

Development of an Operationally Efficient and Cost-Effective System for Removal of Dye from Wastewater Using Novel Adsorbent [†]

Niraj S. Topare ^{1,2,*} , Sunita Raut-Jadhav ^{2,*} and Anish Khan ^{3,4} 

¹ Department of Chemical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune 411038, India

² Department Chemical Engineering, Bharati Vidyapeeth (Deemed to Be University) College of Engineering, Pune 411043, India

³ Chemistry Department, Faculty of Science, King Abdulaziz University Jeddah, Jeddah 21589, Saudi Arabia; akrkhan@kau.edu.sa

⁴ Center of Excellence for Advanced Materials Research, King Abdulaziz University, Jeddah 21589, Saudi Arabia

* Correspondence: niraj.topare@mitwpu.edu.in (N.S.T.); smjadhav@bvucoep.edu.in (S.R.-J.)

[†] Presented at the 1st International Conference on Industrial, Manufacturing, and Process Engineering (ICIMP-2024), Regina, Canada, 27–29 June 2024.

Abstract: An important contributor to environmental degradation is the industrial revolution, which has occurred in developed and developing nations. The present investigation aimed to tackle the escalating apprehensions regarding the discharge of various types of dyes from the paint, textile, and dyeing sectors. This research focuses on the adsorption performance of a newly developed system that uses cotton pod shell powder (CPSP) as a novel adsorbent to remove dye industry wastewater. The system has been designed, manufactured, and tested to be operationally efficient and cost-effective. The CPSP is a new adsorbent with desirable properties such as favorable functional groups and porosity, and analysis of its functional groups and porous nature was carried out using FTIR and SEM. The experimental data from the developed system showed that inlet dye concentration (50, 100, and 150 ppm), bed height (10, 20, and 30 cm), and flow rate (10, 15, and 20 mL/min) significantly affect the adsorption of dye industry wastewater by CPSP. Breakthrough curves were shown to be flow rate and bed depth dependent, according to the data. Significant experimentation was conducted on the developed system, and under optimized conditions. It was shown that the breakthrough point was affected by both bed height and flow rate. Evidence suggested that decreasing flow rate and concentration and raising bed height led to improved breakthrough and exhaustion times. At a concentration of 100 ppm and a flow rate of 15 mL/min, a bed depth of 20 cm was found to have the highest absorption capacity. Adam-Bohart, bed depth service time, and Yoon-Nelson models were utilized to examine the adsorption data. The results revealed that the developed system is effective, and the data obtained in this work can provide optimum operating conditions, suggesting its scalability to an industrial level for dye removal from wastewater by adsorption using CPSP as a novel adsorbent.

Keywords: adsorption; packed bed column; cotton pod shell; breakthrough curve; dyes industry wastewater



Citation: Topare, N.S.; Raut-Jadhav, S.; Khan, A. Development of an Operationally Efficient and Cost-Effective System for Removal of Dye from Wastewater Using Novel Adsorbent. *Eng. Proc.* **2024**, *76*, 102. <https://doi.org/10.3390/engproc2024076102>

Academic Editors: Golam Kabir, Sharfuddin Khan, Mohammad Khondoker and Hussameldin Ibrahim

Published: 19 December 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Dyes are widely utilized in several industrial industries to impart desired colors to final products [1]. These industries include food, pharmaceuticals, textiles, plastics, metals, and many more [2]. At present, various industries use about 700,000 tonnes of dyes annually, with at least 10–15% ending up in wastewater. To maintain a healthy ecosystem, the quality of water must be good [3,4]. Poor water quality is responsible for more than 2 million deaths every year. Around 0.5 billion people are facing the problem of water scarcity in the world,

which is expected to increase to 2.8 billion by 2025 [5]. However, increasing industrial development leads to deterioration of the quality of water as several pollutants such as dyes, heavy metals, pesticides, herbicides, phenols, antibiotics, etc. are discharged into the stream of water day by day causing serious damage to human health and aquatic life [6,7]. Dye is one of the important pollutants among them [8]. Several industries like textile, food, pharmaceuticals, cosmetics, paper, leather, plastic, rubber paint, etc. use dyes to give color to their products [9–11]. Dyes are generally classified into two categories, natural and synthetic dyes. Natural dyes are made from plants, minerals, and animals. Natural dyes are generally less harmful than synthetic dyes and biodegradable. Most dyes are stable and non-biodegradable, hence they are difficult to eliminate from wastewater [12,13].

Dyes are toxic, mutagenic, and carcinogenic. Dyes can harm human beings as well as disturb aquatic life by reducing the transmission of sunlight through the water [14]. A small amount of dye in water is undesirable and makes the water unfit for use. So, it is necessary to remove the dyes from the wastewater [15]. Various dye removal methods are there but these methods are mainly categorized into three main groups, namely chemical methods, physical methods, and biological methods as shown in Figure 1. Adsorption is the preferred method for the removal of dyes by most researchers because of its numerous advantages as the adsorption process is economical, easy technically, eco-friendly, easy to handle, gives better efficiency, and adsorbents can be regenerated [16–18]. Commercially available activated carbons are generally used for adsorption but because of their high cost, their applications are limited [19]. Hence, it is necessary to discover adsorbents that are inexpensive, environmentally friendly, abundantly available, give better efficiency, and can be regenerated [20]. Nowadays researchers are gaining interest in the discovery of biosorbents as they possess removal efficiency comparable to activated carbons, as well as being inexpensive, abundantly available, environmentally friendly, and easily regenerated [21,22].

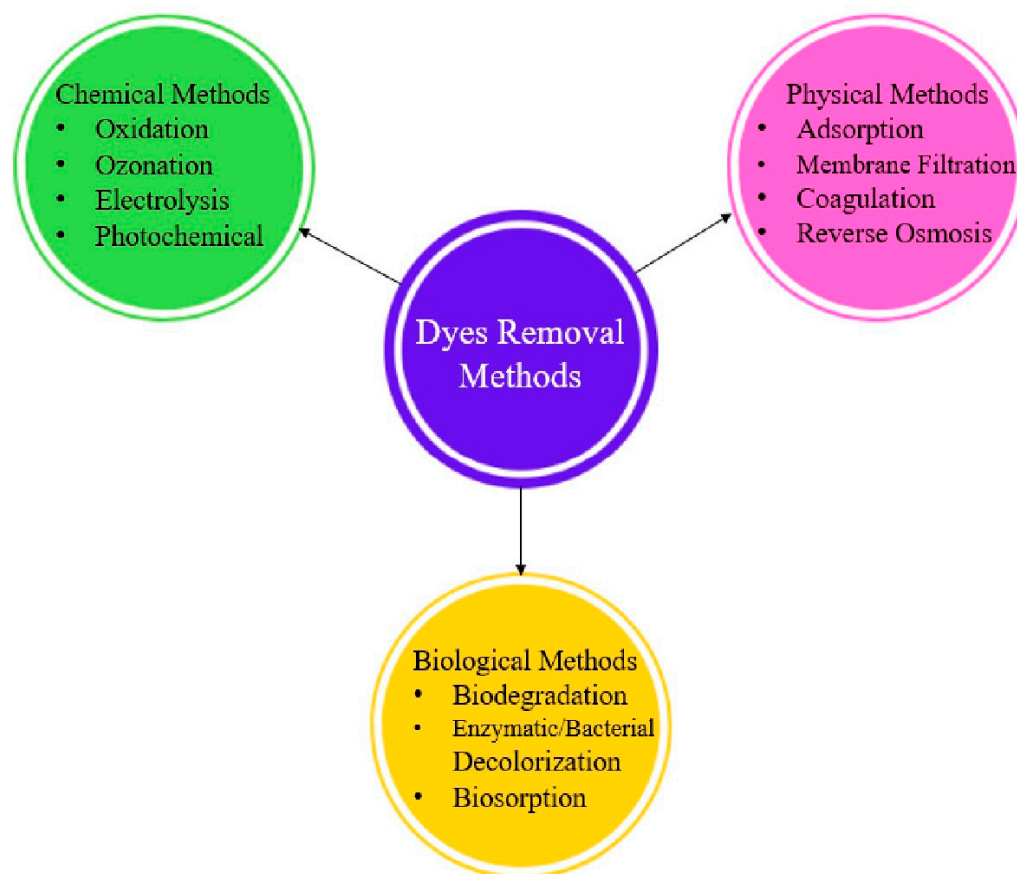


Figure 1. Various dye removal methods.

Dyes can be removed from wastewater by a variety of methods, some of which have been studied and proven effective for quite some time now [23]. Electrolytic recovery and membrane separation are two other examples [24]. It is, therefore, of the utmost importance to create a system that is highly selective, significantly more effective, simple to operate, and cost-effective [25]. There is reason to be positive about adsorption because of its simplicity, technical practicality, economic viability, and social acceptance [26,27]. The capacity of agricultural waste, in the form of biomass, to adsorb dyes has garnered a significant amount of attention in recent years as a potential candidate for the development of an effective, environmentally friendly, and economically viable technology for the treatment of wastewater containing low dye concentrations [28].

Agricultural waste and byproducts are abundantly available and renewable resources. Agricultural wastes have little economic value and create a disposal problem [29]. The generation of agricultural residue in India is more than 400 million tons annually. Many countries produce huge quantities of fruits and other food materials [30–32]. The wastes created from these materials are either burned or dumped, creating problems for the environment [33]. Hence, utilization of agricultural waste as an adsorbent is economical and also reduces the waste disposal problem. Several agricultural byproducts are used for the preparation of adsorbent, such as stalks, husks, straws, peels, stones, shells, seeds, and leaves [34,35]. These wastes are generally divided into two categories. One is the byproduct/waste from industrial processing and the other is the residue remaining in the agricultural field. Agricultural byproducts/wastes contain cellulose, hemicellulose, and lignin and also have several functional groups on the surface such as aldehydes, ketones, alcohol, hydroxyl, carbonyl, aromatic rings, ether groups, etc. This makes agricultural waste a good alternative for utilization as an adsorbent. This research is aimed at a possible method for creating an efficient, low-cost, and easy-to-implement CPSP-based technology for the removal of dye industrial wastewater. In a developed system, the adsorption capacity of the process CPSP was studied in terms of its ability to remove dye from industrial wastewater.

