

Study of Biosorption of RB 222 Dye using *Aspergillus niger* Biomass

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ABSTRACT

Synthetic dyes, especially those released from textile industries, are recognized as one of the most harmful groups of pollutants because of their complex aromatic structures, stability, and resistance to degradation. Conventional treatment methods are often expensive and generate secondary pollutants, which limits their large-scale applicability. In recent years, biosorption has emerged as a sustainable and eco-friendly alternative for dye remediation, as it shows advantages such as low cost, high efficiency, and utilization of biological materials as sorbents. Among various microbial biosorbents, fungal biomass has been particularly promising because of its surface characteristics and availability of functional groups that facilitate pollutant binding. In this study, the biosorption potential of *Aspergillus niger* biomass was evaluated for the removal of Reactive Blue 222 dye from aqueous solutions under varying physicochemical conditions. The results of the study indicated that biosorption performance was strongly influenced by the tested parameters and the maximum dye removal was achieved at pH 3, contact time of 1.5 hours, dye concentration of 50 mg/L, agitation speed of 80rpm and biomass dosage of 200mg. The reusability of the biomass was also examined through desorption experiments, demonstrating its potential for repeated application with minimal loss of efficiency. Overall, the findings confirm that *Aspergillus niger* biomass is a highly effective, low-cost, and environmentally benign biosorbent for the removal of synthetic dyes, making biosorption a useful method for treating dye-contaminated wastewater.

KEYWORDS: Biosorption, *Aspergillus niger*, Reactive Blue 222 dye, Optimization.

1.INTRODUCTION

Synthetic dyes are extensively used in textile, paper, printing industries and dyehouses due to their greater stability, a wider range of colors, cost effectiveness, and easier application compared to natural dyes [2] [12]. Among these, the diversity of colors and intensities of azo dyes, their resistance to physical, chemical, and biological effects as well as long half-life in laboratory tests make them the most widely used dyes in the textile industry [7] [21]. This resistance comes from the presence of azo (-N=N-) bonds connected to aromatic amines and benzene or naphthalene rings, which make them resistant to cleavage. This is an attribute that the industry desires, but it poses a risk to the environment [12]. The annual production of azo dyes is estimated at 9×10^6 tons per year however, 10–25% of the dyes used in textile processing are lost during garment fabrication, and up to 20% are discharged as effluents into water bodies without any treatment [21]. These effluents are heavily coloured, contain high concentrations of salt and exhibit high biological oxygen demand (BOD) and chemical oxygen demand (COD) values [24]. The presence of dyes in water bodies reduces light penetration, thereby inhibiting photosynthesis in aquatic ecosystem, while associated toxic components such as heavy metals and aromatic amines pose serious risks to environmental and human health, including irritation, respiratory complications, methemoglobinemia, and potential carcinogenic effects [2] [3] [16].

Conventional treatment methods for dye-laden wastewater include physical (adsorption, membrane filtration), chemical (coagulation–flocculation, advanced oxidation, electrochemical processes), and biological approaches (microbial and enzymatic degradation). Although these methods have been successfully employed in various contexts, their technical limitations, operational challenges, and environmental drawbacks underscore the need for more sustainable alternatives, paving the way for interest in biosorption as a green technology [16]. Biosorption is a physicochemical process that relies on several mechanisms such as- physical and chemical adsorption, electrostatic attraction, ion exchange, complexation, chelation, and micro-precipitation-which mainly occur on the cell walls of plants and microorganisms [4]. Unlike conventional methods, biosorption is cost-effective, eco-friendly, and capable of achieving high removal efficiency without generating toxic by-products or sludge [16]. Fungal biomass is found to be an attractive biosorbent for removing dyes from dye laden wastewater as it can be produced cheaply and can also be obtained from various industrial fermentation processes [10]. Moreover, biosorption offers advantages such as reusability of biosorbents, applicability to a wide range of pollutants, and effectiveness even at low pollutant concentrations, where many conventional techniques fail. These attributes make biosorption a sustainable and practical approach for addressing the global challenge of dye pollution. Therefore, the present study was undertaken to evaluate the biosorption activity of *Aspergillus niger* biomass and to analyze the effect of different physicochemical parameters on its efficiency for the removal of Reactive Blue 222 dye (Figure 1).

