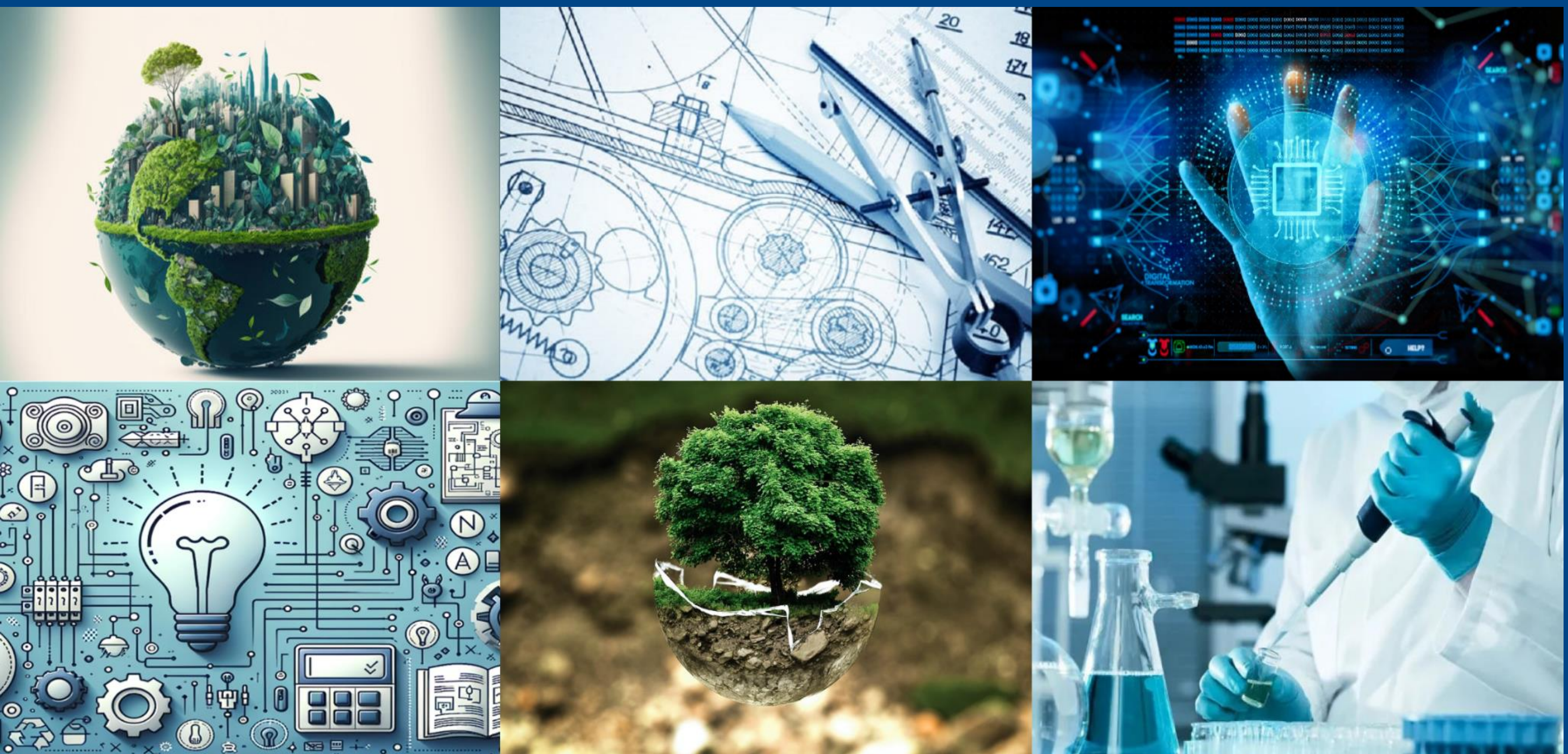
ISSN: 2582-7219

International Journal of Multidisciplinary Research in Science, Engineering and Technology

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.206

Volume 8, Issue 4, April 2025

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ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

Experimental and Optimization Studies on Removal of Micro and Nano Plastics for the Application of Water Treatment using Advanced Technologies

