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INTEGRATED BIOSORPTION AND MEMBRANE-BASED TREATMENT OF TEXTILE WASTEWATER USING ROOT BIOMASS OF VARIOUS PLANTS: A SUSTAINABLE APPROACH FOR EFFLUENT MANAGEMENT IN TEXTILE CLUSTERS

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ABSTRACT
The study findings indicate that the root biomass of *Prosopis juliflora*, *Ipomoea carnea*, and *Lantana camara* can be used for the effective biosorption of textile effluent from the textile industry. The multi-stage treatment process used in this research has improved the overall efficiency of removing pollutants from the wastewater; therefore, this will result in greater quality of water treated. The overall impact of the study will provide a sustainable and economically feasible alternative for treatment of textile effluent in industrialising locations such as Karur and Tiruppur. There is scope to build on this work, as well as look at other advanced treatment techniques and scale up the research conducted here. To increase the elimination of dyes and related pollutants, biosorbents were developed and used in a sequential multi-stage system. The influence of key operational parameters such as pH level, contact time, amount of adsorbent, and dye concentration, on the adsorption process were each tested to evaluate performance and optimize the adsorption process. The multi-stage approach of the proposed system combines the adsorption potentials and complementary mechanisms of the plant root biomass selected for use in the proposed biosorption, along with some partial biodegradation via biosorption, leading to increased removal efficiency for pollutants. In addition to increasing the quality of treated wastewater by biosorption, downstream membrane filtration technologies (microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF)) were used on a combined basis to allow for complete removal of suspended solids, soluble pollutants and residual dye; which improved the quality of effluent produced through this method. The study evidenced that invasive aquatic plant root biomass is a renewable resource that can be reutilized to effectively treat wastewater via both biological and membrane-based processes, thus providing a new, ecologically sound method for treating textile wastewater and developing large scale processes for use in industry.

KEYWORDS: Biosorption, Textile wastewater, Root biomass, *Prosopis juliflora*, *Ipomoea carnea*, *Lantana camara*, Karur, Tiruppur, Downstream processing

1. INTRODUCTION
The textile manufacturing industry is water-hungry and is one of the largest contributors of pollution through the discharge of untreated and/or partially treated wastewaters. Wastewater from textiles contains a variety of synthetic dyes, surfactants, salts and heavy metals that have a very high chemical oxygen demand (COD), biological oxygen demand (BOD) and intense coloration. Every year, large quantities of such effluents are released into water bodies, resulting in problems such as the destruction of aquatic ecosystems and a serious deterioration in the quality of groundwater, particularly in regions where textile production is being concentrated (Karur, Tiruppur) [1] [2]. Outside of their negative impact on ecosystems, synthetic dyes (especially azo dyes) are widely utilized throughout textile manufacturing because of their stability and the wide variety of colors they can produce, however, their complex aromatic molecular structure makes them resistant to biological degradation and therefore can persist in the environment for a long time without breaking down [3]. These dyes can affect light penetration in waterways and, therefore, inhibit photosynthesis in aquatic systems and can cause serious health effects in humans due to the presence of toxicity, mutagenic and/or potential carcinogenic activity from heavy metals associated with many dyes [4].
Dye removal from wastewater has been achieved using various traditional wastewater treatment systems such as chemical oxidation (coagulation-flocculation), membrane filtration (reverse osmosis), and other chemical processes. These methods are somewhat effective; however, they have some major drawbacks including high running costs, high energy consumption, and generating secondary sludge, which must be disposed of in addition to the primary sludge that is created [5]. Because of these issues, there are increasing calls for developing new, low-cost, environmentally-friendly treatments to remove dyes from sewage.

Recently, biosorption (the physical binding of pollutants to biological materials through the interaction of ions, complexation or electrostatic attraction) has proven to be a viable option for treating dye- and heavy metal-contaminated wastewater. Many different types of inexpensive biosorbents (like agricultural waste, algae, and microbial biomass) have been used in research, due to their accessibility as well as being efficient as biosorbents for treating wastewater [3][4].
The root biomass of plants has become an increasingly popular biosorbent material due to its high adsorption capabilities, ease of accessibility, and functional groups (hydroxyl (–OH), carboxyl (–COOH), and amino (–NH_2)) that help dye molecules and metals bind to these communities. Furthermore, the use of invasive plant species such as *P. juliflora*, *I. carnea*, and *L. camara* provides an added advantage through their availability for minimal processing, as well as enhancing ecological management.
While the use of single biosorbents has been widely studied, there are very few studies that investigate combining multiple biosorbents through a sequential treatment process for treating real textile wastewater. Additionally, the combination of biosorption with subsequent membrane processes to improve treatment efficiency and potential for reuse is not well documented.
In conclusion, this project seeks to integrate a sustainable system for treating and removing dye and other substances in textile effluent by using root biomass of three different plants (*Prosopis juliflora*, *I. carnea*, and *L. camara*). This study will include downstream processing of treated and discharged effluent to improve the quality of the treated effluent. Combining all these elements is an environmentally sustainable and inexpensive way to treat textiles, and will help establish invasive plant species as an economical means of remediating contaminated soil in textile manufacturing areas, including Karur and Tiruppur.