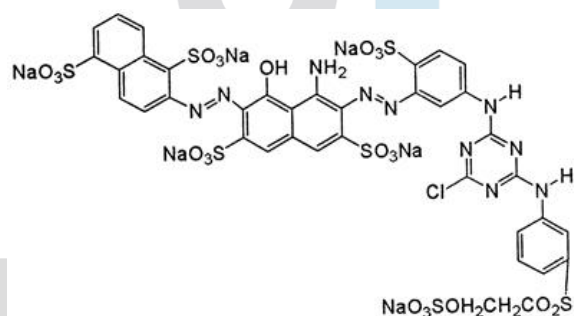


Figure 1. Chemical structure of Reactive Blue 222 dye [26].

2. MATERIALS AND METHODOLOGY

2.1. Microorganism and Growth Condition

Aspergillus niger was used as the biosorbent. Potato Dextrose Agar (PDA) was chosen as the primary solid medium for maintaining and obtaining pure, actively growing *Aspergillus niger* inoculum [23]. Potato Dextrose Agar medium was prepared by suspending 7.2 grams of potato dextrose broth powder and 3.5 grams of agar in 100ml of distilled water. The mixture was heated to dissolve agar completely. The medium was sterilized by autoclaving at 121°C for 30–45 minutes to eliminate any contaminants. Sterile Potato Dextrose Agar was allowed to cool to about 45–50 °C before being poured aseptically into sterile Petri plates; the medium was allowed to solidify before inoculating with *Aspergillus niger*. Once the medium solidified, *Aspergillus niger* was streaked onto solid Potato Dextrose Agar plates using a sterile inoculating wire loop. The inoculated plates were incubated inverted at 37°C until well-developed, sporulating colonies were visible [14]. (Figure 2).



Figure 2. *Aspergillus niger* Fungal Colony

2.2. Preparation of Fungal Biomass

Sterile Potato Dextrose Broth was prepared by adding 4.8 grams of Potato Dextrose Broth powder in 200ml distilled water in conical flasks. The broth was sterilized by autoclaving at 121°C for 30-45 minutes to eliminate any contaminants. For experimental purposes, fungal biomasses were obtained by aseptically transferring mycelia from the Potato Dextrose Agar spread-plate cultures using sterile borer and forceps to 200mL of Potato Dextrose Broth (PDB) [24].

After the completion of submerged cultivation in potato dextrose broth (PDB), the fungal biomass was harvested to prepare it for biosorption experiments [24]. The culture was first filtered to separate the biomass from the liquid medium [14]. The collected biomass was then washed thoroughly with distilled water to remove any residual nutrients and medium components [30]. Following washing, the biomass was subjected to drying at 40°C to reduce moisture content and stabilize the material for subsequent use [30]. The dried biomass was then ground using a mixer to obtain a uniform smaller particle. [14]. It was then passed through a sieve to get uniform particles. The resulting dried and sieved *Aspergillus niger* biomass provided a stable, uniform, and high-surface-area material suitable for subsequent biosorption experiments, ensuring reproducibility and accuracy in evaluating dye removal efficiency [14] [30].

2.3. Preparation of pH Buffers for Biosorption Studies

To investigate the influence of pH on the biosorption efficiency of *Aspergillus niger*, aqueous solutions were prepared at pH values of 2, 3, 5, 7, and 9. These pH levels were selected based on their relevance to environmental conditions and their impact on the biosorption process. The pH of each solution was adjusted using 1N hydrochloric acid (HCl) and 1N sodium hydroxide (NaOH) to achieve the desired pH values [20]. The pH was checked using acidic/ basic litmus paper, monitored and maintained throughout the biosorption experiments to ensure consistency.

2.4. Preparation of the adsorbate

To assess the biosorption capacity of *Aspergillus niger* for Reactive Blue 222, a stock dye solution was prepared by dissolving 300 mg of the dye in 1 litre of distilled water, resulting in a concentration of 300 mg/L [24]. The dye was sourced from DyStar India Pvt.Ltd.

2.5. Decolorization Assay

The biosorption experiments were conducted in BOD bottles containing 50 mL of dye solution of predetermined concentration. A known weight of dried *Aspergillus niger* biomass was added to each flask

containing dye solution, and the mixtures were maintained under specified conditions. To evaluate the influence of different factors on dye removal i.e biosorption efficiency, the following parameters were studied individually while keeping the others constant.