2. Materials and Methods

2.1. Materials

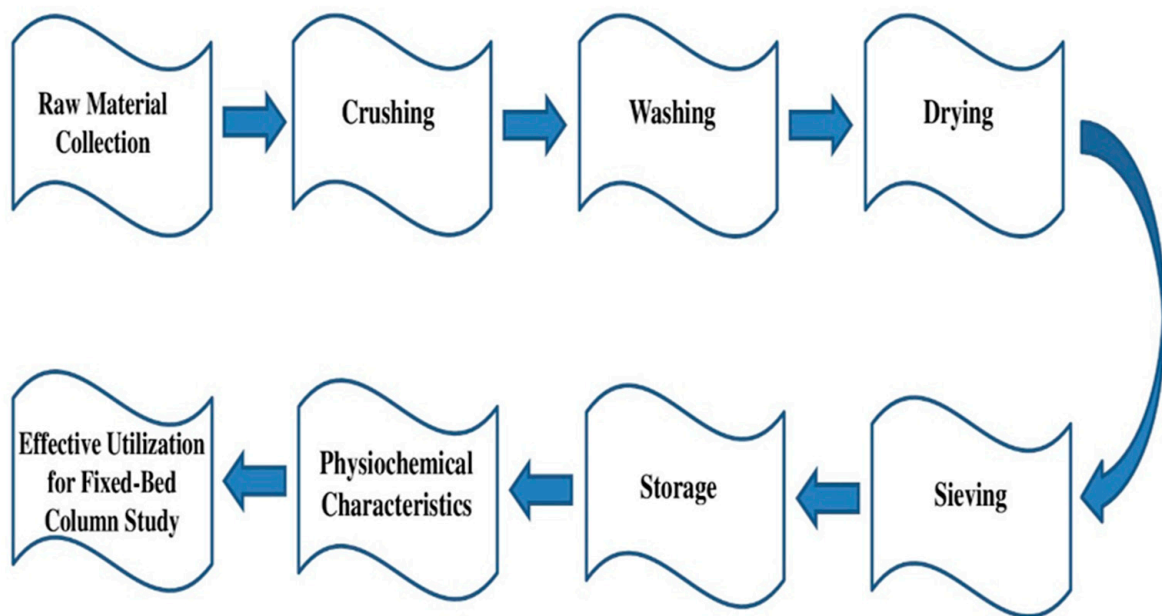
The cotton pod shells were obtained from the agricultural sector/local farms. To carry out the research, a variety of different reagent solutions were prepared in double-distilled water. We used 0.1 N HCl and 0.1 N NaOH so that we could maintain precise control over the acidity and alkalinity of the solutions.

2.2. Preparation/Processing and Characterization of CPSP

The cotton pod shells were collected from the field. Running tap water was used to remove grime and other debris. After collecting them, cotton pod shells were left to dry for an additional week. Regularly, the cotton pod shell moisture levels were checked. So that the cotton pod shells would not get contaminated, they were wrapped in plastic paper. For 24 h, the cotton pod shells were roasted to 80 °C in an oven. When the cotton pod shells were completely dry, they were collected and put through additional processes like grinding and screening. The cotton pod shells were ground down to a fine powder using a regular kitchen mixer. Screening (with screens of mesh size 100) was then used to achieve the desired particle size after grinding. This processed powder served as an adsorbent for dye removal from industrial wastewater. Table 1 shows the characteristics of the CPSP. Figure 2 shows the steps in the processing of CPSP.

Table 1. Characteristics of the CPSP.

Total pore volume (cm ³ /g)	0.31
Average pore radius (Å)	17.86
Pore volume (cc/g)	0.006
Bulk density (g/cm ³)	0.58
Surface area (m ² /g)	25.86
Moisture (%)	7.00
Volatile matter (%)	76.54
C (%)	68.51
O (%)	30.34
Si (%)	0.12
K (%)	0.17
Ca (%)	0.11
Cu (%)	0.22
Zn (%)	0.20
Zr (%)	0.32

**Figure 2.** Processing of CPSP.

2.3. SEM Analysis of CPSP

The scanning electron microscope (FEI Nova NanoSEM 450 Model, Thermo Fisher Scientific, Waltham, MA USA) was utilized to examine CPSP. The SEM equipment is capable of ultra-high-resolution imaging at low voltage and possesses unique imaging capabilities at a low vacuum. Different resolutions (1 nm at 15 kV, 1.4 nm at 1 kV, 1.8 nm at 3 kV, and 30 Pa) were used to capture the SEM images. The SEM image of the CPSP is shown in Figure 3. The illustration demonstrates that CPSP has an uneven porous structure, which is an indication that the exterior surface of the CPSP contains macropores that are open in a uniform manner.

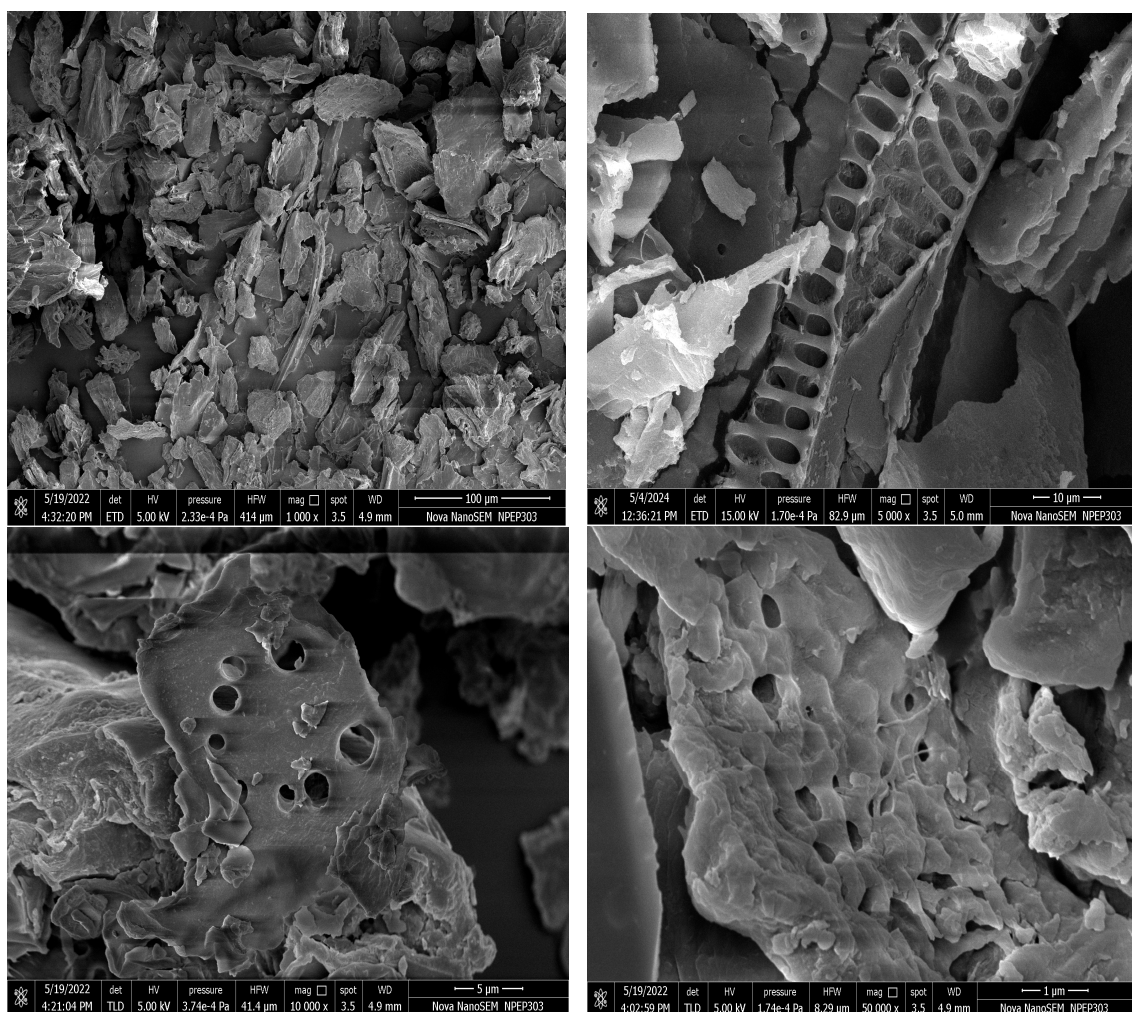


Figure 3. SEM image of CPSP.

2.4. FTIR Analysis of CPSP

The JASCO brand FTIR-6100 spectrophotometer (Jasco International Co., Ltd., Tokyo, Japan) was utilized in order to carry out the FTIR analysis on the CPSP. To measure absorption spectra, pellets (press discs) were utilized. In a mortar and pestle, the materials were pulverized with 200 mg of KBr (spectroscopic grade). Figure 4 shows the results of an FTIR analysis of CPSP. The functional group OH is shown by the peaks at 3265 cm^{-1} , and the functional group CH is indicated by the peak at 1890 cm^{-1} . The functional groups C-O stretch, C-C stretch, C-C bending, and C-H bending are confirmed by the peak values that occur at 1601 , 1433 , 1315 , and 1022 cm^{-1} , respectively.

2.5. Experimental Procedure

The fixed-bed column had a 100 cm height and a diameter of 3.5 cm. Dye adsorption onto CPSP was studied under varying conditions, such as starting concentrations ranging from 50, 100, and 150 ppm, bed heights of 10, 20, and 30 cm, and flow rates of 10, 15, and 20 mL/min. Diaphragm pumping was employed to force a dye industrial wastewater upwards through the column [36,37]. The samples were taken at predetermined intervals throughout the process [38]. All of the experiments relied on an atomic absorption spectrophotometer to quantify the adsorption of dyes [39,40]. The primary goal of most research into adsorption column layouts is to estimate how long the bed will last before needing to be regenerated. The process involves determining when the bed will reach a certain height based on the height at which it was created. The experimental setup for fixed-bed column adsorption investigation is shown in Figure 5.

