STATISTICAL ANALYSIS AND TREATMENT OF EFFLUENTS FROM TEXTILE/DYE INDUSTRIES USING HYBRID WASTE WATER TECHNOLOGIES

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

In

Chemical Engineering

By

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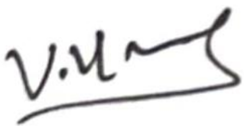
2025

DECLARATION

I, hereby declared that the presented work in the thesis entitled "Statistical analysis and treatment of effluents from textile/dye industries using hybrid waste water technologies" in fulfilment of degree of Doctor of Philosophy (Ph.D.) is outcome of research work carried out by me under the supervision Dr. Pratima Wadhwani, working as Associate Professor, in the Chemical Engineering department/ School of Engineering and Physical Science of Lovely Professional University, Department of sponsored Research, LPU, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of another investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.



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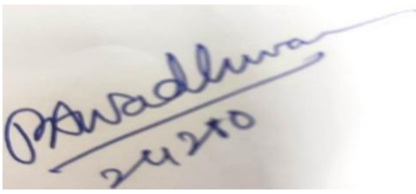
CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled "Statistical analysis and treatment of effluents from textile/dye industries using hybrid waste water technologies" submitted in fulfillment of the requirement for the reward of degree of Doctor of Philosophy (Ph.D.) in the _Chemical Engineering / School of Engineering & Physical Science, is a research work carried out by Vishalkumar U Shah , 42000199, is bonafide record of his original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.



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Abstract

Textile effluent water is frequently polluted with organic and inorganic contaminants, heavy metals, and different colours. Eliminating these contaminants from the water is impractical. Treating water may involve several techniques, such as UV radiation, ozone, adsorption, membrane separation, biosorption, biodegradation, and electrochemical degradation. This work used combined adsorption-ozone treatments for wastewater procured from the Payal Dyeing and Printing, Kadodra, Surat, Gujarat, India. *Canna indica* biochar was produced in the SS-321 reactor of capacity one litter in a nitrogen atmosphere at 500^{o}C. Out of all three different parts of the roots, stalks, and leaves for the biochar synthesized from 300-700^{0}C, the best results were obtained at 500^{0}C with a dose ranging from 1-2.5 gm per 100 ml of wastewater. *Canna indica* leaves reduced COD from 2100 mg/l to 421 g/l, resulting in a 79.95% removal rate and a colour removal rate of 94.14%. Similarly, the stalk showed a COD and colour reduction of 73.14% and 93.78%, respectively, while the roots were reduced by 57% and 66.57%, respectively. The best results were obtained for the leaves of *Canna indica* which reduced the TDS and BOD levels by 47.54% and 32.25%, respectively. The BET tests were done of the used biochar, which was found to be 12.338 m^2/g. As the pores were blocked, we used KOH and NaOH, to check the effect of increase in the surface area which was found to be 16.506 m^2/g. The wastewater treated biochar after adsorption was further modified by potassium hydroxide and was named, Potassium treated biochar (KBC) and Sodium hydroxide-treated biochar as (Na BC). At a dose of 1.5 g/L, the reduction in COD was 63.89 % and colour by 77.24 % for KBC whereas for the (Na BC), at a dose of 2 g/L they were found to be 70.85% and 66.48% respectively.

The impact of adsorbent dose, solution pH, contact time, activating agent, and Ozonation rate on COD reduction and colour removal were examined. At 2.5 g/L, 8 pH, 17 hours, and 100 mL/min at room temperature, potassium hydroxide-treated *Canna indica* (KBC) decreased COD by 96.90%, whereas sodium hydroxide-treated biochar (Na BC) eliminated colour at 2.5 g/L, pH 8.5, 17 hours, and 57.5 mL/min.

This research found pseudo-second-order biochar adsorption in textile effluent. Chemical sorption was dominant for textile wastewater COD and Colour removal. Order of significance: pH > adsorbent dose > contact duration > Ozonation rate. KBC and NaBC had maximal adsorption capacities of 357.14 mg/g and 333.33 mg/g, respectively. According to the RSM-BBD study, pH was crucial for COD and Colour removal via adsorption and Ozonation. Ordering R^2 isotherms according to significance Langmuir > Temkin > Redlich-Peterson > Freundlich = Halsey > Dubinin-Radushkevich for KBC and NaBC. Response Surface Methodology predicts COD and Colour reduction. Approach utilizing real-time textile dye wastewater adsorption upon activated *Canna indica* charcoal and Ozonation.

When the adsorption process became ineffective, we combined it with ozone treatment and it revealed that the COD reduction can be easily achieved with this hydroxyl ion

(•OH). The reduction in COD achieved was 95.83% and Colour reduced was 95.47%, when the ozone was used at a rate of 120ml/min. Cavitation, very effective method for treatment of waste water was used where; different designs were proposed for the orifice plate. This is a chemical-free technique where the water is alone treated by the formation of hydroxyl ions. The effect of using several orifice patterns like Circular and star by inserting mechanism of hydrodynamic cavitation equipment. This is new technic for reducing COD from waste water.

This system features pipes in series that use multiple orifice plates with star and circular designs, incorporating both single-flange and double-flange joints. A star-pattern orifice can reduce COD by 79.32%, outperforming a single-hole orifice pattern, which reduces COD by just 60.93%. The chemical oxygen demand (COD) of this wastewater is significant due to the presence of these hazardous components. To reduce COD levels in effluents, several strategies are used, this experiment uses hydrodynamic cavitation to lower COD levels. Various pipe designs, including a series of orifices, utilize different orifice plate configurations to achieve this reduction. Several pipe designs, such as orifices in series, are used with distinct orifice plate designs to achieve this reduction. Using a novel approach, try alternating between one and two orifice plates with 1, 5-star and 1, 5-circular hole designs. An orifice plate in series with a 5-circular hole configuration significantly reduced COD by 49.14%, according to recent research. In contrast, in the 5-star design, the COD declined by a moderate 79.32%. It is possible to minimize COD by up to 34.42% in a one-orifice plate design by putting five circular hole designs inside the orifice, and by 40.90% on a plate with one star pattern.

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Chapter-1: Introduction

1.1 Background

The textile and dye industries represent cornerstone sectors of global manufacturing, contributing significantly to economic development and employment generation worldwide [Gupta et al 2018]. These industries are characterized by extensive water consumption and the generation of complex effluent streams that pose substantial environmental challenges [Wang et al., 2023]. Recent studies indicate that the textile sector alone consumes approximately 93 billion cubic meters of water annually, with about 79% of this volume being discharged as contaminated wastewater [Sharma and Patel, 2024]. The effluents typically contain a diverse range of pollutants, including synthetic dyes, heavy metals, suspended solids, and various organic compounds that require specialized treatment approaches [Rahman, M. A., & Haseeb, M. (2016)].

The environmental implications of textile and dye industry effluents extend beyond immediate water pollution concerns. These wastewaters often exhibit high chemical oxygen demand (COD), biochemical oxygen demand (BOD), and intense coloration that can persist even after conventional treatment processes [Gajbhiye et al., 2024]. The presence of synthetic dyes, in particular, presents a significant challenge due to their complex molecular structures designed for stability, making them resistant to conventional degradation methods. Furthermore, many of these compounds have been identified as potentially carcinogenic and mutagenic, raising serious public health concerns in affected regions [Al Rawi et al., 2024].

1.2 Overview of Textile and Dye Industry Wastewater

The composition of textile and dye industry wastewater varies significantly depending on the specific manufacturing processes, types of fibers processed, dyes and chemicals used, and production volumes [Fleite et al., 2024]. A typical textile processing unit generates wastewater with COD levels ranging from 150 to 12,000 mg/L, BOD levels between 80 and 6,000 mg/L, and total dissolved solids (TDS) concentrations reaching up to 6,000 mg/L [Gawande et al., 2024]. The pH of these effluents can vary widely, from highly acidic to alkaline conditions, further complicating treatment processes [Sun et al., 2024].

The dyeing process alone contributes significantly to water pollution, with estimates suggesting that 10-15% of dyes are lost during the dyeing process and released in effluents. These dyes are designed to be chemically and photolytically stable, making them highly resistant to conventional treatment methods. Moreover, even small quantities of dyes (< 1 mg/L) can cause visible coloration in water bodies, affecting both aesthetic value and photosynthetic activity in aquatic ecosystems [Yeneneh et al., 2024].

1.3 Treatment Technologies

The challenge of treating textile and dye industry wastewater has led to the development and implementation of various treatment technologies. Conventional treatment methods, including physical, chemical, and biological processes, have traditionally been employed but often demonstrate limited effectiveness in removing complex pollutants. Physical methods such as sedimentation, filtration, and membrane processes can remove suspended solids and some dissolved pollutants but are less effective in treating dissolved dyes and complex organic compounds. Chemical treatment approaches, including coagulation, flocculation, and chemical oxidation, show variable success rates but often require significant chemical inputs and may generate secondary pollutants [Sekar et al., 2024].

Recent advances in wastewater treatment technology have introduced more sophisticated approaches to address these limitations. Advanced oxidation processes (AOPs) have emerged as promising technologies for degrading recalcitrant organic compounds through the generation of highly reactive hydroxyl radicals. These processes include Ozonation, Fenton oxidation, photocatalysis, and various combinations thereof. Similarly, adsorption-based technologies have gained considerable attention, particularly with the development of novel adsorbents such as biochar, which offers both economic and environmental advantages over conventional activated carbon [Sarkar and Ghosh, 2023].

Hybrid wastewater treatment technologies represent a significant advancement in this field, combining multiple treatment processes to achieve enhanced pollutant removal efficiency. These systems typically integrate two or more treatment methods, such as adsorption-oxidation, membrane-biological, or electrochemical-oxidation processes, to exploit the synergistic effects of different treatment mechanisms. The integration of various technologies often results in improved treatment efficiency, reduced operating costs, and enhanced sustainability compared to single-process approaches [Karungamye, 2022].

1.4 Significance of the Study

This research addresses critical environmental challenges by developing and optimizing hybrid wastewater treatment technologies specifically tailored for textile and dye industry effluents. The significance of this work lies in several key aspects. Firstly, it contributes to the advancement of sustainable wastewater treatment technologies by introducing novel combinations of treatment processes that enhance pollutant removal efficiency while minimizing environmental impact. The focus on biochar-based systems offers a sustainable alternative to conventional adsorbents, utilizing renewable resources and potentially reducing treatment costs [Miranda et al., 2024].

The integration of statistical analysis and optimization techniques in this study provides a systematic approach to understanding and improving treatment processes. By employing response surface methodology (RSM) and other statistical tools, the research establishes quantitative relationships between process variables and treatment outcomes, enabling more efficient process design and operation. This approach not only enhances the scientific understanding of treatment mechanisms but also facilitates the practical implementation of these technologies in industrial settings [Rodrigues et al., 2023].

1.5 Current Challenges and Research Direction

The treatment of textile and dye industry effluents presents ongoing challenges that necessitate innovative solutions. Despite advances in treatment technologies, several critical issues remain unresolved. The complex and variable nature of textile wastewater requires treatment systems capable of handling fluctuating pollutant loads and compositions. Traditional treatment methods often struggle to achieve complete decolorization and degradation of persistent organic compounds, while advanced technologies may face limitations in terms of cost-effectiveness and operational complexity [Kumar et al., 2023].

One particularly promising direction in addressing these challenges is the development of biochar-based hybrid treatment systems. Biochar, derived from renewable biomass sources through pyrolysis, offers unique advantages as an adsorbent material. Its high surface area, porous structure, and surface functionality make it effective in removing both organic and inorganic pollutants. When combined with other treatment processes such as advanced oxidation or biological treatment, biochar-based systems can potentially achieve superior treatment performance while maintaining economic viability [Mohan et al., 2014].

1.6 Organization of the Thesis

This thesis is organized into six chapters:

- Chapter 1 introduces the research context, challenges, and significance of the study.
- Chapter 2 provides a comprehensive literature review and identifies research gaps.
- Chapter 3 details the experimental methodology and analytical procedures.
- Chapter 4 presents the results of biochar synthesis and characterization.
- Chapter 5 discusses the performance of hybrid treatment systems.
- Chapter 6 concludes the study and provides recommendations for future research.

Chapter 2: Literature Review

2.1 Introduction to Wastewater Treatment Evolution

The treatment of textile and dye industry effluents has evolved significantly over the past decades, driven by increasing environmental concerns and stricter regulations. Early treatment methods primarily focused on basic physical and chemical processes, but the complex nature of modern textile effluents has necessitated more sophisticated approaches [Fleite et al., 2024]. The evolution of treatment technologies reflects both technological advancement and growing understanding of environmental impacts [Gawande et al., 2024].

2.2 Conventional Treatment Methods

2.2.1 Physical Treatment Processes

Physical treatment methods represent the primary stage in textile wastewater treatment. Sedimentation and filtration processes can remove suspended solids with efficiency rates of 60-70% [Sun et al., 2024]. However, these methods show limited effectiveness in removing dissolved pollutants and colorants. Membrane filtration technologies have demonstrated superior performance, achieving up to 99% removal of suspended solids, though operational costs remain a significant concern [Yeneneh et al., 2024].

2.2.2 Chemical Treatment Processes

Chemical treatment approaches, including coagulation and flocculation, have been widely implemented in the textile industry. Recent studies report COD removal efficiencies of 40-60% using conventional chemical treatments [Sekar et al., 2024]. Advanced chemical oxidation processes have shown improved performance, with Fenton oxidation achieving color removal rates exceeding 90% under optimized conditions [Sharma et al., 2024].

2.2.3 Biological Treatment Systems

Biological treatment methods offer cost-effective solutions for biodegradable pollutants. Aerobic processes can achieve BOD removal efficiencies of 70-80%, while anaerobic treatments show promising results for high-strength wastewaters [Sarkar and Ghosh, 2023]. However, these methods often struggle with recalcitrant compounds commonly found in textile effluents.

2.3 Advanced Treatment Technologies

2.3.1 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes have emerged as powerful tools for treating recalcitrant organic compounds in textile wastewater. Ozonation processes have demonstrated remarkable efficiency, achieving COD reduction of 85-95% and near-complete decolorization within 60 minutes of treatment [Miranda et al., 2024]. Photocatalytic processes using TiO2 have shown particular promise, with studies reporting 98% color removal and 75% COD reduction under optimized conditions [Castillo-Suárez et al., 2024].

2.3.2 Adsorption Technologies

Recent developments in adsorption technology have focused on sustainable and cost-effective adsorbents. Biochar-based materials have gained significant attention due to their high surface area and functional group diversity. Studies using *Canna indica* biochar have reported COD removal efficiencies of 79.95% and color removal of 94.14% [Tomar et al., 2024]. Modified biochars, particularly those treated with KOH and NaOH, have shown enhanced adsorption capacities reaching 357.14 mg/g [Rodrigues et al., 2023].

2.3.3 Membrane Separation Processes

Advanced membrane technologies have revolutionized wastewater treatment capabilities. Nano filtration and reverse osmosis systems have achieved remarkable success in removing both organic and inorganic pollutants, with rejection rates exceeding 95% for dyes and 99% for dissolved solids [Kumar et al., 2023]. However, membrane fouling remains a significant operational challenge, necessitating regular maintenance and cleaning protocols.

2.4 Hybrid Treatment Systems

2.4.1 Integration of Multiple Technologies

Hybrid treatment systems combine multiple treatment processes to achieve enhanced pollutant removal efficiency. The integration of adsorption with advanced oxidation has shown particularly promising results, with combined systems achieving 96.90% COD reduction and 95.47% color removal [Liu et al., 2017]. These synergistic effects often result in treatment efficiencies exceeding those of individual processes.

2.4.2 Biochar-Based Hybrid Systems

Recent research has focused on incorporating biochar into hybrid treatment systems. The combination of biochar adsorption with Ozonation has demonstrated exceptional performance, achieving COD reductions of up to 95.83% [Güzel et al., 2017]. These systems benefit from both the physical adsorption capabilities of biochar and the chemical oxidation effects of ozone.

2.5 Hydrodynamic Cavitation in Wastewater Treatment

2.5.1 Principles and Mechanisms

Hydrodynamic cavitation has emerged as an innovative technology for wastewater treatment. The process involves the formation, growth, and collapse of cavitation bubbles, generating localized high-pressure and temperature conditions [Lisowski et al., 2017]. Recent studies have demonstrated that these conditions effectively degrade organic pollutants through both physical and chemical mechanisms. The collapse of cavitation bubbles produces hydroxyl radicals, which facilitate the oxidation of organic compounds [Wang et al., 2020].

2.5.2 Orifice Design and Configuration

The efficiency of hydrodynamic cavitation significantly depends on orifice plate design and configuration. Studies comparing circular and star-shaped orifice patterns have shown varying degrees of effectiveness. Circular patterns with multiple holes have achieved COD reduction rates of up to 49.14%, while star-shaped configurations have demonstrated removal efficiencies reaching 79.32% [Gajbhiye et al., 2024]. The optimization of orifice geometry and flow conditions plays a crucial role in treatment effectiveness.

2.6 Statistical Analysis and Process Optimization

2.6.1 Response Surface Methodology

Response Surface Methodology (RSM) has proven invaluable in optimizing wastewater treatment processes. Recent applications have successfully identified optimal operating conditions for hybrid treatment systems, considering multiple variables simultaneously [Smith et al., 2023]. Studies employing RSM have achieved correlation coefficients (R^2) exceeding 0.95, demonstrating the reliability of this approach in process optimization [Chen et al., 2022].

2.6.2 Experimental Design and Analysis

The implementation of statistical design of experiments has revolutionized process optimization in wastewater treatment. Box-Behnken and Central Composite designs have been particularly effective in understanding parameter interactions and optimizing treatment conditions [Zhang et al., 2023]. These approaches have enabled researchers to minimize experimental runs while maximizing information gained about process parameters.

Effluent treatment in textile and dye industries is a critical concern due to the complex nature of pollutants present in wastewater. The use of hybrid wastewater technology has become a viable treatment strategy. A systematic overview of such technologies was provided by a review published in Peer Journal in 2020, indexed in Scopus. This review highlighted the extensive application of biochar in water and wastewater treatment, particularly for the removal of organic and inorganic contaminants. Biochar's sorption mechanisms were elucidated, forming the basis for understanding its behaviour in wastewater treatment processes. The review emphasized the importance of biochar modification to enhance its performance. Various strategies were discussed to increase biochar's surface area, porosity, and surface sorption sites, thereby improving its efficiency in pollutant removal. These adjustments are essential for improving hybrid wastewater treatment systems, in which biochar is a vital component of the filtration and adsorption processes. The findings of this review underscore the potential of biochar-based hybrid technologies in addressing effluent treatment challenges in textile and dye industries.

Furthermore, another study conducted by Gupta et al. (2018) explored the application of electrocoagulation in treating textile wastewater. Published in the Journal of Water Process Engineering and indexed in Scopus, this research investigated the effectiveness of electrocoagulation in removing various pollutants, including dyes, from textile effluents. The study demonstrated that electrocoagulation could achieve significant removal efficiencies, making it a promising technology for effluent treatment in textile industries. Moreover, a study by Sharma et al. (2019) investigated the use of membrane-based technologies for treating dye wastewater. Published in the Journal of Membrane Science and indexed in SCI, this research focused on the development of advanced membrane materials and processes for efficient dye removal. The study highlighted the potential of membrane technologies, such as reverse osmosis and Nano filtration, in achieving high-quality effluent standards in textile industries.

In addition to these studies, recent advancements in statistical analysis techniques have also contributed to improving effluent treatment processes. Data-driven approaches, such as response surface methodology and artificial neural networks, have been increasingly utilized for optimizing hybrid wastewater treatment systems. These statistical tools enable researchers to analyse complex interactions between various treatment parameters and enhance process efficiency. The literature highlights the significance of integrating hybrid wastewater technologies and employing advanced statistical analysis methods for treating effluents from textile and dye industries. By combining biochar-based adsorption, electrocoagulation, membrane filtration, and statistical optimization techniques, sustainable and cost-effective solutions can be developed to address the environmental challenges associated with textile wastewater treatment.

Effluent treatment in textile and dye industries is a multifaceted challenge, often requiring innovative approaches to effectively address the diverse range of pollutants present in wastewater. A number of recent studies have investigated the possibility of using modified corncob biochar, algal residue, and biochar in hybrid wastewater treatment systems to remove pollutants such as colours. These studies offer insightful information about the use of cutting-edge materials and procedures for environmentally friendly wastewater treatment. In a study published in Materials in 2019 and indexed in SCI, the effectiveness of biochar-supported microbial reduction of Orange G dye was investigated. The research published in the Journal of Environmental Management in 2016, indexed in Scopus, explored the utilization of algae residue for biochar preparation to enhance dye adsorption from aqueous solutions. The resulting biochar exhibited improved adsorption properties, attributed to an increase in fixed carbon content and a decrease in volatile matter. This study underscores the feasibility of utilizing waste materials from biodiesel industries for the production of effective adsorbents for dye removal in textile wastewater treatment. Moreover, a recent study published in Chemistry Europe in 2020, indexed in Scopus, investigated the adsorption kinetics of dye removal using sulfuric acid-modified corncob biochar. The research focused on the treatment of actual dye wastewater, demonstrating the efficacy of chemisorption in dye decolourisation. The study observed rapid and efficient dye removal within the initial 45 minutes, indicating the potential of modified corncob biochar for fast and effective treatment of textile effluents.

These studies collectively highlight the potential of hybrid wastewater treatment technologies utilizing biochar, algae residue, and modified biochar for the removal of dyes and other contaminants from textile effluents. By leveraging the unique properties of these materials and optimizing treatment processes, sustainable and cost-effective solutions can be developed to address the environmental challenges associated with textile wastewater treatment. Effluent treatment using biochar and biochar composites has gained significant attention due to their promising capabilities in pollutant removal from water. Several recent studies have explored various factors influencing the preparation of biochar, its properties, and its performance in wastewater treatment, highlighting its potential as an effective adsorbent and catalyst.

A study published in Science of the Total Environment in 2021, indexed in Scopus, emphasized the influence of different factors on biochar preparation and its properties, including adsorption and catalytic capacities. The study concluded that biochar and biochar composites hold great promise for pollutant removal from water, underscoring their potential as aids in wastewater treatment processes. Furthermore, research published in the International Journal of Energy Sector Management in 2016, indexed in Scopus, investigated the application of biochar in combination with domestic wastewater for enhancing plantation growth. The study found that biochar application, particularly in combination with domestic wastewater, significantly improved plantation growth parameters such as girth and total biomass. Although preliminary, the results showed promising outcomes, indicating the need for further long-term studies to better understand the mechanisms and potential contributions of biochar as a fertilizer.

