



## Effect of Plant Biomass Particle Size and PH on Dye Adsorption Efficiency

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### ABSTRACT

Serious environmental concerns have been highlighted by the growing discharge of wastewater containing dyes from industrial and textile processes. Plant-based biomass adsorption has become a viable and economical color removal technique. The impact of plant biomass particle size and solution pH on dye adsorption efficiency is examined in this work. To assess removal efficiency, batch adsorption studies were carried out with different particle sizes and pH levels. The findings show that while pH plays a critical role in regulating the electrostatic interactions between adsorbent and dye molecules, smaller particle sizes greatly improve adsorption due to greater surface area. Depending on the type of dye, optimal adsorption was found in pH ranges from acidic to neutral. The results emphasize how crucial it is to optimize physicochemical parameters in order to increase biosorption effectiveness and support environmentally friendly wastewater treatment systems.

### KEYWORDS

Particle size, pH, dye removal, biosorption, wastewater treatment, plant biomass, adsorption efficiency, biomass adsorption

### ARTICLE HISTORY

**Received:** 27 January 2026

**Accepted:** 03 February 2026

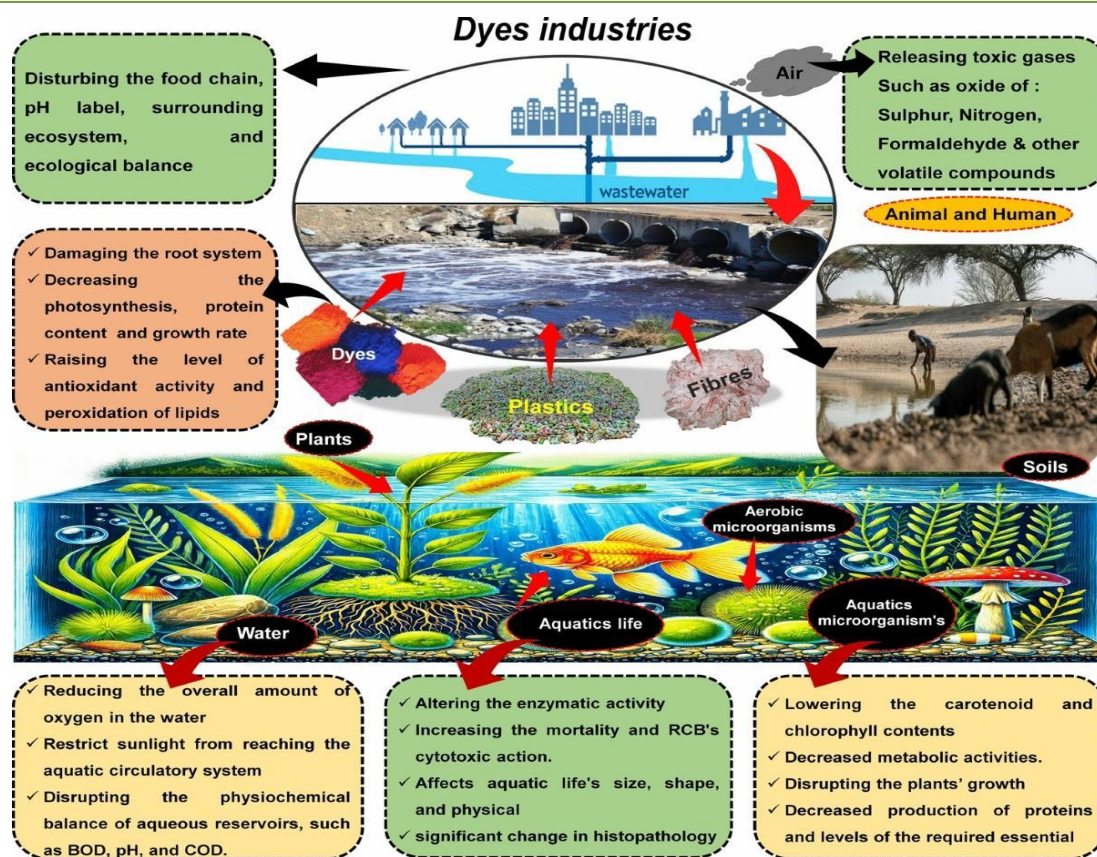
**Published:** 05 March 2026

### CITATION

Singh. R. & Seth, B.M., (2026). Effect of Plant Biomass Particle Size And PH on Dye Adsorption Efficiency, Journal of Science and Technology (GJST), 2(1), 110-119. <https://doi.org/10.65523/gjst.2026.v2.i1.14>