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ABSTRACT: This research investigates the application of goat manure, a bio-waste product, as a sustainable adsorbent for the removal of crystal violet dye from water solutions, to improve soil structure and activate microbial growth for plant well-being. The goat manure was activated to become activated carbon and then made into spherical beads, and their performance was evaluated in column adsorption studies with different parameters including bed height (3 cm, 5 cm, and 7 cm) and flow rate. Breakthrough curves were correlated using the Thomas model to predict dye removal efficiency. The experiments included the preparation of crystal violet dye solutions (1–5 ppm) and their passage through the column, with samples of the effluent taken at regular intervals and analyzed via a calorimeter. Results indicated that the activated carbon from goat manure exhibited impressive dye removing capacity, with the maximum uptake being observed at optimized bed heights and flow rates. The results indicate that adsorbents made from goat manure can be efficient in dye concentration reduction and provide a low-cost, eco-friendly wastewater treatment solution. Furthermore, the process is beneficial with two- fold advantage of enhancing soil structure and stimulating microbial growth, rendering it an interesting candidate for sustainable water treatment and environmental cleaning.

KEYWORDS - Goat manure, Activated carbon, Column adsorption, Crystal violet dye, Dye removal, Adsorption efficiency, Breakthrough curve, Thomas model, Wastewater treatment, Environmental remediation, Sustainable adsorbent, Soil structure, Microbial activity.

I. INTRODUCTION

The widespread and unprecedented global occurrence of micro- and nano plastics (M/NPs) in aquatic ecosystems is an escalating environmental and human health risk, aggravated by the insufficiency of traditional water treatment technologies. The ubiquitous persistent pollutants, with a source that ranges from industrial and domestic to agricultural, are non-biodegradable and tend to bioaccumulate within ecosystems, posing a need for novel and sustainable remediation solutions.

Among the new treatment methods, adsorption using bio-source materials has become increasingly popular owing to its cost-effectiveness, operational ease, and scalability. Although previous works have successfully employed plant-based adsorbents, such as Acalypha indica biomass, for dye removal such as methyl orange, the challenges at present require understanding more stable materials and processes to overcome intricate pollutants such as crystal violet, which is highly molecular in weight and environmental in persistence.This research work is novel in the valorization of agro-biomass waste to form activated carbon-based porous beads suited for crystal violet dye removal under different experimental conditions.

Based on recent developments in chemical and physical removal technologies for M/NPs as discussed in recent literature this research combines the principles of green chemistry with pragmatic engineering design. By converting low-value bio-waste into high-performance adsorbents, we seek to provide a scalable, environmentally friendly solution to the critical problem of micro/nano-pollutant removal, with potential relevance to real-world wastewater treatment processes.

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II. RELATED WORKS

P. R. Rout, A. Mohanty, A. Sharma, M. Miglani, D. Liu, et al. [1] considered multiple mechanisms for the removal of micro and nanoplastics (MNPs) in wastewater treatment systems. They looked into problems and shortfalls in existing methods with an emphasis on optimizing the efficiency of these processes. They also researched possible improvements including enhanced filtration techniques and the use of innovative technologies to curb MNP pollution.

L. Lv, F. Zhou, Z. Wang, K. Wu, X. Li, W. Liao [2] presented an in-depth overview of the situation now and opportunities for future wastewater treatment removal of MNPs. The authors were debating the feasibility of new emerging technologies like electrocoagulation and magnetic separation for enhancing efficiency in removal. The authors recognized that there should be additional work aimed at developing the techniques with enhanced efficiency in addition to reducing environmental impact within wastewater.
M. K. Devi, N. Karmegam, S. Manikandan, et al. [3] were interested in the elimination of nanoplastics during water treatment processes. The authors covered an array otechniques such as adsorption, filtration, and chemical treatments. They evaluated the performance of each technique and summed up that tremendous improvement has been realized, yet elimination of nanoplastics from water is a problematic process needing further sophisticated technology to be invented.

D. A. Hussein and M. M. Al-Hejuje [4] researched the rising occurrence of MNPs in wastewater and its effects on water quality. They researched the origins of these pollutants and their possible effects on both public health and water treatment processes and presented useful insight into the requirements for efficient detection and remediation of MNP.

Z. Liu, L. Liao, H. Yang, Z. Chen, H. Ji [5] investigated the influence of micro and nano plastics on microorganisms and their effects on the effectiveness of drinking water treatment. They showed how the existence of MNPs can interfere with microbial communities that play a crucial role in water purification. The research emphasized the necessity of addressing the influence of MNPs on microbial activity to guarantee the sustained effectiveness of water treatment processes.