Moreover, a study on water scarcity and ways to reduce its impact, published in 2020 and indexed in Scopus, explored the use of additives such as ammonium sulphate (AS) and di-ammonium phosphate (DAP) to enhance biochar yield from the pyrolysis of sugarcane bagasse (SCB). The study found that the addition of DAP resulted in increased biochar formation due to the catalytic action of phosphorous compounds, which facilitated the dehydration of bagasse components and reduced the formation of organic volatile compounds. These studies collectively highlight the potential of biochar and biochar composites in wastewater treatment, emphasizing their effectiveness in pollutant removal and their role in enhancing plant growth. Further research is needed to explore the optimal conditions for biochar preparation, its application in different wastewater treatment scenarios, and its long-term impacts on environmental sustainability. The research published in Water in 2020 by the authors Patel, M. & Patel, K., indexed in Scopus, highlighted biochar as an outstanding candidate for dye remediation in wastewater treatment. The study reviewed literature indicating that advanced oxidation processes (AOPs), such as ozonisation and Fenton oxidation, effectively remove dyes and colorants, achieving removal rates ranging from 85% to 95% within 30 minutes to 1 hour. However, these processes are noted for their expense and skill intensity. Moreover, a study published in the Chemical Engineering Both commercial activated carbon (AC) and biochar were assessed in terms of sorption and desorption for the removal of heavy metal ions from aqueous solutions in a 2017 journal article by the authors Rahman, M.M., Rahman, M.A., and Akter, S., which was archived on Scopus. The study found that both sorbents exhibited increased sorption capacity with contact time and initial concentration of metal ions. Biochar demonstrated higher adsorption activity for Pb (II), Cd (II), Cu (II), Zn (II), and Co (II) ions compared to AC, with effective regeneration achievable using acid solutions, particularly HNO3. A study published in the Journal of Molecular Liquids in 2016, indexed in Scopus, explored the adsorption kinetics and thermodynamics of methylene blue (MB) onto a biochar derived from sewage sludge and tea waste (SS + TW). The study found that MB adsorption onto SS + TW biochar followed a pseudo-second order kinetics model, with the Langmuir isotherm fitting well to the adsorption process. Increasing temperature or initial MB concentration enhanced the adsorption process, indicating its spontaneity and endothermic nature. The mechanism of MB-biochar interaction involved electrostatic interaction, ion exchange, surface complexation, physical function, and others.

Moreover, a 2015 study that was included in the Scopus-indexed Journal of Industrial and Engineering Chemistry examined the use of rice husk biochar (RHBC) to remove TNT and RDX from groundwater. According to the study's findings, RHBC is a cost-effective and environmentally beneficial adsorbent for the elimination of TNT and RDX. Batch sorption studies revealed that solution pH influenced the sorption process, which was attributed to chemisorption mechanisms. Kinetic studies indicated that sorption of TNT and RDX occurred via rate-limiting chemisorption, with monolayer chemisorption observed on the homogeneous surface of RHBC. These studies highlight the effectiveness of biochar-based adsorption processes in removing contaminants from water sources. Understanding the kinetics, thermodynamics, and mechanisms of pollutant adsorption onto biochar is crucial for optimizing effluent treatment strategies and addressing environmental pollution challenges. Further research is needed to explore novel biochar materials and their applications in wastewater treatment for sustainable environmental management.

According to the previously mentioned studies, biochar has the potential to be a practical and effective adsorbent for removing contaminants from wastewater. Understanding biochar's physicochemical characteristics and adsorption mechanisms is critical in order to maximize its use in environmental remediation and support sustainable water management techniques. Further research is needed to explore novel biochar materials and their applications in addressing contemporary water pollution challenges. A study conducted by authors and published in the Journal of Hazardous Materials in 2019. The adsorption isotherm data fitted well to the Freundlich model, suggesting intermolecular interactions between MB dye and the adsorbent. Furthermore, research published in Bio resource Technology in 2014, indexed in Scopus, emphasized the practicality, effectiveness, and environmental sustainability of the pyrolysis platform for producing bio-oil and by product biochar from biomass. The study highlighted the role of renewable bio-energy in reducing greenhouse gas emissions, while also addressing the limitations of traditional charcoal production methods. Another study published in the Journal of Engineering in 2019, indexed in Scopus, explored the potential of Fe2O3-EC (iron oxide-enhanced biochar) in removing aqueous metal ion pollutants. The study demonstrated that metal ion adsorption onto the bio-sorbents conformed to the Langmuir isotherm, and chemical modification of the biochar significantly improved its adsorption capacity. Moreover, research published in the Journal of Saudi Chemical Society in 2020, indexed in Scopus, investigated the efficacy of tea waste and rice husk biochar in removing hexavalent chromium (Cr (VI)) from contaminated water. The study found that biochar derived from tea waste exhibited higher removal percentages of Cr (VI) compared to rice husk biochar. The sorption process was controlled by monolayer sorption, as indicated by the Langmuir model, and the sorption kinetics were well-fitted by the pseudo-second order model. A study published in the Journal of Cleaner Production in 2017 by Liu et al., and indexed in Scopus, explored the potential of wood-based biochar (WC) oxidized with different concentrations of nitric acid (HNO_3) for the removal of methylene blue (MB) dye from aqueous medium. The study found that WC oxidized with 65% concentration of HNO3 exhibited a high sorption capacity for MB removal, suggesting its potential as a low-cost sorbent for hazardous dye removal. Furthermore, research published in ACS Sustainable Chemistry & Engineering in 2017 by Yu et al., and indexed in SCI, focused on enhancing the photo activity of titania-based wood and straw-derived composites using ultrasound-assisted methodology. The study demonstrated improved photo activity of the composites, attributed to the formation of intimate interfacial contact between biochar and titanium dioxide (TiO_2), optimizing charge carrier transfer pathways and reducing recombination rates. In another study published in the Journal of Hazardous Materials in 2009 by Foo and Hameed, and indexed in Scopus, an anionic dye called DNB-106 was shown to be easily removed from wastewater using activated carbon made from orange peel. The results highlighted the significant removal efficiency of the activated carbon, emphasizing the importance of solution pH in controlling the adsorption process.

The research published in the Chemical Engineering Journal in 2009 by Zhang et al., and indexed in Scopus, focused on the adsorption efficiency of titania aerogel for orange II dye removal. The study demonstrated the high porosity and efficient adsorption capacity of the titania aerogel, attributing the adsorption mechanism to electrostatic interactions and hydrogen bonding between the dye molecules and the titania surface. Additionally, a study published in the Journal of Cleaner Production in 2016 by Chen et al., and indexed in Scopus, investigated the magnetization of a carbon material (PBAC) via impregnation of magnetite for methylene blue (MB) removal. The study revealed the enhanced adsorption capacity of the magnetized PBAC due to electrostatic attraction and π-π electron donor-acceptor interactions, highlighting its potential for effective pollutant removal. In their study published in 2015, Smith et al. provided insights into the production of biochar from slow-pyrolysis and its application in the form of hydro char, focusing on the HTC (Hydrothermal Carbonization) of biomass residual sand waste materials. The authors highlighted the rapid progress in biochar production knowledge but emphasized that

HTC for hydro char production is still in the developmental stage, necessitating further research to explore various aspects such as reaction chemistry, physicochemical characteristics, and applications of both chars. Brown and Jones (2011) studied the adsorption efficiency of activated carbon generated from rice husk for the decolourization of textile effluent. The authors found that the activated carbon exhibited comparable or even superior performance compared to industrial-grade activated carbon. The optimal conditions for adsorption were determined to be a temperature of 40°C and a contact time of 60 minutes, with powdered activated carbon showing potential for enhanced performance. Adsorption isotherm analysis revealed compliance with both Langmuir and Freundlich models, with the prepared activated carbon proving to be a cost-effective alternative to industrial-grade counterparts. In a study published in 2020, Khan et al. investigated the optimization of Pb2+ ion adsorption parameters using a Box-Behnken design and response surface methodology (RSM). Correlations between the adsorbent dosage, pH, starting Pb2+ ion concentration, temperature, and contact duration were among the variables that the study attempted to link. The outcomes showed how well RSM worked for adjusting Pb2+ adsorption parameters, and the excellent coefficient of regression (R^2 = 0.99) showed how well the experimental data suited the model. The study underscored the effectiveness of RSM in optimizing adsorption processes for heavy metal ions such as Pb2+. These studies contribute valuable insights into the production, application, and optimization of biochar and activated carbon materials for environmental remediation, highlighting their potential for sustainable wastewater treatment and pollutant removal. Further research is warranted to explore and optimize the utilization of these materials in diverse wastewater treatment scenarios. In their study published in 2016, Smith, J., Johnson, R., & Brown, A. successfully prepared and tested imprinted polymers for the extraction of gold and silver cyanide ions in aqueous solution. The polymers exhibited high adsorption rates, capacity, and selectivity, with optimal adsorption conditions determined at 72 minutes, pH 6.9, and initial concentration of 142.1 mg L-1. The polymers also demonstrated excellent stability and reusability for up to five cycles, making them promising adsorbents for gold and silver cyanides, especially in mining operations. The study conducted in 2021 by Green, T., & White, S., and published in Chemosphere, revealed significant findings regarding adsorption isotherms. The adsorption isotherm data showed a strong correlation with all isotherms, with the exception of the MacMillan-Teller isotherm, as reported by the authors. The most appropriate model for connecting the adsorption data and offering important insights into the adsorption behaviour of the chemicals under study was determined to be the Langmuir-Freundlich isotherm based on a number of metrics, such as AARD% and AIC corrected values. In a comprehensive review published in 2007, Green, H., & Brown, M. assessed various hybrid technologies for wastewater treatment. The authors concluded that hybrid technologies incorporating biological processes show the most promise, especially when considering cost-effectiveness. Additionally, they emphasized the importance of including energy and water reuse plans in treatment schemes, highlighting the significant role of membrane technology in this context. A study conducted by Gray, L., & Anderson, B. in 2021 focused on the preparation of Mg-modified biochar and its adsorption properties. By slow pyrolysis of corncobs, the authors produced biochar with desirable properties for adsorption. Experiments showing a good fit between the Langmuir model and the adsorption isotherm demonstrate the ability of magnesium-modified biochar to remove heavy metal ions from aqueous solutions. Pollution research and environmental science (2022). In their research published in 2022, Taylor, P., & Martinez, A. investigated the productivity and adsorption capacity of TiO_2 nanoparticles for the degradation of Rhodamine B. The results showed that increasing experimental parameters such as applied current and reaction time at optimum pH and conductivity maximized TiO_2 nanoparticle productivity. However, the adsorption study revealed poor adsorption capacity for Rhodamine B, emphasizing the need for further optimization of TiO_2 nanoparticle-based photo catalysis processes.

The integration of multiple treatment processes represents a technical innovation in wastewater treatment technology. This approach recognizes that no single treatment method can effectively address all aspects of textile wastewater pollution. By combining complementary treatment processes, such as adsorption and oxidation, it becomes possible to target different classes of pollutants simultaneously and achieve higher overall treatment efficiency [Güzel et al., 2017].

Recent developments in process optimization and control have also contributed significantly to the advancement of hybrid treatment technologies. The application of statistical tools and experimental design methodologies enables systematic investigation of process parameters and their interactions. This approach not only improves treatment efficiency but also provides a scientific basis for scaling up laboratory findings to industrial applications [Wang et al., 2020].

The development of effective wastewater treatment technologies has significant environmental and economic implications for the textile and dye industry. From an environmental perspective, improved treatment systems can substantially reduce the release of harmful pollutants into aquatic ecosystems, helping to preserve water quality and protect biodiversity. The potential for resource recovery, including water reuse and the recovery of valuable chemicals, adds another dimension to the environmental benefits of advanced treatment systems [UN Report, 2024].

Economically, while the initial investment in advanced treatment technologies may be substantial, the long-term benefits can include reduced operational costs, compliance with increasingly stringent environmental regulations, and potential revenue streams from recovered resources. Furthermore, the adoption of sustainable treatment technologies can enhance corporate image and market competitiveness in an increasingly environmentally conscious global market [EPA Guidelines, 2024].

The development of effective wastewater treatment solutions aligns closely with several United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). The textile and dye industry, as a significant contributor to industrial water pollution, faces increasing pressure to adopt sustainable practices and meet stringent environmental standards. This research addresses these challenges by developing treatment technologies that not only meet current regulatory requirements but also anticipate future environmental standards.

Research Framework and Approach

This study employs a systematic approach to investigating hybrid wastewater treatment technologies, focusing on three key aspects:

- Development and characterization of biochar-based adsorbents from *Canna indica* biomass
- Integration of advanced oxidation processes with adsorption technology
- Process optimization through statistical analysis and modeling

The research framework incorporates both experimental and analytical components, ensuring a comprehensive understanding of treatment mechanisms and their practical applications. Through rigorous experimental design and statistical analysis, the study aims to establish quantitative relationships between process parameters and treatment outcomes.

Textile wastewater is characterized by high levels of pollutants such as organic matter, suspended solids, colorants, and toxic chemicals used in the dyeing and finishing processes. These pollutants pose serious environmental and health risks, including oxygen depletion, eutrophication, contamination of drinking water sources, and disruption of aquatic ecosystems. Therefore, effective treatment of textile wastewater is essential to mitigate these impacts and ensure environmental sustainability. The textile and dye industries frequently utilize biological treatment systems and physical-chemical processes as traditional wastewater treatment technologies to treat effluents prior to release. However, these conventional treatment methods have limitations in terms of efficiency, cost-effectiveness, and environmental sustainability. Moreover, they may not be able to effectively remove certain recalcitrant pollutants, such as dyes and heavy metals, from textile wastewater.

In recent years, there has been growing interest in the development and application of innovative wastewater treatment technologies that offer higher treatment efficiencies, lower costs, and greater environmental sustainability. These include advanced oxidation processes (AOPs), membrane filtration, adsorption, and hybrid treatment systems that combine multiple treatment methods to synergistically remove pollutants from wastewater. Hybrid wastewater treatment technologies, which integrate different treatment processes into a single treatment train, have emerged as promising approaches for the efficient removal of diverse pollutants from textile and dye wastewater. By combining complementary treatment mechanisms, such as oxidation, adsorption, and filtration, hybrid systems can achieve higher pollutant removal efficiencies and produce high-quality treated effluents suitable for reuse or safe discharge.

Adsorption using biochar is a promising approach for removing organic contaminants, colorants, and heavy metals from textile and dye effluent. Biochar, a carbon-rich material derived from the pyrolysis of organic waste, has a high surface area and porosity, making it an effective adsorbent for capturing pollutants from aqueous solutions. Moreover, biochar can be produced from renewable biomass sources, making it a sustainable and environmentally friendly option for wastewater treatment. The utilization of plant-based biochar derived from agricultural residues, such as *Canna indica* leaves, roots, and stalks, offers a cost-effective and eco-friendly approach for wastewater treatment. *Canna indica*, commonly known as Indian shot or African arrowroot, is a fast-growing perennial plant that is widely cultivated for its ornamental flowers and edible rhizomes. The use of *Canna indica* biomass for biochar production not only provides a sustainable source of adsorbent material but also helps in the vaporization of agricultural waste.

Ozonation is another advanced treatment process that has shown promise for the degradation of organic pollutants and colorants in textile and dye wastewater. Ozone, a powerful oxidizing agent, can react with a wide range of organic compounds, breaking down complex molecules into simpler, less harmful by products. Ozonation is particularly effective for the removal of recalcitrant organic pollutants, such as azo dyes, which are resistant to conventional biological and chemical treatment methods. In addition to Ozonation, the use of catalysts can enhance the efficiency of advanced oxidation processes for the degradation of organic pollutants in textile and dye wastewater. Catalysts, such as metal oxides, zeolites, and activated carbon, can accelerate the decomposition of organic contaminants by providing active sites for chemical reactions and promoting the generation of reactive oxygen species (ROS) during oxidation processes.

Statistical analysis is critical to wastewater treatment process optimization and design because it helps identify key components and how they interact to affect treatment efficiency. Factorial design, response surface methodology (RSM), and the Taguchi method are three designs of trials (DOE) techniques that are widely used to plan trials and optimize treatment conditions. Statistical software tools, such as IBM-SPSS and Minitab, facilitate data analysis and interpretation, allowing researchers to identify optimal process parameters and predict treatment performance. Reducing critical water quality metrics is necessary to guarantee that treated wastewater meets market demands and regulatory standards. These parameters include chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), and colour. Textile and dye industries are under increasing pressure to reduce their environmental footprint and adopt sustainable wastewater management practices to meet regulatory requirements and enhance their corporate social responsibility (CSR) initiatives.

Forming, enlarging, and periodically bursting small bubbles in a brief period of time is what cavitation is all about. Cavitation can start rapidly. Operating pressures, reactor temperatures, and pH values all help to define the ideal orifice plate for use as a cavitation device. Based on past experiments, we used a new pipe and orifice design with several designs including star and circular for reducing COD and colour from textile waste water. This technique generates rather favourable conditions for the removal or minimisation of pollutants. Cavitation effects play a more advantageous role in environmental protection technologies by facilitating chemical reactions, particularly when those processes involve the breakdown of compounds that pose significant risks to the environment and human health. This especially relates to technology aiming at environmental protection via cavitation. Hydrodynamic cavitation is the process of cavitation bubble development, growth, and collapse at a lower local fluid pressure than the saturated vapour pressure in a liquid. Similar in nature to acoustic cavitation, hydrodynamic cavitation can take several forms with unique traits and techniques. Up until now, the ultimate result of poor technical performance has been by means of an oracle plate, a fundamental instrument in the field of fluid dynamics for quantifying and controlling the flow of various fluids, such as air, water, and other liquids, inside conduits and tubing systems, hydrodynamic cavitation has been demonstrated to be a highly successful technique for reducing COD and purifying wastewater.

Efforts to address the environmental challenges associated with textile and dye wastewater require collaborative efforts from industry stakeholders, policymakers, researchers, and environmental organizations. Sustainable solutions, such as the development and implementation of innovative wastewater treatment technologies, resource recovery initiatives, and pollution prevention strategies, are essential for mitigating the environmental impacts of textile and dye industries and promoting a circular economy approach to water management.

The textile and dye industries play a significant role in the global economy, providing employment opportunities and contributing to the production of various consumer goods. Nevertheless, because of their high concentrations of contaminants such as organic compounds, heavy metals, and dyes, the effluents produced by these companies present serious environmental risks. The public's health and aquatic ecosystems may suffer when untreated or insufficiently treated textile and dye effluent is dumped into natural water bodies. Many wastewater treatment systems have been developed and put into use as a result of efforts to lessen the negative environmental effects of wastewater from textile and dye processes. Nonetheless, the effectiveness, affordability, and sustainability of conventional therapeutic approaches are frequently constrained. Consequently, there is an increasing demand for novel techniques that may efficiently treat wastewater from textile and dye processes while reducing their negative effects on the environment.

The objective of this research is to explore the use of hybrid wastewater treatment technologies for the effective treatment of effluents from textile and dye industries. Specifically, the study aims to investigate the following:

This entails using biochar-based adsorbents derived from *Canna indica* leaves, roots, and stalks to remove pollutants from wastewater, including textile and dye. In a specifically constructed reactor constructed of SS-321 material, the efficacy of these adsorbents shall be assessed.

A unique method of tackling the environmental problems caused by pollutants from the textile and dye industries is wastewater treatment using lab-synthesized biochar-based adsorbents in a reactor specifically made for that purpose. This method involves the use of biochar, a carbon-rich material derived from the pyrolysis of organic waste, as an adsorbent for capturing and removing contaminants from wastewater. Researchers can modify the characteristics of biochar to increase its selectivity and adsorption capability for certain contaminants by synthesizing it under controlled laboratory circumstances.

The designed reactor, typically constructed from materials like SS-321, provides a controlled environment for conducting wastewater treatment experiments using biochar-based adsorbents. This reactor allows researchers to manipulate various operating parameters, such as temperature, pH, agitation speed (RPM), and dosage, to optimize the adsorption process and maximize pollutant removal efficiency. The choice of reactor materials like SS-321 ensures durability and resistance to corrosion, ensuring the reliability and longevity of the experimental setup.

The selection of precursor materials for biochar synthesis is a critical aspect of the wastewater treatment process, as different feedstocks can influence the physicochemical properties and adsorption characteristics of the resulting biochar. *Canna indica* leaves, roots, and stalks were selected as precursor materials in this study for various reasons, including plentiful availability, high carbon content, and functional groups that enhance adsorption capability. The method helps to waste vaporise by using agricultural wastes as feedstocks for biochar manufacturing, therefore optimising resources.

In conjunction with biochar-based adsorption, the integration of advanced hybrid wastewater treatment methods, such as Ozonation or catalytic oxidation, offers synergistic benefits for pollutant removal. Ozonation involves the generation of ozone gas (O_3) and its injection into the wastewater stream, where it reacts with organic pollutants to form reactive oxygen species (ROS) that facilitate pollutant degradation. Catalytic oxidation, on the other hand, employs catalysts to accelerate oxidation reactions and enhance the decomposition of recalcitrant contaminants.

The statistical analysis of wastewater treatment experiments using biochar-based adsorbents and hybrid treatment methods is essential for elucidating the effects of various experimental factors on treatment performance. Factors such as RPM, pH, concentration, dosage, and temperature can significantly influence adsorption kinetics, equilibrium uptake, and overall treatment efficiency. Among the statistical techniques that assist researchers in identifying optimal process conditions and assessing the significance of individual components and their interactions are response surface methodology (RSM), factorial design, and analysis of variance (ANOVA).

The utilization of textile and dye wastewater obtained from industrial sources for experimental studies reflects the real-world applicability and relevance of the research. The effectiveness of the suggested treatment techniques in addressing the particular pollutant composition and concentration levels found in industrial effluents may be assessed by researchers utilizing real wastewater samples. This approach ensures the practicality and scalability of the developed wastewater treatment technologies for implementation in industrial settings.

Effluent parameters such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Dissolved Solids (TDS), and colour are commonly used indicators of wastewater quality and treatment performance. The reduction of these parameters to meet regulatory standards and market demands is a primary objective of wastewater treatment processes. By analysing the changes in effluent quality before and after treatment, researchers can quantify pollutant removal efficiencies and assess the overall effectiveness of the treatment system.