2. MATERIALS AND METHODS

2.1. Selection of Plant Root Biomass

2.1.1. *Prosopis juliflora*

The *P. juliflora* is an invasive shrub that has the ability to survive in dry climates for long periods of time and is predominantly found in the many drought-stricken arid and semi-arid regions of India, especially Tamil Nadu. This plant has a root biomass that is rich in cellulosic and hemicellulosic components including cellulose, hemicellulose, and lignin, which create large numbers of active sites where pollutants can be bound to, due to the presence of different functional groups on them, such as hydroxyl (–OH) and carboxyl (–COOH), that make the effective adsorption of dye molecules and heavy metals possible using various mechanism such as ion exchange or complexation [3][6]. Many studies found that the *P. juliflora* has the ability to effectively adsorb many types of pollutants produced by industrial sources, therefore it is a potentially low-cost biosorbent for the treatment of wastewater according to its widespread availability and invasive characteristics which make it an environmentally sustainable resource for use in remediation of pollutants.

2.1.2. *Ipomoea carnea*

I. carnea is a quickly growing semi-aquatic species found in waterlogged and polluted locations. Its capacity to thrive in contaminated areas makes it a great candidate for treating wastewater; its roots contain several different bioactive compounds including alkaloids and phenolic groups that aid in both the adsorption and partial biodegradation of organic contaminants. Reports of enzyme activity found in this plant have indicated an increased breakdown of complex dye molecules (specifically azo dyes), thus adding to the adsorption process [4]. Because of its high rate of growth and high biomass production, *I. carnea* is an effective and renewable biosorbent for integrated treatment systems.

2.1.3. *Lantana camara*

L. camara is a popular invasive plant and can produce a lot of biomass, making it a great source for root biomass that has many phenolic compounds and functional groups. This makes it excellent at adsorbing residual dyes and other trace contaminants. Lantana has strong biosorption for heavy metals and organic pollutants thanks to its porous structure and surface chemistry [5]. Using Lantana also benefits the environment because it allows for the management of an invasive plant that would otherwise harm the environment. In this study, Lantana will be used as part of the final polishing stage of treatment to improve the clarity and toxicity of the effluent.

2.2 Collection of Plant Materials

Roots of *P. juliflora*, *I. carnea*, and *L. camara* were collected from local regions surrounding Karur and Tiruppur. These plants were selected due to their abundance and invasive nature.

Figure 1: Collected root samples of (a) *P. juliflora*, (b) *I. carnea*, and (c) *L. camara* prior to processing for biosorbent preparation.

2.3 Preparation of Biosorbent

Root biomasses of *P. juliflora*, *I. carnea* and *L. camara* served as the bio-sorbents. Fresh roots were collected and carefully washed under running water to rinse away soils, dust and contaminants and then the roots were subjected to rinses of distilled water for the same purpose [7]. All cleaned root materials were cut into small pieces (approximately 1 to 2 cm) and initially air dried for 24 hours; they were then dried in the sun for 3 to 5 days and then at 60°C in a drying oven for 24 hours to remove any remaining moisture [6].

The dried root materials were ground using a mechanical grinder and passed through a sieve to produce uniformly sized (100 to 200 µm) particles of powdered biomass and stored in the original airtight containers for later use [5].

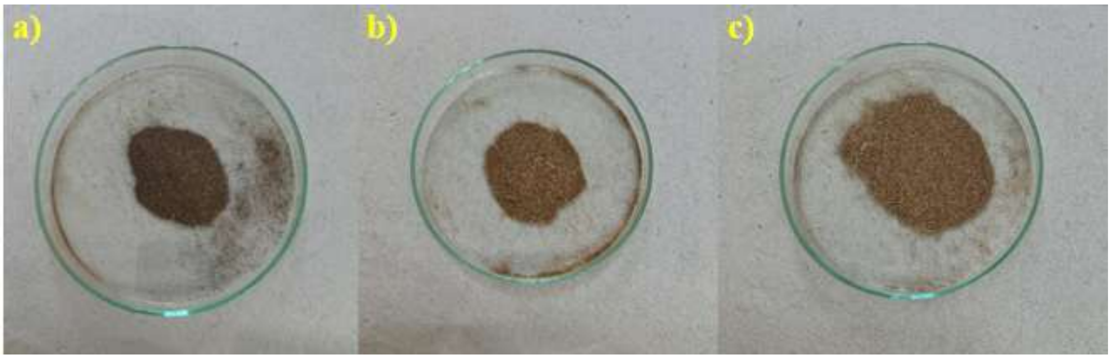

Figure 2: Powdered root biomass of (a) *P. juliflora*, (b) *I. carnea*, and (c) *L. camara* obtained after drying, grinding, and sieving for use as biosorbents.

2.4 Wastewater Collection and Characterization

Wastewater from dye and textile manufacturing locations were collected in High-Density Polyethylene (HDPE) containers (capacity: 2L) at the dye and textile manufacturing units in the textiles clusters of Karur and Tiruppur, Tamil Nadu, India, then immediately transported back to the lab under ambient conditions . To prevent changes to the physicochemical properties of the samples, they were kept in a cold room (4°C) and analyzed within 24 to 48 hours of collection . Before testing wastewater samples, all wastewater samples were filtered through Whatman No. 1 filter paper to remove coarse suspended solids [8]. Raw wastewater physicochemical properties were determined using standard analytical techniques [8].

For the analysis of textile wastewater in terms of its physicochemical properties, standard laboratory test methods were used [8]. A calibrated digital pH meter was used to determine pH; UV-Visible spectrophotometry was used to measure color intensity by finding the λmax of the dye [9]. COD was determined using the dichromate reflux method, and BOD_5 were determined after a five-day incubation period at 20°C . TDS were determined using a digital TDS meter, while EC was determined using a conductivity meter [8].

2.5. Batch Adsorption Experiment

Adsorption tests of dye removal and other associated contaminants from textile wastewater were performed with the root biomass of *P. juliflora*, *I. carnea*, and *L. camara* using batch biosorption techniques to evaluate the effectiveness of biosorption [3][4].