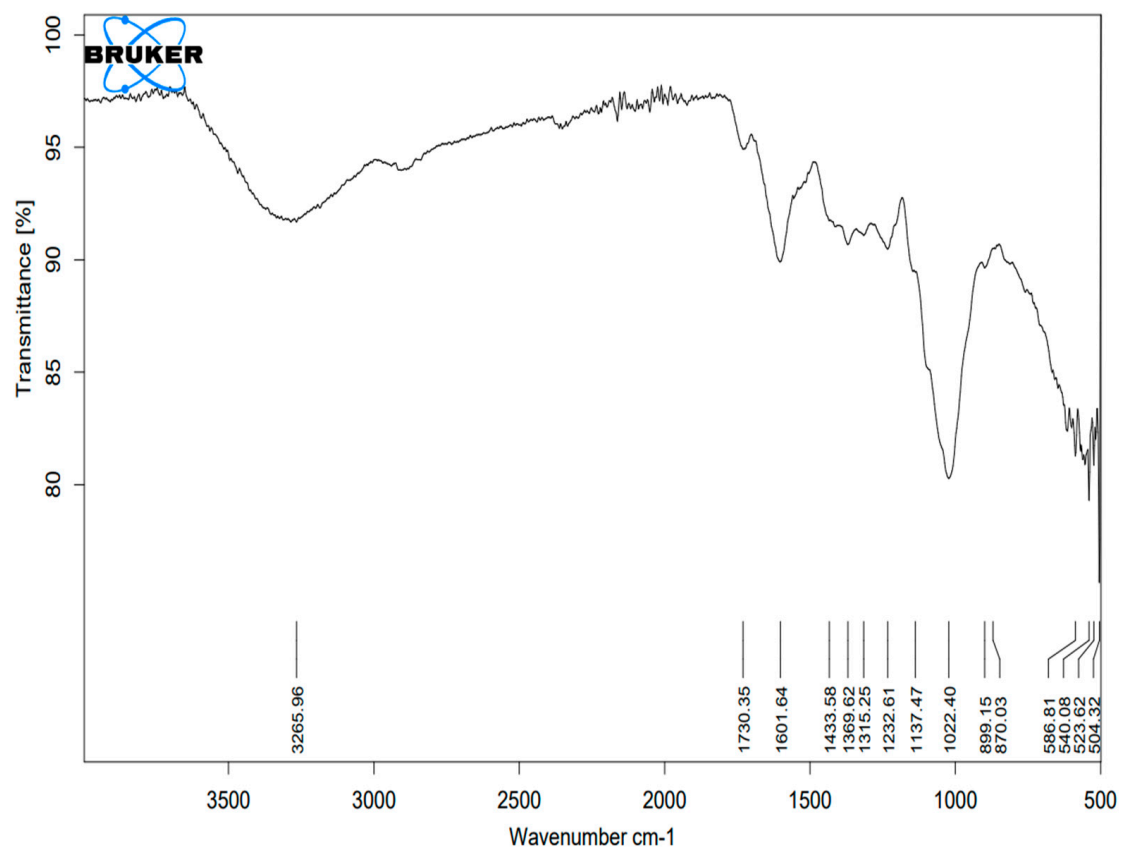


Figure 4. FTIR for CPSP.

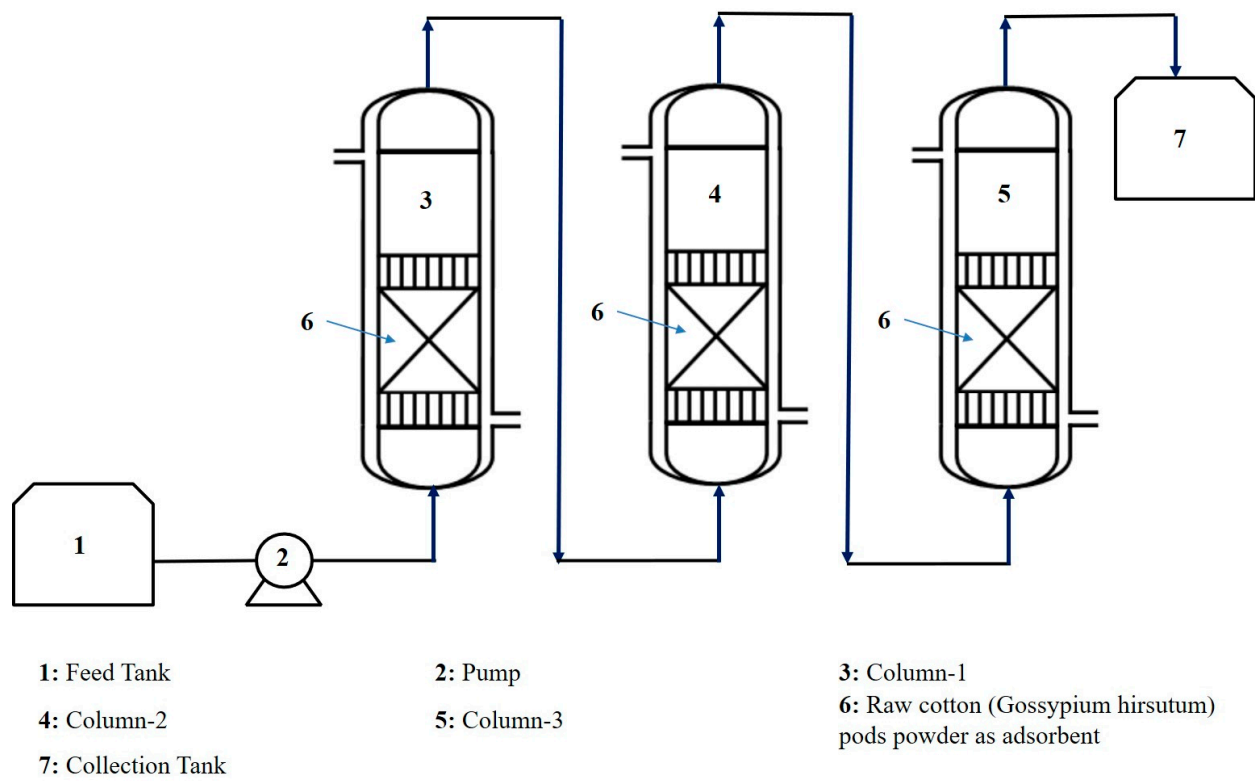


Figure 5. Fixed-bed column adsorption investigation experimental setup.

3. Results

3.1. Effect of Initial Dye Industrial Wastewater Concentrations

To evaluate the effect of the initial concentration, the experiments were performed at a bed height of 20 cm, a flow rate of 15 mL/min, and in concentrations ranging from 50, 100, and 150 ppm. The breakthrough curve is shown in Figure 6. As inlet concentrations were decreased, the breakthrough curve slowed down and the maximum volume treated was reached. Values of C_t/C_o at the inlet that was initially 50, 100, and 150 ppm were stretched to 0.72, 0.53, and 0.96 over 50 min. The higher the inflow concentration, the steeper the breakthrough curve. The increased driving force shortened the adsorption zone.

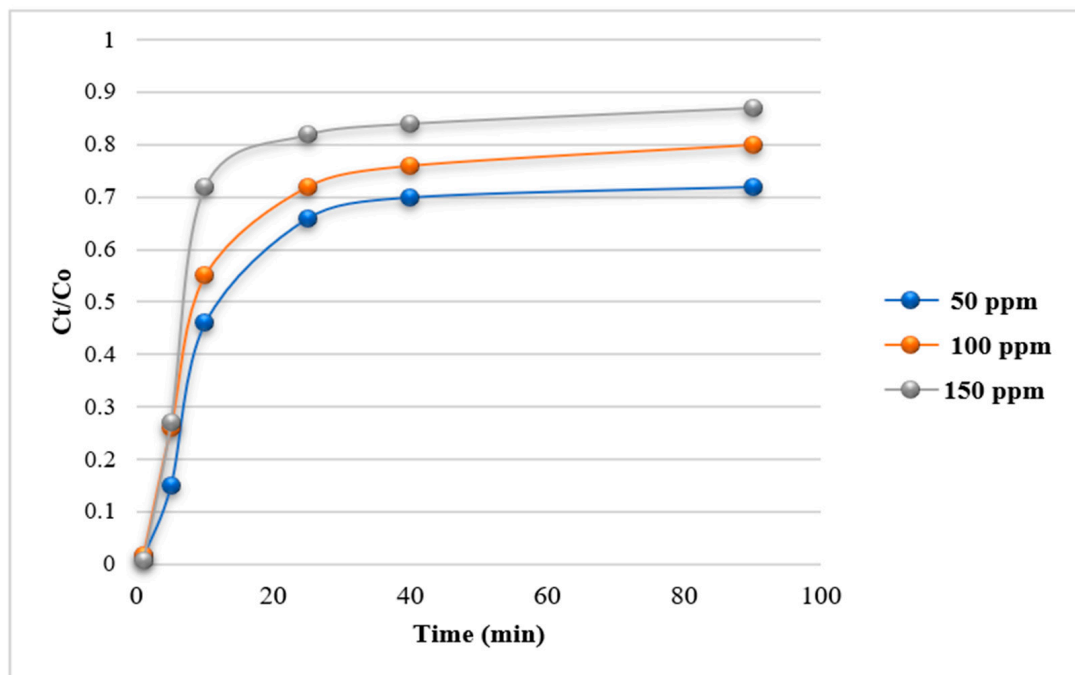


Figure 6. Breakthrough curve for CPSP at an initial dye concentration.

3.2. Effect of Flow Rates

Figure 7 shows the breakthrough curve used to investigate flow rate effects on dye industrial wastewater adsorption. According to the intake starting dye concentration and adsorbent bed height, stability is achieved at 20 cm and 150 ppm. Breakthroughs were more common at greater flow rates. Dye industry wastewater adsorption increased the unit bed height (mass exchange zone) because of the greater flow rate. The shorter contact time at higher flow rates was responsible for the decreasing adsorption behavior [41]. At a slower flow rate, dye industry wastewater has more time to diffuse into the pores of CPSP via intra-particle diffusion, allowing for greater capture by functional group sites around or inside the adsorbent. As the flow rate increased, the breakthrough curve steepened. Because more dyes exchanged with functional group sites at greater flow rates, CPSP's equilibrium column capacity reached its maximum value faster.

3.3. Effect of CPSP Bed Height

When the bed height was changed from 10, 20, and 30 cm, a breakthrough curve was produced for dye industry wastewater adsorption on CPSP at a constant flow rate of 15 mL/min and a dye industry wastewater concentration of 150 ppm. Because of the increase in breakthrough time, the height of the bed was raised (Figure 8). The dye industry wastewater had more opportunities to come into contact with the CPSP as the bed height increased, and its removal efficacy was higher in the column. The larger bed column effects

lead to a decrease in solute concentration. As bed height was increased, the breakthrough curve flattened, creating a larger mass transfer zone.