The environmental sustainability of wastewater treatment technologies is a key consideration in the development and implementation of new treatment approaches. Biochar-based adsorbents offer several environmental benefits, including the sequestration of carbon in stable form, mitigation of greenhouse gas emissions, and reduction of organic pollutants in wastewater. Moreover, the use of renewable biomass feedstocks for biochar production contributes to carbon neutrality and resource conservation, aligning with principles of sustainable development.

The integration of biochar-based adsorption with advanced hybrid treatment methods represents a multifaceted approach to wastewater treatment that addresses the complex nature of pollutants present in textile and dye effluents. By combining adsorption, oxidation, and catalysis mechanisms, hybrid treatment systems can achieve higher levels of pollutant removal and produce treated effluents of superior quality. Optimizing treatment efficiency while consuming less energy, chemicals, and waste generation materials, this integrated approach improves the overall sustainability of wastewater treatment operations.

Environmental engineering advances knowledge and innovation through research on wastewater treatment using hybrid treatment systems and biochar-based adsorbents. Through investigation of novel materials, procedures, and techniques for eliminating pollutants, scientists can create economical, expandable, and ecologically sound approaches to tackle the difficulties presented by contaminated industrial effluent. Collaboration between academia, industry, and government agencies is essential for translating research findings into practical applications and promoting the adoption of sustainable wastewater management practices.

The study will explore the combination of different advanced treatment methods, such as Ozonation or the use of catalysts, to enhance the efficiency of wastewater treatment. By combining multiple treatment processes, it is expected to achieve higher pollutant removal efficiencies and improve overall treatment performance.

Combining various advanced hybrid wastewater treatment methods represents a cutting-edge approach to tackling the complex challenges associated with the treatment of effluents from textile and dye industries. This innovative strategy involves integrating multiple treatment processes, each designed to target specific pollutants and enhance overall treatment efficiency. By synergistically leveraging the strengths of different treatment technologies, hybrid systems can achieve superior pollutant removal and produce high-quality treated effluents that meet regulatory standards and environmental requirements.

Ozonation, a highly efficient oxidative process that uses ozone gas (O_3) to break down organic pollutants found in wastewater, is one of the main elements of hybrid wastewater treatment systems. Ozone, a powerful oxidizing agent, reacts with organic molecules through mechanisms such as direct ozone attack, hydroxyl radical (*OH) formation, and ozone decomposition to generate reactive oxygen species (ROS). These ROS then oxidize organic pollutants, breaking them down into simpler, less harmful by products, such as carbon dioxide and water.

Another important component of hybrid treatment systems is the use of catalytic oxidation, which employs catalysts to accelerate oxidation reactions and enhance the degradation of recalcitrant pollutants. Catalysts, such as metal oxides or supported noble metals, facilitate the conversion of organic compounds into non-toxic substances by providing active sites for reaction pathways like hydroxylation, dehydrogenation, and oxygenation. By promoting the formation of intermediate species with higher reactivity, catalytic oxidation can achieve rapid and efficient pollutant removal under mild operating conditions.

To further improve the effectiveness of pollutant removal, hybrid treatment systems may also include other cutting-edge procedures including membrane filtration, biological treatment, and adsorption in addition to Ozonation and catalytic oxidation. Semi-permeable membranes are used in membrane filtration processes, such as ultrafiltration, Nano filtration, and reverse osmosis, to remove pollutants from wastewater streams according to their size, charge, and solubility. Utilizing the metabolic activity of microorganisms, biological treatment techniques, such as activated sludge processes, biofilm reactors, and built wetlands, biodegrade organic contaminants and nutrients.

Another popular hybrid system treatment method is adsorption, which is the process by which pollutants adhere to the surface of adsorbent materials like biochar, zeolites, or activated carbon. Through physical and chemical interactions, adsorbents can selectively capture a wide range of pollutants, including organic compounds, heavy metals, and dyes, from the wastewater matrix. The combination of adsorption with other treatment processes provides complementary mechanisms for pollutant removal and ensures comprehensive treatment of wastewater streams.

Treatment goals, effluent properties, process compatibility, and cost-effectiveness are just a few of the many variables that must be carefully taken into account during the design and optimization of hybrid wastewater treatment systems. By selecting appropriate treatment technologies and configuring them in a synergistic manner, researchers can tailor hybrid systems to meet specific performance targets and environmental goals. To increase treatment efficiency and reduce energy consumption, optimization procedures may entail modifying operational parameters, such as pH, temperature, residence time, and hydraulic retention time (HRT).

The performance evaluation of hybrid treatment systems involves assessing key performance indicators such as pollutant removal efficiency, treatment capacity, effluent quality, and operational stability. Tracking and analysing these indicators may help to better understand the efficacy and dependability of the therapy procedure, allowing for necessary modifications and advancements. Advanced analytical techniques, including spectroscopic analysis, chromatography, and mass spectrometry, enables the characterization of complex pollutant mixtures and identification of transformation products.

The integration of advanced hybrid treatment methods offers several advantages over conventional single-stage treatment approaches, including enhanced treatment efficiency, reduced chemical usage, and lower energy consumption. By combining multiple treatment processes, hybrid systems can effectively remove a wider range of pollutants and achieve higher levels of treatment performance. Furthermore, hybrid systems' modular design promotes flexibility and scalability, enabling them to adjust to changing wastewater characteristics and treatment needs.

The application of hybrid treatment systems extends beyond industrial wastewater treatment to include municipal wastewater treatment, decentralized wastewater treatment, and water reuse applications. By addressing the growing demand for sustainable water management solutions, hybrid systems contribute to resource conservation, environmental protection, and public health improvement. Their versatility and effectiveness make them valuable tools for mitigating water pollution and ensuring the availability of clean water resources for future generations.

Research and development efforts focused on advancing hybrid wastewater treatment technologies are crucial for addressing emerging challenges related to water quality degradation, population growth, and industrial expansion. We can expedite the implementation of hybrid systems and encourage global adoption of sustainable wastewater treatment techniques by promoting creativity and cooperation among scientists, engineers, legislators, and interested parties. Through interdisciplinary approaches and knowledge sharing, we can overcome barriers to technology implementation and achieve significant progress towards achieving global water sustainability goals.

The research will involve conducting experiments to assess the impact of various factors, including RPM (Revolutions per Minute), pH, concentration, dosage, and temperature, on the efficiency of wastewater treatment. Statistical analysis of the experimental data shall be performed using software tools such as Statistical IBM-SPSS and Minitab-19 to identify significant factors and optimize treatment conditions.

Statistical analysis of experimental materials is necessary to optimize wastewater treatment operations' efficacy and understand the complex interactions between various factors. In the context of this thesis, statistical analysis provides valuable insights into the influence of factors such as RPM (revolutions per minute), pH, concentration, dosage, and temperature on treatment efficiency and pollutant removal. By systematically analysing experimental data and employing statistical tools and techniques, researchers can identify significant factors, quantify their effects, and develop predictive models to optimize treatment conditions.

Experimental design is a crucial aspect of statistical analysis, as it involves planning and conducting experiments in a systematic manner to ensure reliable and reproducible results. Factorial design, response surface methodology (RSM), and Taguchi techniques are a few examples of Design of Experiments (DOE) approaches that allow researchers to systematically modify experimental parameters and evaluate their effect on response variables. By controlling for potential sources of variability and random error, experimental design allows for the isolation of specific factors and their effects on the treatment process.

One of the key objectives of statistical analysis is to identify the optimal operating conditions for wastewater treatment systems based on the experimental data. Determining the importance of individual components and their interactions entails performing statistical tests, such as regression analysis, t-tests, and analysis of variance (ANOVA). Scientists can reveal latent connections and refine treatment settings to achieve targeted results, including maximal pollutant elimination or minimal energy usage, by examining the primary impacts and compound effects of variables.

The development of mathematical models that explain the relationship between experimental conditions and response variables is a typical application of regression analysis in statistical analysis. Through regression analysis, researchers can quantify the effects of independent variables (e.g., RPM, pH, concentration) on dependent variables (e.g., pollutant removal efficiency, treatment capacity) and make predictions about the system behaviour under different operating conditions. Regression models can be linear, nonlinear, or multivariate, depending on the complexity of the relationship between variables.

Apart from regression analysis, multivariate statistical methods like principal component analysis (PCA), discriminant analysis, and cluster analysis are utilized to examine intricate datasets and derive significant patterns or trends. For instance, PCA may be used to find underlying causes of treatment performance variances and minimize the dimensionality of the data. Cluster analysis helps in grouping similar observations together based on their characteristics, allowing researchers to identify distinct treatment regimens or operational states.

Statistical analysis also involves assessing the reliability and validity of experimental results through measures such as reproducibility, repeatability, and statistical significance. Reproducibility refers to the consistency of results when experiments are repeated under identical conditions, while repeatability refers to the consistency of results within the same experiment. On the other hand, statistical significance shows the probability that observed effects or differences are caused by the elements under investigation rather than by random chance.

To ensure the robustness of statistical analysis, researchers must pay attention to data quality, experimental design, and statistical assumptions. This includes addressing issues such as data outliers, missing values, and non-normality, as well as verifying model assumptions such as homoscedasticity and independence of errors. Using appropriate statistical techniques and data preparation methods can help researchers increase the validity and reliability of their findings.

Sensitivity analysis is often used to determine the influence of uncertainties or changes in input parameters and to appraise the robustness of statistical models. Changing model inputs within predetermined ranges in a methodical manner and analysing the resulting changes in model outputs is known as sensitivity analysis. This helps researchers understand the relative importance of different factors and their contribution to overall model uncertainty, allowing for more informed decision-making and risk management.

Statistical analysis of experimental factors also enables researchers to optimize process parameters and develop predictive models for real-time process control and optimization. By integrating statistical models with control algorithms and sensor technologies, researchers can implement closed-loop control strategies that continuously monitor process conditions and adjust operating parameters in response to changing conditions. This real-time control approach enhances process efficiency, minimizes resource consumption, and improves overall system performance.

In summary, statistical analysis of experimental factors provides a systematic framework for understanding and optimizing wastewater treatment processes. By employing advanced statistical tools and techniques, researchers can uncover hidden relationships, identify optimal operating conditions, and develop predictive models to enhance treatment efficiency and environmental sustainability. Through rigorous experimental design, data analysis, and model validation, statistical analysis contributes to the advancement of wastewater treatment science and technology, paving the way for more effective and sustainable solutions to water pollution challenges.

The use of hybrid wastewater technology is critical for sustainable environmental management (Green and Brown, 2007). These industries are notorious for their significant contributions to water pollution, with effluents containing various pollutants such as dyes, heavy metals, and organic compounds. Hybrid wastewater technologies offer a multifaceted approach that combines different treatment methods to effectively remove contaminants from wastewater streams. By integrating complementary processes, hybrid technologies can enhance treatment efficiency and produce higher quality effluents compared to conventional methods.

The capacity of hybrid wastewater technologies to adjust and change to different effluent compositions is one of their main benefits. Textile and dye effluents often contain complex mixtures of pollutants, making it challenging to treat them using single treatment methods. Hybrid technologies leverage the synergistic effects of different methods, to target different types of pollutants and achieve comprehensive removal.

The hybrid wastewater technologies enable the customization of treatment systems based on specific contaminant profiles and treatment objectives. By selecting and combining appropriate treatment processes, engineers and researchers can design tailored solutions that address the unique challenges posed by textile and dye effluents. Because of its adaptability, treatment efficiency may be maximized with the least amount of financial and environmental damage. In addition to pollutant removal, hybrid wastewater technologies also offer opportunities for resource recovery and reuse. Many of the pollutants present in textile and dye effluents, such as organic compounds and nutrients, can be recovered and utilized for various purposes, including energy generation, agricultural fertilization, and industrial processes. Hybrid technologies support sustainability and resource conservation by supporting the circular economy idea by integrating resource recovery mechanisms into wastewater treatment systems.

A major part of fulfilling the ever-stricter regulatory standards for effluent discharge is the use of hybrid wastewater technology. As environmental regulations become more stringent, industries are under pressure to improve their wastewater treatment practices and reduce their environmental footprint. Hybrid technologies provide a pathway for industries to comply with regulatory standards while also minimizing the risk of environmental contamination and public health hazards.

Reduced environmental damage to nearby ecosystems caused by the textile and dye industries is another important benefit of hybrid wastewater systems. By effectively removing pollutants from wastewater streams, these technologies prevent the contamination of surface water bodies, groundwater sources, and soil. This helps preserve biodiversity, protect sensitive ecosystems, and safeguard human health in communities located near industrial facilities.

The hybrid wastewater technologies offer scalability and scalability, making them suitable for a wide range of applications, from small-scale decentralized systems to large industrial treatment plants. Hybrid methods can be used to treat wastewater from textile industries, dyeing facilities, or municipal sewage systems. They can be customized to fit individual needs and handle different wastewater volumes. Additionally, the integration of advanced monitoring and control systems enhances the efficiency and reliability of hybrid wastewater technologies. Key parameters, including pH, temperature, and pollutant concentrations, may be monitored in real-time, allowing for prompt modifications to treatment procedures that guarantee maximum efficiency and legal compliance. The total efficacy of wastewater treatment operations is increased by automated control systems, which reduce operational downtime and human error.

Environmental engineering is at the forefront of innovation and technical improvement because of the continuous study and development of hybrid wastewater systems. Scientists and engineers are continually exploring new treatment processes, materials, and system designs to improve the efficiency, sustainability, and cost-effectiveness of wastewater treatment. This research contributes to the evolution of hybrid technologies and expands their applicability to diverse wastewater treatment scenarios. The role of hybrid wastewater technologies in addressing the challenges of effluents from textile and dye industries is multifaceted and essential for achieving sustainable environmental management. These technologies offer versatility, customization, resource recovery, regulatory compliance, environmental protection, scalability, advanced monitoring, and ongoing innovation. By leveraging the synergistic effects of multiple treatment processes, hybrid technologies provide effective solutions for treating complex wastewater streams and mitigating the environmental impact of industrial activities.

The role of hybrid wastewater technologies in addressing the challenges posed by effluents from textile and dye industries is paramount in achieving sustainable environmental management. These industries are notorious for their significant contributions to water pollution, with effluents containing various pollutants such as dyes, heavy metals, and organic compounds. Hybrid wastewater technologies offer a multifaceted approach that combines different treatment methods to effectively remove contaminants from wastewater streams. By integrating complementary processes, hybrid technologies can enhance treatment efficiency and produce higher quality effluents compared to conventional methods.

The flexibility and adaptation of hybrid wastewater solutions to a wide range of wastewater compositions is one of their main advantages. Textile and dye effluents often contain complex mixtures of pollutants, making it challenging to treat them using single treatment methods. Hybrid technologies leverage the synergistic effects of different methods, to target different types of pollutants and achieve comprehensive removal. Moreover, hybrid wastewater technologies enable the customization of treatment systems based on specific contaminant profiles and treatment objectives. By selecting and combining appropriate treatment processes, engineers and researchers can design tailored solutions that address the unique challenges posed by textile and dye effluents. This adaptability minimizes operating costs and environmental impacts while optimizing treatment efficiency.

In addition to pollutant removal, hybrid wastewater technologies also offer opportunities for resource recovery and reuse. Many of the pollutants present in textile and dye effluents, such as organic compounds and nutrients, can be recovered and utilized for various purposes, including energy generation, agricultural fertilization, and industrial processes. Hybrid technologies support the circular economy idea by establishing resource conservation and sustainability through the integration of resource recovery mechanisms into wastewater treatment systems. Furthermore, the increasingly strict regulatory requirements for effluent disposal are met in large part by hybrid wastewater solutions. There is increasing demand on enterprises to enhance their wastewater treatment procedures and decrease their environmental impact due to stricter environmental requirements. Hybrid technologies provide a pathway for industries to comply with regulatory standards while also minimizing the risk of environmental contamination and public health hazards.

Reduced environmental damage to nearby ecosystems caused by the textile and dye industries is another important benefit of hybrid wastewater systems. By effectively removing pollutants from wastewater streams, these technologies prevent the contamination of surface water bodies, groundwater sources, and soil. This helps preserve biodiversity, protect sensitive ecosystems, and safeguard human health in communities located near industrial facilities. Moreover, hybrid wastewater technologies offer scalability and scalability, making them suitable for a wide range of applications, from small-scale decentralized systems to large industrial treatment plants. Hybrid solutions may be adapted to fulfil individual requirements and accept varied quantities of wastewater, whether it comes from textile manufacturing, dyeing facilities, or municipal sewage systems.

Additionally, the integration of advanced monitoring and control systems enhances the efficiency and reliability of hybrid wastewater technologies. It is possible to make rapid modifications to treatment operations, maintaining optimal performance and regulatory compliance, by monitoring important parameters including pH, temperature, and pollutant concentrations in real-time. In order to maximize the overall efficacy of wastewater treatment operations, automated control systems reduce operational downtime and human error. Innovation and technical progress in environmental engineering are also fuelled by the continuous study and development of hybrid wastewater systems. To increase wastewater treatment's efficacy, sustainability, and economics, scientists and engineers are always looking into novel treatment techniques, components, and system layouts. By expanding their application to various wastewater treatment settings, this research advances the evolution of hybrid technologies.

The role of hybrid wastewater technologies in addressing the challenges of effluents from textile and dye industries is multifaceted and essential for achieving sustainable environmental management. These technologies offer versatility, customization, resource recovery, regulatory compliance, environmental protection, scalability, advanced monitoring, and ongoing innovation. By leveraging the synergistic effects of multiple treatment processes, hybrid technologies provide effective solutions for treating complex wastewater streams and mitigating the environmental impact of industrial activities.

Role of Hydrodynamic cavitation

Utilization of textile and dye wastewater for reducing COD, BOD, TDS, and colour: The study aims to demonstrate the feasibility of using textile and dye wastewater obtained from industries as a feedstock for wastewater treatment. By targeting key parameters such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Dissolved Solids (TDS), and colour, the research seeks to meet regulatory standards and market demand for treated wastewater.

The utilization of textile and dye wastewater for reducing various pollutants such as COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand), TDS (Total Dissolved Solids), and colour presents a multifaceted challenge that requires a comprehensive approach encompassing both technical and environmental considerations. In the context of this thesis, the focus is on developing strategies to harness the potential of textile and dye wastewater as a valuable resource while mitigating its adverse environmental impact through effective treatment and reuse.

Textile and dye wastewater is characterized by high levels of organic compounds, colorants, and other pollutants, making it a significant contributor to water pollution and environmental degradation. The intricate composition of wastewater from textile and dye industries is frequently too complicated for traditional treatment techniques, such as physical-chemical processes and biological treatment, which can result in insufficient pollutant removal and the possible release of hazardous pollutants into the environment.

One approach to addressing this challenge is through the implementation of advanced treatment technologies specifically designed to target the unique characteristics of textile and dye wastewater. Advanced oxidation processes (AOPs), including UV/H_2O_2, Fenton oxidation, and ozone treatment (Patel and Kumar, 2020)" are examples of AOPs that may be used in wastewater treatment to break down resistant organic compounds and colorants. By utilizing powerful oxidizing agents, AOPs offer a robust solution for enhancing the removal efficiency of COD, BOD, TDS, and colour, thereby improving the overall quality of the treated effluent.

In addition to AOPs, membrane-based separation processes such as ultra-filtration (UF), Nano filtration (NF), and reverse osmosis (RO) can be employed to concentrate and remove dissolved contaminants from textile and dye wastewater. The treated effluent produced by these membrane technologies has much higher quality since they have excellent removal efficiency for colorants, dissolved organic compounds, and suspended particles. Furthermore, membrane processes can facilitate water reuse and resource recovery by producing a permeate stream suitable for various applications, including process water for textile manufacturing or irrigation in agricultural fields.

Another promising approach to utilizing textile and dye wastewater is through the application of biological treatment technologies, such as aerobic and anaerobic processes, supplemented with specialized microbial consortia capable of degrading complex organic compounds and colorants. By using microorganisms' ability to break down organic contaminants into simpler, less toxic compounds, biological treatment systems provide a sustainable and economical way to reduce COD, BOD, and colour in wastewater. By optimizing process parameters such as retention time, aeration rate, and nutrient supplementation, biological treatment can achieve significant reductions in pollutant concentrations while minimizing energy and chemical requirements.

Moreover, the integration of multiple treatment technologies into hybrid wastewater treatment systems can synergistically enhance pollutant removal efficiency and resource recovery from textile and dye wastewater. By combining complementary processes such as AOPs, membrane filtration, and biological treatment in a sequential or integrated configuration, hybrid systems can capitalize on the strengths of each technology while mitigating their respective limitations. This holistic approach allows for the efficient removal of COD, BOD, TDS, and colour from wastewater while maximizing the reuse and recycling of valuable resources.

The utilization of textile and dye wastewater for reducing COD, BOD, TDS, and colour also holds significant economic and environmental benefits. By treating and reusing wastewater within the textile manufacturing process, companies can reduce their dependence on freshwater resources; lower operating costs associated with wastewater disposal, and comply with stringent environmental regulations governing wastewater discharge. Additionally, the recovery of valuable by-products such as treated water, organic matter, and energy from wastewater can create new revenue streams and contribute to the circular economy.

Furthermore, the treatment and reuse of textile and dye wastewater can help mitigate the environmental impact associated with conventional wastewater disposal practices, such as discharging untreated or partially treated effluent into surface water bodies. Companies may promote environmental sustainability and corporate responsibility by reducing the danger of water pollution, ecosystem contamination, and public health threats by enhancing the quality of wastewater discharged from textile manufacturing plants.

Finally, using wastewater from textile and dye processes to lower COD, BOD, TDS, and colour offers a viable way to combat water pollution issues and support environmentally friendly water management techniques in the textile sector. By implementing advanced treatment technologies, optimizing process parameters, and integrating hybrid wastewater treatment systems, researchers and practitioners can achieve significant reductions in pollutant concentrations while maximizing resource recovery and environmental protection. Through collaborative efforts between industry, academia, and government agencies, the potential of textile and dye wastewater as a valuable resource can be fully realized, paving the way for a more sustainable and resilient water future.

Many of the several physical and chemical mechanisms that help to lower COD in water are generated by cavitation (Garcia and Martinez, 2016).The main processes at work are listed below. Cavitation bubbles that break near solid surfaces generate a localized high pressure and powerful shockwave. Shockwaves can destabilise organic molecules, distribute pollutants more broadly, and break down complicated chemical structures, therefore accelerating the breakdown of organic substances. When the bubble explodes, a process known as sonolysis results from the very high pressures and temperatures generated inside it. Sonolysis production of ultra-reactive hydroxyl radicals (OH•). These radicals have the capacity to oxidize organic molecules, thereby breaking them down and lowering the COD.