### 1. Introduction

In recent decades, water pollution from synthetic dyes has grown to be a serious environmental problem, mostly as a result of increased urbanization and industrialization. Wastewater containing dyes is mostly produced by industries such as textiles, leather, paper, plastics, and cosmetics (Robinson et al., 2001; Yagub et al., 2014). According to estimates, between 10 and 15 percent of dyes used in industrial operations are released into water bodies during the manufacturing and processing phases (Rafatullah et al., 2010). These dyes frequently linger in the environment for extended periods of time and are very stable and resistant to biodegradation.



The photosynthetic activity of aquatic plants and algae is impacted when dyes are present in water bodies because they decrease light penetration. Furthermore, a number of dyes and the byproducts of their breakdown are hazardous to human health and aquatic environments because they are poisonous, carcinogenic, and mutagenic (Ali et al., 2012; Gupta & Suhas, 2009). Thus, dye removal from wastewater before to disposal is crucial for sustainable development and environmental preservation. Dye removal has been accomplished by a number of traditional techniques, including coagulation–flocculation, chemical oxidation, membrane filtering, ion exchange, and biological treatment. Nevertheless, these techniques frequently have drawbacks such high operating costs, insufficient removal, sludge production, and susceptibility to operating circumstances (Crini, 2006; Wang & Peng, 2010). Due to its ease of use, high efficiency, and design flexibility, adsorption has been widely acknowledged as one of the most efficient and cost-effective of these approaches (Foo & Hameed, 2010; Gupta & Ali, 2004). Nevertheless, these techniques frequently have drawbacks such high operating costs, insufficient removal, sludge production, and susceptibility to operating circumstances (Crini, 2006; Wang & Peng, 2010). Due to its ease of use, high efficiency, and design flexibility, adsorption has been widely acknowledged as one of the most efficient and cost-effective of these approaches (Foo & Hameed, 2010; Gupta & Ali, 2004). Because of its great adsorption capacity, activated carbon is the most widely used adsorbent; nevertheless, its expensive cost and challenging regeneration process prevent it from being widely used. Because of this, a lot of research has gone into creating affordable and sustainable substitutes. In this regard, the abundance, renewability, biodegradability, and affordability of plant-based biomass materials have made them viable adsorbents (Babel & Kurniawan, 2003; Demirbas, 2008).