- 1) Effect of pH-The influence of pH on biosorption was studied using buffer solutions of varying pH (2,3,5,7 and 9). Each flask contained 50 mL of Reactive Blue 222 solution of fixed concentration and a known amount of biomass i.e. 0.05g/50ml. The pH was maintained throughout the experiment, and samples were withdrawn after 30 mins to measure residual dye concentration [24].
- 2) Effect of Time- To study the kinetics of biosorption, flasks containing biomass and dye solution were placed on the shaker (80rpm) and at different time intervals (10 minutes, 30 minutes, 1 hour, 1.5 hours, and 2 hours) the samples were withdrawn to measure residual dye concentration [20].
- 3) Effect of Initial Dye Concentration-A series of dye solutions with concentrations ranging from 50 to 300 mg/L were prepared. A fixed amount of fungal biomass i.e. 0.05g/50ml was added to each flask, and biosorption was carried out under identical conditions. The residual concentration after 1.5 hours was measured to determine the effect of dye loading on biosorption efficiency [18].
- 4) Effect of Agitation Speed-To examine the role of mixing intensity, biosorption experiments were performed at different agitation speeds (70,80 and 90 rpm) using a shaker. Dye removal efficiency was compared under these conditions, keeping other parameters constant i.e. pH 3, Contact time-1.5 hours and initial dye concentration-50mg/L [27].
- 5) Effect of Biomass Concentration-Different amounts of fungal biomass (50,100,150 and 200 mg/50 mL) were added to dye solutions of constant concentration. The percentage decolorization was measured to evaluate the effect of biosorbent dosage [21].

After the shaking period, samples were filtered using a strainer and a filter paper to separate biomass from the supernatant.

The residual dye concentration in the supernatant was analysed using a colorimeter at 620nm which is the λ_{max} of Reactive Blue 222 dye.

The percentage decolorization (biosorption efficiency) was calculated using the following formula:

$$\% \text{ sorption} = \frac{(C_i - C_f)}{C_f} * 100$$

where

C_i is the initial dye concentration (mg/L) and

C_f is the final dye concentration (mg/L) after biosorption. [24].

3.RESULT AND DISCUSSION

3.1. Factors Affecting Biosorption

This study focused on evaluating the factors affecting the biosorption of Reactive Blue 222 dye using *Aspergillus niger* dry biomass. Five key parameters were investigated: pH, contact time, initial dye concentration, agitation speed, and biosorbent concentration. In addition, desorption and reusability experiments were conducted to assess the regeneration potential of the biosorbent.

The efficiency of dye removal was expressed as percent sorption (%S), which was calculated using a formula. Using this approach, the impact of each parameter on dye removal efficiency was systematically analyzed and the results are presented in the following sections.

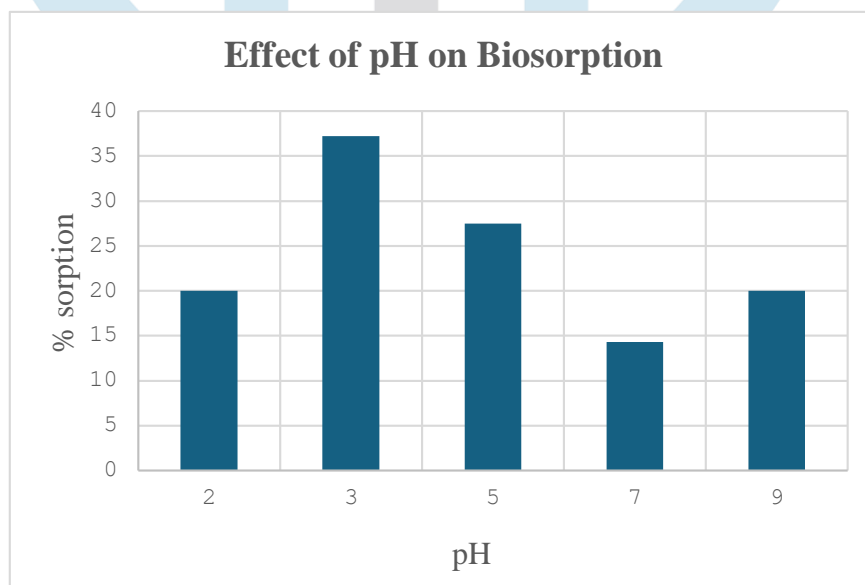
The efficiency of biosorption is strongly influenced by several operational parameters, including pH, contact time, initial dye concentration, agitation and biosorbent dosage. These factors determine the interaction between dye molecules and the functional groups present on the biosorbent surface, thereby influencing the overall adsorption capacity.