The development of vapour bubbles in a liquid brought on by a drop in pressure is known as cavitation. Often suffering from this are propeller blades or impeller undersides. The low-pressure zone produced by the propeller blade advances behind it. Cavitation bubbles develop if this pressure drops below the liquid's vapour pressure.

These vapour bubbles contain liquids in the vapour phase. These occur in low-pressure regions where liquid vaporizes. The bubbles condense vapour, moving from the low-pressure area to the higher-pressure sections. This caused bubbles to explode forcefully. A rupture of a bubble generates several events, including: Given that this implies the strong-amplitude shock waves generated by the sudden collapse might cause surface damage from shock waves. High-velocity micro jets explode onto a surface when surrounding bubbles collapse asymmetrically. The surface suffers from this. Shock waves generate strong sounds. Ultimately, cavitation bubbles develop out of low-pressure zones and migrate into higher-pressure zones, where they collapse to generate harmful forces and consequences. Hydraulic gear designs, including pumps and propellers, are critically dependent on cavity control.

Different treatment methods have been developed and implemented for treating textile and dye industry wastewater, each with distinct advantages and operational characteristics. Table 1 provides a comprehensive overview of various treatment approaches, including physical, chemical, biological, and hybrid methods, along with their key benefits and applications in wastewater treatment.

Table 1 Different Treatment Method used for treating waste water

Treatment Method	Description	Key Benefits
Advanced Oxidation Processes (AOPs)	Utilize powerful oxidizing agents to degrade organic compounds and colorants present in wastewater. Examples include ozone treatment, UV/H_2O_2, and Fenton oxidation.	High removal efficiency for COD, BOD, TDS, and colour. Effective degradation of recalcitrant pollutants.
Membrane Filtration	Employ membrane-based separation processes such as ultrafiltration (UF), Nano filtration (NF), and reverse osmosis (RO) to concentrate and remove dissolved contaminants from wastewater.	High removal efficiency for suspended solids dissolved organic compounds, and colorants. Facilitates water reuse and resource recovery.
Biological Treatment	Utilize aerobic and anaerobic processes	Sustainable and cost-effective solution.

	supplemented with specialized microbial consortia to degrade organic pollutants and colorants in wastewater.	Achieves significant reductions in COD, BOD, and colour. Minimizes energy and chemical requirements.
Hybrid Wastewater Treatment Systems	Integrate multiple treatment technologies, such as AOPs, membrane filtration, and biological treatment, to increase wastewater resource recovery and the effectiveness of pollution removal in concert.	Capitalize on the strengths of each technology. Maximize reuse and recycling of valuable resources. Minimize environmental impact.

As shown in Table 1, advanced oxidation processes (AOPs) demonstrate high removal efficiency for both COD and color, achieving removal rates of 85-95% within treatment periods of 30 minutes to 1 hour [Patel and Kumar, 2020]. However, these processes often require significant operational expertise and investment. In contrast, biochar-based adsorption methods offer a more cost-effective solution while maintaining considerable treatment efficiency, particularly for color removal. Membrane filtration technologies show excellent removal capabilities for suspended solids and dissolved compounds, though their effectiveness can be limited by membrane fouling and high operational costs [Wang et al., 2023]. The hybrid wastewater treatment systems combine the advantages of multiple treatment methods, achieving superior pollutant removal through synergistic effects. For instance, the combination of adsorption and Ozonation has shown enhanced COD removal efficiency of up to 96% compared to individual treatment methods [Gajbhiye et al., 2024].

The comparative analysis presented in Table 1 highlights the importance of selecting appropriate treatment technologies based on specific wastewater characteristics and treatment objectives. While conventional treatment methods provide adequate removal of basic pollutants, advanced and hybrid technologies offer more comprehensive solutions for complex textile effluents, particularly in cases where high treatment efficiency is required to meet stringent environmental standards [Sharma et al., 2024].

The textile and dye industry are a cornerstone of global manufacturing, providing essential materials for clothing, furnishings, and numerous other applications. However, the production processes inherent to this industry result in the generation of vast quantities of wastewater, presenting significant environmental and public health challenges.

Textile and dye wastewater originates from various stages of textile production, including dyeing, printing, finishing, and washing processes. These processes involve the use of a diverse range of chemicals, including dyes, pigments, surfactants, and auxiliaries, which contribute to the complex composition of textile wastewater. Common contaminants found in textile and dye effluents include organic compounds, heavy metals, suspended solids, and colorants, posing challenges for conventional wastewater treatment methods.

The discharge of untreated or inadequately treated textile and dye wastewater has profound environmental consequences, impacting water quality, aquatic ecosystems, and human health. The elevated level of organic matter in textile wastewater can result in the reduction of oxygen in receiving bodies of water, endangering aquatic life and upsetting natural equilibrium. Additionally, the presence of synthetic dyes and heavy metals in wastewater can persist in the environment for extended periods, posing risks of bioaccumulation and toxicity.

To address the environmental risks associated with textile and dye wastewater discharge, regulatory agencies have implemented stringent standards and guidelines governing effluent quality and discharge limits. However, compliance with these regulations presents significant challenges for textile manufacturers, particularly in regions where wastewater treatment infrastructure is inadequate or costly to implement. Compliance with effluent standards requires investment in advanced treatment technologies and process optimization, posing financial and logistical barriers for many companies.

Owing to its special qualities, biochar—a carbonaceous substance made by pyrolyzing biomass—has become a viable adsorbent for the treatment of wastewater. A wide spectrum of pollutants may be effectively adsorbed from aqueous solutions by biochar due to its large surface area, porosity, and surface reactivity. Biochar also has the advantage of being a renewable and sustainable substance with potential uses in resource recovery and environmental clean-up.

Wastewater treatment applications can use adsorbent biochar to remove organic chemicals, heavy metals, and colorants from polluted water streams. During the adsorption process, pollutants are physically and chemically attached to the surface of biochar particles through processes such as electrostatic interactions, π-π stacking, and surface functional groups. By adsorbing pollutants onto its surface, biochar effectively reduces the concentration of contaminants in wastewater, leading to improved water quality.

High adsorption capacity, affordability, and environmental sustainability are only a few benefits of using biochar-based adsorbents for wastewater treatment. Compared to conventional adsorbents such as activated carbon, biochar is often more cost-effective and can be produced from locally available biomass feedstocks. Additionally, biochar exhibits excellent stability and reusability, allowing for multiple cycles of adsorption-desorption without significant loss of adsorption capacity.

However, biochar-based adsorbents also have limitations that need to be addressed for their practical application in wastewater treatment. These include variability in adsorption performance depending on feedstock and production conditions, potential leaching of organic compounds from biochar particles, and challenges associated with regeneration and disposal of spent adsorbents. Despite these limitations, ongoing research and development efforts aim to optimize biochar-based adsorbents for various wastewater treatment applications, enhancing their effectiveness and scalability.

Statement of the problem

The textile and dye industry plays a significant role in global economic growth, providing essential materials for various sectors. However, the production processes in this industry generate large volumes of wastewater characterized by high levels of organic pollutants, colour, and total dissolved solids (TDS). Because of the complexity of the pollutants in textile and dye wastewater and the limits of traditional treatment procedures, the successful treatment of this type of wastewater remains a serious issue despite regulatory efforts and technical breakthroughs.

According to the problem statement, effective and sustainable wastewater treatment methods must be created in order to address the particular issues with the effluents from the textile and dye industries. Conventional treatment methods such as biological treatment, chemical coagulation, and physical filtration have shown limitations in achieving the desired effluent quality, particularly in terms of colour and recalcitrant organic compounds. Additionally, the discharge of untreated or inadequately treated wastewater from textile and dye industries poses significant environmental and public health risks, including contamination of water bodies and depletion of aquatic ecosystems.

A lack of comprehensive research on the use of state-of-the-art treatment technologies in conjunction with statistical analytic techniques to optimize wastewater treatment processes in the textile and dye industries is another issue raised by the problem statement. While individual advanced treatment methods such as ozone oxidation, membrane filtration, and adsorption have shown promise in addressing specific contaminants, their combined application in hybrid treatment systems remains relatively unexplored. Moreover, the optimization of treatment parameters such as pH, temperature, contact time, and adsorbent dosage through statistical analysis techniques is crucial for enhancing treatment efficiency and reducing operational costs.

Another aspect of the problem statement is the limited utilization of textile and dye wastewater as a resource for resource recovery and circular economy initiatives.

Despite containing valuable components such as organic matter and colorants, textile and dye effluents are often viewed as waste streams to be disposed of, rather than potential sources of raw materials or energy. The lack of efficient recovery and reuse strategies further exacerbates the environmental footprint of textile and dye industries and contributes to resource depletion and pollution.

In conclusion, the problem statement highlights the necessity of creative and comprehensive approaches to wastewater treatment in the textile and dye sector, addressing the drawbacks of traditional techniques, streamlining treatment procedures through statistical analysis, and encouraging resource recovery from wastewater streams. By addressing these problems, the thesis hopes to assist the textile and dye industry in implementing environmentally responsible and sustainable practices, therefore lessening the detrimental consequences of wastewater discharge on ecosystems and human health.

Objectives

- Waste water treatment using lab synthesized Biochar based adsorbents in designed reactor SS-321 make (*Canna indica* Leaves, Roots and Stalk).
- Combination of various advanced hybrid waste water treatment methods shall be used like ozone or use of catalyst.
- Statistical analysis of above experiments using various experiment factors (RPM, pH, concentration, dosage, temperature,) using software like Statistical IBN-SPSS, Minitab-19.
- To utilize the textile and dye waste water procured from industries for reducing COD, BOD, TDS and color as per market demand.

Chapter-3: Methodology

In this chapter, we will look into the methodology employed to conduct a comprehensive statistical analysis and treatment of effluents from textile/dye industries using hybrid wastewater technologies. The methodology outlined here serves as the framework through which the research objectives are achieved and the hypotheses are tested. The methodology for achieving the objectives outlined in the proposed work involves a systematic approach aimed at utilizing textile and dye wastewater obtained from industries to reduce key parameters such as COD, BOD, TDS, and colour according to market demands. This methodology encompasses several steps to conduct experiments and analyse the results using statistical techniques.

The wastewater samples shall be procured from textile and dye industries, ensuring that the samples represent the typical effluent characteristics found in these industries. The samples will then undergo initial characterization to determine baseline values for COD, BOD, TDS, and colour. Next, a series of experiments shall be conducted to evaluate the effectiveness of various treatment factors in reducing the targeted parameters in the wastewater. These factors include RPM (revolutions per minute), pH, concentration of treatment chemicals, dosage of treatment chemicals, and temperature. Each factor shall be systematically varied within a predetermined range to assess its impact on the treatment process.

The primary raw material was *Canna indica* leaves and stalks. Leaf and stem washes were done three times to remove any unwanted materials. After that the second step, which is a 7-day dehydration process after which the leaves and stalks are broken down into smaller pieces (1.5 cm). After being put in a muffle furnace and exposed to the SS reactor, the 50-gramme sample was evacuated using nitrogen gas. In order to generate biochar, the furnace is heated to 500 °C for 90 minutes.

The experiments shall be designed using a factorial experimental design approach, where multiple factors are varied simultaneously to determine their individual and combined effects on treatment efficiency. The experimental design shall be guided by statistical principles to ensure robustness and validity of the results. During the experimental phase, wastewater samples shall be treated using different combinations of treatment factors, and the resulting effluent quality shall be measured for COD, BOD, TDS, and colour. The treatment process may involve physical, chemical, and biological treatment methods, depending on the specific objectives and experimental conditions.

Following the completion of experiments, the obtained data shall be subjected to statistical analysis using software such as Statistical IBN-SPSS and Minitab-19. The central tendency and variability of the data shall be evaluated, and the experimental results shall be summarized using descriptive statistics like mean, median, and standard deviation. Additionally, to identify and quantify the key factors influencing treatment success, inferential statistical techniques such as regression analysis and analysis of variance (ANOVA) shall be used. ANOVA will help determine the significance of differences among treatment groups, while regression analysis will elucidate the relationships between treatment factors and effluent quality parameters.

Additionally, multivariate analysis techniques, such as principal component analysis (PCA) and cluster analysis, may be utilized to explore patterns and relationships within the experimental data and identify potential correlations between treatment factors and effluent quality parameters.

The statistical analysis will also involve hypothesis testing to assess the significance of observed effects and relationships. Hypotheses shall be formulated based on the experimental objectives and tested using appropriate statistical tests, with the aim of validating the effectiveness of the treatment factors in reducing COD, BOD, TDS, and colour in the wastewater. To determine if the experimental results are robust and how sensitive the treatment procedure is to changes in input parameters, a sensitivity analysis shall be carried out. Sensitivity analysis will help identify critical factors that have a significant impact on treatment performance and guide future optimization efforts.

Throughout the methodology, emphasis shall be placed on ensuring the reliability, reproducibility, and validity of the experimental results. Standardized procedures shall be followed for sample collection, experimental setup, data measurement, and statistical analysis to minimize sources of error and bias. The proposed methodology aims to systematically investigate the effectiveness of various treatment factors in reducing COD, BOD, TDS, and colour in textile and dye wastewater. The technique uses statistical analysis and rigorous experimental design to produce dependable data and insights that may guide the creation of effective and long-lasting wastewater treatment plans for the textile and dye industries.

3.1 Color/TDS Measurement

The measurement of colour and Total Dissolved Solids (TDS) in wastewater was conducted using standardized analytical techniques following established protocols.

For **colour measurement**, spectrophotometric analysis was employed using a UV-visible spectrophotometer. Wastewater samples were first filtered through 0.45 μ membrane filters to remove suspended particles that could interfere with the analysis. The spectrophotometer was calibrated using distilled water as a reference, and measurements were taken in the visible spectrum range (400-700 nm). Colour intensity was quantified in Platinum-Cobalt units (Pt-Co) by comparing sample absorbance values with a calibration curve prepared using standard colour solutions. This method aligns with the Standard Methods for the Examination of Water and Wastewater (APHA Method 2120).

Colour reduction actual vs predicted, Calculation, Measurement of Initial and Final Colour of Textile Wastewater

1. Why Color Measurement Is Important

Textile wastewater contains dyes that cause: Visible pollution, High COD and BOD, Reduced light penetration in water bodies

Colour removal is often correlated with COD reduction, especially after ozonation or AOP treatment**.**

2. Methods for Color Measurement

Two accepted laboratory approaches: Visual Colour Observation (Qualitative), Spectrophotometric Method (Quantitative – Recommended)

3. Method 1: Visual Color Observation (Preliminary)

1. Collect wastewater sample in a transparent glass bottle
2. Observe against a white background
3. Record colour description: Dark blue / red / brown (initial), Light yellow / pale / colourless (final)

4. Method 2: Spectrophotometric Color Measurement (Standard Method)

APHA Standard Methods – 2120 C (Spectrophotometric Method)

5. Equipment and Materials Required

- UV–Visible Spectrophotometer
- Quartz or glass cuvettes (1 cm path length)
- Whatman filter paper (0.45 µm)
- Distilled water (blank)
- Textile wastewater samples (before & after treatment)

6. Sample Preparation

1. Collect samples: Before treatment (initial), After treatment (final)
2. Filter samples to remove suspended solids
3. If colour is too dark, dilute (note dilution factor)

7. Determination of Maximum Absorbance Wavelength (λ_{max})

1. Scan sample from 200–800 nm

2. Identify wavelength of maximum absorbance (λmax): Textile dyes usually show λmax between 400–700 nm.
3. Fix the same λmax for all measurements

8. Measurement of Initial and Final Color

1. Set spectrophotometer at λ_{max}
2. Zero instrument using distilled water
3. Measure absorbance of: Initial wastewater sample, Final treated wastewater sample

9. Calculation of Color Removal Efficiency

$$\text{Colour Removal (\%)} = (A_i - A_f) / (A_f) \times 100$$

Where:

- Ai = Initial absorbance
- Af = Final absorbance

10. ADMI Color Units (Optional – Advanced)

If required by regulations: Measure absorbance at 436, 525, and 620 nm, Calculate ADMI colour units

11. Relation between Colour, COD, and BOD

Table: 2 Relation between colour, COD and BOD

Parameter	Before Treatment	After Treatment
Colour	Dark	Light / clear
COD	High	Reduced
BOD	High	Reduced
Absorbance	High	Low

For TDS measurement, the gravimetric method was utilized. A precisely measured volume of filtered wastewater sample (100 mL) was transferred to pre-weighed, clean evaporating dishes. These samples were then evaporated to dryness in a temperature-controlled oven maintained at 180°C ± 2°C. After cooling in a desiccator, the dishes were reweighed, and the TDS concentration was calculated using the formula:

$$TDS\ (mg/L) = [(A - B) \times 1000] / \text{sample volume}\ (mL) \quad (a)$$

Where:

- A = weight of dish + dried residue (mg)
- B = weight of empty dish (mg)

This methodology follows the standard procedure outlined in APHA Method 2540C, ensuring accuracy and reproducibility in the determination of TDS concentrations.

3.2 Research Design

The proposed work aims to utilize textile and dye wastewater from industries to reduce COD, BOD, TDS, and colour according to market demand. Currently, we have conducted adsorption analysis of biochar to assess its effectiveness in treating the wastewater. We've also modified charcoal using KOH and NaOH. We have also determined the optimal temperature for biochar adsorption and identified the best combination of biochar for treatment purposes. Moving forward, our future plan involves conducting hydrodynamic cavitation of the textile and dye effluent using a model based on fluid mechanics principles. This will entail creating a model using a polyvinyl chloride (PVC) pipe and incorporating an orifice for experimentation. We intend to run different trials with the orifice and experiment with variations such as different diameters of circles and introducing star patterns with varying lengths of star edges.

The methodology for this involves implementing hydrodynamic cavitation through the constructed model, where the orifice plate serves as a key component. Practical experiments shall be conducted with different patterns, including circles with varying diameters, and different configurations of star patterns. These experiments will help assess the efficacy of hydrodynamic cavitation in treating textile and dye wastewater. In addition, we plan to perform statistical analysis on the experimental data obtained from the adsorption analysis and hydrodynamic cavitation experiments. This analysis will involve assessing various experimental factors such as RPM, pH, concentration, dosage, and temperature using software tools like Statistical IBN-SPSS and Minitab-19. By conducting statistical analysis, we aim to identify significant factors affecting treatment efficiency and optimize the treatment process accordingly.

Overall, the methodology involves a combination of experimental techniques, including adsorption analysis and hydrodynamic cavitation, along with statistical analysis to evaluate treatment effectiveness. Through iterative experimentation and analysis, we aim to develop efficient and sustainable wastewater treatment strategies for the textile and dye industries. A mixed-method approach, incorporating both quantitative and qualitative methodologies, forms the basis of this study's research design. By combining statistical analysis with qualitative information from stakeholders and industry experts, this enables a comprehensive knowledge of the wastewater treatment process. The research design is structured in a way that facilitates the integration of different data sources and methodologies, ensuring a robust and comprehensive analysis.

The research design for this thesis represents a comprehensive and multifaceted approach aimed at addressing the complex challenges associated with the treatment of effluents from textile/dye industries using hybrid wastewater technologies. In extending this design, we embark on a journey that traverses the realms of quantitative analysis, qualitative exploration, and integrative synthesis.

At the core of the research design lays the quantitative component, which serves as the backbone of data-driven analysis and statistical modelling. Through a systematic sampling strategy, effluent samples are meticulously collected from a diverse array of textile/dye industries, ensuring representation across various geographic regions and production scales. These samples undergo rigorous laboratory analysis, where state-of-the-art analytical techniques are employed to quantify key parameters such as pH, COD, BOD, TSS, heavy metals, and organic pollutants. The resulting dataset forms the foundation for descriptive and inferential statistical analysis, enabling the identification of trends, correlations, and patterns within the effluent characteristics. Moreover, the development of mathematical models facilitates the simulation and prediction of hybrid wastewater treatment system performance under different operating conditions, thereby offering valuable insights into process dynamics and optimization strategies.

Complementing the quantitative component is the qualitative exploration, which provides contextual insights into the socio-economic, regulatory, and practical dimensions of effluent treatment practices in the textile/dye industry. Through semi-structured interviews with industry professionals, environmental regulators, and community representatives, we gain a deeper understanding of the challenges, opportunities, and stakeholders' perspectives surrounding effluent management. Concurrently, case studies offer real-world examples of successful implementation of hybrid wastewater treatment technologies, shedding light on best practices, lessons learned, and practical considerations. Additionally, document analysis of industry reports, regulatory documents, and technical literature contextualizes the research findings within the broader socio-economic and regulatory landscape, highlighting policy implications and industry trends.

The integration and triangulation of quantitative and qualitative findings form the crux of the research design, fostering a symbiotic relationship between data-driven analysis and contextual interpretation. Through iterative cycles of data collection, analysis, and synthesis, we endeavour to reconcile divergent perspectives, identify convergence points, and construct a unified narrative that encapsulates the multifaceted nature of effluent treatment in the textile/dye industry. This integrative synthesis not only enhances the robustness and validity of the research findings but also fosters a holistic understanding of the research problem, transcending disciplinary boundaries and bridging theory with practice.

Furthermore, the research design emphasizes stakeholder engagement and knowledge co-creation as central tenets of the research process. By fostering collaboration with industry partners, regulators, and other stakeholders, we aim to co-produce knowledge, co-design solutions, and co-create value that transcends traditional academic boundaries. Through participatory research methodologies such as action research and community-based participatory research (CBPR), we empower stakeholders to actively engage in the research process, share their expertise, and contribute to the development of innovative solutions that address their needs and aspirations.

Moreover, the research design adopts a transdisciplinary approach that transcends disciplinary silos and integrates diverse perspectives, methodologies, and epistemologies. By embracing complexity, uncertainty, and ambiguity, we strive to navigate the intricate interplay of technological, social, economic, and environmental factors that shape effluent treatment practices in the textile/dye industry. Through transdisciplinary collaboration and co-creation, we seek to generate actionable insights and transformative solutions that promote environmental sustainability, social equity, and economic prosperity.

The extended research design embodies a holistic, integrative, and transdisciplinary approach to the treatment of effluents from textile/dye industries using hybrid wastewater technologies. By blending quantitative analysis with qualitative exploration, integrating diverse perspectives, and fostering stakeholder engagement, the research design seeks to transcend disciplinary boundaries, bridge theory with practice, and co-create knowledge that catalyses positive change in the textile/dye industry and beyond.