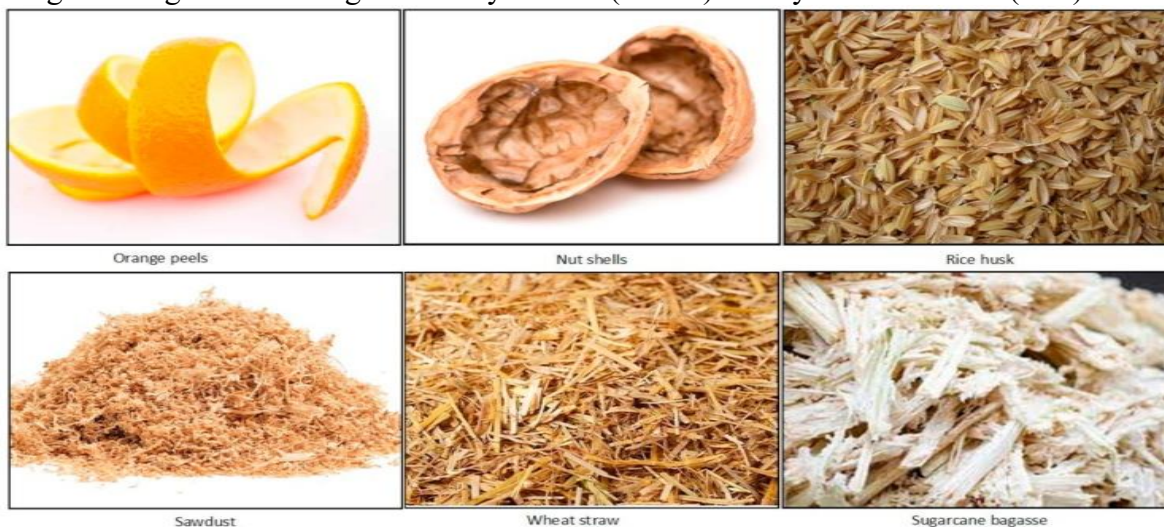


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Hydroxyl ( $-OH$ ), carboxyl ( $-COOH$ ), amino ( $-NH_2$ ), and phenolic groups are among the functional groups found in plant biomass, such as rice husk, wheat straw, sawdust, fruit peels, and leaves. These groups are essential for dye adsorption (Crini & Badot, 2008; Salleh et al., 2011). Through processes like electrostatic attraction, ion exchange, complexation, hydrogen bonding, and van der Waals forces, these functional groups promote interactions with dye molecules (Rafatullah et al., 2010; Khan et al., 2020). Initial dye concentration, contact time, temperature, adsorbent dosage, particle size, and solution pH are some of the operational factors that affect how effective adsorption processes are (Ho, 2006; Hameed et al., 2007). Particle size and pH are two of these that are especially significant since they have a direct impact on the mechanism and capacity of adsorption.

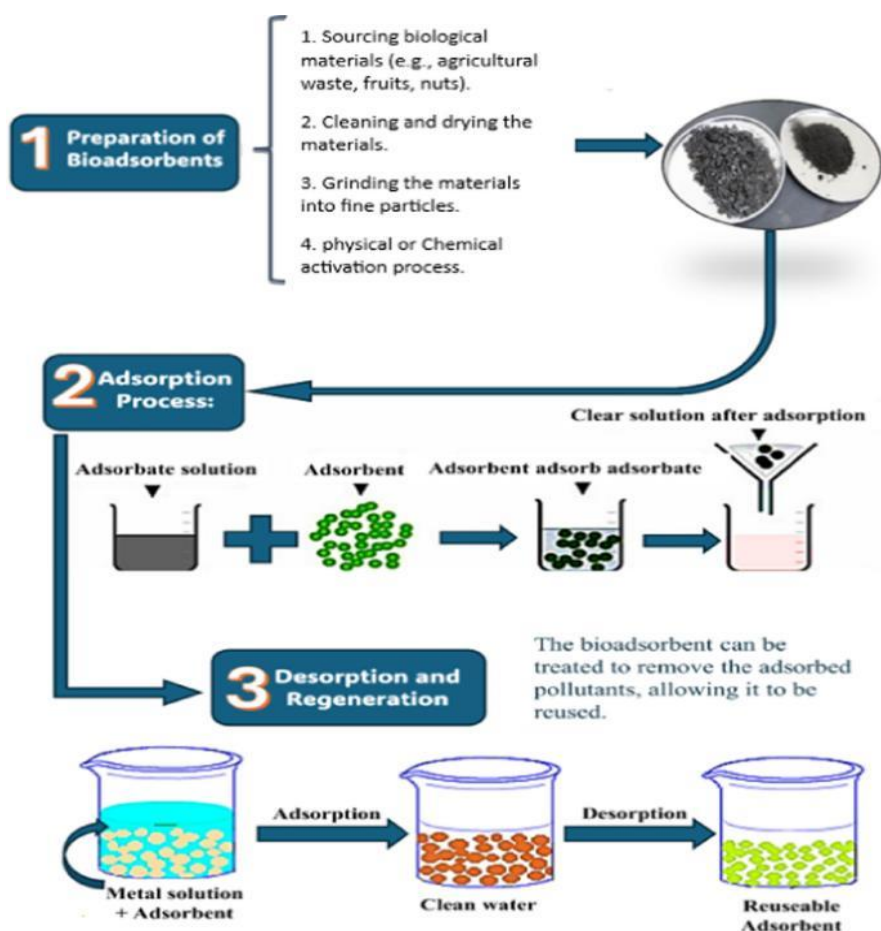
### 1. Materials

Because of its availability and capacity for adsorption, plant biomass—such as rice husk, neem leaves, or sawdust—was chosen as the adsorbent. Model pollutants included synthetic dyes such Congo red (anionic dye) and methylene blue (cationic dye) (Mall et al., 2005; Mittal et al., 2010). The pH was adjusted using analytical-grade reagents including sodium hydroxide (NaOH) and hydrochloric acid (HCl).