Among these parameters, solution pH plays a crucial role, as it affects both the ionization state of the dye molecules and the surface charge of the biosorbent.

3.1.1. Effect of pH on biosorption of Reactive Blue 222 dye:

In this study, the influence of solution pH on the biosorption efficiency of dead *Aspergillus niger* biomass was tested across pH values 2, 3, 5, 7, and 9.

The results showed that pH 3 yielded the highest %sorption of Reactive Blue 222. At pH 2, the removal was lower, while beyond pH 5 the biosorption efficiency gradually decreased (Graph 1).



Graph 1. Effect of pH on biosorption

The dye molecule has net negative charges in aqueous solution which are favourable for positive sites present on the fungal biomass. The strong performance at pH 3 can be explained by the ionization states of the biomass functional groups and the dye molecules. As the pH of the solution decreases and becomes more acidic, the concentration of protons (H^+ ions) in the solution increases. These protons interact with the amino groups ($-NH_2$) present on the chitosan molecules of the fungal cell wall. When these amino groups accept protons, they get converted into positively charged $-NH_3^+$ groups. The presence of these positive charges enhances the electrostatic attraction between the chitosan on the biomass and the negatively charged groups on the dye

molecules. As a result, more dye molecules are attracted and bound to the fungal biomass, leading to an increase in dye adsorption [2].

At very low pH (e.g., pH 2), the excess of H^+ ions compete with dye molecules for negatively charged binding sites, leading to reduced uptake.

In contrast, under alkaline or basic conditions (higher pH), the surface of the fungal biomass develops more negative charges. These negatively charged sites repel the negatively charged dye molecules, which reduces the biosorption capacity. Moreover, at higher pH, the concentration of hydroxide ions (OH^-) in the solution increases. These OH^- ions compete with the dye molecules for the available adsorption sites on the biomass. This competition further lowers the amount of dye that can be adsorbed. Therefore, the overall sorption efficiency decreases as the solution becomes more basic [24].

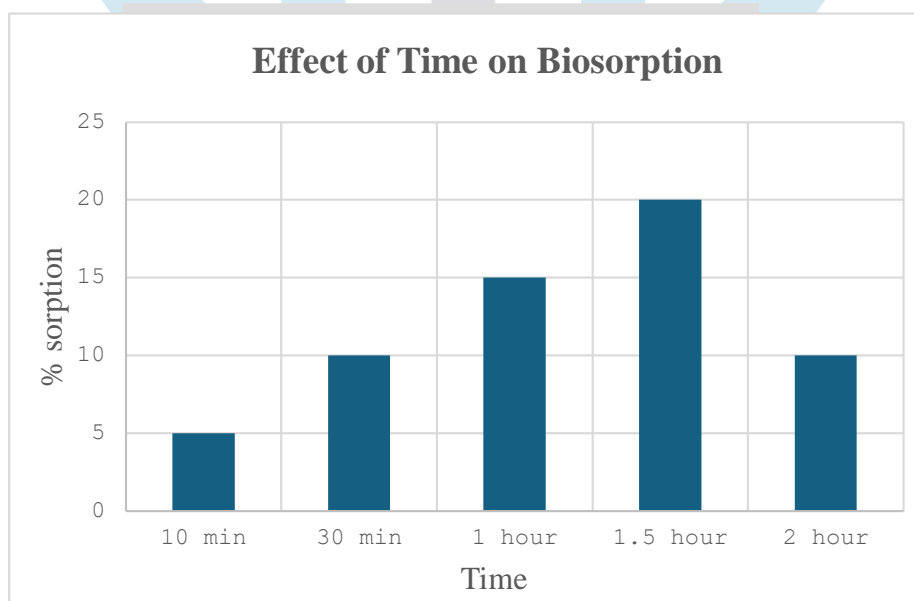
Saraf & Vaidya, (2015) performed comparative study of biosorption of textile dyes using fungal biosorbents and reported that the maximum sorption for all the anionic dyes was seen at pH 2, similar results were seen for Acid Red 151, while there was a sudden decrease in biosorption at pH 3 for Reactive Orange 16.