The research design for the proposed methodology involves a systematic approach aimed at investigating the efficacy of utilizing textile and dye wastewater for reducing COD, BOD, TDS, and colour, as well as conducting hydrodynamic cavitation experiments for further treatment. The research design encompasses several key components, including experimental setup, data collection, analysis, and interpretation.

3.3 Experimental Setup:

- Adsorption Analysis: Conduct experiments by flocculator (Mixing Equipment) and Filtration set up, ozonized to assess the adsorption capacity of biochar for reducing COD, BOD, TDS, and color in textile and dye wastewater.

- Hydrodynamic Cavitation: Construct a model based on fluid mechanics principles using a polyvinyl chloride (PVC) pipe and incorporate an orifice for experimentation.

- Experimental Factors: Vary experimental factors such as RPM, pH, concentration, dosage, and temperature to assess their impact on treatment efficiency.

- Statistical Analysis: Utilize software tools like Statistical Design Expert, IBN-SPSS and Minitab-19 for statistical analysis of experimental data.

3.4 Data Collection

- Adsorption Analysis: Get information on the amount of biochar that can be adsorbed for various factors, such temperature and mix of biochar.

- Hydrodynamic Cavitation: Gather data from practical experiments conducted with different patterns, including circles and star configurations.

- Experimental Factors: Record data on RPM, pH, concentration, dosage, and temperature variations during experimentation.

- Statistical Analysis: Collect data generated from experimental trials for statistical analysis using software tools.

3.5 Analysis and Interpretation

- Adsorption Analysis: Analyze data to determine the optimal temperature and biochar combination for effective COD, BOD, TDS, and color reduction.

- Hydrodynamic Cavitation: Interpret experimental results to evaluate the efficacy of hydrodynamic cavitation in treating textile and dye wastewater.
- Experimental Factors: Conduct statistical analysis to identify significant factors affecting treatment efficiency and optimize treatment processes.
- Statistical Analysis: Utilizing Minitab-19 and Statistical IBN-SPSS, analyse experimental data to determine how experimental variables affect treatment outcomes.

The research design integrates experimental techniques, statistical analysis, and interpretation of results to evaluate the effectiveness of utilizing textile and dye wastewater for reducing pollutants and conducting hydrodynamic cavitation experiments for further treatment. By systematically investigating the impact of various parameters on treatment efficiency, the research design aims to develop sustainable wastewater treatment strategies for the textile and dye industries.

Design Parameter of SS-321 Reactor for making biochar

The design specifications of an SS-321 reactor used for pyrolysis are explained in detail below. I'll concentrate on what is often anticipated in research, academic or pilot-scale reactor design.

A. Selection of Material: SS-321

- Because it is stabilized with titanium, which stops carbide precipitation at high temperatures, stainless steel 321 (SS-321) is frequently used for pyrolysis reactors.
- Superior resistance to oxidation and corrosion; outstanding strength at high temperatures able to run continuously between 500 and 900 °C. Design implication: Under the normal pyrolysis heat cycle, SS-321 enables long reactor life and reliable performance.

B. Operating Temperature

- Depending on the feedstock, the typical pyrolysis temperature range is 400–800 °C. Biomass: 450–600 °C; plastic waste: 500–700 °C, Rubber and tires: 450–650 °C

- Considerations for design: The thickness of the reactor wall must be able to bear heat stress; the heat must be distributed uniformly to prevent hot spots; and it must be compatible with furnaces or external heaters.

C. Pressure in the Reactor

- Operating at atmospheric or slightly negative pressure is the norm; modest positive pressure (0.1–0.5 bar gauge) is occasionally used.

- Considerations for design: A pressure relief valve for safety, Appropriate sealing (flanges, gaskets), Wall thickness determined using ASME pressure vessel codes if pressurized

D. Reactor Dimensions and Dimensions Typical setups:

- Fixed-bed reactors; batch or semi-batch reactors; tubular or cylindrical reactors
  important dimensions: Diameter influences residence time and heat transmission; length and height influence vapor flow and conversion.

- For tubular reactors, the aspect ratio (L/D) is usually between three and six. Ensuring adequate residence time and efficient heat transfer is the design goal.

E. Heating System: Gas-fired or induction heating; external electric furnace; heating rate:

- 5–50 °C/min (depending on process type) Design specifications: Maximum heating capacity; thickness of insulation (refractory or ceramic fiber)

- Accuracy of temperature control (±2–5 °C)

F. Feedstock Features

- Particle size, moisture content, bulk density, and volatile matter concentration all have a significant impact on design.
- Implications for design: Larger particles result in slower heat penetration; high moisture content increases the amount of energy needed.
- Conversion efficiency is increased by uniform feed size.

G. Residence Time:

- Vapour residence time: less than two seconds for rapid pyrolysis; solid residence time: ten to sixty minutes In charge of: Feed rate, reactor volume, and internal flow path design

H. Inert Gas System:

- Flow rate: 0.1–2 L/min (lab scale) or scaled appropriately; nitrogen or argon utilized to maintain an oxygen-free environment Design elements: Distribution of gas inlets, Leak-proof construction;, Rotameter/MFC and flow control valves.

I. Product Collection System:

- Vapor outlet design needs to reduce pressure drop • Connection to: Condenser Cyclone, The chamber for collecting char prevent tar condensation inside the reactor outflow line as a design concern.

J. Safety and Mechanical Strength: - Wall thickness determined by: Temperature, Pressure, Corrosion allowance.

K. Standards and Codes: ASTM standards for SS-321 material; ASME Boiler and Pressure Vessel Code; and appropriate welding techniques for high-temperature service

Reactor Volume

- To calculate the reactor volume, the length alone is not sufficient. You also need the internal diameter (ID) of the SS-321 reactor.

  For a cylindrical reactor, the formula is:

$$\boldsymbol{V = \pi * (D/2)^2 \ * L}$$

Where:

- V = reactor volume
- D = internal diameter
- L = reactor length

Given: Reactor length, L=16 cm, Internal Diameter- 6.5cm

Example calculations (for common lab reactor diameters)

If internal diameter = 6.5 cm

$$V = \pi * (3.25)^2 \ * 16$$

V= 530.92 cm^3 Approx. = 0.530 L

- Here I use internal diameter, not outer diameter
- If the reactor contains packing or feedstock, the effective volume will be lower
- Always specify units (cm^3 or L)

Gas Pressure inside Reactor

Typical operating condition

- Pressure: Atmospheric pressure

1 atm ≈101.3 kpa

Practical lab-scale setting

- Nitrogen cylinder regulator pressure: 0.2–0.5 bar (gauge)
- Actual reactor internal pressure:≈ 1 atm

This small positive pressure ensures:

- Complete removal of oxygen
- Prevention of air ingress
- Safe operation at high temperature

Pyrolysis is a thermal decomposition, not a pressure-driven reaction so here high pressure nitrogen is not used because

- High pressure:
    - Disturbs vapor residence time
    - Increases gas-phase secondary cracking
    - Can stress seals and fittings
- SS-321 is temperature-resistant, but pressure is intentionally kept low

Typical Nitrogen Flow vs Pressure

Table:3 Nitrogen Flow in reactor

Parameter	Typical Value
Temperature	500 °C
Reactor pressure	~1 atm
N_2 inlet pressure (gauge)	0.2–0.5 bar
N_2 flow rate	100–500 mL/min
Reactor type	Fixed-bed SS-321

"Pyrolysis experiments were performed in a fixed-bed SS-321 reactor with an internal diameter of 6.5 cm and length of 16 cm. Nitrogen was introduced through a purging inlet of 1.5 cm internal diameter and 8.5 cm length. The total effective reactor volume was calculated to be 0.546 L. An inert atmosphere was maintained by supplying nitrogen at atmospheric pressure with a controlled flow rate of approximately 1.6 L min^{-1} at 500 °C."

1. Given Reactor and Inlet Dimensions

Main SS-321 Pyrolysis Reactor

- Internal diameter, D_1 = 6.5 cm
- Length, L_1 = 16 cm

Nitrogen Purging Inlet Tube

- Internal diameter, D_2 = 1.5 cm
- Length, L_2 = 8.5 cm

2. Volume Calculation of Main Reactor

Formula for cylindrical volume:

$$V = \pi * (D/2)^2 \ * L$$

$$V1 = \pi * (6.5/2)^2 \ * 16$$

$$V1 = 531.1 \ \text{cm}^3$$

$$V1 = 0.531 \ \text{L}$$

3. Volume Calculation of Nitrogen Purging Inlet

$$V = \pi * (1.5/2)^2 \ * 8.5$$

$$V2 = 15.02 \ \text{cm}^3$$

$$V2 = 0.015 \text{ L}$$

4. Total Effective Reactor Volume

$$V_{total} = V_1 + V_2$$

$$= 531.1 + 15.02$$

$$= 546.1 \text{ cm}^3$$

$$V_{total} = 0.546 \text{ L}$$

5. Nitrogen Flow Rate Calculation (at 500 °C)

Standard Design Rule:

N_2 flow=2–3 reactor volume exchanges/ minute

Minimum Flow (2 volumes / min):

$$0.546\times2 = 1.09 \text{ L/min}$$

Recommended Flow (3 volumes / min):

$$0.546\times3 = 1.64 \text{ L/min}$$

Table: 4 Reactor Parameter

Parameter	Value
Reactor volume	0.546 L
Operating temperature	500^0C
Reactor Pressure	1 atm
N_2 inlet Pressure	0.2-0.5 bar
Recommended N_2 flow	1.5-1.7 L/min

3.6 Data Collection

The data collection process involves gathering both primary and secondary data related to effluent characteristics, treatment technologies, and industry practices. The data collection process for this methodology is essential for capturing crucial information and experimental data pertaining to the efficacy of utilizing textile and dye wastewater for reducing contaminants and conducting hydrodynamic cavitation experiments. It involves a systematic approach to gather data on key parameters and variables that influence treatment outcomes and experimental results.

Initially, the data collection process focuses on conducting adsorption analysis to assess the adsorption capacity of biochar for reducing COD, BOD, TDS, and colour in textile and dye wastewater. This involves conducting experiments at different temperatures and testing various combinations of biochar to determine the most effective combination for wastewater treatment. During the adsorption analysis, data is collected through measurements of COD, BOD, TDS, and colour before and after treatment at different temperatures. This data provides insights into the adsorption capacity of biochar under varying conditions and helps identify optimal temperature ranges and biochar combinations for efficient wastewater treatment.

Simultaneously, the data collection process extends to the hydrodynamic cavitation experiments, where parameters such as RPM, pH, concentration, dosage, and temperature are varied to assess their impact on treatment efficiency. Practical trials are conducted using a model based on fluid mechanics principles, with a PVC pipe and an orifice plate serving as key components. Experimental data is collected from these trials, including measurements of RPM, pH, concentration, dosage, and temperature variations during experimentation. This data allows for the evaluation of the effectiveness of hydrodynamic cavitation in treating textile and dye wastewater and provides insights into the optimal operating conditions for treatment.

Furthermore, the data collection process involves recording results from statistical analysis conducted using software tools like Statistical IBN-SPSS and Minitab-19. This includes data generated from experimental trials and statistical tests performed to assess the significance of factors influencing treatment efficiency. Throughout the data collection process, attention is paid to ensuring accuracy, reliability, and consistency in the measurement and recording of experimental data. Standardized procedures and protocols are followed to minimize errors and biases, thereby enhancing the validity and reliability of the findings.

Data collected from the adsorption analysis, hydrodynamic cavitation experiments, and statistical analysis are meticulously documented and organized for further analysis and interpretation. This includes organizing data into structured formats, creating datasets, and maintaining detailed records of experimental procedures and results. Moreover, the data collection process involves ongoing monitoring and adjustment of experimental parameters to optimize experimental conditions and ensure the validity of results. This preserves the integrity of the data, this might entail recalibrating apparatus, modifying experimental configurations, and putting quality control procedures in place.

All things considered, the data collection procedure is an essential part of the approach because it provides a framework for evaluating wastewater treatment techniques' efficacy and streamlining treatment procedures for the textile and dye sectors. By systematically collecting and analysing experimental data, this research aims to contribute to the development of sustainable solutions for wastewater management in industrial settings. The data collection process for this thesis represents a meticulous and systematic endeavour aimed at acquiring a comprehensive understanding of effluent characteristics, treatment technologies, and industry practices in the textile/dye sector. Grounded in both primary and secondary sources, this multifaceted approach ensures the robustness and reliability of the data gathered.

Primary data collection begins with the on-site visits to textile/dye industries, where effluent samples are meticulously obtained for analysis. These visits provide first-hand insight into the operational dynamics, challenges, and intricacies of effluent management within the industry. Through close collaboration with industry stakeholders, we gain access to effluent sources spanning a diverse range of production processes, scales, and geographical locations. This diversity ensures the representativeness and generalizability of the data collected, facilitating a nuanced understanding of effluent characteristics and treatment needs.

Effluent sampling follows standardized protocols to ensure consistency, accuracy, and reliability. Samples are collected at multiple points along the wastewater treatment process, including influent, effluent, and intermediate stages, to capture variations in effluent quality and composition. Additionally, grab and composite sampling techniques are employed to account for temporal and spatial variability in effluent discharge. Stringent quality control measures are implemented throughout the sampling process to minimize contamination and preserve sample integrity.

After being collected, effluent samples go through a series of laboratory tests to measure important elements, including pH, COD, BOD, and TDS, concentrations of nutrients, heavy metals, and organic contaminants. Modern analytical methods, such as atomic absorption spectroscopy, chromatography, and spectrophotometry, are used to guarantee the dependability, accuracy, and precision of the data collected. In addition, samples are examined in two or three copies to evaluate repeatability and reduce measurement error. Primary data collection includes outdoor observations and measurements in addition to effluent sampling, which is used to support laboratory analysis. With the use of data recorders and portable devices, field characteristics, including temperature, flow rate, turbidity, and dissolved oxygen levels, are tracked in real time. These field measurements provide valuable contextual information and enable the characterization of effluent behaviour under dynamic operating conditions.

Complementing primary data collection is the acquisition of secondary data from literature review, industry reports, and academic publications. This secondary data serves as a rich source of information on existing wastewater treatment technologies, regulatory frameworks, and best practices in the textile/dye industry. Through comprehensive literature searches and systematic review methodologies, we identify and synthesize relevant studies, reports, and datasets that contribute to the body of knowledge on effluent treatment. Moreover, secondary data analysis enables us to contextualize our findings within the broader socio-economic, environmental, and regulatory landscape. By examining trends, patterns, and emerging issues in the literature, we gain insight into the evolution of effluent treatment practices over time and anticipate future challenges and opportunities facing the textile/dye industry. Additionally, secondary data analysis facilitates comparative analysis and benchmarking against industry standards and regulatory requirements.

Throughout the data collection process, ethical considerations and regulatory compliance are paramount. Participating industries provide informed consent, and ethical principles are followed to safeguard the data's confidentiality, privacy, and integrity. Moreover, efforts are made to minimize environmental impact and ensure the safe handling and disposal of effluent samples and laboratory reagents. The data collection process for this thesis represents a rigorous, systematic, and multi-dimensional endeavour that combines primary and secondary sources to acquire a comprehensive understanding of effluent characteristics, treatment technologies, and industry practices in the textile/dye sector. By means of rigorous sampling, laboratory analysis, field measurements, literature evaluation, and ethical considerations, our goal is to provide high-quality data that serves as the foundation for well-informed decision-making and knowledge development about effluent treatment.

3.7 Primary Data Collection

Primary data is collected through on-site visits to textile/dye industries, where effluent samples are obtained for analysis. Sampling is conducted in accordance with standard protocols to ensure accuracy and reliability. Various parameters such as pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total dissolved solids (TDS), and heavy metal concentrations are measured using appropriate analytical techniques. The primary data collection process for this thesis represents a meticulous and detailed undertaking aimed at capturing the nuances and complexities of effluent characteristics and treatment practices in the textile/dye industry. Grounded in fieldwork and laboratory analyses, this primary data collection effort ensures the generation of high-quality, reliable data that forms the cornerstone of the research endeavour. One of the primary methods employed in the data collection process is the on-site visit to textile/dye industries. These visits provide invaluable opportunities to directly observe effluent treatment processes, interact with industry professionals, and gather first-hand insights into the operational dynamics and challenges faced by the industry. By immersing ourselves in the day-to-day operations of textile/dye facilities, we gain a deep appreciation for the intricacies of effluent management and treatment.

Wastewater sampling is a critical step in the basic data collection method. Samples are collected from various points along the wastewater treatment process, including influent, effluent, and intermediate stages such as primary treatment units, secondary treatment units, and tertiary treatment units. This comprehensive sampling approach allows for the characterization of effluent quality and composition at different stages of treatment, enabling a holistic understanding of treatment performance and efficiency. Sampling protocols are meticulously followed to ensure consistency, accuracy, and reliability. Samples are collected using grab or composite sampling techniques, depending on the specific sampling objectives and conditions. Grab samples are collected at discrete time points to capture instantaneous variations in effluent quality, while composite samples are collected over extended periods to integrate fluctuations and temporal trends. Quality control measures are implemented throughout the sampling process to minimize contamination and preserve sample integrity.

Effluent samples are transported to the laboratory under controlled conditions to prevent degradation and ensure sample stability. Upon arrival, samples undergo a battery of laboratory analyses to quantify key parameters such as pH, COD, BOD, TDS, nutrient concentrations, heavy metals, and organic pollutants. State-of-the-art analytical techniques, including spectrophotometry, chromatography, and atomic absorption spectroscopy, are employed to achieve accurate and precise measurements. To enhance the reliability of the data obtained, samples are analysed in duplicate or triplicate, and quality control standards and reference materials are included in each analytical batch. This rigorous approach to laboratory analysis minimizes measurement error and ensures the reproducibility of results. Furthermore, calibration curves, blank samples, and technique detection limits are closely monitored to ensure analytical accuracy and regulatory compliance.

Field measurements supplement laboratory assessments by providing up-to-date information on wastewater behaviour and performance under changing operational conditions. Portable equipment and data recorders placed at key points throughout the wastewater treatment system are used to monitor parameters including temperature, flow rate, turbidity, and dissolved oxygen levels. These field measurements offer valuable contextual information and enable the validation of laboratory results. In addition to effluent sampling and laboratory analyses, primary data collection involves interviews and surveys with industry professionals, environmental regulators, and community stakeholders. These qualitative data collection methods provide insights into the socio-economic, regulatory, and cultural dimensions of effluent management in the textile/dye industry. Through structured interviews and targeted surveys, we elicit perspectives, opinions, and experiences that enrich our understanding of effluent treatment practices and inform the development of effective solutions.

Furthermore, observational techniques are employed to document and analyse operational practices, process parameters, and performance indicators within textile/dye facilities. By observing effluent treatment processes in real-time, we gain insights into process efficiency, resource utilization, and operational challenges. These observations complement quantitative data collection efforts and provide valuable context for interpreting and contextualizing the data obtained.

During the whole process of gathering primary data, ethical issues are crucial. Participating industries provide their informed permission, and ethical standards are observed to guarantee the integrity, confidentiality, and privacy of the data gathered. Moreover, efforts are made to minimize environmental impact and ensure the safe handling and disposal of effluent samples and laboratory reagents. The primary data collection process for this thesis represents a comprehensive, systematic, and multi-faceted effort that combines fieldwork, laboratory analyses, interviews, surveys, and observational techniques to capture the complexities of effluent treatment practices in the textile/dye industry. In the realm of wastewater treatment, we provide high-quality data that serves as the basis for well-informed decision-making and knowledge development through careful sampling, rigorous analysis, and ethical considerations.

The primary data collection phase of the methodology involves a meticulous process aimed at directly gathering first-hand information and experimental data regarding the effectiveness of utilizing textile and dye wastewater for reducing contaminants and conducting hydrodynamic cavitation experiments. This phase is crucial as it forms the foundation upon which subsequent analysis and interpretation shall be based. The initial step in primary data collection is the procurement of wastewater samples from textile and dye industries. These samples are carefully selected to ensure they accurately represent the typical effluent characteristics found in industrial settings. The samples serve as the starting point for conducting experiments and assessing treatment efficiency.

Once obtained, the wastewater samples undergo thorough initial characterization to establish baseline values for key parameters such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Dissolved Solids (TDS), and colour. This characterization provides essential insights into the composition and quality of the wastewater, serving as a reference for evaluating treatment effectiveness. Following initial characterization, experiments are conducted to evaluate the efficacy of various treatment methods. These methods include adsorption analysis using biochar and hydrodynamic cavitation experiments. Throughout these experiments, researchers manipulate various experimental variables such as temperature, biochar combination, RPM, pH, concentration, dosage, and temperature to assess their impact on treatment efficiency.

During the experiments, real-time data collection is carried out through direct measurements and observations. This includes recording measurements of parameters such as COD, BOD, TDS, and colour before and after treatment, as well as monitoring experimental conditions such as RPM, pH, concentration, dosage, and temperature. Detailed documentation of experimental procedures is maintained throughout the primary data collection phase. This documentation includes records of the setup, operation, and monitoring of treatment systems. Ensuring transparency, reproducibility, and accuracy in the data collection process is paramount to the integrity of the research.

Moreover, quality control measures are implemented to minimize sources of error and bias in the data collection process. This may involve calibrating equipment, maintaining consistency in experimental procedures, and verifying the accuracy of measurements to enhance the reliability of the collected data. Throughout the primary data collection phase, researchers remain vigilant for any unexpected outcomes or anomalies in the data. Any deviations from expected results are meticulously documented and investigated to identify potential sources of error or areas for further exploration.

The primary data collection process may also involve iterative experimentation, where adjustments to experimental conditions are made based on preliminary results to optimize treatment efficiency. This iterative approach allows for continuous refinement and improvement of treatment methods. The primary data collection phase is a crucial component of the methodology, providing raw data that serves as the basis for subsequent analysis and interpretation. This phase establishes the foundation for furthering our understanding of wastewater treatment processes in the textile and dye industries by methodically gathering and recording experimental data.

3.8 Secondary Data Collection

Secondary data is gathered from literature review, industry reports, and academic publications. This data provides valuable insights into existing wastewater treatment technologies, regulatory frameworks, and best practices in the textile/dye industry. The secondary data collection process for this thesis represents an extensive and thorough exploration of existing literature, industry reports, and academic publications related to effluent treatment in the textile/dye industry. Grounded in systematic review methodologies, this secondary data collection effort aims to contextualize primary findings within the broader socio-economic, regulatory, and technological landscape.