A. Kundu, N. P. Shetti, S. Basu, K. R. Reddy, et al. [6] investigated the identification and elimination of micro and nano plastics using cost-effective approaches. They discussed numerous removal processes and evaluated their effectiveness in laboratory and real-world scenarios. The paper highlighted the necessity of low-cost and scalable solutions to mitigate MNP contamination, particularly in areas with scarce resources.

I. Ali, T. Ding, C. Peng, I. Naz, H. Sun, et al. [7] presented the need for better treatment processes and stressed the major environmental hazards posed by MNPs. They stated that it is difficult to remove these pollutants effectively and presented a need for multiple approaches towards addressing the problem.
Y. Zhang, Y. Li, F. Su, L. Peng, D. Liu [8] researched wastewater systems and ultimately their fate. They researched how wastewater treatment plants can mitigate MNP pollution and concluded that the advanced stages of treatment should be used to curb the menace.

M. Shen, Y. Zhao, S. Liu, T. Hu, K. Zheng, Y. Wang, et al. [9] discussed recent developments in the understanding of micro and nanoplastic pollution and its effect on membrane fouling during water treatment. The research pointed out how the deposition of MNPs can impair the performance of membrane filtration systems, which are commonly employed in water treatment. The authors elaborated on methods to counteract this problem and enhance membrane efficiency in the presence of MNPs.

V. Kumar, E. Singh, S. Singh, A. Pandey, et al. [10] analyzed the environmental effect of micro and nano plastics (MNPs) as new pollutants in groundwater systems. Their study emphasized the threats from MNPs in groundwater and wastewater systems and proposed possible solutions for reducing their influence. The authors also discussed the limitations of existing water treatment technologies in eliminating MNPs from groundwater resources.

J. N. Meegoda and M. C. Hettiarachchi [11] suggested a route to the mitigation of micro and nanoplastics pollution through novel wastewater treatment technologies and stormwater management practices. Their study emphasized the importance of a more sustainable strategy for the management of plastic waste and touched upon the challenges in minimizing the environmental impact of micro and nanoplastics.

E. A. López-Maldonado, N. A. Khan, S. Singh, et al. [12] examined such composites for wastewater treatment procedures and identified the benefits of using magnetic composites in removing MNPs effectively.

M. R. K. Estahbanati, M. Kiendrebeogo, et al. [13] presented a state-of-the-art overview of treatment processes for microplastics and nanoplastics in water. Their article summed up the various techniques used in the removal of these pollutants, such as filtration, adsorption, and advanced oxidation processes. They also touched upon the efficacy of each technique in different scenarios and proposed future research areas.

M. Sarcletti, H. Park, J. Wirth, S. Englisch, A. Eigen, et al. [14] emphasized the removal of nano and microplastics from water with various materials and processes. Their research explored the application of functionalized nanoparticles and other materials for the improvement of MNPs' removal from water, providing findings for new techniques in addressing these pollutants.

A. Vega-Herrera, M. Llorca, X. Borrell-Diaz, et al. [15] examined the efficiency of existing water treatment processes to eliminate MNPs. They also addressed the health effects of MNPs in potable water and the necessity for better treatment systems.

P. Liu, J. Dai, K. Huang, Z. Yang, Z. Zhang, et al. [16] have researched the origin of micro and nano plastics and their co-pollution with other impurities in wastewater treatment plants. The research explained how MNPs can make it difficult to remove other impurities, stressing the importance of holistic treatment systems that handle various types of contaminants at once.

G. Pulido-Reyes, L. Magherini, C. Bianco, R. Sethi, et al. [17] performed laboratory- and pilot-scale experiments to investigate the removal of nanoplastics during drinking water treatment. The study investigated various filtration methods and their efficiency in removing nanoplastics from water. The study gave useful data on the removal efficiency of various treatment processes and the difficulties of treating drinking water for MNPs.

Y. Huang, K. K. Wong, W. Li, H. Zhao, T. Wang, et al. [18] surveyed the composition of nano-plastics in packaged drinking water. Their work considered the incidence of MNPs in packaged water, the possible sources of contamination, and the resultant public health implications of ingesting water polluted with these contaminants. The authors advocated stricter regulation of water quality in packaged water for public protection.