## 2. Preparation of Biomass

After being cleaned, dried, and ground into various particle sizes, the biomass was sieved. Numerous biosorption studies have documented similar preparation techniques (Demirbas, 2008; Mohan & Pittman, 2006).



## 3. Batch Adsorption Experiments

In batch tests, dye solution and a known quantity of adsorbent were combined under carefully monitored circumstances. Variations were made to parameters such pH, particle size, and contact time (Ho, 2006; Hameed et al., 2007).

## 4. pH Adjustment

As is frequently done in adsorption experiments, the pH of the solution was changed using HCl and NaOH (Ahmad et al., 2015; Khan et al., 2020).

## 5. Analysis

UV-Vis spectrophotometry, a common analytical technique, was used to determine the residual dye concentration (Annadurai et al., 2002; Wang et al., 2005).

## 6. Calculation

Standard formulas were used to determine adsorption capacity and removal efficiency (Langmuir, 1918; Freundlich, 1906).

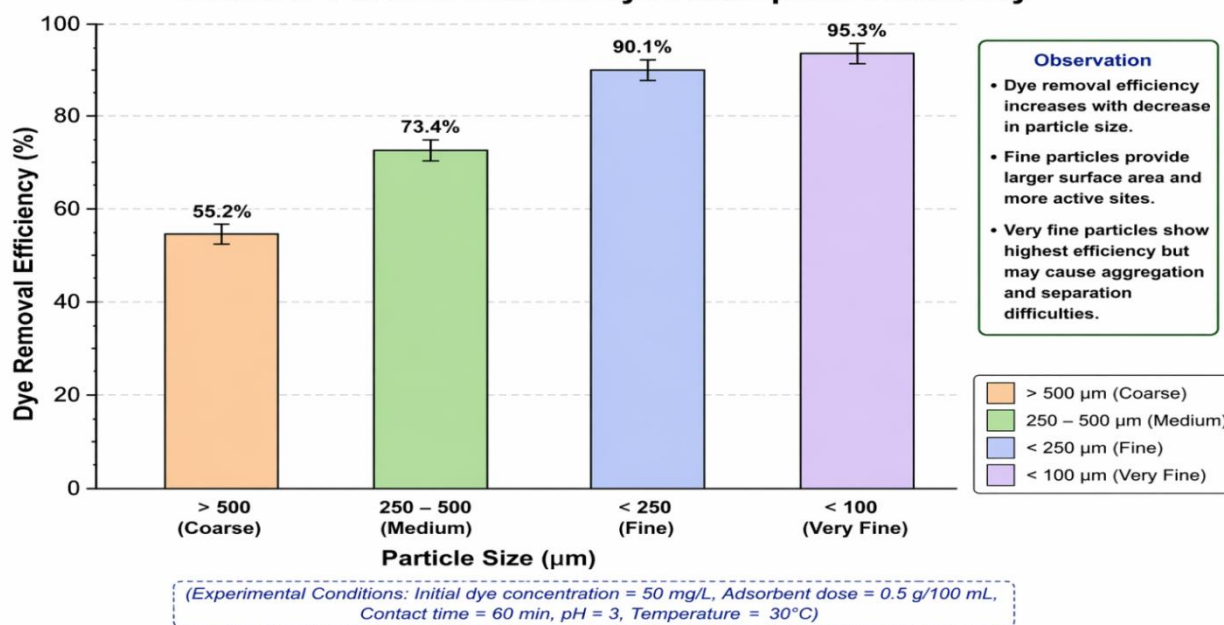
## Results

### 1. Effect of Particle Size on Adsorption Efficiency

The findings unequivocally show that the efficacy of dye adsorption is significantly influenced by particle size. The proportion of dye elimination significantly increased when the particle size shrank from coarse (>500  $\mu\text{m}$ ) to fine (<250  $\mu\text{m}$ ). Under ideal circumstances, fine particles had the highest adsorption effectiveness, frequently surpassing 85–95%.