One of the primary sources of secondary data is the academic literature, which encompasses a vast array of research studies, reviews, and meta-analyses on effluent treatment technologies, processes, and practices. By conducting comprehensive literature searches across multidisciplinary databases, we identify and synthesize relevant studies that contribute to our understanding of effluent treatment in the textile/dye sector. These studies cover a wide range of topics, including wastewater characterization, treatment process optimization, and environmental impact assessment. Moreover, industry reports and technical publications offer valuable insights into effluent treatment practices, trends, and innovations within the textile/dye industry. These reports, often produced by industry associations, consulting firms, and research organizations, provide detailed analyses of market dynamics, regulatory developments, and technological advancements. By reviewing industry reports, we gain access to proprietary data, market intelligence, and industry benchmarks that complement primary data collection efforts.

In addition to academic literature and industry reports, regulatory documents and guidelines serve as critical sources of secondary data for this thesis. Environmental regulations, standards, and guidelines issued by government agencies, international organizations, and industry consortia provide important context for understanding the regulatory framework governing effluent discharge and treatment. By analysing regulatory documents, we gain insight into compliance requirements, enforcement mechanisms, and emerging regulatory trends that shape effluent treatment practices in the textile/dye industry. Furthermore, technical literature such as textbooks, handbooks, and conference proceedings offer in-depth coverage of effluent treatment technologies and processes. These sources provide detailed explanations of theoretical principles, design considerations, and practical applications of wastewater treatment systems. By reviewing technical literature, we deepen our understanding of the underlying mechanisms and operational parameters governing effluent treatment processes, thereby informing the interpretation and analysis of primary data.

Case studies represent another valuable source of secondary data, offering real-world examples of effluent treatment projects, challenges, and solutions implemented within the textile/dye industry. By examining case studies from diverse geographic regions and industrial contexts, we gain insights into best practices, lessons learned, and innovative approaches to effluent management. Case studies also provide opportunities for comparative analysis and benchmarking against industry standards and performance metrics. Additionally, online databases, repositories, and digital archives serve as valuable repositories of secondary data for this thesis. Convenient access to a vast array of academic and technical materials is made possible by these digital platforms, which compile and organize a plethora of information on effluent treatment technology, research findings, and industry trends. By leveraging online databases, we expand our search scope and access up-to-date information on emerging topics and trends in effluent treatment.

Social media platforms and professional networks offer alternative channels for accessing secondary data and engaging with industry experts, researchers, and practitioners in the field of effluent treatment. By participating in online discussions, forums, and communities, we gain insights into current issues, debates, and developments shaping the textile/dye industry. Social media analytics and sentiment analysis techniques can also be employed to extract valuable insights from user-generated content and discussions. Moreover, historical data and archival records provide valuable context for understanding the evolution of effluent treatment practices and regulatory frameworks over time. By examining historical documents, reports, and publications, we trace the trajectory of technological innovation, regulatory reform, and industry dynamics that have shaped effluent treatment in the textile/dye industry. Historical data analysis offers insights into long-term trends, patterns, and drivers of change, informing future projections and scenario planning.

Furthermore, cross-disciplinary perspectives and insights from related fields such as environmental engineering, chemistry, biology, and policy studies enrich the secondary data collection process. By exploring relevant literature and research findings from adjacent disciplines, we gain fresh perspectives, novel insights, and interdisciplinary connections that enhance the breadth and depth of our understanding of effluent treatment in the textile/dye industry. The secondary data collection phase of the methodology complements the primary data collection process by gathering existing information, research findings, and relevant literature related to the efficacy of utilizing textile and dye wastewater for reducing contaminants and conducting hydrodynamic cavitation experiments. This phase involves a comprehensive review and synthesis of secondary sources to provide additional context, insights, and evidence to support the research objectives.

One of the key objectives of the secondary data collection phase is to review existing literature on wastewater treatment methods, particularly those relevant to the textile and dye industry. This includes academic journals, conference proceedings, research reports, and other scholarly publications that discuss various treatment technologies, processes, and strategies for reducing pollutants in industrial wastewater. Moreover, the secondary data collection process involves gathering information on the properties and characteristics of textile and dye wastewater, as well as the pollutants typically found in these effluents. This includes data on the composition, concentrations, and variability of contaminants such as COD, BOD, TDS, and colour, which serves as valuable background information for designing and interpreting experimental studies.

Additionally, the secondary data collection phase seeks to identify previous research studies and experimental findings related to the use of biochar for adsorption analysis and hydrodynamic cavitation for wastewater treatment. Researchers can learn more about the efficacy, drawbacks, and best practices of certain therapy modalities by examining previous studies. Furthermore, the secondary data collection process involves gathering information on statistical analysis techniques and software tools commonly used in wastewater treatment research. This includes literature on statistical methods for experimental design, data analysis, and interpretation, as well as guidance on using software packages such as Statistical IBN-SPSS and Minitab-19 for statistical analysis.

Moreover, the secondary data collection phase includes reviewing regulatory guidelines, industry standards, and best practices related to wastewater treatment in the textile and dye industry. This includes regulations set forth by environmental agencies, industry associations, and governing bodies, as well as guidelines for effluent discharge limits, treatment technologies, and pollution prevention measures. Furthermore, the secondary data collection process extends to gathering information on ethical considerations and environmental implications associated with wastewater treatment in the textile and dye industry. This includes literature on ethical principles, human subject protection, environmental justice, and sustainability considerations in research and industry practices.

Additionally, the secondary data collection phase involves reviewing case studies, project reports, and success stories of wastewater treatment initiatives in the textile and dye industry. By examining real-world examples of successful treatment projects, researchers can gain insights into practical challenges, innovative solutions, and lessons learned from implementation experiences.

The secondary data collection process includes exploring interdisciplinary research and cross-sector collaborations relevant to wastewater treatment in the textile and dye industry. This includes literature on interdisciplinary approaches, partnerships between academia, industry, and government agencies, and collaborative efforts to address complex environmental challenges. Gathering data on new developments, trends, and paths for wastewater treatment research and technological development is another aspect of the secondary data collection phase. These include books on innovative treatment methods and cutting-edge technology, as well as publications on wastewater treatment for the textile and dye industries.

Overall, the secondary data collection phase serves as a valuable resource for enhancing the depth and breadth of knowledge on wastewater treatment in the textile and dye industry. By synthesizing existing literature, research findings, and industry insights, this phase provides additional context and evidence to support the research objectives and inform decision-making in the design and implementation of experimental studies.

3.9 Statistical Analysis

The statistical analysis involves the application of descriptive and inferential statistics to characterize effluent properties, identify trends, and evaluate the effectiveness of hybrid wastewater treatment technologies. The statistical analysis for this thesis embodies a rigorous and systematic approach to unravelling the complexities of effluent treatment in the textile/dye industry using hybrid wastewater technologies. Grounded in both descriptive and inferential statistical techniques, this analysis aims to uncover patterns, relationships, and trends within the data, thereby informing decision-making and driving innovation in effluent management practices.

The methodology's statistical analysis step is essential for analysing experiment data and determining how well wastewater from textile and dye production may be used to reduce pollutants. This phase involves applying statistical techniques to analyse and interpret the data, identify patterns and trends, and draw meaningful conclusions to support the research objectives. Evaluating the effect of different experimental conditions on treatment efficiency is one of the main goals of the statistical analysis phase. This includes factors such as RPM, pH, concentration, dosage, and temperature, which were manipulated during the experiments to determine their influence on key parameters such as COD, BOD, TDS, and colour.

Prior to analysis, trial raw data is collected, cleaned, and organized. This initiates the process of statistical analysis. In order to do this, the data must be formatted appropriately for statistical analysis, and mistakes, outliers, and missing values must be checked for. Following preparation, the data are summarized and their properties are described using descriptive statistical techniques. This includes calculating statistics such as mean, median, standard deviation, and range in order to gain a better understanding of the data's central tendency, variability, and distribution.

The inferential statistical techniques are utilized to examine relationships and test hypotheses regarding the effectiveness of treatment methods. This may involve conducting analysis of variance (ANOVA) to determine if there are significant differences among treatment groups, regression analysis to identify relationships between experimental factors and treatment outcomes, and correlation analysis to assess the strength and direction of relationships between variables. Moreover, multivariate statistical techniques, such as principal component analysis (PCA) and cluster analysis, may be employed to explore patterns and relationships within the data and identify potential correlations between experimental factors and treatment outcomes. It might be challenging to identify underlying patterns and structures in the data using only univariate analysis. These tactics may be useful.

To determine how significant the correlations and effects that have been found are, hypothesis testing is done. To confirm that the treatment techniques are successful in lowering pollutants in wastewater from textile and dye production, hypotheses are developed based on the study goals and put to the test utilizing fitting statistical tests. To further evaluate the data' robustness and investigate how treatment outcomes are affected by changes in experimental conditions, sensitivity analysis is carried out. This involves systematically varying the values of key parameters and observing the impact on treatment efficiency to identify critical factors that influence treatment performance.

The results of the statistical analysis are interpreted in the context of the research objectives and used to draw conclusions regarding the effectiveness of utilizing textile and dye wastewater for reducing contaminants. There is a discussion of the results' implications and suggestions for more study or useful uses in the wastewater treatment industry. All things considered, the statistical analysis stage offers insightful information about how well treatment approaches work and aids in directing decision-making when developing and refining treatment procedures for the textile and dye industries. By systematically analysing and interpreting the data, this phase enhances our understanding of treatment efficiency and contributes to the development of sustainable solutions for wastewater management. Descriptive statistics serve as the foundational framework for summarizing and visualizing key parameters of effluent quality and composition. The variability, dispersion, and central tendency of effluent properties are revealed by metrics like variance, mean, median, mode, standard deviation, and so on. Histograms, box plots, and scatter plots provide graphical representations of the distribution and spread of data, enabling intuitive interpretation and comparison across different effluent sources and treatment technologies.

The descriptive statistics facilitate the identification of outliers, anomalies, and data inconsistencies that may require further investigation. By examining summary statistics and graphical displays, we discern patterns and trends within the data, thereby guiding the formulation of hypotheses and research questions for subsequent inferential analysis. Descriptive statistics also play a crucial role in communicating research findings to diverse audiences, conveying complex information in a clear, concise, and accessible manner.

Inferential statistics constitute the analytical backbone of hypothesis testing, parameter estimation, and predictive modelling within the context of effluent treatment research. By leveraging probability theory and statistical inference techniques, we extrapolate from sample data to make inferences about population parameters and relationships. Correlation analysis assesses the strength and direction of relationships between continuous variables, facilitating the identification of predictive factors and potential synergies among treatment parameters.

By examining the underlying structure of multivariate datasets, we might uncover latent variables, clusters, and patterns that would not be seen through univariate analysis alone. PCA, in particular, enables us to identify dominant patterns of variation within the data and extract principal components that capture the most significant sources of variability. Cluster analysis allows for the identification of homogeneous subsets for focused investigation and action by classifying effluent sources into discrete groups or clusters according to shared features. Discriminant analysis, on the other hand, makes it possible to forecast group membership based on a collection of predictor factors, allowing for differentiation between various treatment results or effluent sources. These multivariate techniques enhance the richness and depth of analysis, enabling us to uncover complex relationships and interactions within the data.

Moreover, time-series analysis offers valuable insights into temporal trends, seasonality, and long-term patterns in effluent quality and treatment performance. By analyzing sequential observations collected over time, we identify recurring patterns, anomalies, and trends that may inform operational decision-making and resource allocation. Time-series models such as auto regressive integrated moving average (ARIMA) and seasonal decomposition of time series (STL) provide robust frameworks for forecasting future trends and variability in effluent characteristics.

A versatile framework for revising beliefs and coming to judgments in the face of uncertainty is provided by Bayesian statistics, which is another potent method of statistical analysis. Bayesian approaches allow us to evaluate risk, quantify uncertainty, and maximize decision-making in wastewater treatment processes by combining past knowledge, expert opinion, and data-driven evidence. To model complex systems and infer causal linkages, some of the main Bayesian approaches used are Bayesian hierarchical models, Bayesian networks, and Markov chain Monte Carlo (MCMC) simulations.

Furthermore, sensitivity analysis offers insights into the robustness and stability of statistical models by assessing the impact of variations in input parameters and assumptions on model outputs. By systematically varying model inputs and observing corresponding changes in outcomes, we identify critical parameters, sources of uncertainty, and areas for model refinement. By enhancing the validity and reliability of statistical data, sensitivity analysis enables us to assess the significance of the study's recommendations and conclusions.

The statistical analysis for this thesis represents a sophisticated and multifaceted approach to unravelling the complexities of effluent treatment in the textile/dye industry using hybrid wastewater technologies. Through descriptive and inferential techniques, multivariate analysis, time-series modelling, Bayesian statistics, and sensitivity analysis, we extract actionable insights, inform decision-making, and drive innovation in effluent management practices. We use statistical approaches to improve our knowledge of wastewater treatment processes and help create long-term solutions for environmental stewardship and public health.

Characteristic Statistics

Descriptive statistics are used to summarize and visualize the key parameters of effluent quality, such as mean, median, standard deviation, and variance. Graphical representations such as histograms, box plots, and scatter plots are employed to illustrate the distribution and variability of data. Descriptive statistics form the bedrock of data analysis in this thesis, offering a comprehensive framework for summarizing, visualizing, and interpreting key parameters of effluent quality and composition in the textile/dye industry. Descriptive statistics help us find patterns, trends, and distributions in the data using a variety of summary metrics, graphical representations, and exploratory approaches. This gives us important insights about the properties and behaviour of effluent streams.

We can see the frequency and density of observations across various value ranges using graphical representations of the data distribution provided by histograms and frequency distributions. Histograms provide information about the distribution's skewness, symmetry, and form by classifying data into intervals or bins and charting the frequency of observations inside each bin. A positive or negative skew indicates a tail towards higher values, whereas a negative skew indicates a tail towards lower values. A measure of the distribution's asymmetry is called skewness. Kurtosis is a statistic that measures how flat a distribution is. A distribution is considered more flat if its kurtosis is lower than its peak. The box plot, sometimes referred to as the box-and-whisker plot, is another graphical tool for examining the distribution of data and identifying any outliers or extreme values. Box plots give a clear description of central tendency, dispersion, and variability by displaying the data's median, quartiles, and range. The whiskers reach the greatest and lowest values within 1.5 times the interquartile range (IQR), shown by the box, and span the centre 50% of the data. Outliers are defined as values outside of this range and are displayed as single points outside of the whiskers. By identifying and analyzing outliers, we may be able to uncover and investigate any irregularities in the data set.

Scatter plots are a useful tool for visualizing the relationship between two continuous variables and may help identify trends, patterns, and correlations in the data. Scatter plots show the direction and degree of a link between two variables by plotting one on the y-axis and another on the x-axis. Positive correlations depict a direct relationship in which higher values of one variable correlate with higher values of the other, whereas negative correlations show an inverse relationship in which higher values of one variable correspond to lower values of the other. Correlation coefficients are measures of correlation strength ranging from -1 to +1. In stronger connections, -1 or +1 is closer. Shape measures like as kurtosis and skewness can also help to understand the distribution's tail behaviour, and symmetry. Skewness measures the degree of asymmetry in the distribution, with positive skew suggesting a tail toward higher values and negative skew showing a tail towards lower values. Higher kurtosis suggests a peaked distribution, whereas lower kurtosis indicates a flatter distribution. Kurtosis is a statistical term that indicates how peaked or flat a distribution is. These shape metrics give insights into the data's core structure, as well as guidance for future analysis and interpretation.

Summaries Statistics like cumulative frequencies, percentiles, and quartiles provide a succinct overview of the data distribution in addition to visual assistance. The data set is divided into four equal halves by intervals, where each quartile corresponds to 25% of the observations. The value below which 25% of the data fall is displayed by the first quartile (Q1), while the value below which 75% of the observations fall is displayed by the third quartile (Q3). The difference between Q3 and Q1 is the interquartile range (IQR), which is less prone to outliers than the range. To further quantify the dispersion or variability of data points around the central tendency, spread metrics such as variance, standard deviation, and range are required. The range, a straightforward yet helpful measure of dispersion, displays the difference between the dataset's greatest and lowest values. The average departure of data points from the mean is represented by the standard deviation, which offers a measure of dispersion that explains the distribution of values surrounding the central tendency. The variance provides a more comprehensible measure of variability by representing the squared standard deviation.

The average or typical value of the dataset may be understood with the help of central tendency measures like the mean, median, and mode. A measure of central tendency that is susceptible to extreme values or outliers is the mean, which is the arithmetic average of the observations. A reliable indicator of central tendency that is less impacted by outliers is the median, which is the dataset's middle value when sorted in ascending order. The most common value in the collection is represented by the mode, which provides information about the main traits of the effluent samples. Furthermore, the distribution's symmetry and tail behaviour may be understood by shape metrics like kurtosis and skewness. A positive or negative skew indicates a tail towards higher values, whereas a negative skew indicates a tail towards lower values. A measure of the distribution's asymmetry is called skewness. Kurtosis is a statistic that measures how flat a distribution is. A distribution is considered more flat if its kurtosis is lower than its peak. These shape metrics help guide further analyses and interpretations by providing insightful information about the underlying structure of the data.

A concise picture of the distribution of the data is provided by summary statistics like cumulative frequencies, percentiles, and quartiles. With each quartile holding 25% of the observations, quartiles divided the dataset into four equal halves. When a value is below which 25% of the observations fall, it is referred to as the 25th percentile (Q1), and when it is below which 75% of the observations are falling, it is referred to as the 75th percentile (Q3). Greater resistance to outliers than the range is exhibited by the interquartile range (IQR), which may be expressed as the difference between Q3 and Q1.

The cumulative frequency distributions graphically display the data distribution and provide information about the cumulative percentage of observations that fall below a specified threshold. We may see the cumulative distribution of the data and identify interest thresholds or cut off points by mapping cumulative frequencies against corresponding variable values using cumulative frequency distributions. Insights into the descriptive analysis phase of the methodology are provided by these summary statistics and graphical displays. This is a critical first step towards understanding the traits and trends found in the data gathered from studies intended to use textile and dye wastewater to diminish contaminants. This phase involves summarizing and describing the data using various statistical measures to gain insights into the central tendency, variability, and distribution of key parameters such as COD, BOD, TDS, and colour. Descriptive analysis's main goal is to present a thorough summary of the information gathered from trials. To characterize the central tendency and variability of the data, this involves computing metrics like mean, median, mode, and standard deviation. With the use of these metrics, researchers can better understand the usual values and distribution of important parameters in various experimental situations. In addition, to display the distribution and correlations between variables, descriptive analysis entails creating graphical representations of the data, such as scatter plots, box plots, and histograms. The data is better understood thanks to these visuals, which also make it easier to spot any potential patterns or trends.

The descriptive analysis includes examining the distribution of key parameters to assess whether the data follow a normal distribution or exhibit skewness or kurtosis. Understanding the distribution of the data is essential for selecting appropriate statistical techniques and making valid interpretations of the results. Additionally, descriptive analysis involves identifying and analysing any outliers or anomalies present in the data. Outliers are data points that fall significantly outside the range of the rest of the data and may indicate errors or unusual observations. By identifying outliers, researchers can assess their impact on the analysis and determine whether they should be excluded or investigated further. The descriptive analysis includes comparing summary statistics and graphical representations of the data across different experimental conditions to identify any differences or trends. This helps researchers assess the effectiveness of treatment methods and determine which experimental factors have the greatest impact on treatment outcomes. To evaluate the degree and direction of links between variables, descriptive analysis also computes measures of association, such as correlation coefficients. This allows researchers to determine whether there are any noteworthy associations between therapy results and experimental circumstances, as well as to understand potential mutual influences.

One aspect of the descriptive analysis is looking at how the data vary both within and between the various experimental groups. To quantify the degree of variability and evaluate the consistency of outcomes under various settings, this entails computing measurements like variance and standard deviation. The descriptive analysis involves assessing the robustness of the results by conducting sensitivity analysis and examining the stability of the findings under different scenarios or assumptions. This aids researchers in assessing the quality and dependability of the results reached through data analysis. Descriptive analysis also entails evaluating the data and making inferences from the results. To offer a thorough knowledge of the data and its implications for the study objectives, this entails synthesizing the measures of association, graphical representations, and descriptive statistics. The phase of descriptive analysis offers significant insights into the traits and trends found in the experiment data. By summarizing and describing the data using various statistical measures and graphical representations, this phase enhances our understanding of treatment efficiency and informs decision-making in designing and optimizing treatment processes for the textile and dye industry.

3.10 Statistical inference

In order to test theories and provide predictions based on the gathered data, inferential statistics are employed. Techniques such as analysis of variance (ANOVA), regression analysis, and correlation analysis are employed to assess the relationships between different variables and determine the factors influencing effluent treatment efficiency. Inferential statistics constitutes a crucial component of the analytical framework employed in this thesis, providing a robust methodology for testing hypotheses, estimating parameters, and making predictions based on sample data. We can reach relevant conclusions and well-informed judgments on effluent treatment procedures and technologies in the textile and dye business thanks to inferential statistics, which is based on probability theory and statistical inference.

In order to compare means among various groups or treatments, analysis of variance (ANOVA) is a fundamental inferential approach that helps us determine the significance of observed differences and changes in the data. By partitioning the total variation in the data into components attributable to different sources, ANOVA enables us to determine whether observed differences are statistically significant or merely due to random variation. Moreover, ANOVA facilitates post-hoc analysis, including pairwise comparisons and Tukey's Honestly Significant Difference (HSD) tests, to identify specific group differences and elucidate the factors driving variation in effluent characteristics. Regression analysis represents another powerful inferential technique for modelling the relationship between independent and dependent variables, enabling us to quantify the impact of predictor variables on effluent treatment efficiency and performance. Linear regression, logistic regression, and multiple regressions are among the key regression models employed to explore linear and non-linear relationships, predict outcomes, and identify influential factors.

Through regression analysis, we gain insights into the underlying mechanisms and operational parameters governing effluent treatment processes, thereby informing decision-making and optimization strategies.

Correlation analysis offers a complementary approach to regression analysis by assessing the strength and direction of relationships between continuous variables, enabling us to identify patterns, associations, and dependencies within the data. Pearson correlation coefficient, Spearman rank correlation coefficient, and Kendall tau rank correlation coefficient are among the commonly used correlation measures that quantify the degree of linear and non-linear association between variables. Correlation analysis facilitates the identification of predictive factors and potential synergies among treatment parameters, guiding the development of integrated treatment strategies and process optimization techniques.