M. Kumar, H. Chen, S. Sarsaiya, S. Qin, H. Liu, et al. [19] discussed recent trends in research on micro and nano-plastics as new global environmental threats. They discussed the extensive distribution of MNPs in the environment and the difficulties encountered in plastic pollution management. The research highlighted the need to create more efficient and sustainable methods for addressing MNP contamination.

S. Gündoğdu, F. C. Mihai, E. K. Fischer, et al. [20] discussed the occurrence of micro and nano plastics in groundwater systems. They explored the identification of MNPs in groundwater and the risks associated with these contaminants. They also explored the difficulties involved in the removal of MNPs from groundwater and the necessity of further research for the improvement of remediation technologies for these water sources.

III. PROPOSED METHODOLOGY

The novelty of this research lies in the use of goat manure collected from the Thenkasi District, which demonstrated significant efficiency in achieving high levels of nitrogen, phosphorus, and potassium (as noted by Kar and Pishanam). Goat manure typically exhibits the natural properties of compost, promoting plant growth and serving as a fertilizer. Analytical instrumentation techniques were employed at Kalasalingam Academy of Research and Education (Deemed University) and St. Joseph's College (Autonomous). The equipment used included FT-IR, XRD, magnetic stirrers, shakers, pH meters, flow meters, pressure gauges, fixed-bed columns, peristaltic pumps, and calorimeter, along with standard laboratory glassware.

The work's research methodology was tactically structured to examine the removal performance of micro- and nanoplastics (M/NPs) and crystal violet dye from water using an ecofriendly adsorbent from goat manure. Experimental strategy involved integration of materials characterization, batch and column adsorption tests, and mathematical modeling to optimize and analyze performance under different operating conditions. All levels of the methodology were specifically designed to advance the study's purpose of creating a sustainable and scalable water treatment solution.

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IV. PREPARATION OF ADSORBENT MATERIAL

Goat manure was retrieved from agricultural farms in the Thenkasi District of Tamil Nadu, India. The raw material was initially dried under sunlight for 3 to 5 days to evaporate moisture content before oven drying at 105°C for 24 hours to make it completely dehydrated. After drying, the manure was ground and sieved to have a consistent particle size, which was then subjected to carbonization. Carbonization was conducted in a muffle furnace at 500°C for 2 hours under an inert nitrogen atmosphere to produce biochar.

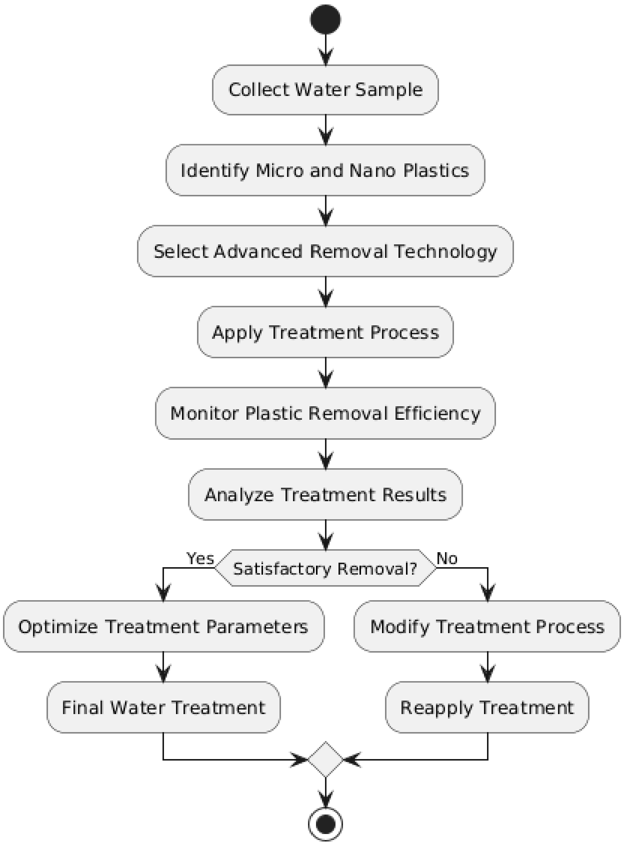

Fig 1. Methodology diagram

As evident in Figure 1, the experimental and optimization process for water treatment of micro and nano plastics with advanced technology has been mapped by the methodology diagram. Following water sample collection and micro and nano plastic identification, an ideal advanced removal technique is chosen followed by applying treatment processes and analyzing removal efficiency. The results are evaluated, and if the removal is acceptable, the treatment parameters are optimized for final water treatment. If the removal is unsatisfactory, the treatment process is adjusted and reapplied for further optimization.

