2
25	0.296	0.999
50	0.211	0.998
75	0.176	0.997
100	0.138	0.996
125	0.119	0.995
150	0.105	0.994

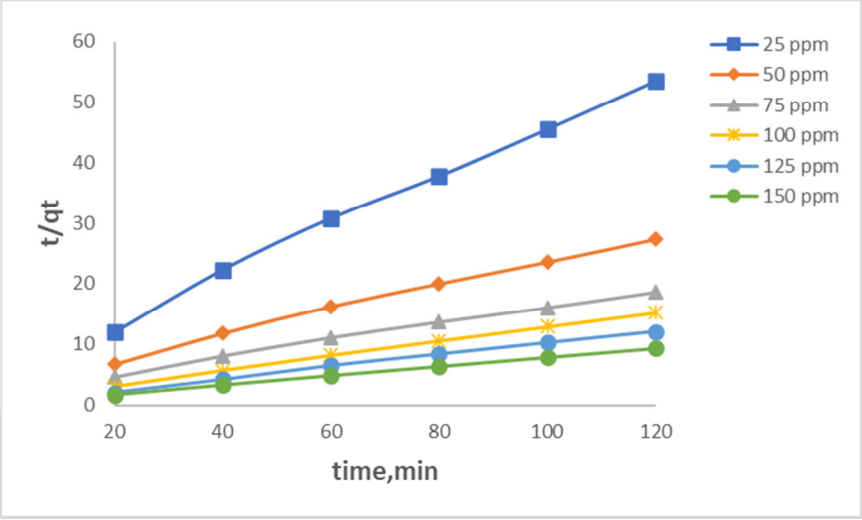

Fig. 7. Pseudo Second Order Model

VI. RESUABILITY STUDY

A strong reusability potential of the adsorbent is an important factor for environmental sustainability and economic feasibility.The regeneration ability of blue-green algae was evaluated for four consecutive adsorption-desorption cycles using Reactive Red dye under optimized conditions. After each cycle, the dye-loaded biomass was washed with 0.1 M NaOH solution, rinsed with distilled water, and dried at 60°C before reuse. The removal efficiency was found to be 90% for the first cycle, which gradually decreased to 86%, 82%, and 78% for the second, third, and fourth cycles respectively. The major reason was the active sites of dye molecules. Despite this decrease, the adsorbent retained more than 75% efficiency after four cycles, demonstrating good regeneration potential, structural stability, and suitability for sustainable wastewater treatment applications.

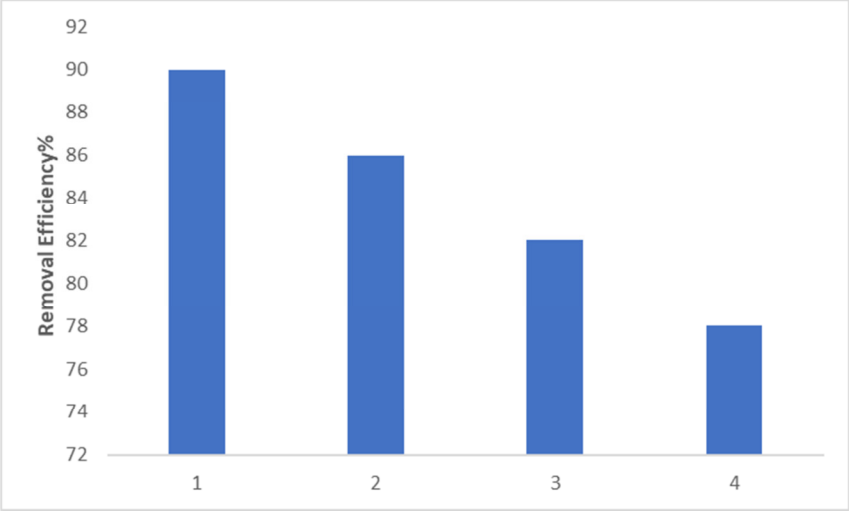

Fig. 8. Reusability of adsorbent

VII. CONCLUSION

The present study demonstrated that blue-green algae is an effective and eco-friendly biosorbent for the removal of Reactive Red dye from aqueous solutions. The adsorption process was influenced by parameters such as adsorbent dose, contact time, temperature, agitation speed, and pH, with the optimum conditions found to be 1 g dose, 80 min contact time, 30°C, 60 rpm and pH 6. Under these conditions, a maximum dye removal efficiency of about

90% was achieved. Kinetic studies indicated that the adsorption followed the pseudo second order model, suggesting chemisorption as the rate-controlling mechanism, while the intraparticle diffusion model confirmed a multi-step diffusion process. The reusability tests showed that the adsorbent maintained more than 75 % efficiency even after four cycles, highlighting its good regeneration capability. Overall the study confirms that blue-green is a sustainable, low-cost and efficient biosorbent suitable for industrial waste water treatment applications.

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