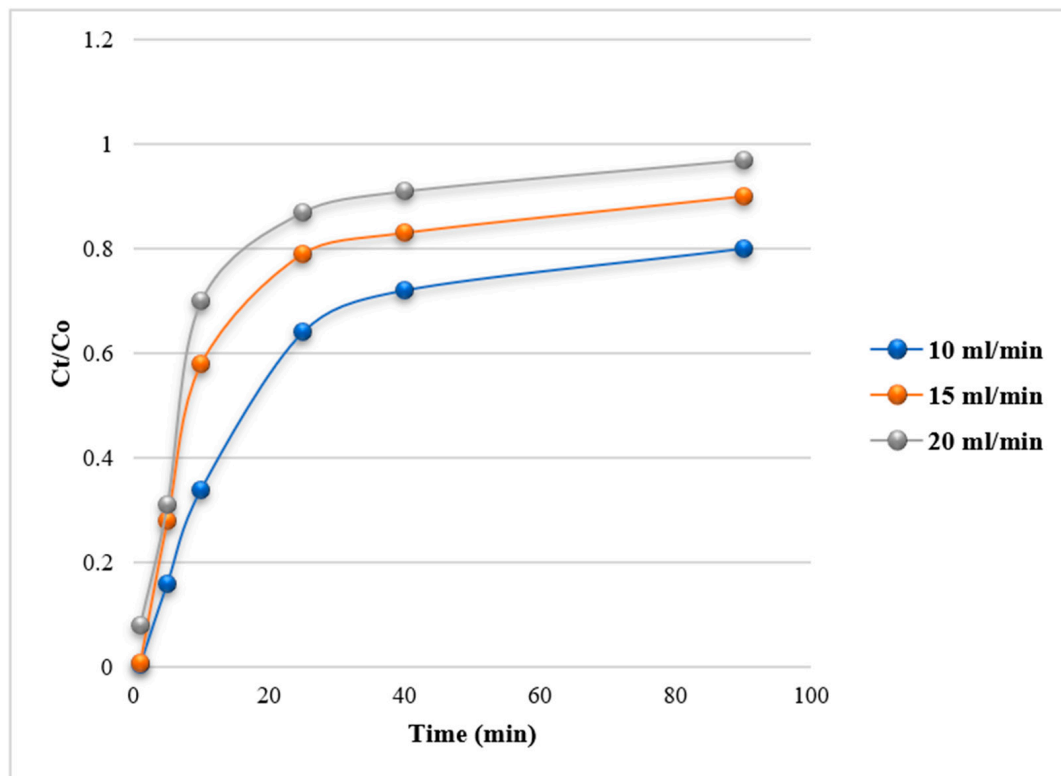


Figure 7. Breakthrough curve for dye on CPSP at different flow rates.

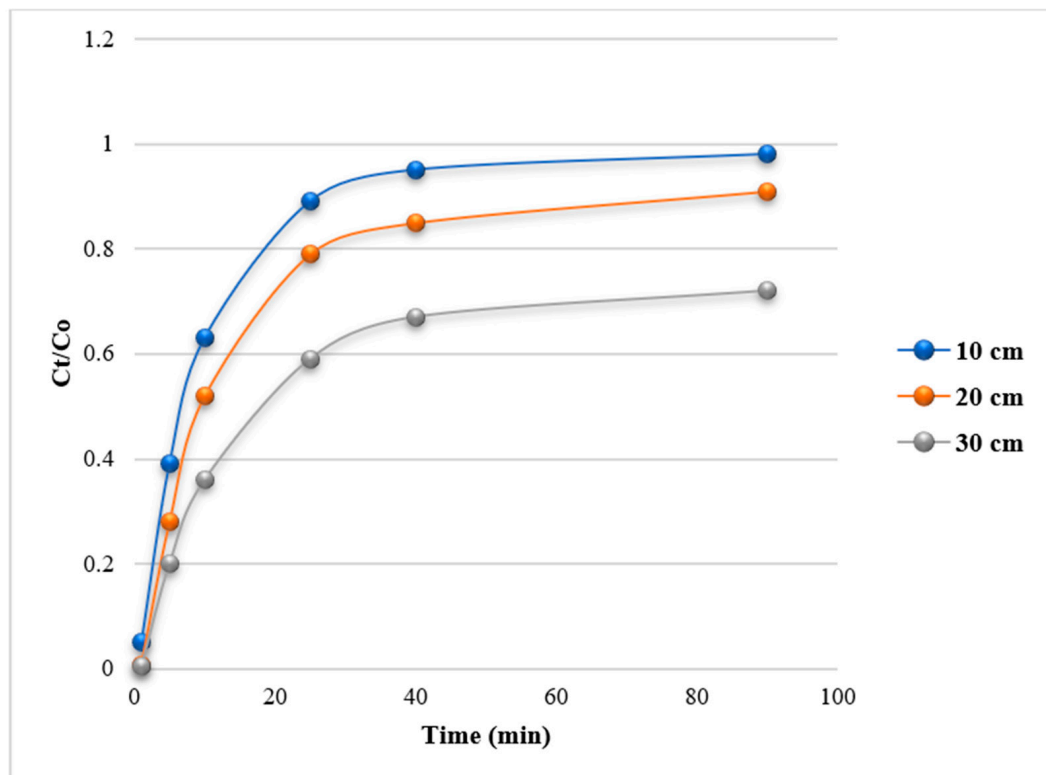


Figure 8. Breakthrough curve for dye on CPSP at different bed heights.

The breakthrough curve is used to determine the efficiency of a packed bed system. An adsorption column's operation and dynamic response are heavily influenced by several variables, including but not limited to, the timing and form of the breakthrough curve [23]. Adsorption column design relies heavily on the ability to predict the output concentration-time profile, often known as the breakthrough curve. The kinetics of adsorption in columns have been extensively evaluated for the Bohart-Adams model. However, the bed depth service time (BDST) and the Yoon-Nelson model have been found to sometimes provide a superior explanation of the adsorption kinetics. Because of this, the goal of this research was to determine the optimal model for characterizing the kinetics of adsorption in a column.

3.4. Bohart-Adams Model

The initial portion of the breakthrough curve was described by applying the Bohart-Adams model to experimental data. Maximum adsorption capacity (N_0), mass transfer coefficient, and other defining characteristics were the primary targets of this method for an estimate (k_{AB}). For the purposes of this investigation, we studied the period spanning the initial stages of the breakthrough curve to its final stages [42]. Different flow rates, bed heights, and initial dye industry wastewater concentrations were used to generate a plot of $\ln(C_t/C_0)$ with time. Mass transfer coefficient (k_{AB}) and saturation concentration (N_0) were determined using the curve's slope and intercept, respectively. Figure 9, Figure 10, and Figure 11 represent the Bohart-Adams model to CPSP for different bed heights, flow rates, and initial dye concentration, respectively. Table 2 represents the summary of constants from the Bohart-Adams model for CPSP.

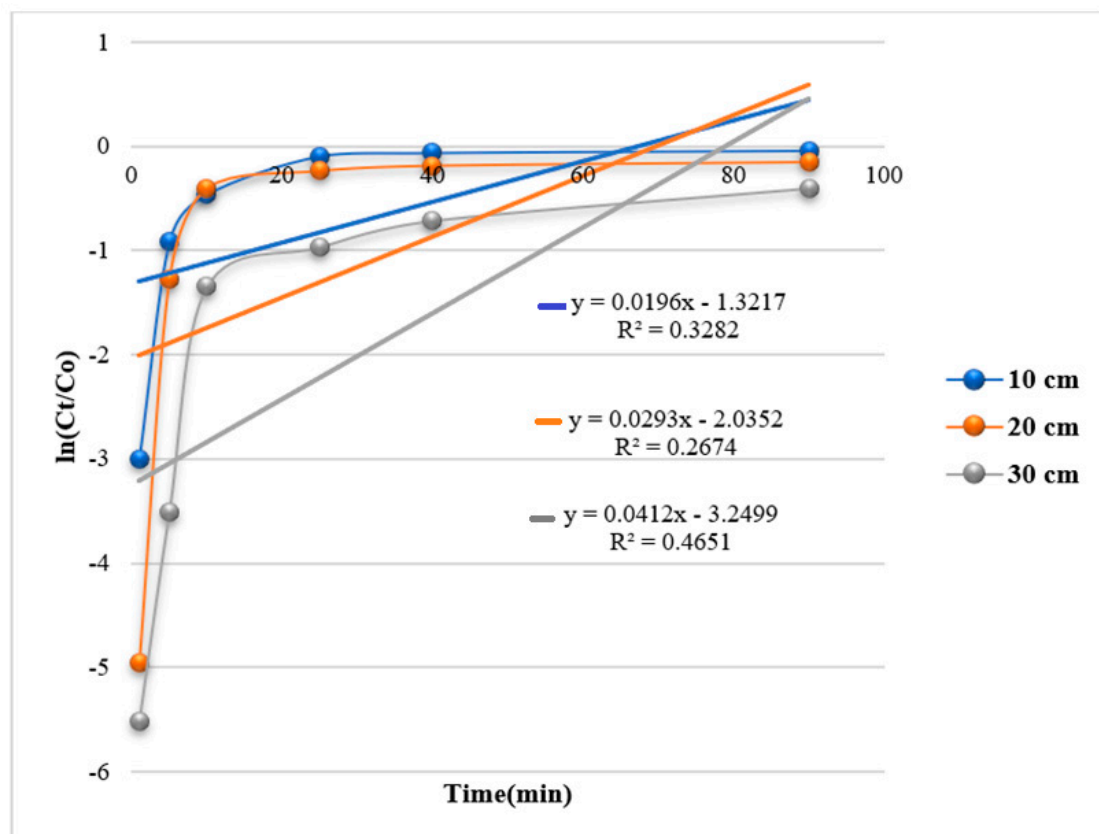


Figure 9. Bohart-Adams model to CPSP for different bed heights.

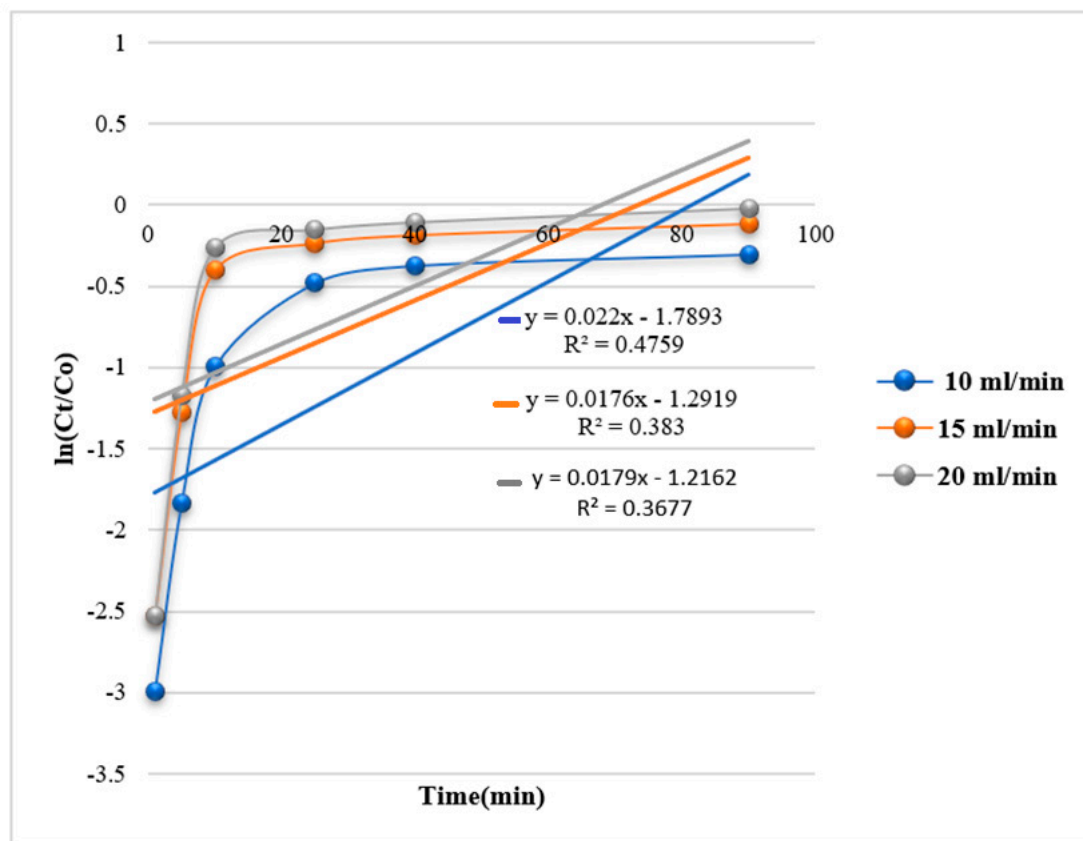


Figure 10. Bohart-Adams model to CPSP for different flow rates.