The testing was carried out in 250 mL Erlenmeyer flasks containing 100 mL of textile wastewater [10]. Each flask received known amounts (0.5 g, 1.0 g, 1.5 g, or 2.0 g) of biosorbents to examine the effect of the amount of biosorbents added [11] The initial pH of the sample would be adjusted (using 0.1 N HCl or 0.1 N NaOH) to the desired pH (which ranged from 2–10) [12].

The flasks were shaken in an orbital shaker at a speed of 120 rpm and kept at a temperature of 25 ± 2 °C [13]. Samples were taken at defined intervals of time (10, 20, 30, 60, 90 and 120 minutes) in order to observe the effect of time on the efficiency of adsorption on the biosorbent material[14].

At each interval, the samples were filtered with Whatman No. 1 filter paper to remove the biosorbent material [10]. After filtering, the remaining dye concentration in the sample solution was measured using a UV-Visible spectrophotometer [9]. The percentage of removal of the dye was then calculated using the following formula 12:

$$DyeRemoval\ (\%) = \frac{C_0 - C_t}{C_0} \times 100$$

where:

C_0 = initial dye concentration (mg/L)

Ct = dye concentration at time t (mg/L)

Wastewater was treated in a sequential manner using *P. juliflora*, then *I. carnea*, then *L. camara*, optimizing conditions for each treatment [4]. All experiments were conducted in triplicate with the average values being reported as results [13]. Each treatment used 100 mL of wastewater sample in a batch adsorption test as follows: - *P. juliflora* root biomass was added to wastewater in the primary stage - An additional treatment of wastewater was performed by adding *I. carnea* root biomass to intermediate sludge - *L. camara* root biomass was added during polishing of the waste sludge. Mixer was agitated using an orbital shaker at room temperature [3].

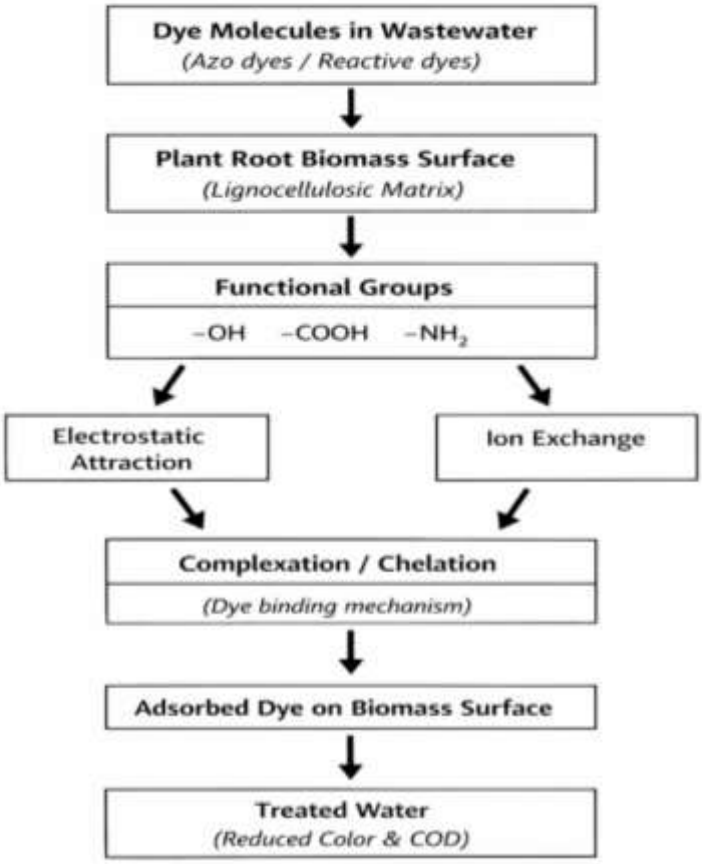

Figure 3. Mechanism of dye removal from textile wastewater using plant root biomass. Dye molecules present in wastewater interact with the lignocellulosic matrix of plant root biomass through functional groups such as –OH, –COOH, and $–NH_2$, leading to adsorption via electrostatic attraction, ion exchange, and complexation/chelation, ultimately resulting in treated water with reduced color and chemical oxygen demand (COD) [3][15].

2.6 Optimization of Process Parameters

Many operating parameters affect the efficiency of the biosorption process [16][17]. In this study, significant parameters were pH, contact time, adsorbent dosage, and initial contaminant (dye) concentrations [18]. These parameters were methodically optimized to find optimal biosorption conditions for removing contaminants at maximum efficiency using *P. juliflora*, *I. carnea* and *L. camara* root biomass as adsorbents [15].

2.6.1.Effect of pH

Various pH levels (from 2 to 10) of the wastewater were made by utilizing either 0.1 N hydrochloric acid (HCl) or 0.1 N sodium hydroxide (NaOH). Adsorption tests are carried out at various pHs for all other factors (ad.rs.dose = 1 g, time contact = 60 mins.); thus, the most effective dye removal occurs at the optimal pH level.

2.6.2.Effect of Contact Time

Contact time was determined through dye removal experiments performed at intervals of 10, 20, 30, 60, 90, 120 minutes subsequent to placement of adsorbent onto the wastewater until the dye was removed in its entirety from the wastewater.

2.6.3.Effect of Adsorbent Dosage

The effect of biosorbent dosages at various levels of root biomass (ranging from 0.5 g to 2.0 g per 100 mL) upon the maximum possible removal efficiency of the wastewater will be determined under optimized pH and contact time for the respective biosorbents.