These results confirm that *Aspergillus niger* biomass is most effective under slightly acidic conditions, making pH control an essential factor in optimizing biosorption of Reactive Blue 222.

3.1.2. Effect of Contact Time on biosorption of Reactive Blue 222 dye:

The effect of contact time on the biosorption of Reactive Blue 222 by *Aspergillus niger* dry biomass was studied at different intervals: 10 minutes, 30 minutes, 1 hour, 1.5 hours, and 2 hours.

The results showed that the biosorption efficiency increased with increasing contact time, with the maximum % sorption observed at 1.5 hours. Beyond this period, no significant increase in dye removal was recorded, indicating that equilibrium had been reached (Graph 2).



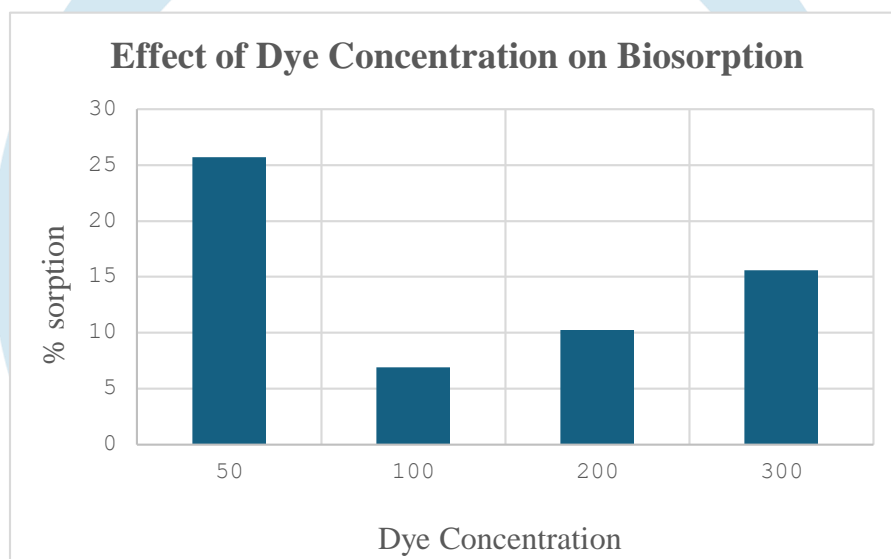
Graph 2. Effect of time on biosorption

The rapid increase in sorption during the initial stages (10–60 minutes) can be attributed to the abundant availability of vacant binding sites on the fungal cell wall surface, which allowed dye molecules to be readily adsorbed. As the contact time increased, the rate of sorption gradually slowed due to the progressive saturation of available sites and the development of repulsive forces between the dye molecules on the biomass surface and those in solution. At 1.5 hours, equilibrium was established, with the maximum biosorption efficiency recorded. The lack of significant change between 1.5 and 2 hours suggests that nearly all accessible active sites were occupied repulsive forces between the dye molecules on the biomass surface and those in solution. K.

Nanthakumar *et al.*,(2009) reported that the equilibrium time required for the maximum removal of Reactive blue 140 by *Aspergillus niger* dead biomass was 135 minutes at all dye concentrations studied, and it remained constant after the equilibrium time period. Thus, the present study confirms that 1.5 hours is the optimum contact time for maximum biosorption of Reactive Blue 222 by *Aspergillus niger*.

3.1.3. Effect of Initial Dye Concentration on biosorption of Reactive Blue 222 dye:

The influence of initial dye concentration on the biosorption efficiency of *Aspergillus niger* dry biomass was investigated using four concentrations: 50 mg/L, 100 mg/L, 200 mg/L, and 300 mg/L. The results showed that maximum percent sorption was observed at 50 mg/L, while a progressive decline in percentage removal occurred as the initial concentration increased (Graph 3).