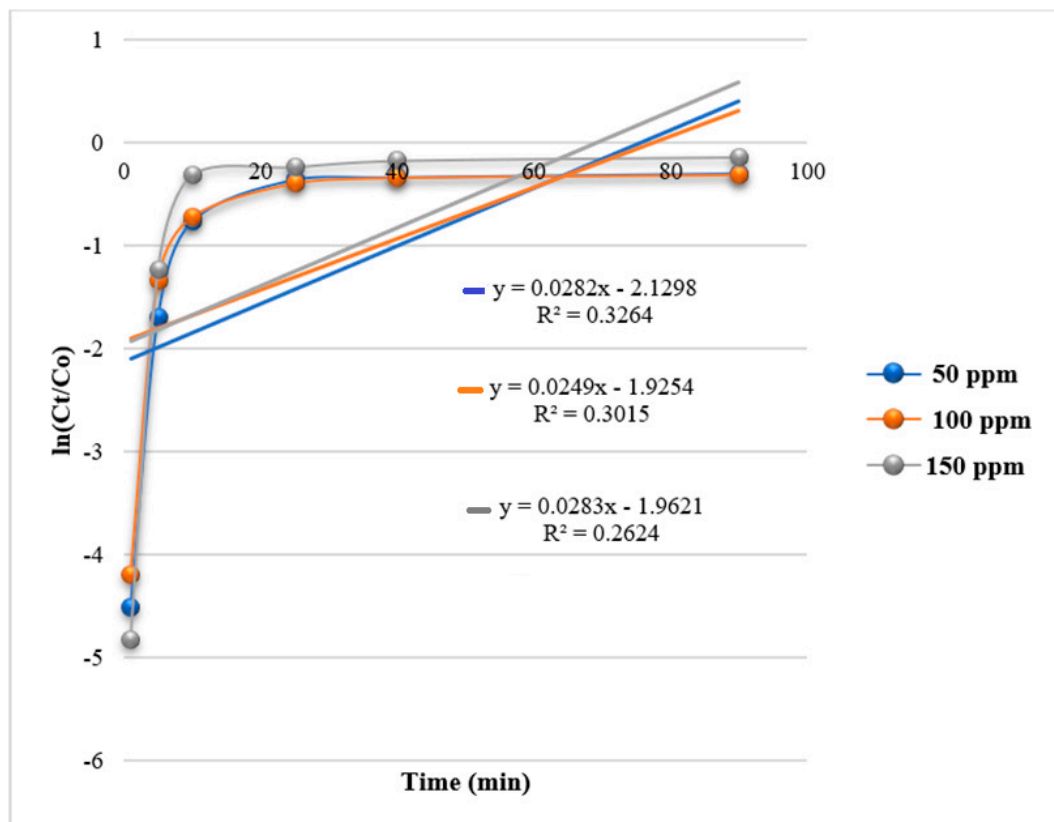


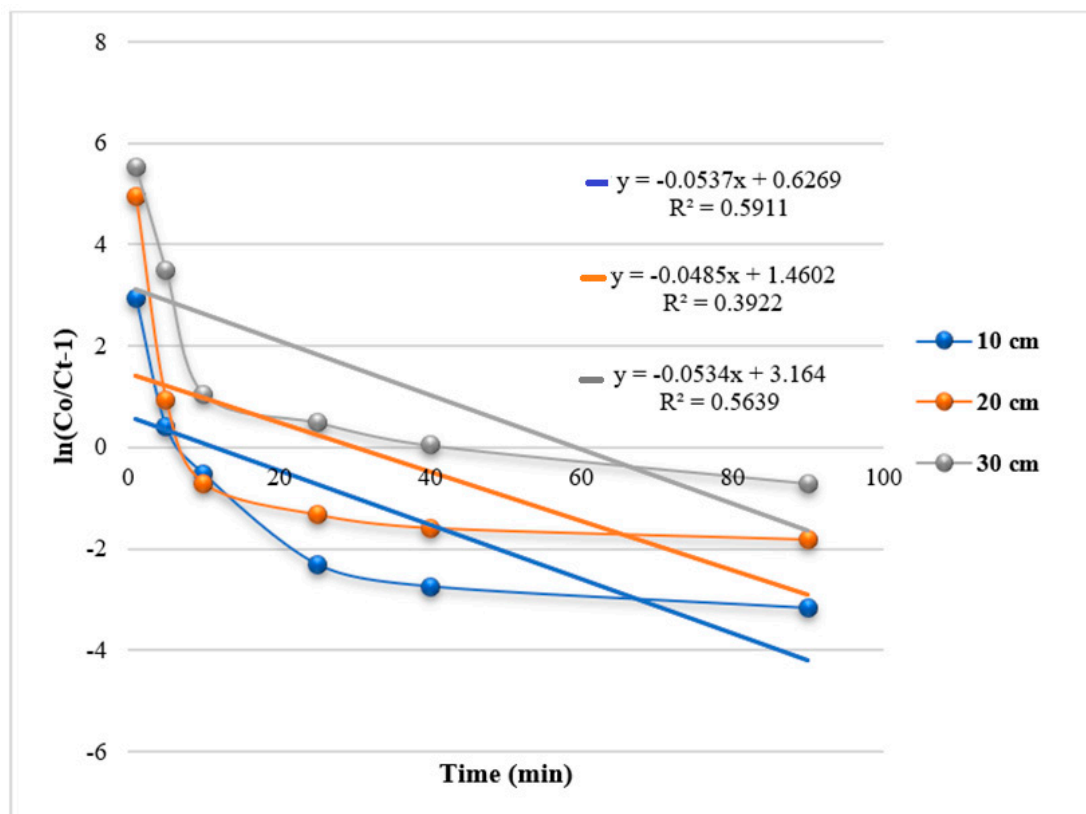
Figure 11. Bohart-Adams model to CPSP for different initial dye concentrations.

Table 2. Summary of constants from Bohart-Adams model for CPSP.

Parameter	Value	K_{AB} (lit/mg·min)	N_0 (mg/lit)
Bed Height (cm)	10	0.002	2101
	20	0.002	2097
	30	0.003	1446
Flow Rate (mL/min)	10	0.003	1005
	15	0.002	2081
	20	0.001	3671
Initial Concentration (ppm)	50	0.003	1922
	100	0.002	2057
	150	0.002	2125

3.5. BDST Model

In order to plot the BDST curve, experimental data that were collected from the column studies were utilized. Values for K and N_0 can be determined by examining the relationships between the adsorption rate, bed height, and inlet dye industry wastewater concentration, among other variables. Figure 12, Figure 13, and Figure 14 represent the BDST model to RGHP for different bed heights, flow rates, and initial dye concentrations, respectively. The estimated values of K , N_0 , and other statistical parameters are shown in Table 3.

**Figure 12.** BDST model to CPSP for different bed heights.

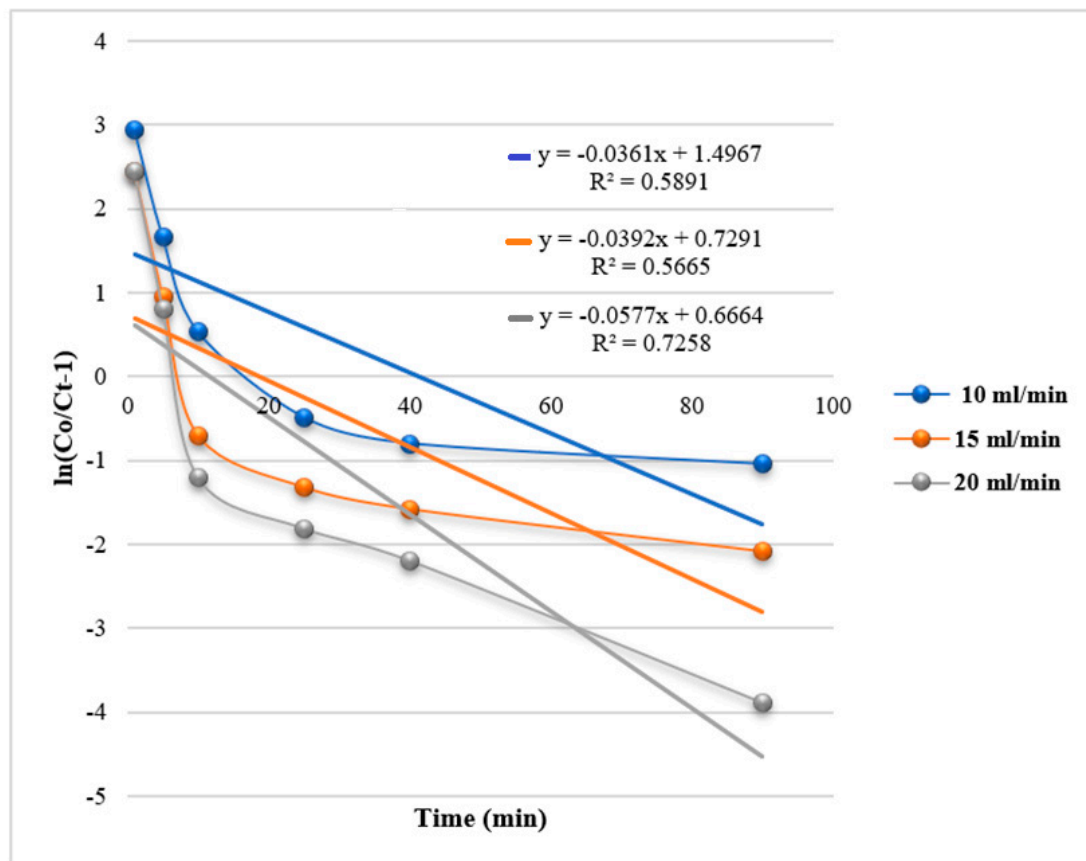


Figure 13. BDST model to CPSP for different flow rates.