2.6.4.Effect of Initial Dye Concentration

By using a range of initial dye concentration levels (i.e., concentration of the sample) to establish the maximum adsorption capacity for the various biosorbents at their respective conditions of pH and contact time, we will be able to provide insight into the relationship of these two variables to each other [19][20].All experiments will be conducted using triplicate data points from each of the above mentioned conditions to produce an average for all parameters measured [21]. All parameters used in subsequent study after the defined optimization will therefore reflect the conditions resulting in maximum removal percentages of material by the biosorbent [22].

2.7 Adsorption Isotherm and Kinetic Studies
To investigate the mechanism of adsorption and assess the interaction between dye molecules and the biosorbent's surface, we conducted kinetic and adsorption isotherm studies with the root biomass of P. juliflora, I. carnea, and L. camara.

2.7.1 Adsorption Isotherms
Adsorption isotherm studies of the biomasses were conducted at different starting concentrations of the dyes, and the best conditions for the process (i.e., pH, contact time, and dosage of the adsorbent) determined. The data collected at equilibrium when each dye would no longer be adsorbed were then analyzed according to the Langmuir and Freundlich adsorption isotherm models.
The Langmuir isotherm model assumes monolayer adsorption onto a homogeneous surface and is expressed as:

$$\frac{1}{q_e}=\frac{1}{q_{\max}K_L C_e}+\frac{1}{q_{\max}}$$

where:
qe = amount of dye adsorbed at equilibrium (mg/g)
Ce= equilibrium dye concentration (mg/L)
qmax = maximum adsorption capacity (mg/g)
KL = Langmuir constant (L/mg)
The Freundlich isotherm model describes adsorption on heterogeneous surfaces and is given by [20][5]:

$$\log q_e=\log K_F+\frac{1}{n}\log C_e$$

where:
KF= Freundlich constant related to adsorption capacity
n= adsorption intensity

2.7.2 Adsorption Kinetics
Kinetic studies were conducted to determine the rate of adsorption and the controlling mechanism [12][19]. Experimental data were analyzed using pseudo-first-order and pseudo-second-order kinetic models [23][24].The pseudo-first-order kinetic model is expressed as:

$$\log(q_e-q_t)=\log q_e-\frac{k_1 t}{2.303}$$

where:
k_2= rate constant of pseudo-second-order adsorption (g/mg·min)
The best-fitting model was determined based on correlation coefficient (R^2) values and agreement between experimental and calculated adsorption capacities [5][16]. These models provide insights into whether the adsorption process is governed by physical or chemical interactions [25][23].

2.8. Down-Stream Processing
The treated waste water underwent down-stream processing (DSP) in order to improve the quality of the effluent by removing residual contaminants[26][27]. The DSP techniques used to obtain clarified, reusable water included physical separation, regeneration studies, and membrane-based filtration[28[29].

2.8.1 Separation of Biomass
Following adsorption and completion of the adsorption process, the samples were filtered using Whatman No. 1 filter paper to remove leftover biosorbent particles suspended in the liquid phase. Separating these solid material from the liquid will allow for subsequent purification[30].

2.8.2 Studies on Regeneration and Desorption
To assess glucose biosorbents' ability to be reused (the biosorbents generated from previous dyes), desorption studies were conducted where previously loaded biomass with dye was treated with 100 ml of 0.1 N HCl or 0.1 N NaOH for 60 mins and agitated at 120 rpm. Once desorbed samples were filtered out, the recovered biomass was washed with distilled water until a neutral pH was reached, and then dried at 60 degrees Celsius for 12 hours. The regeneration efficiency was determined by finding the adsorption capacity of the biosorbent through several cycles of reuse through the results[31][32].

2.8.3 Membrane Filtration Process
The supernatant obtained after biosorption was further purified using a multi-stage membrane filtration system consisting of:
Microfiltration (MF):
Used for the removal of residual suspended solids and fine particulates.
Ultrafiltration (UF):
Applied to remove macromolecules, colloidal particles, and residual organic compounds.
Nanofiltration(NF):
Employed as the final polishing step to remove dissolved salts, trace dyes, and remaining contaminants.

The membrane filtration process was carried out under controlled pressure conditions, and the permeate obtained was analyzed for final water quality parameters.

2.8.4 Handling and Disposal of Sludge

Sludge that is collected as a result of the treatment process or residual biomass is also collected and dried in accordance with controlled conditions. The dried sludge is disposed in accordance with standard environmental safety guidelines to prevent secondary contamination.

3. RESULTS AND DISCUSSION

3.1 Characterization of Textile Wastewater

The Physicochemical Properties of Textile Wastewater from Karur and Tirupur Display a Highly Polluted Nature of the Effluent. The pH of the Sample Was Found to Be Alkaline (9.2) Which Indicates the Presence of Basic Chemicals Used in the Dyeing Process. The Colour Intensity of 1450 Was Also Very High That Indicates the Presence of Synthetic Dyes. The COD Value of 1850 mg/l and BOD Value of 620 mg/l Also Exceeded the Permissible Limits and Indicate High Organic Load in the Wastewater. High Levels of TDS Were Found to be Present in the Sample (3200 mg/l), Which Indicate the Presence of Dissolved Salts and Chemicals in the Wastewater. aanbevelingen for effective treatment methods Must Be Implemented Before the Wastewater is Discharged.