The produced biochar was chemically activated with phosphoric acid (H_3PO_4) at a concentration of 1 M, which increased its surface area and pore volume. The biochar was activated and then neutralized using distilled water, filtered, and dried in a hot air oven at 100°C. To get a uniform shape of adsorbent appropriate for packed column investigations, the powder was blended with a gelatinous binder and rolled into spherical beads. These beads were calcined at 300°C to make them structurally stable. The final product was kept in airtight containers for future experimentation.

Characterization of Adsorbent

A thorough physicochemical analysis of the synthesized adsorbent was carried out employing several sophisticated analytical methods. Surface functional groups that are accountable for adsorption were identified using Fourier

© 2025 IJMRSET | Volume 8, Issue 4, April 2025 |DOI:10.15680/IJMRSET.2025.0804449

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Transform Infrared Spectroscopy (FT-IR).

Preparation of Synthetic Pollutant Solution

Crystal violet dye with analytical purity of 98.9% was obtained from Sigma-Aldrich and employed without purification. A stock solution of 1000 mg/L was prepared by dissolving the dye in double-distilled water. Working concentrations of 1, 2, 3, 4, and 5 ppm were made by suitable serial dilutions. Distilled water used during the experiment was double-distilled and obtained from the Chemical Reaction Engineering Laboratory to prevent external variables.

Column Adsorption Studies

The central experimental apparatus consisted of a fixed-bed column filled with the synthesized activated carbon beads. The column was made of clear acrylic with an internal diameter of 2.5 cm and a length of 30 cm. Adsorbent bed lengths were changed (3 cm, 5 cm, and 7 cm) to study the influence of adsorbent volume on dye removal.

Effluent samples were taken at 30-second intervals until breakthrough. The breakthrough time was the time at which the dye concentration in the effluent was 5% of the influent concentration. Each sample was measured using a colorimeter to determine the absorbance at the maximum wavelength (λ_max) of crystal violet, and the respective concentrations were determined from a pre-established calibration curve.

Experimental Design and Optimization

To determine the most significant parameters and maximize the adsorption performance, a statistical design of experiments (DOE) strategy was employed. A full factorial experimental design was created to analyze the effect of bed height, dye concentration, and contact time. This enabled the determination of both main effects and interaction effects between the parameters. Response Surface Methodology (RSM) was also contemplated to build a predictive model and optimize conditions for maximum dye removal efficiency.

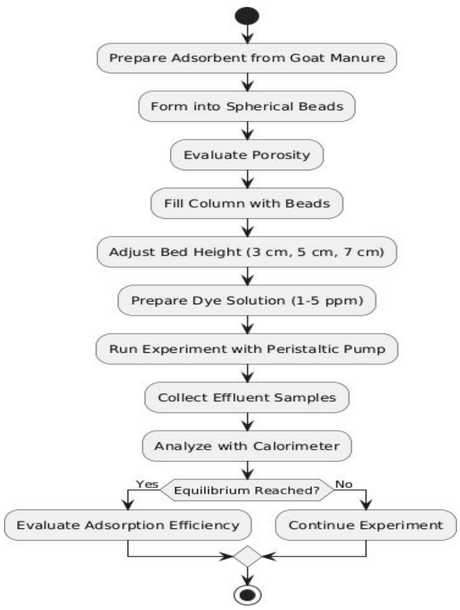
Mathematical Modeling

Adsorption behavior was examined through Thomas, Yoon-Nelson, and Bohart–Adams models to correlate the experimental data and find kinetic parameters. Thomas model was mainly utilized to explain the breakthrough curves and estimate adsorption capacity and rate constants. The models were able to predict dynamic behavior of the adsorption system and confirmed the applicability of goat manure-derived activated carbon beads in actual applications.