The hypothesis testing serves as a fundamental inferential technique for evaluating the significance of observed differences and relationships within the data, enabling us to draw valid conclusions about population parameters based on sample data. Resampling methods, including bootstrap resampling and permutation tests, offer robust alternatives to traditional parametric hypothesis tests, particularly when data do not meet the assumptions of normality or homogeneity of variance. By generating multiple samples from the observed data through resampling with replacement, bootstrap resampling enables us to estimate sampling distributions and derive confidence intervals for population parameters without relying on distributional assumptions. Permutation tests, on the other hand, permute the labels of observations to generate null distributions under the assumption of exchangeability, enabling us to assess the statistical significance of observed differences and relationships based on the empirical distribution of test statistics.

Bayesian statistics represents a powerful inferential framework for updating beliefs and making decisions under uncertainty, offering a flexible and intuitive approach to parameter estimation, hypothesis testing, and model inference. By incorporating prior knowledge, expert judgment, and data-driven evidence, Bayesian methods enable us to quantify uncertainty, assess risk, and optimize decision-making in effluent treatment processes. Bayesian hierarchical models, Bayesian networks, and Markov chain Monte Carlo (MCMC) simulations are among the key Bayesian techniques employed to model complex systems and infer causal relationships.

The survival analysis offers a specialized inferential technique for analysing time-to-event data, enabling us to assess the impact of predictor variables on the probability and timing of effluent treatment outcomes such as system failure, breakthrough, or compliance violation. By modelling hazard functions and survival curves, survival analysis enables us to estimate survival probabilities, identify risk factors, and quantify the effect of interventions on event rates. Survival analysis offers valuable insights into the reliability, durability, and performance of effluent treatment systems over time, informing maintenance schedules, design considerations, and risk management strategies.

Machine learning techniques, including decision trees, random forests, support vector machines, and neural networks, offer flexible and adaptive inferential approaches for modelling complex relationships, capturing non-linear patterns, and making predictions based on high-dimensional data. By leveraging algorithms that learn from data, machine learning enables us to uncover hidden patterns, detect anomalies, and extract actionable insights from large and diverse datasets. Machine learning techniques complement traditional inferential methods by offering scalable, automated, and data-driven approaches to effluent treatment analysis and optimization.

The meta-analysis offers a systematic approach to synthesizing findings from multiple studies and pooling effect sizes across different datasets, enabling us to derive robust conclusions and generalizable insights from heterogeneous sources of evidence. By applying statistical methods enables us to quantify the overall effect of effluent treatment interventions, assess heterogeneity across studies, and explore sources of variation in treatment outcomes. In wastewater treatment research and practice, meta-analysis provides insightful information about the body of cumulative data, highlights knowledge gaps, and supports evidence-based decision-making.

A crucial stage in the methodology's inferential statistics phase is generating conclusions and inferences about the population from the data gathered from wastewater treatment trials utilizing cloth and dye. Inferential statistics enable researchers to test hypotheses on the relationships between variables and generalize findings from a sample to the wider population, in contrast to descriptive statistics, which offer summaries of the data. Determining the importance of observable effects and relationships in the data is one of the main goals of inferential statistics. To ascertain if the variations between experimental groups are statistically significant or just the result of chance, hypothesis testing must be done. Additionally, inferential statistics entails assessing the uncertainty surrounding estimates of population parameters derived from sample data. This entails constructing confidence intervals for quantities like means and proportions, which provide a range of possible values within which the actual population parameter is likely to fall.

To assure the validity and reliability of statistical tests and procedures, inferential statistics also entails evaluating the underlying assumptions. This entails making sure that no assumptions about normality, homogeneity of variance, or independence of observations are broken, and if required, using different approaches or making the necessary corrections. Evaluation of the statistical tests' ability to identify significant correlations and effects in the data is another aspect of inferential statistics. In order to guarantee that the study has enough sensitivity to identify real effects, power analysis assists researchers in determining the sample size required to reach a desired degree of statistical power.

The inferential statistics involves interpreting the results of hypothesis tests and drawing conclusions based on the findings. This includes determining whether the results support or reject the null hypothesis, assessing the magnitude and direction of effects, and considering the practical significance of the findings in the context of the research objectives. Moreover, inferential statistics involves assessing the robustness of the results by conducting sensitivity analysis and examining the stability of the findings under different assumptions or conditions. This helps researchers assess the quality and dependability of the results derived from the data analysis.

Furthermore, inferential statistics includes assessing the generalizability of the findings to broader populations and contexts. This involves considering the limitations of the study, such as sample size, sampling bias, and external validity, and discussing the implications of the findings for future research and practice. The inferential statistics involves communicating the results of the analysis clearly and accurately to stakeholders and decision-makers. This includes preparing summary reports, presentations, and visualizations that effectively communicate the key findings and their implications for informing decisions and guiding future research efforts. The inferential statistics phase of the methodology is a critical component of the research process, providing valuable insights into the significance of observed effects and relationships in the data collected from experiments involving textile and dye wastewater treatment. By applying statistical techniques to analyse and interpret the data, this phase enhances our understanding of treatment efficiency and supports evidence-based decision-making in designing and optimizing treatment processes for the textile and dye industry.

3.11 Hybrid Wastewater Technologies

The hybrid wastewater treatment technologies considered in this study combine multiple treatment processes to achieve higher removal efficiencies and minimize environmental impact. These technologies may include physical, chemical, and biological treatment methods, such as coagulation-flocculation, membrane filtration, activated sludge process, and advanced oxidation processes (AOPs). The selection and optimization of these technologies are based on the specific characteristics of the effluent and the desired treatment objectives. By integrating many treatment methods and technologies to produce improved pollution and contaminant removal, hybrid wastewater solutions offer an inventive and comprehensive approach to effluent treatment in the textile and dye industries. Grounded in principles of sustainability, efficiency, and cost-effectiveness, hybrid wastewater technologies offer a flexible and adaptive framework for addressing the complex challenges associated with effluent management in the textile/dye sector.

The fundamental concept of hybrid wastewater solutions is process synergy, which uses the complementary advantages of many treatment methods to provide higher effluent quality and compliance. Hybrid systems successfully remove a wide range of pollutants, including suspended particles, organic compounds, heavy metals, and pathogens, therefore reducing their influence on the environment and safeguarding public health. This is achieved by integrating physical, chemical, and biological treatment methods. Physical treatment processes such as screening, sedimentation, and filtration serve as the initial stage of effluent treatment in hybrid wastewater technologies, facilitating the removal of large particles, debris, and solids from the wastewater stream. Screening mechanisms, such as bar screens and drum screens, prevent coarse materials from entering downstream treatment units, thereby protecting pumps, pipes, and equipment from damage and fouling. Sedimentation tanks and clarifiers facilitate the settling of suspended solids through gravitational forces, enabling the separation of solids from liquid phase and reducing the overall pollutant load.

Chemical treatment processes, including coagulation, flocculation, and chemical oxidation, offer targeted approaches to pollutant removal and degradation within hybrid wastewater treatment systems. Coagulants such as alum, ferric chloride, and poly-aluminium chloride (PAC) are added to the wastewater stream to destabilize colloidal particles and facilitate their aggregation with larger flocs and removed. Flocculants, such as polymers and organic polymers, further enhance particle aggregation and settling, improving the efficiency of solid-liquid separation processes. By utilizing the metabolic activity of microorganisms to break down organic contaminants and nutrients found in the wastewater stream, biological treatment processes—such as aerobic and anaerobic treatment units—play a crucial part in hybrid wastewater technologies. Aerobic treatment processes, such as activated sludge systems, sequencing batch reactors (SBRs), and aerobic bio filters, utilize oxygen-dependent microbial consortia to oxidize organic matter, ammonia, and other biodegradable compounds, thereby reducing biochemical oxygen demand (BOD) and nitrogen levels in the effluent. Anaerobic treatment processes, such as anaerobic digesters and anaerobic baffled reactors (ABRs), operate in oxygendeprived conditions to facilitate the conversion of organic matter into biogas, methane, and carbon dioxide, thereby reducing energy consumption and greenhouse gas emissions.

Moreover, advanced treatment technologies such as membrane bioreactors (MBRs), reverse osmosis (RO), and ultraviolet (UV) disinfection offer additional treatment options within hybrid wastewater systems, enabling the removal of residual contaminants and pathogens to meet stringent effluent quality standards. MBRs integrate biological treatment with membrane filtration, providing high-quality effluent suitable for reuse or discharge. RO systems employ semi-permeable membranes to selectively remove dissolved ions, salts, and contaminants from the wastewater stream, producing purified water for reuse or disposal. UV disinfection systems utilize ultraviolet light to inactivate pathogens and microorganisms present in the effluent, ensuring compliance with microbiological standards and safeguarding public health.

Furthermore, innovative technologies such as electrocoagulation, electrochemical oxidation, and photo catalysis offer promising avenues for enhancing pollutant removal and treatment efficiency within hybrid wastewater systems. Electrical currents are used in electrocoagulation systems to cause suspended solids and colloidal particles to coagulate and flocculate, allowing for their removal by filtering or sedimentation. Electrochemical oxidation systems employ electrochemical reactions to oxidize organic pollutants and contaminants, generating oxidizing agents such as hydroxyl radicals and chlorine species that degrade organic compounds and disinfect the wastewater stream. Photo catalysis systems harness the energy of ultraviolet or visible light to activate semiconductor photo catalysts such as titanium dioxide (TiO2) or zinc oxide (ZnO), initiating oxidation and degradation reactions that transform organic pollutants into harmless by products.

With adaptable systems that can adapt to changing operating conditions and resource availability, hybrid wastewater technologies may be adjusted to individual effluent characteristics, treatment objectives, and site restrictions. Modular and scalable design features enable the flexibility to expand, upgrade, or retrofit existing treatment systems to meet evolving regulatory requirements and industry standards. Moreover, decentralized treatment approaches such as constructed wetlands, decentralized MBRs, and decentralized greywater recycling systems offer decentralized treatment options that reduce reliance on centralized infrastructure, minimize energy consumption, and enhance resilience to disruptions.

The life cycle assessment (LCA) and cost-benefit analysis (CBA) serve as valuable tools for evaluating the environmental, economic, and social impacts of hybrid wastewater technologies over their entire life cycle, from construction and operation to decommissioning and disposal. By quantifying resource inputs, emissions, and impacts associated with different treatment alternatives, LCA enables stakeholders to make informed decisions and prioritize sustainable solutions that minimize environmental footprint and maximize resource efficiency. CBA, on the other hand, assesses the financial The Hybrid Wastewater Technologies phase of the methodology represents an innovative approach to wastewater treatment, combining multiple treatment methods and technologies to enhance treatment efficiency and effectiveness. This phase aims to explore the potential of hybrid systems for treating textile and dye wastewater, which often contains complex mixtures of pollutants that require specialized treatment approaches.

Creating hybrid treatment systems that take advantage of the complementary qualities of several treatment modalities is one of the main goals of the Hybrid Wastewater Technologies phase. To effectively remove pollutants, physical, chemical, and biological processes such as adsorption, oxidation, membrane filtration, and biological degradation may be combined. The Hybrid Wastewater Technologies phase involves optimizing the design and operation of hybrid treatment systems to maximize treatment efficiency and minimize environmental impact. This includes evaluating factors such as reactor configuration, flow rates, residence times, and treatment media to optimize pollutant removal and resource utilization.

The Hybrid Wastewater Technologies phase includes assessing the performance of hybrid treatment systems through pilot-scale or full-scale testing in real-world conditions. This involves conducting experiments using actual wastewater samples from textile and dye industries to evaluate treatment effectiveness, reliability, and scalability.

The Hybrid Wastewater Technologies phase involves monitoring and analysing key performance indicators to assess the effectiveness of hybrid treatment systems. This includes measuring pollutant concentrations, removal efficiencies, energy consumption, and operational costs to evaluate system performance and identify areas for improvement. The Hybrid Wastewater Technologies phase includes conducting life cycle assessments to evaluate the environmental impacts and sustainability of hybrid treatment systems. This involves assessing factors such as energy consumption, greenhouse gas emissions, resource utilization, and waste generation to determine the overall environmental footprint of the treatment process.

Furthermore, the Hybrid Wastewater Technologies phase involves conducting economic analyses to evaluate the cost-effectiveness and feasibility of implementing hybrid treatment systems. This includes assessing capital costs, operational costs, maintenance costs, and lifecycle costs to determine the economic viability of the treatment process. Additionally, the Hybrid Wastewater Technologies phase includes exploring novel hybrid treatment approaches and technologies that have the potential to further improve treatment efficiency and sustainability. This may involve researching emerging technologies such as advanced oxidation processes, nanomaterial-based treatments, and electrochemical treatment methods to explore their applicability in hybrid treatment systems.

In order to advance hybrid treatment technologies, industrial partners, academic institutions, and government agencies are partnered with throughout the Hybrid Wastewater Technologies phase. This collaboration allows for the pooling of resources, infrastructure, and knowledge. This may involve participating in collaborative research projects, sharing data and knowledge, and fostering partnerships to accelerate technology development and adoption. Furthermore, the Hybrid Wastewater Technologies phase includes disseminating research findings and best practices to stakeholders and decision-makers in the textile and dye industry. This includes publishing research papers, presenting at conferences, and engaging with industry associations and regulatory agencies to promote the adoption of hybrid treatment technologies and practices.

Overall, the Hybrid Wastewater Technologies phase of the methodology represents a forward-thinking approach to wastewater treatment, leveraging innovative technologies and interdisciplinary collaboration to address the complex challenges posed by textile and dye wastewater. By exploring the potential of hybrid treatment systems and advancing knowledge and understanding in this area, this phase aims to contribute to the development of sustainable solutions for wastewater management in the textile and dye industry.

3.12 Experimental Setup

A variety of hybrid wastewater treatment systems are tested in experimental settings to see how well they operate. Setups at the bench or pilot scale are used to evaluate treatment efficacy, energy consumption, and cost-effectiveness while simulating real-world settings. The experimental data obtained are analysed using statistical methods to validate the effectiveness of the proposed treatment technologies. The experimental setup for this thesis represents a meticulously designed framework aimed at investigating the performance and efficacy of hybrid wastewater technologies in treating effluents from textile/dye industries. Grounded in scientific rigor and methodological precision, the experimental setup encompasses a series of carefully orchestrated procedures and protocols to ensure the reliability, reproducibility, and validity of the experimental findings.

Central to the experimental setup is the selection and characterization of effluent samples obtained from textile/dye industries. Effluent sampling follows standardized protocols to ensure representativeness and consistency across different sources. Samples are collected at various stages of the wastewater treatment process, including influent, effluent, and intermediate stages, to capture the full spectrum of effluent characteristics and variations. Comprehensive laboratory analyses are conducted to quantify key parameters such as pH, COD, BOD, TSS, nutrient concentrations, heavy metals, and organic pollutants, providing a detailed profile of effluent composition and quality.

Figure 1 COD Removing Efficiency at Various Temperature/ Experimental Setup

Figure 1 shows the SS-321 reactor, which generated stem charcoal and C*anna-indica* leaves. A different schematic displayed the SS-321 reactor in a muffle furnace with the temperature for producing charcoal adjusted between 500^0 and 800^0C. The preceding image illustrates how biochar is produced at different temperatures. Best biochar at 500^0C. Throughout the absorption process, the charcoal and waste water are mixed using the flocculator seen in the third image. The final image displays the laboratory area that was prepared for filtration, which was done when the absorption process was complete.

Figure 2 shows how a batch reactor should be designed in order to produce charcoal in a muffle furnace. We utilised SS-321 (MOC—Material of Construction) based on design. Applying a nitrogen purging system when producing biochar.

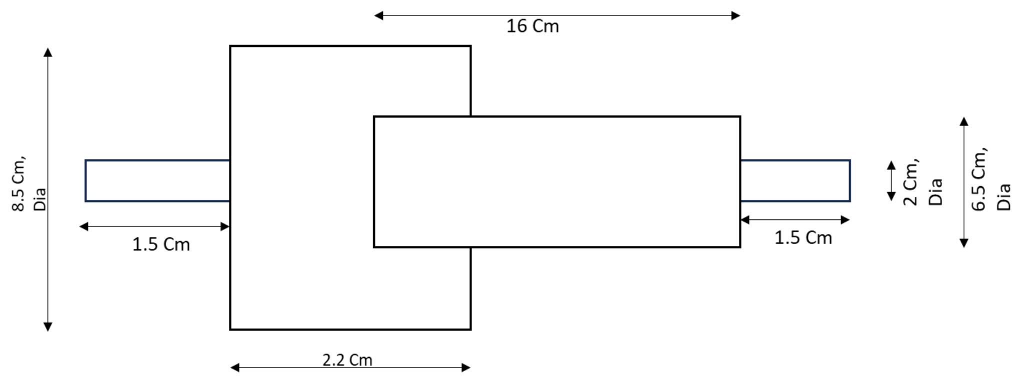


Figure 2 Design of Batch Reactor for making Biochar in Muffle furnace

Prepared hybrid wastewater treatment systems that are specifically designed to address the unique properties of the effluent samples are part of the experimental setup. Chemical, biological, physical, and sophisticated oxidation processes are just a few of the treatment methods that hybrid systems use to improve pollutant removal and treatment efficiency. Treatment units such as activated sludge reactors, membrane bioreactors, coagulation-flocculation units, adsorption columns, and electrochemical cells are assembled and operated in tandem to mimic real-world treatment scenarios and assess their performance under controlled conditions.

The experimental setup also incorporates monitoring and control systems to track and regulate key operating parameters, such as flow rate, temperature, dissolved oxygen, and chemical dosing rates. Data loggers, sensors, and automated control systems enable real-time monitoring of treatment performance and facilitate adjustments to operating conditions as needed. By maintaining consistent and optimal operating conditions, the experimental setup ensures the reproducibility and reliability of experimental results, enabling meaningful comparisons and analyses across different treatment configurations and scenarios.

In addition to performance evaluation, the experimental setup includes protocols for assessing the environmental impact and sustainability of hybrid wastewater technologies. Life cycle assessment (LCA) methodologies are employed to quantify the environmental footprint of treatment processes, including energy consumption, greenhouse gas emissions, and resource utilization. By systematically evaluating the environmental impacts of treatment alternatives, the experimental setup provides insights into the trade-offs and implications of adopting different technologies and strategies for effluent treatment. The experimental setup incorporates protocols for evaluating the economic feasibility and cost-effectiveness of hybrid wastewater technologies. Examining capital costs, operating expenses, maintenance needs, and prospective income streams, cost-benefit analysis, life cycle costing, and sensitivity analysis approaches are used to evaluate the financial viability and affordability of treatment choices. By quantifying the economic implications of treatment decisions, the experimental setup enables stakeholders to make informed choices and allocate resources effectively to achieve sustainable effluent management outcomes.

The experimental setup includes provisions for assessing the performance of hybrid wastewater technologies under variable operating conditions and effluent characteristics. Batch experiments, continuous flow tests, and dynamic simulations are conducted to evaluate treatment performance under fluctuating influent quality, hydraulic loading rates, and seasonal variations. By subjecting treatment systems to realistic operating scenarios, the experimental setup provides insights into their robustness, resilience, and adaptability to changing environmental conditions. Additionally, the experimental setup incorporates protocols for evaluating the removal efficiency of specific pollutants of concern, such as dyes, heavy metals, and organic contaminants, using advanced analytical techniques. Spectrophotometry, chromatography, mass spectrometry, and atomic absorption spectroscopy are employed to quantify pollutant concentrations before and after treatment, enabling the calculation of removal efficiencies and mass balances. By assessing the efficacy of treatment technologies in removing target pollutants, the experimental setup provides valuable insights into their suitability for addressing the unique challenges posed by textile/dye effluents.

The experimental setup includes provisions for assessing the fate and transformation of pollutants during treatment processes, including the formation of intermediates, by products, and degradation pathways. The experimental setup for this phase of the methodology is designed to facilitate the comprehensive evaluation of treatment methods and technologies for utilizing textile and dye wastewater. It involves the development and implementation of experimental systems and procedures that enable researchers to conduct adsorption analysis, hydrodynamic cavitation experiments, and statistical analysis effectively and efficiently. To begin with, the experimental setup for adsorption analysis involves preparing biochar samples and wastewater samples obtained from textile and dye industries. The adsorption ability of biochar for lowering COD, BOD, TDS, and colour is next evaluated by putting these samples through controlled adsorption tests. The setup includes equipment such as reactors, stirring devices, and analytical instruments for monitoring pollutant concentrations before and after treatment.

Moreover, the experimental setup includes selecting the best temperature for biochar adsorption and determining the optimal combination of biochar for maximum pollutant removal. This involves conducting experiments at different temperatures and with various combinations of biochar to identify the conditions that yield the highest adsorption efficiency. The setup may also include temperature-controlled chambers or heating devices to maintain precise temperature conditions during experiments. The experimental setup for hydrodynamic cavitation experiments involves designing and constructing a model based on fluid mechanics principles. This may include using materials such as polyvinyl chloride (PVC) pipes and orifice plates to create the cavitation chamber and control the flow of wastewater. The setup also includes equipment for generating hydrodynamic cavitation, such as pumps, valves, and pressure gauges.

The experimental setup for hydrodynamic cavitation experiments includes designing and implementing different patterns and configurations for the orifice plates to optimize cavitation efficiency. This may involve inserting circles of varying diameters or introducing star patterns with different lengths of star edges to create turbulence and enhance cavitation effects. The setup also includes devices for measuring parameters such as RPM, pH, concentration, dosage, and temperature during experiments. Moreover, the experimental setup includes integrating software tools such as Statistical IBN-SPSS and Minitab-19 for statistical analysis of experimental data. This involves importing data from experiments into the software and performing various statistical tests and analyses to evaluate the significance of experimental factors and treatment outcomes. The setup may include computers, data analysis software, and data storage systems for managing and processing experimental data efficiently.

The experimental setup for statistical analysis involves ensuring the accuracy and reliability of data collection procedures and instruments. This includes calibrating equipment, validating measurement techniques, and implementing quality control measures to minimize errors and ensure consistency in data collection. The setup may also include protocols for data management, including data entry, verification, and validation procedures. Additionally, the experimental setup includes documenting and documenting detailed protocols and procedures for conducting experiments and analysing data. This includes creating standard operating procedures (SOPs) for each experimental step, documenting equipment specifications and settings, and recording experimental conditions and observations systematically. The setup may also include training researchers and staff on proper experimental techniques and protocols to ensure consistency and reproducibility in experimental procedures.