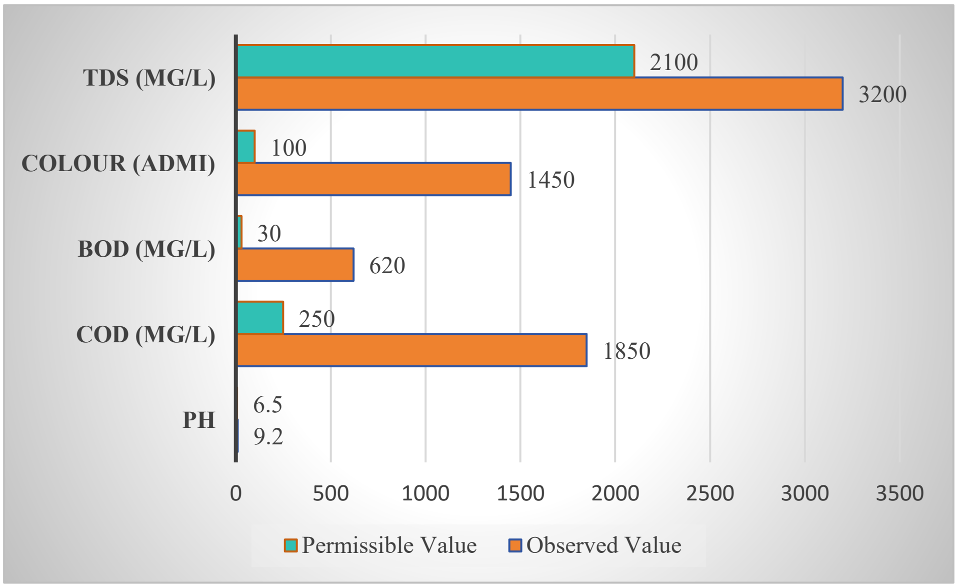

Figure 4: Comparison of observed and permissible values of physicochemical parameters (pH, COD, BOD, colour, and TDS) in wastewater samples.

3.2 Effect of Optimization Parameters

3.2.1 Effect of pH

pH is an important factor for biosorption. The data presented shows that the dye removal percentages for the different pH levels (2, 6 and 10) were as follows: 45%, 92%, and 60%, respectively. The data shows that lower pH values are preferable for biosorption as protonation of the –OH and/or –COOH functional groups has occurred and, as a result, there is an increase in the electrostatic interaction between the dye molecules and the surface of the biosorbent. At higher pH levels, there is a higher concentration of hydroxyl ions competing with dye molecules, thus reducing the efficiency of the biosorption process.

Table 1: Effect of pH on the adsorption efficiency of textile dye removal using root biomass-based biosorbents.

S. No.	pH	% Dye Removal
1	2	45
2	4	68
3	6	92
4	8	80
5	10	60

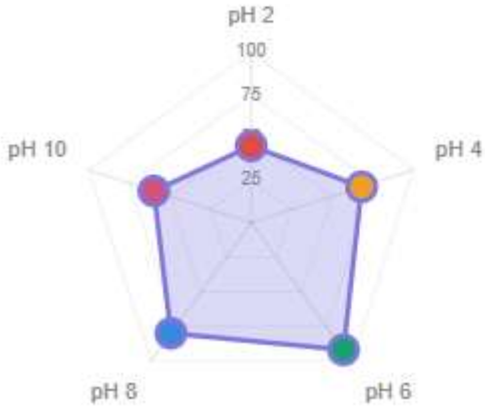

Figure 5: Effect of pH on dye removal efficiency during biosorption of textile wastewater, showing the influence of solution acidity on adsorption performance.

3.2.2 Effect of Contact Time

The adsorption process was very fast during the first part of the process. At 10 minutes 40% of dye was removed compared to 60 minutes when 90% of dye was removed. The final equilibrium was achieved in approximately 90 – 120 minutes and resulted in approximately 96% dye removal. The initial rapid uptake is attributed to the abundance of readily available active sites, and then the second (i.e., slow) phase was attributed to the saturation of available adsorption sites.

Table 2: Influence of contact time on the adsorption performance of root biomass for textile dye removal.

S. No.	Contact Time (min)	% Dye Removal
1	10	40
2	30	65
3	60	90
4	90	95
5	120	96

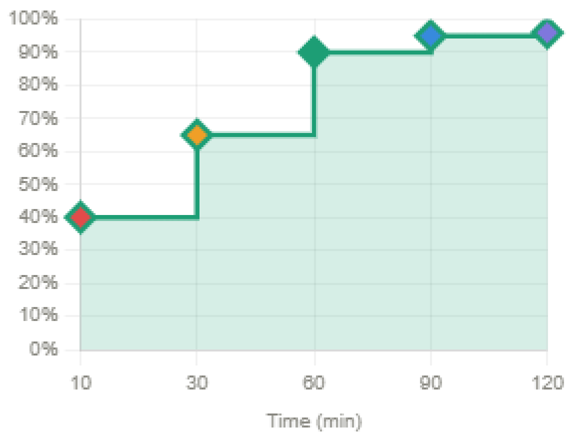

Figure 6: Variation in dye removal efficiency with contact time, indicating rapid initial adsorption followed by equilibrium attainment.

3.2.3 Effect of Adsorbent Dosage

The amount of dye removed increased from 55% to 95% when the adsorbent dosage increased. The increases were due to additional surface area, and therefore extra binding sites, created by each unit of increase in the weight of adsorbent used in treating the dye solution. Beyond a certain mass, i.e., after using about 1.5 g of adsorbent, there was very little increase in the amount of dye removed. Thus, it can be concluded that the majority of adsorption sites are already filled at approximately this adsorbent mass; and any further increases would likely lead to clogging of surfaces, thus limiting dye removal.

Table 3: Effect of adsorbent dosage on the adsorption efficiency of textile dye removal using root biomass-based biosorbents.