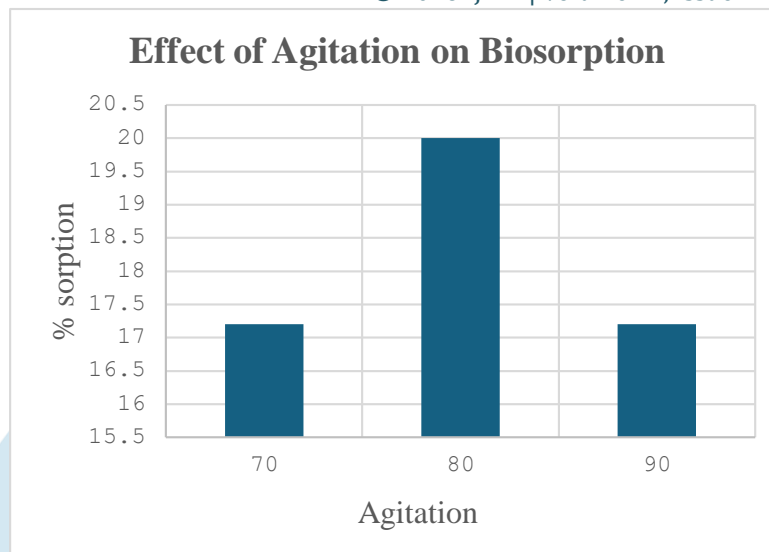


Graph 3. Effect of dye concentration on biosorption

At lower dye concentrations (50 mg/L), the biosorbent surface had a large number of available and unoccupied binding sites relative to the number of dye molecules present. This favourable ratio allowed for higher sorption efficiency, resulting in maximum dye removal. However, as the dye concentration increased to 100–300 mg/L, the availability of binding sites became a limiting factor. With more dye molecules competing for the same number of sites, the biosorbent reached saturation more quickly, leading to a reduced percentage removal despite the higher absolute amount of dye adsorbed. This behaviour is consistent with adsorption principles, where %removal is typically higher at lower solute concentrations due to excess binding site availability, whereas biosorption capacity (mg/g) increases with concentration until equilibrium is reached. These findings are consistent with previous studies reported by Kumud Kumari *et al.*,(2007), where adsorption by *S. cerevisiae* and *R. nigricans* was found to be highest for all dyes at an initial dye concentration of 50 mg/ml, hence maximum percentage dye removal was achieved at lower concentrations, and efficiency decreased as initial dye concentration increased. Thus, the present results demonstrate that *Aspergillus niger* biomass is most effective at treating effluents with lower initial dye concentrations (e.g., 50 mg/L), highlighting the importance of optimizing dosage and pre-treatment strategies for higher concentration wastewaters.

3.1.4. Effect of Agitation Speed on biosorption of Reactive Blue 222 dye:

The impact of agitation speed on the biosorption efficiency of *Aspergillus niger* dry biomass was studied at 70 rpm, 80 rpm, and 90 rpm. The results showed that maximum %sorption was achieved at 80 rpm, while both lower (70 rpm) and higher (90 rpm) agitation speeds resulted in comparatively lower dye removal (Graph 4).