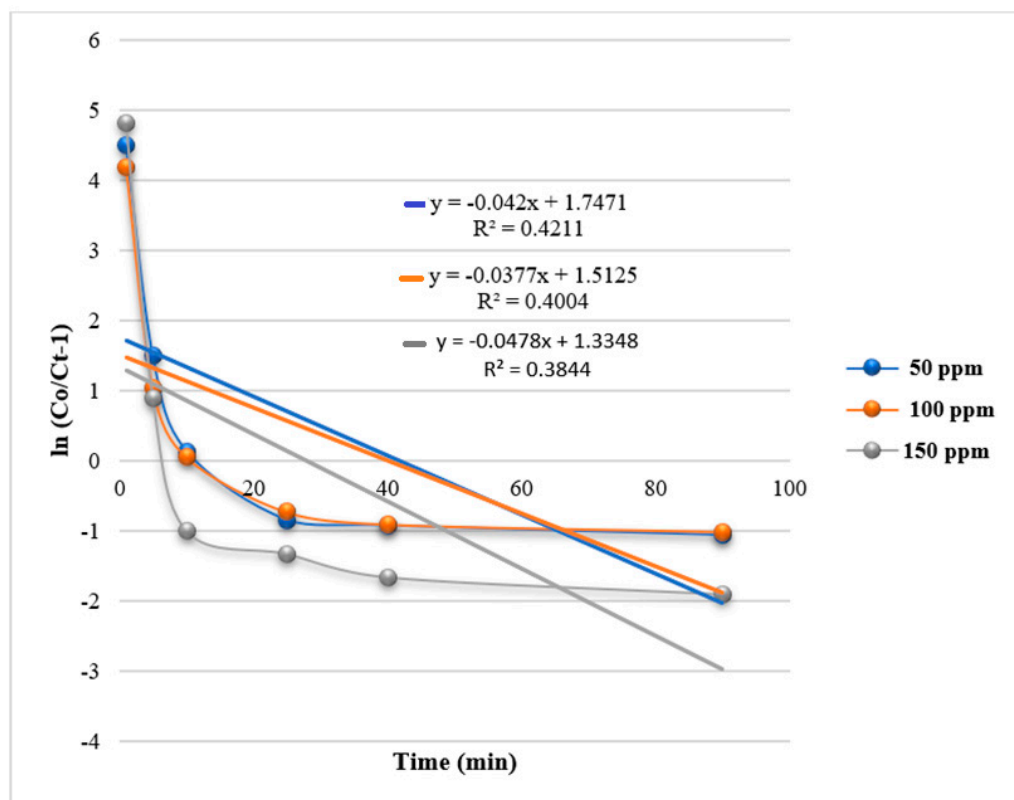


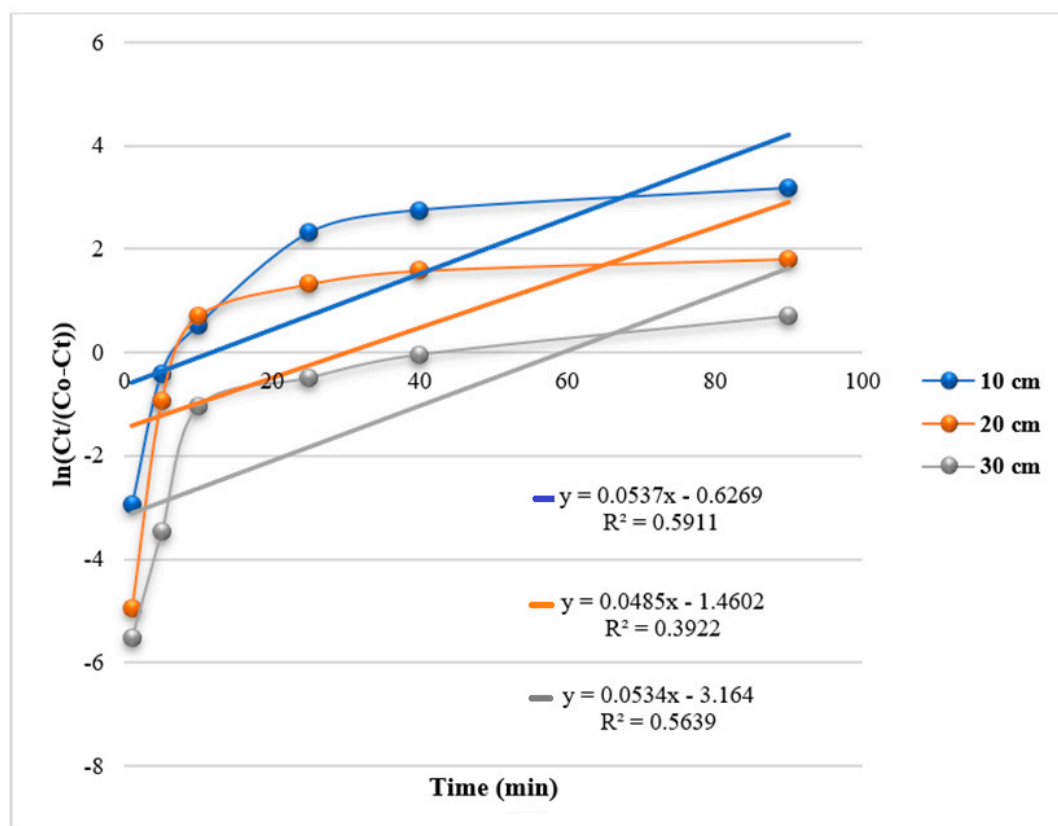
Figure 14. BDST model to CPSP for different initial dye concentrations.

Table 3. Summary of constants from BDST model for CPSP.

Parameter	Value	K (mg/min)	N ₀ (mg/gm)
Bed Height (cm)	10	0.005	378
	20	0.004	781
	30	0.005	1016
Flow Rate (mL/min)	10	0.003	648
	15	0.003	531
	20	0.005	415
Initial Concentration (ppm)	50	0.004	960
	100	0.003	1078
	150	0.004	712

3.6. Yoon-Nelson Model

The CPSP breakthrough behavior of dye industry wastewater was studied using a straightforward theoretical model created by Yoon-Nelson. From a graph of $\ln(C_t/C_0 - C_t)$ vs 't' for varying flow rates, bed heights, and initial dye industry wastewater concentrations, values for ' K_{YN} ' and ' τ ' were calculated. Figure 15, Figure 16, and Figure 17 represent the Yoon-Nelson model to CPSP for different bed heights, flow rates, and initial dye industry wastewater concentration, respectively. Table 4 displays the results of our computations for K_{YN} . The table shows that the Yoon-Nelson model can successfully simulate the entire breakthrough curve at greater flow rates and inlet dye industry wastewater concentrations.

**Figure 15.** Yoon-Nelson model to CPSP for different bed heights.

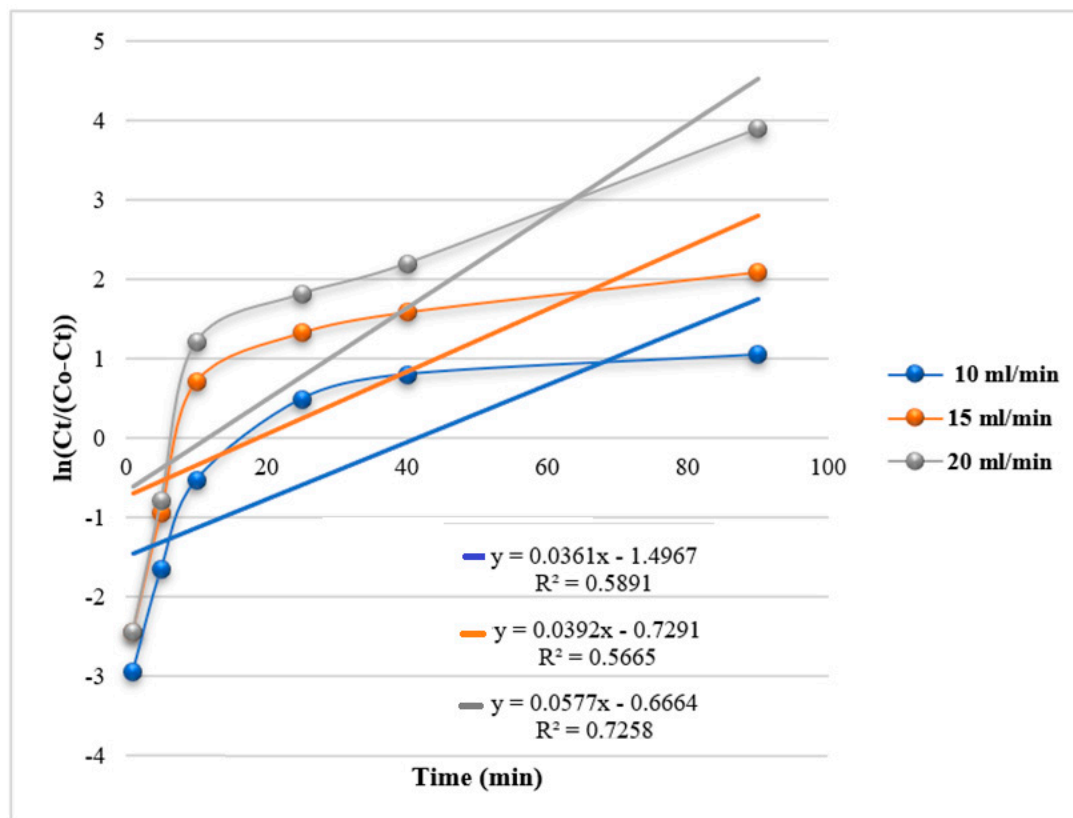


Figure 16. Yoon-Nelson model to CPSP for different flow rates.