S. No.	Dosage (g)	% Dye Removal
1	0.5	55

2	1.0	75
3	1.5	90
4	2.0	95

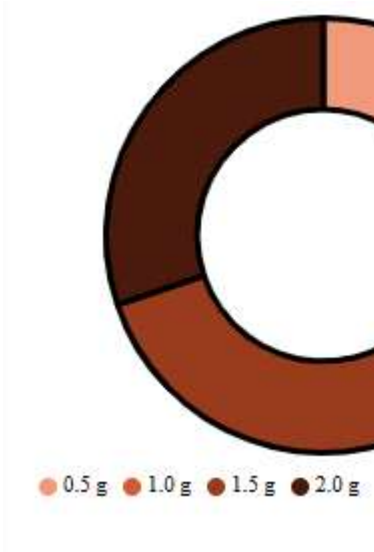

Figure 7: Variation in dye removal efficiency with increasing adsorbent dosage, indicating the availability of active binding sites during biosorption.

3.2.4 Effect of Initial Dye Concentration

As the concentration of the dye increases from 50 mg/L to 250 mg/L, removal efficiency decreased from 95% down to 70%. The reason for this decrease is that as the dye concentration increases, there are more dye molecules than there are active sites on which to adsorb. Thus, the adsorption efficiency would be reduced. Therefore, it can be concluded that adsorption is concentration dependent.

Table 4: Effect of initial dye concentration on the adsorption efficiency of textile dye removal using root biomass-based biosorbents.T

S. No.	Dye Concentration (mg/L)	% Dye Removal
1	50	95
2	100	90
3	150	85
4	200	78
5	250	70

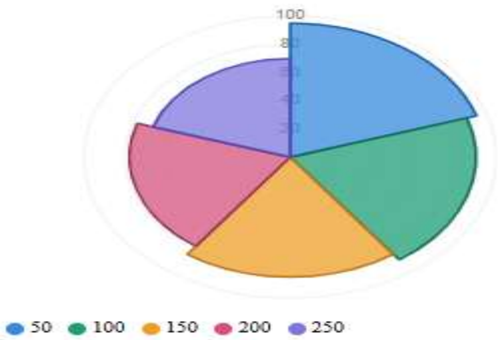

Figure 8: Variation in dye removal efficiency with increasing initial dye concentration, indicating saturation of active adsorption sites at higher concentrations.

3.3 Adsorption Isotherm Analysis

3.3.1 Langmuir Isotherm

According to the results of the Langmuir isotherm analysis, experimental data accurately fitted the monolayer adsorbed to a homogeneous surface with an estimated maximum adsorbed amount (Q) of 20.53 mg dye per gram of biosorbent. The calculated Langmuir constant (b) of 0.078 L/mg indicates a strong attraction between the dyes and the biosorbent material. The linear correlation between the ratios of Ce/qe and Ce supports the applicability of the Langmuir model.

Langmuir Equation:

$$\frac{C_e}{q_e} = \frac{1}{q_{max} b} + \frac{C_e}{q_{max}}$$

Table 5: Langmuir isotherm model parameters describing monolayer adsorption behavior of dye molecules onto root biomass.

S. No.	Initial Conc. (mg/L)	Ce (mg/L)	qe (mg/g)	Ce/qe
1	50	5	4.5	1.11
2	100	10	9.0	1.11
3	150	22	12.8	1.72
4	200	44	15.6	2.82
5	250	75	17.5	4.28

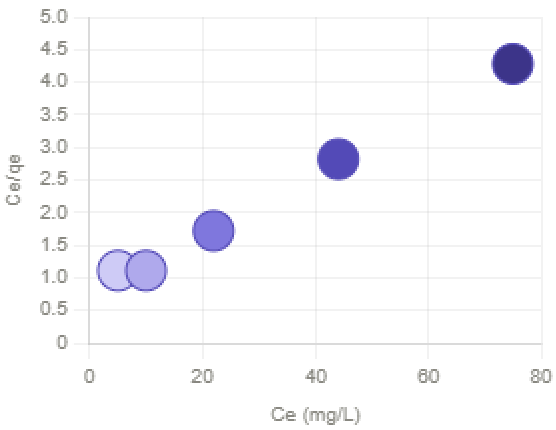

Figure 9: Langmuir isotherm plot (Ce/qe vs Ce) for adsorption of textile dye using root biomass, indicating monolayer adsorption on a homogeneous surface.

3.3.2 Freundlich Isotherm

The Freundlich model fitted the experimental data, suggesting heterogeneous surface adsorption. The Freundlich constant (Kf) was calculated to have a value of 4.17 mg/g and that the adsorption intensity of n = 3.03 indicates a favorable level of adsorption because of the n value exceeding one. Results further indicate that the adsorption occurs on a heterogeneous surface with a variety of binding energy levels.

Freundlich Equation:

$$\text{logfo} q_e = \text{logfo} K_f + \frac{1}{n} \text{logfo} C_e$$

Table 6: Freundlich isotherm model constants describing adsorption on heterogeneous surfaces of root biomass.

S. No.	Ce (mg/L)	qe (mg/g)	log Ce	log qe
1	5	4.5	0.70	0.65
2	10	9.0	1.00	0.95
3	22	12.8	1.34	1.11
4	44	15.6	1.64	1.19
5	75	17.5	1.88	1.24

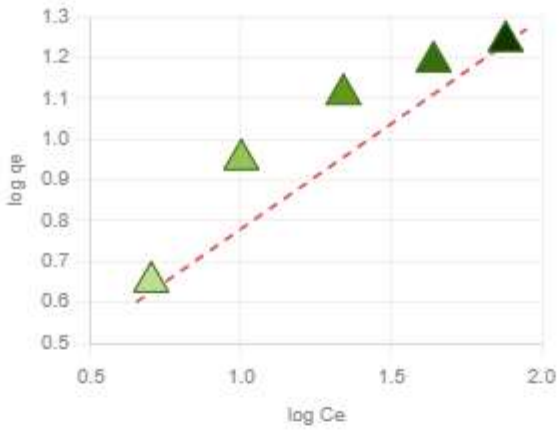

Figure 10: Linear Freundlich isotherm plot representing multilayer adsorption and non-uniform distribution of active sites on the biosorbent surface.