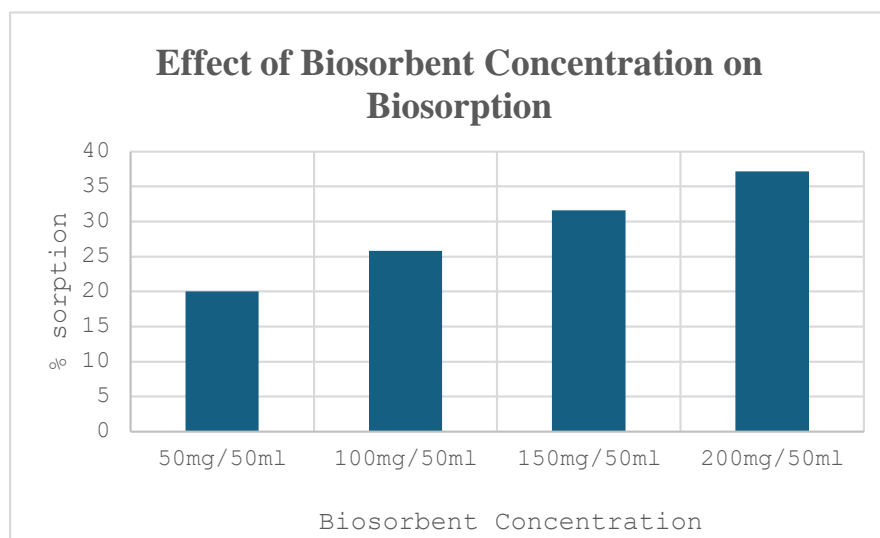


Graph 4. Effect of agitation on biosorption

Agitation plays a crucial role in biosorption as it influences the distribution of dye molecules in solution and the mass transfer rate between the bulk liquid and biosorbent surface. At lower agitation speeds (70 rpm), the limited mixing may have reduced the contact between dye molecules and the biosorbent surface, leading to lower sorption efficiency. Increasing agitation to 80 rpm enhanced the interaction between biomass and dye molecules by preventing settling of the biosorbent and improving surface availability, thereby achieving maximum dye removal. However, further increasing agitation speed to 90 rpm resulted in a decrease in biosorption efficiency. This reduction may be attributed to shear forces and turbulence, which can disrupt the dye–biosorbent interactions and cause desorption of dye molecules from the biomass surface. Moreover, excessive agitation may damage the surface structure of the biosorbent, reducing the effective number of available binding sites. These results are consistent with earlier studies, where an optimum agitation rate was reported for maximum biosorption, beyond which removal efficiency decreased due to desorption and reduced contact stability. Saraf and Vaidya (2016) performed the statistical optimization for competitive biosorption of Reactive Orange 13 and Reactive Blue 222 by *Rhizopus arrhizus* and reported that the maximum sorption for Reactive Orange 13 and Reactive Blue 222 was achieved at the speed of agitation of 80 rpm. The findings of the present study thus confirm that *Aspergillus niger* biomass performs best at moderate agitation (80 rpm) for removal of Reactive Blue 222.

3.1.5. Effect of Biosorbent Concentration on biosorption of Reactive Blue 222 dye:

The effect of biosorbent concentration on dye removal efficiency was examined using varying amounts of *Aspergillus niger* biomass (50 mg, 100 mg, 150 mg, and 200 mg) in a fixed volume of 50 mL of dye solution. The results showed that the maximum percent sorption was observed at 200 mg of biomass, with sorption efficiency increasing progressively as the biosorbent concentration increased (Graph 5).



Graph 5. Effect of biosorbent concentration on biosorption

The increase in biosorption efficiency with rising biomass concentration can be attributed to the greater number of available binding sites provided by the higher amount of *A. niger* biomass. At lower biomass concentrations (50–100 mg), the limited surface area restricted the number of dye molecules that could be adsorbed. As the biosorbent concentration increased to 200 mg, the availability of functional groups such as carboxyl, hydroxyl, amino, and phosphate groups on the fungal cell wall increased significantly, allowing more dye molecules to bind and resulting in maximum percent sorption. This trend has been widely reported in biosorption studies, where increasing biomass dosage enhances the removal efficiency due to the presence of more active sites for sorption. However, it is also known that beyond a certain concentration, the efficiency may plateau or even decrease due to aggregation of biomass particles, which reduces the effective surface area and accessibility of binding sites. In the present study, the maximum sorption observed at 200 mg indicates that this concentration was optimal under the experimental conditions (Graph 5) Neves, A.G.D. *et al.*, (2024) studied the effect of *Aspergillus* biomass for the removal of Direct Black 22 dye in which it was reported that the decolorization was directly proportional to the amount of biosorbent applied; thus, the more biomass, the faster the decolorization.

Thus, the findings confirm that biosorbent concentration is a crucial parameter, with higher biomass amounts favouring increased dye removal up to an optimum level.

The study revealed that biosorption of Reactive Blue 222 by *Aspergillus niger* biomass is strongly influenced by multiple parameters. The optimum conditions were found at pH 3, contact time of 1.5 hours, dye concentration of 50 mg/L, agitation speed of 80 rpm, and biomass dosage of 200 mg. Desorption and reusability studies further confirmed that the biomass can release adsorbed dye under alkaline conditions and be reused, though with reduced efficiency. These results highlight the potential of *A. niger* biomass as a low-cost, eco-friendly, and reusable biosorbent for textile dye wastewater treatment.

3.2. Desorption and Reusability Studies of *Aspergillus niger* biomass-

3.2.1. Desorption

The desorption of Reactive Blue 222 from *Aspergillus niger* biomass was evaluated to determine whether the dye-loaded biomass could release the adsorbed dye under alkaline conditions. For this, 200 mg of dye-loaded biomass was treated with 50 mL of alkaline solution at pH 10.5, with a contact time of 1.5 hours and agitation speed of 80 rpm. The initially transparent alkaline solution turned blue, indicating that the dye previously bound to the biomass was released and the λ_{max} of the desorbed solution matched that of Reactive Blue 222

dye (620 nm), confirming that the released compound was the same dye. The desorption efficiency was calculated to be 83.67%, confirming that the biomass had successfully adsorbed dye in the biosorption stage and could release it under alkaline conditions [22].