Instrumentation and Analytical Methods

All instruments employed during the study were handled and calibrated by following regular laboratory procedures. The analytical operations entailed FT-IR (Bruker Alpha), XRD (Rigaku Ultima IV), SEM (ZEISS Evo-18), and BET analyzers. Standard laboratory glassware, peristaltic pumps, digital pH meters, magnetic stirrers, and calorimeters were employed for column studies. Each experiment was done in triplicate for quality control purposes, and mean values were quoted. Column adsorption procedure

Fig 2. Column adsorption procedure



In Figure 2, the column adsorption process is described. It starts with the adsorbent preparation from goat manure, which is shaped into spherical beads and tested for porosity. The beads are filled in a vertical column, and the bed height is set to 3 cm, 5 cm, and 7 cm. A crystal violet dye solution is prepared, and a peristaltic pump controls its flow through the column. Effluent samples are taken at periodic intervals and analyzed in a calorimeter to determine the dye concentration and test adsorption efficiency. The process is repeated under varied conditions for maximizing dye removal. In this research, a sustainable adsorbent was created from (Goat manure) bio-waste, which was converted into activated carbon and formed into uniform spherical beads ideal for column experiments. The material's porosity was evaluated to confirm its suitability for adsorption purposes. A vertical column was filled with these beads, and experiments were carried out by adjusting the bed height to 3 cm, 5 cm, and 7 cm to examine its effect on dye removal efficiency. Solutions of crystal violet dye at various concentrations (1–5 ppm) and time intervals (0-330 min) were prepared, with a peristaltic pump regulating the flow rate of the dye solution through the column. For each experiment, a specific combination of dye concentration and duration was chosen, and effluent samples were taken at 30-second intervals until the absorbance values stabilized, indicating that equilibrium had been reached. The samples were analyzed using a calorimeter to assess the dye concentration in the effluent and to evaluate the adsorption efficiency. The experiment was methodically repeated under varying conditions of bed height, dye concentration, and time to enhance performance. The findings offered valuable insights into the adsorption characteristics of the activated carbon beads, underscoring their potential as a cost-effective and environmentally friendly solution for water treatment.

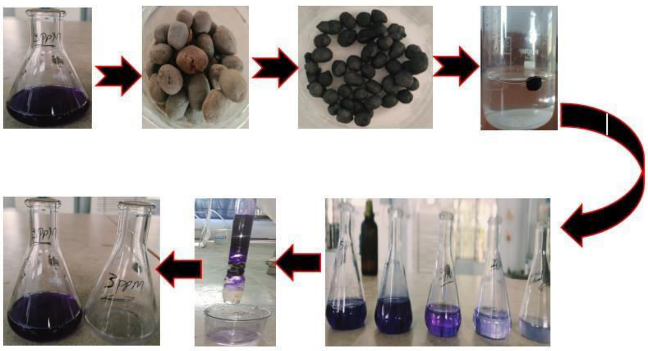


Fig 3. Column studies based on mechanism adsorption

Figure 3 shows column studies according to the adsorption mechanism, with the gradual flow of the dye solution through a column filled with a fixed-bed of activated carbon beads. The arrangement depicts the contact of the adsorbate (crystal violet dye) with the adsorbent surface, placing emphasis on the dynamic removal under different conditions of bed height, flow rate, and contact time

IV. RESULT AND DISCUSSION

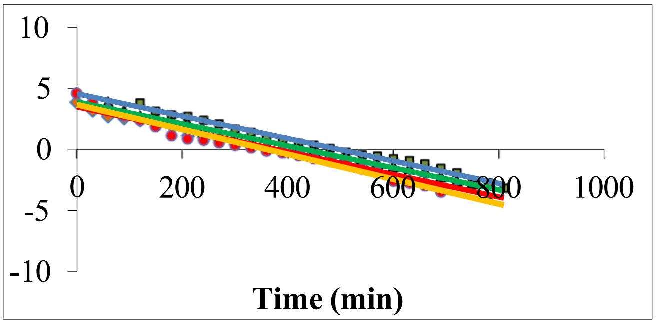


Fig 4: Column Studies of Thomas Model Representation

Figure 4 displays the column studies modeled according to the Thomas model, with the breakthrough curves observed during the adsorption of crystal violet dye. The graph indicates the effluent concentration versus time, confirming the suitability of the Thomas model in determining the adsorption capacity and kinetics of the fixed-bed column system.