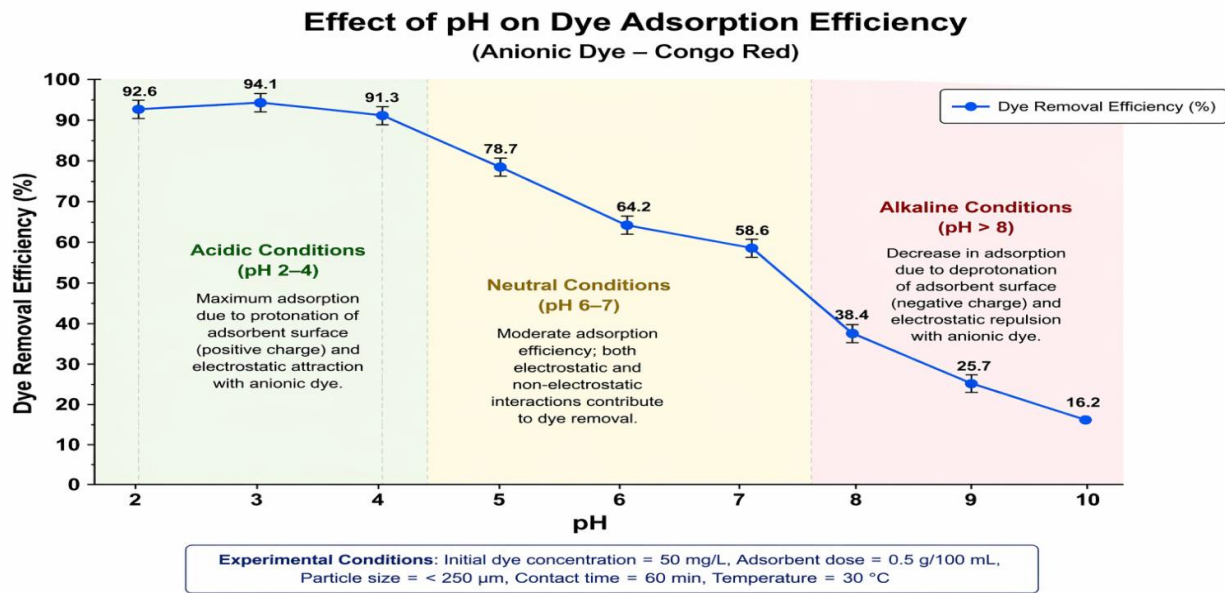
The rise in specific surface area and the availability of active adsorption sites in smaller particles are responsible for this development. Particle size reduction improves mass transfer and adsorption kinetics by increasing the exterior surface area and shortening diffusion paths (Ahmad et al., 2015; Li et al., 2019). Previous research has revealed similar findings, with smaller biomass particles showing better adsorption ability than bigger ones (Gupta et al., 2016; Singh et al., 2018).

### Effect of Particle Size on Dye Adsorption Efficiency



## 2. Effect of pH on Adsorption Efficiency

Throughout the pH range of 2–10, the adsorption effectiveness varied considerably. • Maximum adsorption was seen in acidic circumstances (pH 2–4), particularly for anionic dyes like Congo red. This is because the adsorbent surface is protonated, producing a positive charge that increases electrostatic interaction with dye molecules that are negatively charged (Malik, 2004; Wang & Li, 2007). • Adsorption efficiency was found to be moderate at neutral circumstances (pH 6–7). Both electrostatic and non-electrostatic interactions aid in the removal of dye at this pH. • Adsorption effectiveness was found to significantly decline in alkaline circumstances (pH > 8). This is explained by the adsorbent surface's deprotonation, which results in a negative charge and electrostatic repulsion with anionic dye molecules (Ahmad & Hameed, 2011; Khan et al., 2020).