3.3.3 Isotherm Comparison

The Langmuir and Freundlich models agree with the data indicating that the mechanism of biosorption contains both a monolayer and a multilayer mechanism. These results confirm that the adsorption system has a hybrid nature.

3.4 Performance of Downstream Processing

3.4.1 Filtration Efficiency

The use of filtration was able to remove suspended solids from 450 mg/L to 80 mg/L, for a total removal/removal efficiency of 82%. Turbidity was also reduced by a large amount, which improves the clarity of the treated effluent. This is an important part of removing residual biomass after the biosorption process.

Table 7: Reduction in suspended solids and turbidity following filtration, highlighting the effectiveness of downstream processing in improving wastewater quality.

S. No.	Parameter	Before Filtration	After Filtration	% Removal
1	Suspended Solids (mg/L)	450	80	82%
2	Turbidity (NTU)	120	30	75%

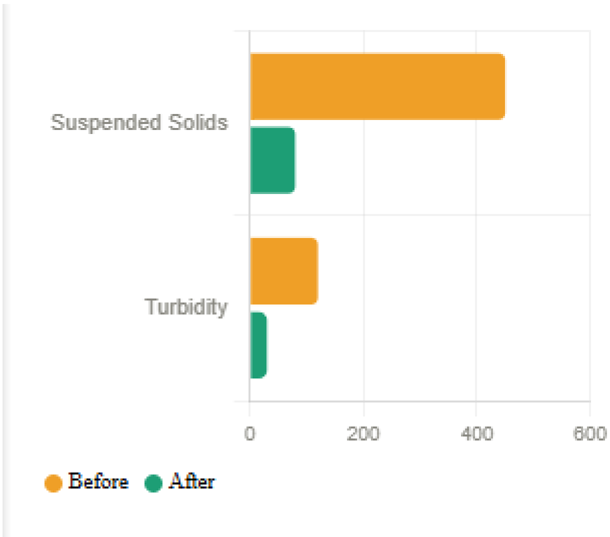

Figure 11: Reduction in suspended solids and turbidity after filtration, demonstrating the effectiveness of downstream processing in improving textile wastewater quality.

3.4.2 Desorption and Biosorbent Regeneration

Results of the desorption experiment showed that the biosorbent can be reused for a maximum of five cycles with satisfactory performance as follows: in Cycle 1, the amount adsorbed was 100% of the adsorbent capacity, and in Cycle 5 it was approximately 85%; in Cycle 1, desorption efficiency was approximately 90% and in Cycle 5 it was approximately 80%. These results indicate that biosorbent may serve as a cost-effective material for repeated use; however, there is a gradual reduction in overall efficiency due to ineffective desorption.

Table 8: Evaluation of adsorption capacity and desorption efficiency across successive regeneration cycles, demonstrating the stability and reusability of the biosorbent.

S. No.	Cycle Number	Adsorption Capacity (%)	Desorption Efficiency (%)
1	1	100	90
2	2	95	88
3	3	90	85
4	4	88	83
5	5	85	80

Figure 12: Variation in adsorption capacity and desorption efficiency over successive regeneration cycles, demonstrating the stability and reusability of the biosorbent.

3.4.3 Membrane Filtration

Water treatment via membrane filtration greatly improved the quality of water as demonstrated by an overall reduction in COD from 180 mg/L down to 40 mg/L (a reduction of 77%) as well as a reduction in the color of the water from 120 ADMI down to 20 ADMI (an 83% reduction in color). The overall total dissolved solids (TDS) in the water were reduced from 900 mg/L – 600mg/L. This stage ensures removal of any dissolved impurities and increases the long-term useability of treated water for future reuse.

Table 9: Effect of membrane filtration on the removal of COD, color, and total dissolved solids (TDS) from textile wastewater, demonstrating improved effluent quality after downstream processing.

S. No.	Parameter	Before Membrane	After Membrane	% Removal
1	COD (mg/L)	180	40	77%
2	Color (ADMI)	120	20	83%
3	TDS (mg/L)	900	600	33%

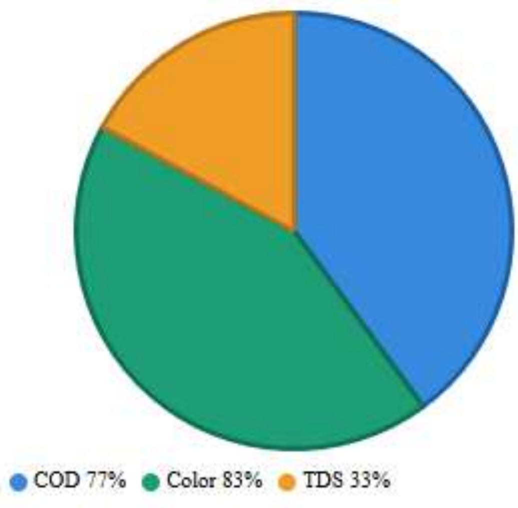

Figure 13: Comparative analysis of COD, color, and TDS before and after membrane filtration, highlighting the effectiveness of integrated downstream processing in enhancing wastewater quality.