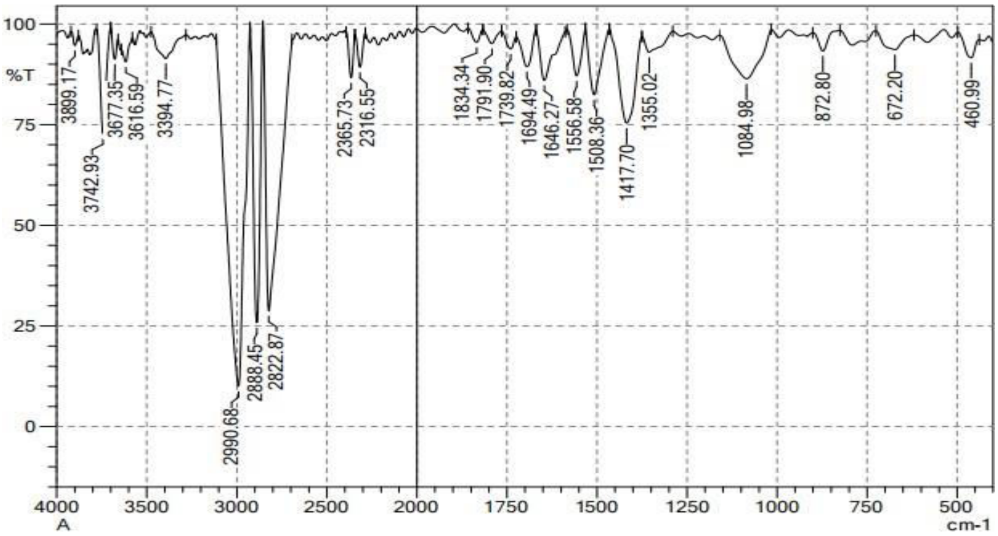


Fig 5: Column Study Breakthrough Curves 1

Figure 5 presents the breakthrough curves of the first column study, indicating the change in effluent concentration with time at various bed heights. The curves indicate the time at which theadsorbent is saturated, and the effect of bed height on the efficiency of adsorption and breakthrough time of the fixed-bed column system.

Result:

The breakthrough curve indicates the trend of dye adsorption within the column system with time, graphing the normalized concentration (C/C_0) against time or effluent volume.

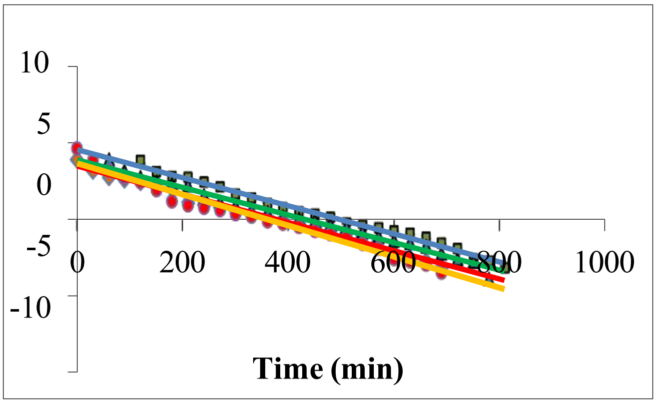


Fig 6: Column Study Breakthrough Curves 2

Figure 6 illustrates the second column study breakthrough curves, specifically addressing the impact of changing dye concentration on adsorption efficiency. The plot shows that increased initial concentrations of the dye result in increased breakthrough rate, reflecting lower adsorption effectiveness and faster saturation of the adsorbent with increasing pollutant load.The curve finally levels off close to $C/C_0 = 1$, representing full saturation (exhaustion) of the adsorbent bed. The breakthrough curve's shape indicates the column's performance: a more acute curve implies good mass transfer and greater adsorptive capacity. Breakthrough time, exhaustion time, and length of the mass transfer zone (MTZ) can be approximated from this curve, all of which are crucial in designing scaled-up column systems.