3.2.2. Reusability

The reusability of the biomass after desorption was then tested by reapplying the same 200 mg of *A. niger* biomass under the previously optimized biosorption conditions: pH 3, contact time 1.5 hours, dye concentration 50 mg/L, agitation speed 80 rpm, and biosorbent concentration 200 mg. After 1.5 hours, the absorbance of the solution at 620 nm was found to be 0.26, corresponding to a final dye concentration of 37.14 mg/L (as determined from the standard calibration curve). From these values, the percent sorption was calculated as 25.72%, showing that the biomass retained some capacity to adsorb dye even after one complete sorption–desorption cycle.

The high desorption efficiency (83.67%) indicates that alkaline conditions effectively reverse the dye–biomass interactions, likely due to the deprotonation of functional groups (carboxyl, hydroxyl, and phosphate groups) on the fungal cell wall, which leads to electrostatic repulsion with the anionic dye molecule. The subsequent reusability test, however, demonstrated a reduced sorption efficiency (25.72%) compared to fresh biomass. This reduction can be explained by partial loss or inactivation of active sites during the desorption process and possible structural changes to the biomass surface caused by alkaline treatment. Although the efficiency decreased, the ability of the biomass to adsorb dye again confirms its potential for repeated use in wastewater treatment, making *A. niger* a cost-effective and sustainable biosorbent [21].

CONCLUSION

The findings of this study establish that biosorption using *Aspergillus niger* biomass is a highly promising, eco-friendly, and cost-effective technique for the removal of synthetic azo dyes such as Reactive Blue 222 from aqueous environments. Through systematic experimentation, it was observed that the biosorption process is not static but rather highly influenced by several physicochemical parameters, including pH, contact time, initial dye concentration, agitation speed and biomass dosage. Optimization of these parameters was found to significantly enhance the removal/biosorption efficiency, indicating that careful adjustment of experimental conditions is crucial for maximizing the performance of biosorbents. Among the tested variables, pH and biomass dosage were particularly critical, as they determined the availability of active binding sites and the surface charge interactions between dye molecules and fungal cell wall functional groups.

The structural composition of *Aspergillus niger* biomass, enriched with diverse functional groups such as hydroxyl, carboxyl, amino, phosphate, and sulphate groups, played a decisive role in the adsorption of dye molecules. These functional groups facilitated electrostatic interactions, hydrogen bonding, and complexation mechanisms, thereby enhancing the biosorption potential. The results obtained are consistent with earlier reports on the ability of fungal biosorbents to act as efficient dye-binding agents, thereby validating the broader scientific understanding of microbial biomass as a renewable resource for wastewater treatment.

This study shows that biosorption is not only cost-effective but also overcomes one of the biggest challenges in bioremediation which is eliminating the need for constant biomass production when moving toward large-scale applications. Reusability further strengthens the argument for biosorption as a sustainable alternative to conventional treatment methods such as activated carbon adsorption, chemical precipitation, or advanced oxidation processes, which are often energy-intensive and generate hazardous by-products.

In a broader environmental context, this study provides evidence that microbial biosorbents like *Aspergillus niger* biomass can play a valuable role in the mitigation of water pollution caused by industrial effluents. Textile dyes are known to persist in the environment due to their complex aromatic structures and resistance to biodegradation. By employing biosorption, industries can adopt a low-cost, green, and efficient strategy to

meet environmental regulations while minimizing ecological damage. The eco-friendly nature of this process also aligns with the principles of sustainable development and the growing demand for cleaner production technologies.

In conclusion, this work not only highlights the efficiency of *Aspergillus niger* biomass as a biosorbent for Reactive Blue 222 dye but also strengthens the case for biosorption as a practical and scalable solution for wastewater treatment. Future research could emphasize a deeper understanding of the binding mechanisms through advanced analytical tools, conducting pilot-scale experiments on actual industrial wastewater, and exploring the combination of biosorption with other biological or physicochemical approaches to improve treatment efficiency. Thus, the present research contributes to bridging the gap between laboratory investigations and industrial applications, reinforcing the role of biosorption as a viable, sustainable, and impactful technology for environmental protection.

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