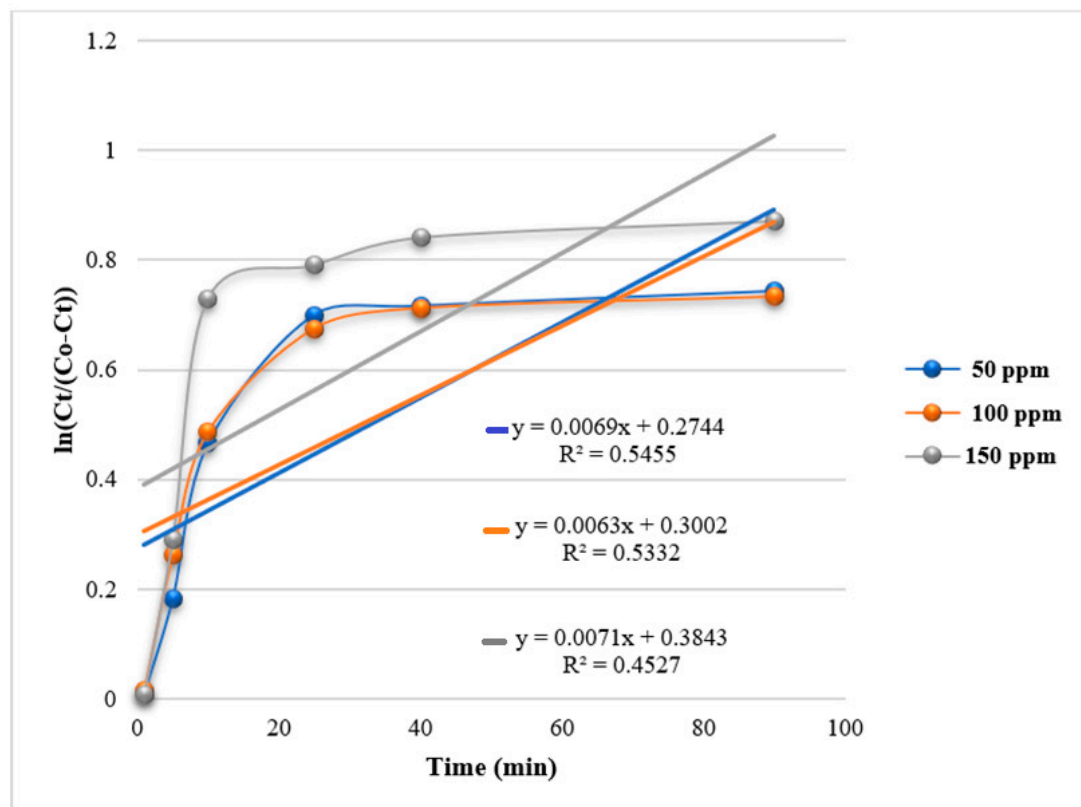


Figure 17. Yoon-Nelson model to CPSP for different initial dye concentrations.

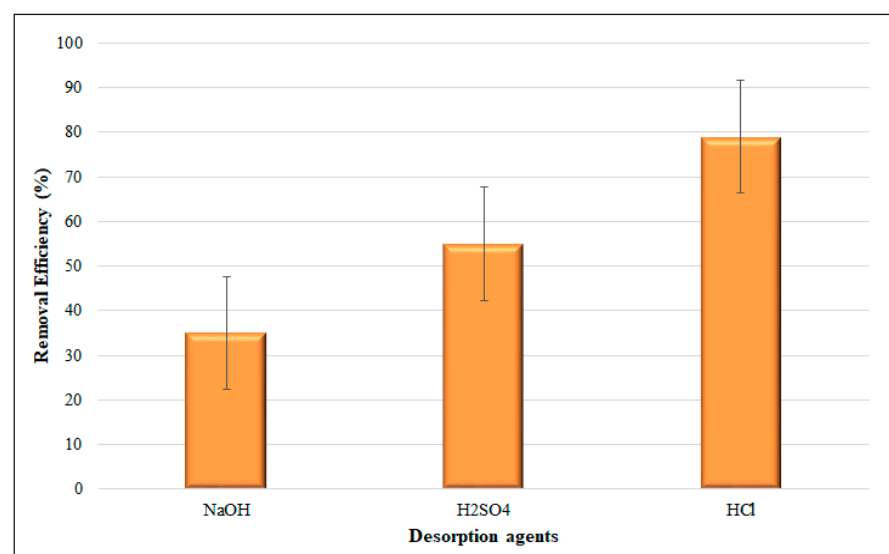
Table 4. Summary of constants from the Yoon-Nelson Model for CPSP.

Parameter	Value	$K_{YN} \text{ (min}^{-1}\text{)}$	$\tau \text{ (min)}$
Bed Height (cm)	10	0.062	11.21
	20	0.052	28.01
	30	0.045	57.11
Flow Rate (mL/min)	10	0.047	48.21
	15	0.052	27.19
	20	0.053	11.08
Initial Concentration (ppm)	50	0.050	48.68
	100	0.036	44.75
	150	0.048	28.66

4. Recovery and Regeneration Approach

Adsorption's ability to regenerate is crucial to its success from both financial and ecological perspectives. One of the challenges that are involved with the adsorption procedures is the proper disposal of the adsorbent. The process of regeneration can lessen the requirement for fresh adsorbent and also alleviate the issue of where to dispose of wasted adsorbent [43]. Different strategies for regeneration have been tried, each with varying degrees of effectiveness. These techniques include thermal, chemical, and electrochemical regeneration in addition to washing with solvents. The process of regenerating used adsorbents can be carried out multiple times; however, the regenerated adsorbent will have a lower adsorption capacity when compared to fresh adsorbents [44]. The approach that this work takes is that the proposed modified adsorbent may be desorbed in an acidic medium and can be reused for subsequent adsorption studies in addition to having a multifold efficiency of the same when compared to current adsorbents. Columns that use this particular form of the adsorption–desorption cycle have the potential to be built for the removal of the highest amounts of hazardous dyes.

Desorption helps regenerate used biosorbents and recover and separate dyes from industrial wastewater. A study on desorption was carried out to determine the most effective desorbing solution for use in subsequent regeneration cycles. The column capacity of CPSP remained nearly constant despite an increase in the reuse time, and breakthrough curves for each adsorption cycle were provided. Approximately 36%, 55%, and 79% of the dye adsorbed on the adsorbent surface was retrieved by the NaOH, H₂SO₄, and HCl in the desorption experiments illustrated in Figure 18. The study indicated that dyes accumulated onto the CPSP could be desorbed and the maximum percentage recovery of dye industrial wastewater was 79% 0.1 M HCl.

**Figure 18.** Desorption of dye industry wastewater adsorbed on CPSP.

5. Conclusions

The results of these experiments demonstrate that the bed height (determined by the starting weight of the loaded CPSP), the concentration of dye industry wastewater in the input, and the flow rate all have a significant impact on the adsorption of dye industry wastewater. These results are based on adsorption experiments performed in the developed system i.e., fixed-bed column for the removal of dye industry wastewater. The most useful results of this study are that dye industry wastewater may be removed from CPSP's aqueous solution using a fixed-bed adsorption column. A lower dye industry wastewater content, low flow rate, and higher CPSP bed height were all optimized for operation in the fixed-bed adsorption system. Both the time required to make a breakthrough and the time required to reach exhaustion increase with the height of the bed, while the concentration of the dye entering the bed decreases. The breakthrough curve also became steeper with increasing flow rates. When the flow rate is increased, it takes less time for the system to reach its breaking point and to be completely exhausted. Bohart-Adams, BDST, and Yoon-Nelson models were applied to dynamic experiments in a fixed-bed column to predict breakthrough curves and determine column parameters. According to statistical analysis, the experimental data are consistent with the Bohart-Adams model. The results also demonstrated a desorption effectiveness of 79% for dye industry wastewater in most desorbing solutions.

Due to their economic impact, and little or no environmental pollution, the innovative approach has become more and more energy efficient. This process is used in place of conventional processes to increase the removal efficiency of dye industrial wastewater. A designed and developed system has improved the performance of the process by obtaining higher removal efficiency in the presence of CPSP in three different columns arranged in series. The use of CPSP in three different columns arranged in series in one system is an operationally efficient, innovative, and environmentally friendly solution to solid waste disposal.

Author Contributions: All authors contributed to the study's conception and design. Conceptualization, methodology, material preparation, data collection, and analysis were performed by N.S.T., S.R.-J. and A.K. The first draft of the manuscript was written by N.S.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Dr. Vishwanath Karad Research Funding Scheme, MITWPU, Pune, India for their support of a minor research project (Ref.: VCS/GC/02-2022).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

CPSP	Cotton Pod Shell Powder
H ₂ SO ₄	Sulfuric Acid
HCl	Hydrochloric Acid
NaOH	Sodium Hydroxide
C	Carbon
O	Oxygen
Si	Silicon
K	Potassium
Ca	Calcium
Cu	Copper
Zn	Zinc

Zr	Zirconium
SEM	Scanning Electron Microscope
FTIR	Fourier-Transform Infrared Spectroscopy
KBr	Potassium Bromide