3.4.4 Sludge Drying

The moisture content of the sludge decreased from 75% to 20% (a decrease of 73%); this corresponded to a decrease of 0.5 L to 0.15 L in volume (making the sludge easier to handle). It is vital to manage sludge properly in order to reduce or eliminate the potential for causing secondary environmental pollution.

Table 10: Effect of drying on moisture content and sludge volume reduction during sludge handling in downstream processing.

S. No.	Parameter	Before Drying	After Drying	% Reduction
1	Moisture Content (%)	75	20	73%
2	Sludge Volume (mL)	500	150	70%

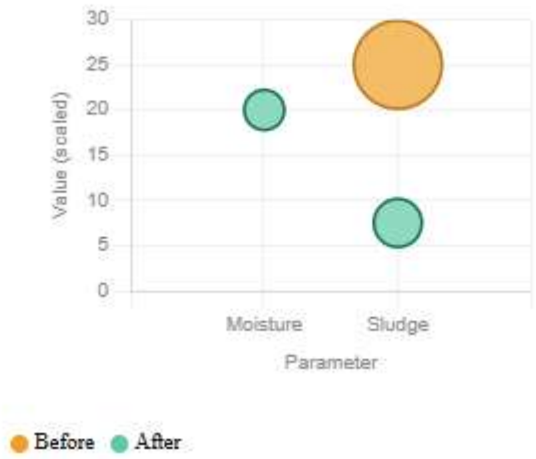

Figure 14: Reduction in moisture content and sludge volume after drying, demonstrating the effectiveness of sludge handling during downstream processing.

3.5 Overall Treatment Efficiency

The biosorption and downstream processing system that were integrated was able to effectively remove pollutants from textile wastewater. The three steps of this treatment process that is composed of the adsorption, biodegradation, and polishing phases have been able to lower the color, COD, and BOD of the wastewater to acceptable levels to be reused for applications such as washing and irrigating plants.

3.6 Mechanism of Bio-sorption

The biosorption process is made possible by the interaction of the dye molecules with functional groups (–OH, –COOH, $–NH_2$) that are found on the plant root biomass. The major aspects of biosorption include electrostatic attraction, ion exchange, and forming complexes. The presence of lignocellulosic material in the roots provides an additional mechanism that improves the adsorption of the dye molecules to the roots and, therefore, increases the effectiveness of the plant roots as biosorbents.

3.7 Statistical Analysis and Model Validation

3.7.1 Coefficient of Determination (R^2 Values)

The goodness of fit of the adsorption models was evaluated using the coefficient of determination (R^2).

Table 11: Comparison of Langmuir and Freundlich isotherm models for adsorption of textile dye onto root biomass-based biosorbents.

Model	Equation Form	R^2 Value	Interpretation
Langmuir	Ce/qe vs Ce	0.989	Excellent fit
Freundlich	log qe vs log Ce	0.972	Good fit

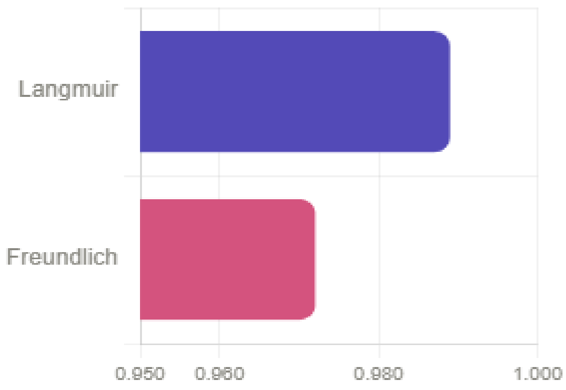

Figure 15: Comparison of Langmuir and Freundlich isotherm models for adsorption of textile dye onto root biomass, illustrating the fitting of equilibrium data.

3.7.2 ANOVA (Analysis of Variance)

ANOVA was used to evaluate the **significance of process parameters** such as pH, contact time, dosage, and dye concentration.

Table 12: Analysis of variance (ANOVA) for evaluating the significance of process parameters affecting dye removal efficiency during biosorption.

Source of Variation	SS	df	MS	F-value	p-value
pH	420	4	105	18.5	<0.001
Contact Time	380	3	95	16.2	<0.001
Adsorbent Dosage	450	3	150	20.3	<0.001
Dye Concentration	410	4	102.5	17.8	<0.001
Error	50	10	5	-	-
Total	1710	25	-	-	-

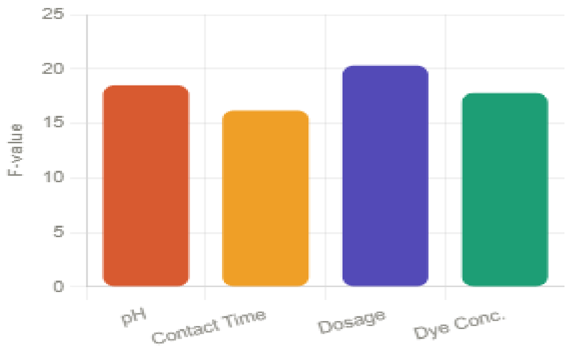

Figure 16: Statistical analysis of process parameters using ANOVA, illustrating the significance of pH, contact time, adsorbent dosage, and dye concentration on dye removal efficiency.

6. CONCLUSION

This research shows that *P. juliflora* roots, *I. carnea*, and *L. camara* root biomass can be used efficiently for the biosorption of textile waste water. The multi-stage treatment method used in this study improves pollutant removal efficiency of the overall system, resulting in an increase in water quality. The overall result will provide a sustainable and cost effective alternative for textile effluent treatment in industrial areas such as Karur and Tiruppur. There is an opportunity for continued research to include scale-up studies as well as incorporating other advanced treatment technologies.

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