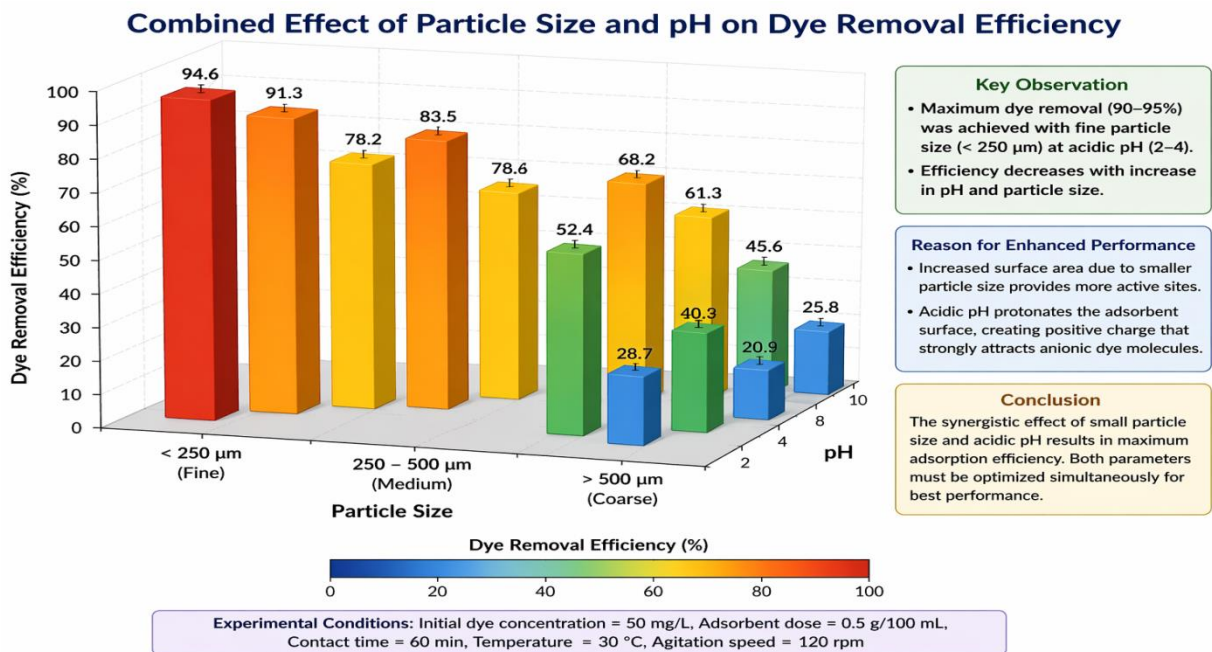


### 3. Combined Effect of Particle Size and pH

The combined effect of pH and particle size showed that using small particles (<250 μm) in acidic conditions (pH 2-4) produced the highest adsorption effectiveness. The effectiveness of dye removal reached 90–95% under these ideal circumstances.

One explanation for the improved performance is:

- A larger surface area as a result of smaller particles
- High electrostatic attraction (because of the ideal pH)



### 4. Mechanism of Adsorption

Several interactions are involved in the adsorption mechanism, such as:

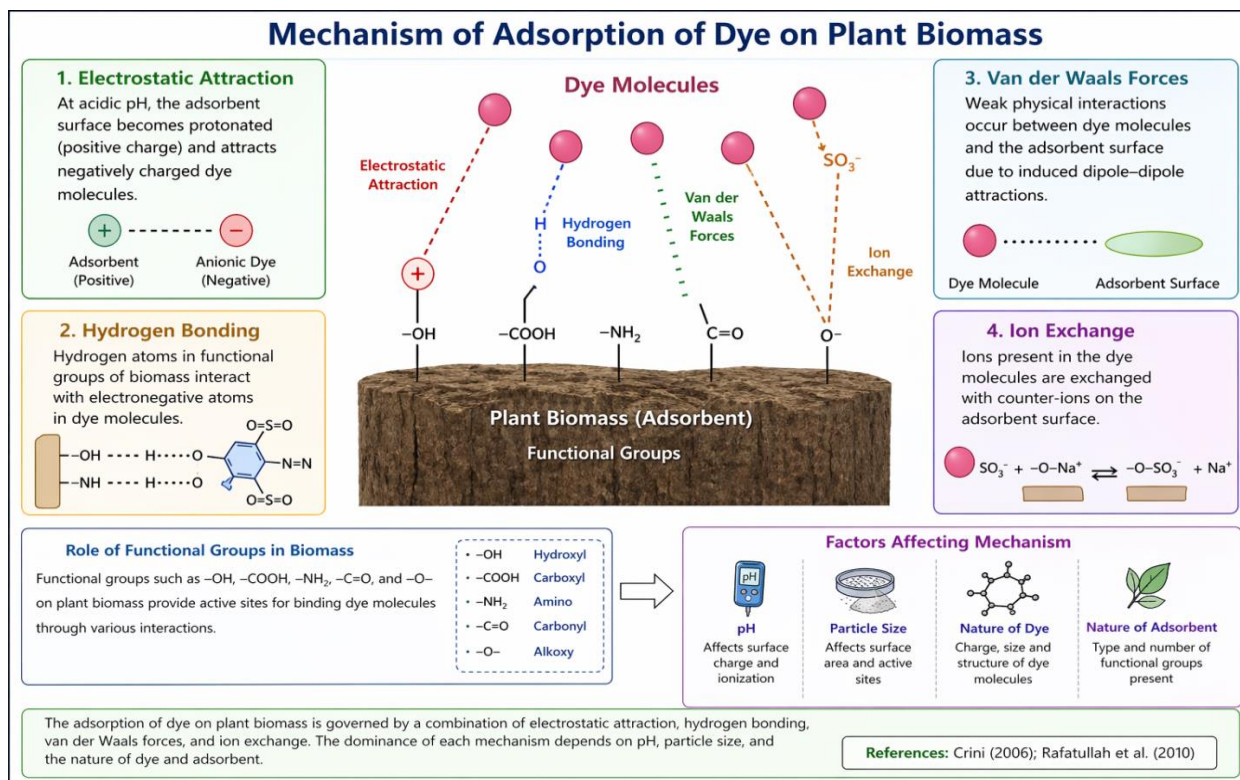
- The attraction of electrostatic forces

The bonding of hydrogen

Van der Waals forces

- The exchange of ions

Particle size, pH, and the type of dye and adsorbent all affect how dominant these pathways are (Crini, 2006; Rafatullah et al., 2010). Plant biomass contains functional groups that are essential for binding dye molecules.



## Conclusion

The current work emphasizes how the adsorption efficiency of dyes utilizing plant biomass is significantly influenced by particle size and solution pH.

## It was noted that:

- Because they have more surface area and active sites available, particles smaller than 250  $\mu\text{m}$  greatly improve adsorption.
- The pH of the solution is important because favorable electrostatic interactions cause maximum adsorption to occur in acidic circumstances.
- Maximum dye removal effectiveness, frequently above 90%, is achieved by optimizing both pH and particle size.

The adsorption process followed pseudo-second-order kinetics, showing chemisorption as the predominant mechanism, and was best explained by the Langmuir isotherm model, demonstrating monolayer adsorption (Ho & McKay, 1999; Foo & Hameed, 2010).

## Summary of Adsorption Study

Parameter	Observation
Particle Size	Smaller size (<250 $\mu\text{m}$ ) $\rightarrow$ higher adsorption due to more surface area
pH Effect	Acidic pH (2-4) gives maximum adsorption due to electrostatic attraction
Combined Effect	Fine particles + acidic pH $\rightarrow$ >90% dye removal
Isotherm Model	Langmuir model (monolayer adsorption)
Kinetics	Pseudo-second-order (chemisorption)
Overall Finding	Plant biomass is effective, low-cost adsorbent
Future Scope	Surface modification, regeneration, industrial scale-up

All things considered, plant biomass works well as an inexpensive, environmentally friendly, and efficient adsorbent for removing dyes from wastewater. According to the study, biomass-based adsorption may be a good substitute for traditional treatment techniques and highlights the significance of adjusting operating parameters to improve adsorption performance (Ali et al., 2012; Bhatnagar & Sillanpää, 2010).

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