References

1. Fu, F.; Wang, Q. Removal of heavy metal ions from wastewaters: A review. *J. Environ. Manag.* **2011**, *92*, 407–418. [\[CrossRef\]](#)
2. Sharma, A.; Anjana; Rana, H.; Goswami, S. A Comprehensive Review on the Heavy Metal Removal for Water Remediation by the Application of Lignocellulosic Biomass-Derived Nanocellulose. *J. Polym. Environ.* **2022**, *30*, 1–18. [\[CrossRef\]](#)
3. Acharya, J.; Kumar, U.; Rafi, P.M. Removal of heavy metal ions from wastewater by chemically modified agricultural waste material as potential adsorbent—a review. *Int. J. Curr. Eng. Technol.* **2018**, *8*, 526–530. [\[CrossRef\]](#)
4. Ashtoukhya, E.S.Z.; Amina, N.K.; Abdelwahab, O. Removal of lead (II) and copper (II) from aqueous solution using pomegranate peel as a new adsorbent. *Desalination* **2008**, *223*, 162–173. [\[CrossRef\]](#)
5. Bhatnagar, A.; Sillanpaa, M.; Krowiak, A.W. Agricultural waste peels as versatile biomass for water purification—A review. *Chem. Eng. J.* **2015**, *270*, 244–271. [\[CrossRef\]](#)
6. Topare, N.S.; Wadgaonkar, V.S. A review on application of low-cost adsorbents for heavy metals removal from wastewater. *Mater. Today Proc.* **2023**, *77*, 8–18. [\[CrossRef\]](#)
7. Bandara, T.; Xu, J.; Potter, I.D.; Franks, A.; Chathurika, J.B.A.J.; Tang, C. Mechanisms for the removal of Cd(II) and Cu(II) from aqueous solution and mine water by biochars derived from agricultural wastes. *Chemosphere* **2020**, *254*, 126745. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Mpongwana, N.; Rathilal, S. A Review of the Techno-Economic Feasibility of Nanoparticle Application for Wastewater Treatment. *Water* **2022**, *14*, 1550. [\[CrossRef\]](#)
9. Imdad, S.; Dohare, R.K. A Critical Review on Heavy Metals Removal Using Ionic Liquid Membranes from The Industrial Wastewater. *Chem. Eng. Process.—Process Intensif.* **2022**, *173*, 108812. [\[CrossRef\]](#)
10. Zaimee, M.Z.A.; Sarjadi, M.S.; Rahman, M.L. Heavy Metals Removal from Water by Efficient Adsorbents. *Water* **2021**, *13*, 2659. [\[CrossRef\]](#)
11. Carolin, C.F.; Kumar, P.S.; Saravanan, A.; Joshiba, G.J.; Naushad, M. Efficient techniques for the removal of toxic heavy metals from aquatic environment: A review. *J. Environ. Chem. Eng.* **2017**, *5*, 2782–2799. [\[CrossRef\]](#)
12. Azimi, A.; Azari, A.; Rezakazemi, M.; Ansarpour, M. Removal of Heavy Metals from Industrial Wastewaters: A Review. *ChemBioEng Rev.* **2017**, *4*, 37–59. [\[CrossRef\]](#)
13. Crini, G.; Lichtfouse, E. Advantages and disadvantages of techniques used for wastewater treatment. *Environ. Chem. Lett.* **2019**, *17*, 145–155. [\[CrossRef\]](#)
14. Renu; Agarwal, M.; Singh, K. Heavy metal removal from wastewater using various adsorbents: A review. *J. Water Reuse Desalination* **2017**, *7*, 387–419. [\[CrossRef\]](#)
15. Turcanu, A.A.; Matei, E.; Rapa, M.; Predescu, A.M.; Coman, G.; Predescu, C. Biowaste Valorization Using Hydrothermal Carbonization for Potential Wastewater Treatment Applications. *Water* **2022**, *14*, 2344. [\[CrossRef\]](#)
16. Deshmukh, S.; Topare, N.S.; Raut-Jadhav, S.; Thorat, P.V.; Bokil, S.A.; Khan, A. Orange peel activated carbon produced from waste orange peels for adsorption of methyl red. *AQUA—Water Infrastruct. Ecosyst. Soc.* **2022**, *71*, 1351–1363. [\[CrossRef\]](#)
17. Driehaus, W.; Jekel, M.; Hildebrandt, U. Granular ferric hydroxide—A new adsorbent for the removal of arsenic from natural water. *J. Water Supply Res. Technol.-Aqua* **1998**, *47*, 30–35. [\[CrossRef\]](#)
18. Gupta, S.A.; Vishesh, Y.; Sarvshrestha, N.; Bhardwaj, A.S.; Kumar, P.A.; Topare, N.S.; Raut-Jadhav, S.; Bokil, S.A.; Khan, A. Adsorption isotherm studies of Methylene blue using activated carbon of waste fruit peel as an adsorbent. *Mater. Today Proc.* **2021**, *57*, 1500–1508. [\[CrossRef\]](#)
19. Singh, V.; Pant, N.; Sharma, R.K.; Padalia, D.; Rawat, P.S.; Goswami, R.; Singh, P.; Kumar, A.; Bhandari, P.; Tabish, A.; et al. Adsorption Studies of Pb(II) and Cd(II) Heavy Metal Ions from Aqueous Solutions Using a Magnetic Biochar Composite Material. *Separations* **2023**, *10*, 389. [\[CrossRef\]](#)
20. Dwivedi, C.P.; Sahu, J.N.; Mohanty, C.R.; Mohan, B.R.; Meikap, B.C. Column performance of granular activated carbon packed bed for Pb(II) removal. *J. Hazard. Mater.* **2008**, *156*, 596–603. [\[CrossRef\]](#)
21. Farooq, U.; Kozinski, J.A.; Khan, M.A.; Athar, M. Biosorption of heavy metal ions using wheat based biosorbents—A review of the recent literature. *Bioresour. Technol.* **2010**, *101*, 5043–5053. [\[CrossRef\]](#)
22. Yang, H.; Kim, N.; Park, D. Superior Removal of Toxic Cr(VI) from Wastewaters by Natural Pine Bark. *Separations* **2023**, *10*, 430. [\[CrossRef\]](#)
23. Guan, J.; Hu, C.; Zhou, J.; Huang, Q.; Liu, J. Adsorption of heavy metals by Lycium barbarum branch-based adsorbents: Raw, fungal modification, and biochar. *Water Sci. Technol.* **2022**, *85*, 2145–2160. [\[CrossRef\]](#)
24. Seth, D.; Rastogi, S. Application of vendor rationalization strategy for manufacturing cycle time reduction in engineer to order (ETO) environment: A case study. *J. Manuf. Technol. Manag.* **2019**, *30*, 261–290. [\[CrossRef\]](#)
25. Bocşa, M.; Pintea, S.; Lung, I.; Opris, O.; Stegarescu, A.; Humayun, M.; Bououdina, M.; Soran, M.-L.; Bellucci, S. Biochar-Based Adsorbents for Pesticides, Drugs, Phosphorus, and Heavy Metal Removal from Polluted Water. *Separations* **2023**, *10*, 533. [\[CrossRef\]](#)

26. Iheanacho, O.C.; Nwabanne, J.T.; Obi, C.C.; Onu, C.E. Packed bed column adsorption of phenol onto corn cob activated carbon: Linear and nonlinear kinetics modeling. *S. Afr. J. Chem. Eng.* **2021**, *36*, 80–93. [\[CrossRef\]](#)
27. Seth, D.; Tripathi, D. Relationship between TQM and TPM implementation factors and business performance of manufacturing industry in Indian context. *Int. J. Qual. Reliab. Manag.* **2005**, *22*, 256–277. [\[CrossRef\]](#)
28. Chen, H.; Zhang, R.; Qu, X.; Yuan, Y.; Zhu, B.; Zhao, S.; Jiang, T. Adsorption Properties and Mechanism of Copper Ions from Wastewater by *Lessonia nigrescens* and *Lessonia nigrescens* Residue. *Separations* **2023**, *10*, 559. [\[CrossRef\]](#)
29. Duan, R.; Fedler, C.B. Competitive adsorption of Cu^{2+} , Pb^{2+} , Cd^{2+} , and Zn^{2+} onto water treatment residuals: Implications for mobility in stormwater bioretention systems. *Water Sci. Technol.* **2022**, *86*, 878–893. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Kwikimaa, M.M.; Mateso, S.; Chebude, Y. Potentials of agricultural wastes as the ultimate alternative adsorbent for cadmium removal from wastewater. A review. *Sci. Afr.* **2021**, *13*, e00934. [\[CrossRef\]](#)
31. Lavinia, T.; Carmen, P.; Carmen, T.; Ovidiu, T. Fixed bed column study on the removal of chromium (III) ions from aqueous solutions by using hemp fibers with improved sorption performance. *Cellul. Chem. Technol.* **2015**, *49*, 219–229.
32. Topare, N.S.; Surange, S.; Chaudhari, A.; Raut-Jadhav, S.; Khedkar, S.V.; Bokil, S.A. Adsorption of Rhodamine-B by Using Citrus Peel Powder: Influence of Operating Parameters. *J. Indian Chem. Soc.* **2020**, *97*, 2188–2194.
33. Mohanty, B.; Das, A. Heavy metals in agricultural cultivated products irrigated with wastewater in India: A review. *AQUA—Water Infrastruct. Ecosyst. Soc.* **2023**, *72*, 851–867. [\[CrossRef\]](#)
34. Seth, D.; Rehman, M.A.A. Critical success factors-based strategy to facilitate green manufacturing for responsible business: An application experience in Indian context. *Bus. Strategy Environ.* **2022**, *31*, 2786–2806. [\[CrossRef\]](#)
35. Naseem, K.; Farooqi, Z.H.; Rehman, M.Z.U.; Rehman, M.A.U.; Begum, R.; Huma, R.; Shahbaz, A.; Najeeb, J.; Irfan, A. A systematic study for removal of heavy metals from aqueous media using *Sorghum bicolor*: An efficient biosorbent. *Water Sci. Technol.* **2018**, *77*, 2355–2368. [\[CrossRef\]](#)
36. Radhika, R.; Jayalatha, T.; Rekha, K.G.; Jacob, S.; Rajeev, R.; George, B.K. Adsorption performance of packed bed column for the removal of perchlorate using modified activated carbon. *Process Saf. Environ. Prot.* **2018**, *117*, 350–362.
37. Renu, Agarwal, M.; Singh, K. Simultaneous removal of heavy metals and dye from wastewater: Modelling and experimental study. *Water Sci. Technol.* **2023**, *87*, 193–217. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Seth, D.; Pandey, M.K. A multiple-item inventory model for a non-stationary demand. *Prod. Plan. Control* **2009**, *20*, 242–253. [\[CrossRef\]](#)
39. Shahzadi, I.; Mubarak, S.; Farooq, A.; Hussain, N. Apple peels as a potential adsorbent for removal of Cu and Cr from wastewater. *AQUA—Water Infrastruct. Ecosyst. Soc.* **2023**, *72*, 914–929. [\[CrossRef\]](#)
40. Parimelazhagan, V.; Jeppu, G.; Rampal, N. Continuous Fixed-Bed Column Studies on Congo Red Dye Adsorption-Desorption Using Free and Immobilized *Nelumbo nucifera* Leaf Adsorbent. *Polymers* **2022**, *14*, 54. [\[CrossRef\]](#)
41. Topare, N.S.; Bokil, S.A. Adsorption of textile industry effluent in a fixed bed column using activated carbon prepared from agro-waste materials. *Mater. Today Proc.* **2021**, *43*, 530–534. [\[CrossRef\]](#)
42. Tovar, C.T.; Ortiz, A.V.; Toro, R.O. Batch and Packed Bed Column Study for the Removal of Cr (VI) and Ni (II) Using Agro-Industrial Wastes. *Appl. Sci.* **2021**, *11*, 9355. [\[CrossRef\]](#)
43. Vieira, M.L.G.; Martinez, M.S.; Santosa, G.B.; Dottob, G.L.; Pinto, L.A.A. Azo dyes adsorption in fixed bed column packed with different deacetylation degrees chitosan coated glass beads. *J. Environ. Chem. Eng.* **2018**, *6*, 3233–3241. [\[CrossRef\]](#)
44. Wang, S.; Li, X.; Zhu, Y. Comparison of the adsorption capacity and mechanisms of mixed heavy metals in wastewater by sheep manure biochar and *Robinia pseudoacacia* biochar. *Water Sci. Technol.* **2023**, *87*, 3083–3094. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.