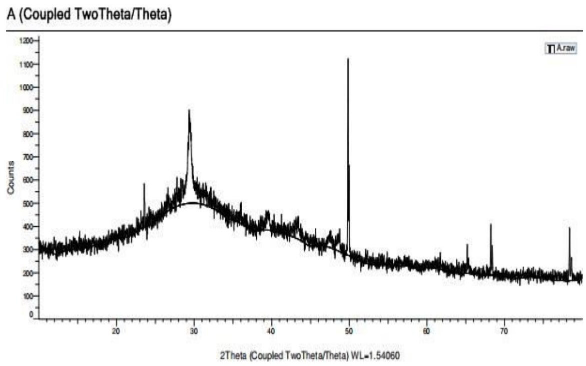


Fig 7: XRD (X-ray Diffraction) Representation

Figure 7 shows the XRD (X-ray Diffraction) pattern of the goat manure-derived activated carbon beads used in the adsorption study. The peaks in the diffraction pattern indicate the crystalline and amorphous regions within the material structure. This analysis confirms the successful activation and structural transformation of the agro-waste, validating its suitability as an effective adsorbent in advanced water treatment applications—particularly relevant for your environmentally conscious project direction.

The XRD pattern of the carbonate material exhibits intense peaks at 2θ values for calcite and other crystalline phases, establishing the crystalline nature of the adsorbent. The intense and sharp peaks at 29.4°, 36.0°, and 39.4° 2θ are characteristic of well-crystallized calcite, which has a strong affinity toward organic dyes based on surface charge interactions. Lack of broad humps or amorphous peaks indicates high purity and low amorphous content in the sample. These observations indicate that the structure of the carbonate material is appropriate for the adsorption of dyes, and crystallinity is responsible for structural stability and stable performance in column operation.

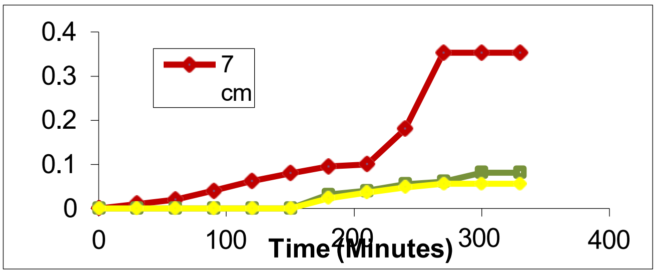


Fig 8: Illustration of FT-IR (Fourier Transform Infrared Spectroscopy)

Figure 8 shows the FT-IR (Fourier Transform Infrared Spectroscopy) spectrum of activated carbon beads from goat manure. The spectrum identifies several functional groups including hydroxyl, carboxyl, and carbonyl, which are essential in the adsorption of crystal violet dye. The functional groups ensure chemical activation of the adsorbent and its capabilities to efficiently interact with dye molecules during the adsorption process.

The FT-IR spectrum of the carbonate material prior to adsorption showed characteristic bands at ~1400 cm^{-1} and ~870 cm^{-1}, which are due to the symmetric and asymmetric stretching vibrations of the carbonate (CO_3^{2-}) groups. A broad band at ~3430 cm^{-1} was seen, which is due to the presence of surface hydroxyl groups (-OH), which can engage in hydrogen bonding with dye molecules. On adsorption, slight displacement and intensity decrease of these peaks were observed, indicating interaction between the dye molecules and the active functional groups present on the material surface. These changes assure the participation of carbonate and hydroxyl groups in the process of adsorption, probably via electrostatic attraction, hydrogen bonding, and conceivable π–π interactions with the aromatic rings of the dye.

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V. CONCLUSION

This study delved into the valorization of goat waste biomass into an economical adsorbent via acid-promoted carbonization and assessed its viability in decolorizing dyes from water solutions. Raw biomass was sulfuric acid treated and carbonized at 400°C, generating a porous carbon material with attractive surface characteristics. Initial tests–such as floating test, adsorption of methylene blue, and burning stability–verified the low density, good adsorbability, and heat resistance of the material. The column adsorption experiment employing a 5 ppm crystal violet solution (pH 7.25) also confirmed the performance of the adsorbent, which showed definite visual decolorization, thus proving effective uptake of the dye. The findings are in line with existing literature, which highlights the effectiveness of carbon materials synthesized from agro-waste for the removal of organic contaminants from wastewater.

Overall, the work presents goat waste as a renewable and environmentally friendly raw material precursor to activated carbon synthesis. Its column-based removal performance of dye places it in line as an alternative for sustainable wastewater treatment with the potential of further use for nano and micropollutant removals in the future. Optimization with thorough physicochemical characterization will advance its application to real-life environmental remediation processes.

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