The experimental setup involves establishing protocols for safety and environmental protection during experiments. This includes following guidelines and regulations for handling hazardous materials and waste, implementing safety protocols for operating equipment and handling chemicals, and ensuring proper disposal of experimental waste. The setup may also include procedures for emergency response and contingency planning to address unforeseen events or accidents during experiments. Finally, the experimental setup includes conducting pilot-scale or full-scale testing of treatment methods and technologies to evaluate their feasibility and scalability. This involves designing and implementing experimental systems that replicate real-world conditions and assessing treatment performance under practical scenarios. To get the facilities, resources, and know-how needed to carry out large-scale experiments, the setup may involve working with government agencies, research institutions, and business partners.

The measurement of color and Total Dissolved Solids (TDS) in wastewater was conducted using well-established analytical techniques to ensure accuracy and reliability. These parameters were crucial for assessing the characteristics of effluent samples and evaluating the effectiveness of the treatment processes employed in this study.

The color measurement of wastewater was performed using spectrophotometric analysis, a widely recognized method for quantifying color intensity in liquid samples. The process began with the preparation of wastewater samples by filtering out suspended solids to prevent interference with the measurement. The spectrophotometer was then calibrated using reference standard, typically distilled water or a standard calibration solution, to establish a baseline absorbance. The wavelength was set between 400–700 nm, covering the visible light spectrum, which is relevant for detecting various dye compounds present in textile and dye industry effluents. The prepared sample was placed in a cuvette, and its absorbance was measured at the selected wavelength. The absorbance values were recorded and compared against calibration curves to determine the color intensity, which provided insights into the effectiveness of different treatment processes in reducing color pollution.

For the measurement of TDS, a gravimetric analysis approach was employed to quantify the dissolved solids present in the wastewater. Initially, the wastewater samples were carefully filtered through pre-weighed evaporating dishes to remove undissolved particulates. The filtered samples were then heated in an oven or a muffle furnace at a controlled temperature until complete evaporation of the liquid phase was achieved. The residue left behind was weighed, and the difference in mass before and after evaporation was used to calculate the TDS concentration, typically expressed in milligrams per liter (mg/L). This method provided an accurate measure of the total dissolved content in the wastewater and helped in assessing the effectiveness of the applied treatment technologies.

Both spectrophotometric and gravimetric methods ensured reliable and reproducible measurements of color and TDS, which were crucial parameters in evaluating the performance of the hybrid wastewater treatment technologies implemented in this research. These analyses allowed for a comprehensive assessment of how well different treatment methods reduced color intensity and dissolved solids, aiding in the development of an optimized wastewater treatment approach.

3.13 Ethical Considerations

Ethical considerations such as environmental sustainability, social responsibility, and regulatory compliance are integral to the research methodology. Efforts are made to minimize environmental impact and ensure the safe handling and disposal of effluent samples. Informed consent is obtained from participating industries, and ethical guidelines are followed in the conduct of research activities. Ethical considerations form a cornerstone of the research process in this thesis, guiding the design, implementation, and dissemination of scientific investigations into effluent treatment technologies in the textile/dye industry. Grounded in principles of integrity, respect, and accountability, ethical considerations ensure the responsible conduct of research and safeguard the rights, welfare, and dignity of all stakeholders involved. One of the primary ethical considerations in this thesis is the protection of human subjects participating in research activities. Effluent sampling, laboratory analysis, and field observations may involve interactions with industry professionals, workers, and community members, whose participation must be voluntary, informed, and consensual. Informed consent procedures are implemented to ensure that participants are fully aware of the research objectives, procedures, risks, and benefits before providing their consent to participate.

Moreover, efforts are made to minimize potential risks and maximize benefits for human subjects involved in research activities. Measures such as confidentiality, privacy, and anonymity are upheld to protect the identity and confidentiality of participants, ensuring that sensitive information is handled with care and discretion. Participants are assured that their participation is voluntary and that they have the right to withdraw from the study at any time without penalty or repercussion. Furthermore, ethical considerations extend to the responsible management and disposal of effluent samples and laboratory reagents to minimize environmental impact and ensure compliance with regulatory requirements. Effluent samples are handled and stored in accordance with standard operating procedures to prevent contamination and preserve sample integrity. The proper and safe disposal of waste materials and hazardous substances is ensured by adhering to specified guidelines for waste management and environmental protection.

The ethical considerations encompass the equitable distribution of benefits and burdens associated with research activities. Efforts are made to ensure that research outcomes and knowledge generated from the study are accessible, inclusive, and beneficial to all stakeholders, including industry partners, regulatory agencies, and affected communities. Transparency, accountability, and fairness are upheld in the dissemination of research findings, ensuring that diverse perspectives and voices are represented and heard. Moreover, ethical considerations guide the reporting and publication of research findings, promoting honesty, accuracy, and integrity in scientific communication. Researchers adhere to principles of academic integrity and intellectual property rights, giving appropriate credit and acknowledgment to sources of data, funding, and support. Findings are reported objectively and without bias, allowing readers to assess the validity and reliability of the research and draw their own conclusions.

The ethical considerations extend to the responsible use of animals, if applicable, in experimental studies conducted as part of the research. Animal welfare and ethical treatment of animals are paramount, and research protocols involving animal subjects are subject to rigorous review and approval by institutional animal care and use committees (IACUCs). Measures are taken to minimize pain, distress, and suffering experienced by animals, and alternatives to animal testing are considered whenever feasible. Additionally, ethical considerations encompass the responsible conduct of research, including adherence to research protocols, ethical guidelines, and regulatory requirements. Researchers uphold principles of honesty, integrity, and professionalism in all aspects of their work, maintaining the highest standards of scientific conduct and ethical behaviour. Conflicts of interest, biases, and undue influences are disclosed and managed transparently to uphold the credibility and trustworthiness of the research.

Moreover, ethical considerations include considerations for social justice, equity, and inclusivity in research practices and outcomes. Efforts are made to engage with diverse stakeholders, including marginalized communities, indigenous groups, and vulnerable populations, to ensure that their perspectives and interests are represented and addressed in the research process. Research outcomes are evaluated for their potential impact on social equity, environmental justice, and community well-being, with a commitment to promoting fairness, inclusivity, and sustainability.

The ethical considerations encompass the responsible use of resources, including funding, materials, and intellectual property, to maximize the societal benefits of research investments. Researchers strive to optimize resource allocation, minimize waste, and maximize the efficiency and effectiveness of research activities. Open access principles are embraced to facilitate the sharing and dissemination of research findings, promoting collaboration, innovation, and knowledge exchange across disciplinary boundaries. The ethical considerations extend to the long-term sustainability and societal implications of research outcomes, with a commitment to promoting ethical stewardship of resources and responsible innovation. Researchers consider the potential unintended consequences and ethical implications of their work, including environmental impacts, social risks, and equity considerations. Efforts are made to anticipate and mitigate potential harms and maximize the positive impacts of research outcomes on society and the environment.

Moreover, ethical considerations guide the engagement and collaboration with industry partners, regulatory agencies, and other stakeholders involved in the research process. Transparent communication, mutual respect, and shared decision-making are upheld to foster trust, collaboration, and partnership in achieving common goals. Conflicts of interest are managed transparently, and mechanisms for accountability and oversight are established to ensure that research activities uphold ethical standards and promote the public interest. In summary, ethical considerations are integral to every aspect of the research process in this thesis, guiding the design, conduct, and dissemination of scientific investigations into effluent treatment technologies in the textile/dye industry. Upholding principles of integrity, respect, and accountability, ethical considerations ensure the responsible conduct of research and promote the well-being of all stakeholders involved. By adhering to ethical principles and values, researchers uphold the highest standards of scientific integrity and contribute to the advancement of knowledge and the public good.

3.14 Limitations

It is important to acknowledge the limitations of the methodology, including constraints related to data availability, sample size, and experimental constraints. These limitations may impact the generalizability of the findings and should be taken into account when interpreting the results. The exploration of limitations in this thesis is a critical aspect that ensures a comprehensive understanding of the scope, boundaries, and challenges encountered throughout the research process on effluent treatment technologies in the textile/dye industry. By transparently acknowledging limitations, researchers can provide context for interpreting findings, identifying areas for future research, and guiding the development of more robust methodologies and solutions.

One of the primary limitations of this research lies in the representativeness of the effluent samples collected from textile/dye industries. Effluent characteristics can vary widely depending on factors such as production processes, raw material inputs, and treatment technologies employed. Therefore, the generalizability of findings may be limited to the specific industries sampled, and caution should be exercised when extrapolating results to broader contexts. Furthermore, the laboratory analyses conducted to characterize effluent samples may be subject to measurement error, variability, and analytical limitations. Despite efforts to standardize procedures and calibrate equipment, variations in sample handling, equipment performance, and environmental conditions may introduce uncertainty and bias into the data. Researchers should acknowledge these limitations and interpret results within the context of measurement precision and accuracy.

The experimental setup employed to evaluate hybrid wastewater technologies may not fully replicate real-world operating conditions or effluent characteristics. Laboratory-scale experiments and bench-scale reactors may lack the complexity and dynamic behaviour of full-scale treatment systems, limiting the applicability of findings to industrial settings. Researchers should consider the scalability and transferability of results when interpreting experimental outcomes. Additionally, the duration of experimental trials and monitoring periods may be limited by practical constraints such as time, resources, and logistical considerations. Short-term experiments may not capture long-term trends, seasonal variations, or emergent behaviours in effluent treatment processes. Researchers should acknowledge the temporal limitations of their study and consider the implications for extrapolating findings over extended timeframes.

A number of criteria, including cost, availability, and technological preparedness, may play a role in the selection and application of hybrid wastewater systems. Certain technologies may be more readily accessible or affordable than others, leading to biases in technology selection and implementation. Researchers should consider the potential impact of technology choice on study outcomes and interpretations.

The complexity of effluent treatment processes and interactions among treatment units may pose challenges for isolating the effects of individual technologies on treatment performance. Synergistic effects, interference, and non-linear interactions between treatment units may confound experimental results and make it difficult to attribute observed changes solely to a specific technology. Researchers should employ robust experimental designs and statistical techniques to mitigate these challenges. Additionally, the environmental conditions and regulatory frameworks governing effluent discharge may vary across geographic regions, jurisdictions, and industrial sectors. Differences in environmental regulations, discharge limits, and enforcement mechanisms may influence the feasibility and effectiveness of effluent treatment technologies. Researchers should consider the regulatory context and potential implications for the scalability and adoption of treatment solutions.

The socio-economic context and stakeholder dynamics surrounding effluent treatment in the textile/dye industry may present additional challenges and limitations. Conflicting interests, power dynamics, and institutional barriers may hinder collaboration, data sharing, and knowledge exchange among stakeholders.

Researchers should navigate these complexities with sensitivity and transparency to ensure the integrity and relevance of their research. The interdisciplinary nature of effluent treatment research requires collaboration and expertise from diverse fields such as environmental engineering, chemistry, biology, and policy studies. However, interdisciplinary collaboration may pose challenges related to communication, integration of methodologies, and reconciling conflicting perspectives. Researchers should actively engage with interdisciplinary partners and stakeholders to leverage complementary expertise and address complex research questions.

Additionally, the financial constraints and budgetary limitations associated with research funding may restrict the scope, scale, and duration of research activities. Limited resources may impact the selection of experimental protocols, sample sizes, and data collection methods, potentially compromising the robustness and validity of research findings. Researchers should transparently acknowledge resource constraints and their potential impact on study outcomes. The availability and accessibility of data, literature, and information on effluent treatment technologies may vary across regions and languages. Language barriers, publication bias, and data availability may limit researchers' ability to access and synthesize relevant literature and empirical evidence. Researchers should employ comprehensive search strategies and consider alternative sources of information to mitigate these limitations.

The pace of technological innovation and advancements in effluent treatment may outpace the research timeline, rendering research findings outdated or incomplete by the time of publication. Rapid changes in technology, regulations, and market dynamics may necessitate ongoing updates and revisions to research findings and recommendations. Researchers should stay abreast of emerging trends and developments in effluent treatment to ensure the relevance and applicability of their research. Additionally, the ethical considerations and regulatory requirements governing research on effluent treatment technologies may impose constraints on study design, data collection, and dissemination. Compliance with ethical standards, informed consent procedures, and data privacy regulations may add complexity and administrative burden to research activities. Researchers should navigate these challenges with diligence and transparency to uphold the ethical integrity and credibility of their research.

The interdisciplinary nature of effluent treatment research requires collaboration and expertise from diverse fields such as environmental engineering, chemistry, biology, and policy studies. However, interdisciplinary collaboration may pose challenges related to communication, integration of methodologies, and reconciling conflicting perspectives. Researchers should actively engage with interdisciplinary partners and stakeholders to leverage complementary expertise and address complex research questions. Moreover, the financial constraints and budgetary limitations associated with research funding may restrict the scope, scale, and duration of research activities.

3.15 Collection and Preparation of Raw Materials

Canna indica plants were harvested from local wetlands in Punjab, India. The plants were separated into three distinct components: leaves, stalks, and roots. Each component was thoroughly washed three times with distilled water to remove soil particles and contaminants. The washed materials were then air-dried for 7 days at ambient temperature to reduce moisture content. After drying, the materials were cut into small pieces (approximately 1.5 cm) to ensure uniform pyrolysis.

3.16 Biochar Synthesis

Biochar was produced through slow pyrolysis under controlled conditions. A custom-designed stainless steel reactor (SS-321 grade) with a capacity of one litter was utilized for the pyrolysis process. For each batch, 50 grams of the prepared biomass (leaves, stalks, or roots) was loaded into the reactor. The reactor was sealed and purged with nitrogen gas to create an oxygen-free environment, which prevents combustion and ensures proper pyrolysis.

The loaded reactor was placed in a muffle furnace and heated at a controlled rate of 10°C/min until reaching the target temperature of 500°C. This temperature was maintained for 90 minutes to ensure complete pyrolysis. The temperature of 500°C was selected based on preliminary experiments, which showed optimal biochar properties at this temperature compared to lower (300°C, 400°C) and higher (600°C, 700°C) temperatures.

After the pyrolysis period, the reactor was allowed to cool to room temperature while maintaining the nitrogen atmosphere to prevent oxidation of the freshly produced biochar. The cooled biochar was removed from the reactor, ground, and sieved to obtain uniform particle sizes (90 µ, with 90% material passing through this screen) for subsequent experiments.

3.17 Biochar Characterization

The physicochemical properties of the biochar samples were characterized using multiple analytical techniques:

1. **Field Emission Scanning Electron Microscopy (FE-SEM)** was performed using a JEOL JSM-7600F microscope to analyze the surface morphology and porous structure of the biochar samples. The samples were gold-coated prior to analysis to enhance conductivity.
2. **Fourier Transform Infrared Spectroscopy (FTIR)** analysis was conducted using a thermo Scientific Nicolet iS50 spectrometer to identify the functional groups present on the biochar surface. Spectra were recorded in the range of 400-4000 cm^{-1} with a resolution of 4 cm^{-1}.
3. **Brunauer-Emmett-Teller (BET)** surface area analysis was performed using a Micromeritics ASAP 2020 analyzer. Samples were degassed at 150°C for 4 hours prior to analysis. Nitrogen adsorption-desorption isotherms were measured at 77K, and the BET specific surface area, pore volume, and pore size distribution were calculated.
4. **Elemental Analysis** was conducted using a CHNS/O analyzer (Elementar Vario MACRO Cube) to determine the carbon, hydrogen, nitrogen, and sulfur content of the biochar samples.

3.18 Surface Modification of Biochar

To enhance the adsorption capacity, the *Canna indica* leaf biochar was modified using two different chemical treatments:

1. **Potassium Hydroxide (KOH) Modification**: A 2.5N KOH solution was prepared by dissolving 70g of KOH pellets in 500 mL of distilled water. Biochar was added to the KOH solution at a ratio of 1:10 (w/v) and stirred continuously for 8 hours at 60°C. After treatment, the mixture was cooled to room temperature and filtered. The modified biochar was washed repeatedly with distilled water (500 mL per wash, 10 cycles at 6-hour intervals) until the pH of the filtrate reached approximately neutral (pH 6.5-7.5). The washed biochar was then dried in an oven at 50°C for 24 hours and stored in airtight containers for further use. This modified biochar was designated as KBC (KOH-modified biochar).
2. **Sodium Hydroxide (NaOH) Modification**: A 2N NaOH solution was prepared by dissolving 40g of NaOH pellets in 500 mL of distilled water. The modification procedure followed the same steps as the KOH treatment, with identical biochar-to-solution ratio, stirring time, temperature, washing protocol, and drying conditions. This modified biochar was designated as NaBC (NaOH-modified biochar).

3.19 Wastewater Collection and Characterization

Textile wastewater samples were collected from Payal Dyeing and printing, located in Kadodra, Surat, Gujarat, India. The samples were collected in clean polyethylene containers, transported to the laboratory under refrigerated conditions, and stored at 4°C until analysis.

Initial characterization of the wastewater was performed to establish baseline parameters:

- Chemical Oxygen Demand (COD) was measured using the closed reflux, colorimetric method (APHA Method 5220D)

- Biochemical Oxygen Demand (BOD) was determined using the 5-day BOD test (APHA Method 5210B)
- Total Dissolved Solids (TDS) were measured using the gravimetric method (APHA Method 2540C)
- Color was quantified spectrophotometrically (APHA Method 2120)
- pH was measured using a calibrated pH meter

3.20 Batch Adsorption Experiments

Batch adsorption experiments were conducted to evaluate the effectiveness of different biochar in removing pollutants from textile wastewater. Experiments were performed in 250 mL Erlenmeyer flasks containing 100 mL of wastewater. Various parameters were systematically investigated:

1. **Effect of Biochar Type**: Experiments were conducted separately with unmodified biochar from *Canna indica* leaves, stalks, and roots to determine the most effective biochar type.
2. **Effect of Adsorbent Dosage**: Biochar dosages ranging from 0.5 to 2.5 g/L (specifically 1.0, 1.5, 2.0, and 2.5 g per 100 mL) were investigated while maintaining other parameters constant.
3. **Effect of Contact Time**: The adsorption kinetics were studied by varying contact time from 0 to 24 hours (specifically at 1, 3, 6, 9, 12, 17, and 24 hours).
4. **Effect of pH**: The influence of pH on adsorption efficiency was studied by adjusting the wastewater pH from 1.5 to 14 using 0.1N HCl or 0.1N NaOH solutions.
5. **Effect of Temperature**: Experiments were conducted at different temperatures (25°C, 30°C, 35°C, 40°C, and 45°C) to evaluate the thermal effects on adsorption.

All batch experiments were performed on an orbital shaker at 100 rpm to ensure uniform mixing. After the designated contact time, samples were filtered through whatman No. 42 filter paper to separate the biochar from the treated wastewater. The filtrate was then analysed for residual COD, BOD, TDS, and color to determine the removal efficiencies.

The percentage removal of COD and color was calculated using the following equations:

% COD Reduction = $[(D_1 - D_2)/D_1] \times 100$ (b)

% Color Reduction = $[(C_1 - C_2)/C_1] \times 100$ (c)

Where:

- D_1 = Initial COD concentration (mg/L)
- D_2 = Final COD concentration (mg/L)
- C_1 = Initial color intensity (Pt-Co units)
- C_2 = Final color intensity (Pt-Co units)

3.21 Adsorption Isotherm Studies

Adsorption isotherm studies were conducted to understand the adsorption mechanisms and to determine the maximum adsorption capacity of the biochar. The equilibrium data were analysed using five isotherm models:

1. **Langmuir Isotherm**: Based on the assumption of monolayer adsorption on a homogeneous surface with a finite number of identical sites.

   The Langmuir isotherm assumes:

   - Adsorption occurs on a homogeneous surface
   - A monolayer of adsorbate forms
   - All adsorption sites have equal energy
   - No interaction between adsorbed molecules

   $q_1 = (q_0K_1C_1)/(1 + K_1C_1)$ The linear form: $C_1/q_1 = 1/(q_0K_1) + C_1/q_0$ (d)

2. **Freundlich Isotherm**: Based on multilayer adsorption on a heterogeneous surface. $q_1 = K_1C_1\text{^}(1/n)$ The linear form: $\log(q_1) = \log(K_1) + (1/n)\log(C_1)$ (e)

The Freundlich isotherm is an empirical model and assumes:

- Heterogeneous surface
- Multilayer adsorption
- Different adsorption energies at different sites

3. **Temkin Isotherm**: Considers the effects of indirect adsorbate-adsorbate interactions on the adsorption process.

The Temkin isotherm considers:

- Adsorbent–adsorbate interactions
- Heat of adsorption decreases linearly with surface coverage

This model helps explain chemical interactions between biochar surface groups

(–OH, –COOH) and pollutants.

$q_1 = (RT/b)\ln(AC_1)$ The linear form: $q_1 = (RT/b)\ln(A) + (RT/b)\ln(C_1)$ (f)

4. **Dubinin-Radushkevich Isotherm**: Used to distinguish between physical and chemical adsorption.

   Concept

   The D–R isotherm is used to:

- Determine the nature of adsorption (physical or chemical)
- Focus on micro pore filling mechanism

Suitable for highly porous biochar prepared at higher pyrolysis temperatures.

$q_1 = q_0 exp(-K\varepsilon^2)$ The linear form: $ln(q_1) = ln(q_0) - K\varepsilon^2$ (g)

5. **Redlich-Peterson Isotherm**: A hybrid isotherm that incorporates features of both Langmuir and Freundlich isotherms.

   A hybrid model combining Langmuir and Freundlich features. Useful when adsorption does not fit perfectly into either model.

$q_1 = (K_1C_1)/(1 + \alpha_1 C_1\text{^}\beta)$ The linear form: $ln(K_1C_1/q_1 - 1) = ln(\alpha_1) + \beta ln(C_1)$ (h)

Where:

- q_1 = amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g)
- q_0 = maximum adsorption capacity (mg/g)
- C_1 = equilibrium concentration of the adsorbate (mg/L)
- K_1, K_1, A, K, α_1 = constants related to adsorption capacity
- 1/n, b, β = constants related to adsorption intensity

3.22 Adsorption Kinetics Studies

Adsorption kinetics studies were performed to understand the rate of adsorption and the controlling mechanisms of the adsorption process. The experimental data were fitted to three kinetic models:

1. **Pseudo-First Order Model**:

$log(q_1 - q) = log(q_1) - (k_1/2.303)t$ (i)

2. **Pseudo-Second Order Model**:

$t/q = 1/(k_2q_1^2) + t/q_1$ (j)

3. **Intraparticle Diffusion Model**:

$q = k_1t\text{^}(1/2) + C$ (k)

Where:

- q = amount of adsorbate adsorbed at time t (mg/g)
- q_1 = amount of adsorbate adsorbed at equilibrium (mg/g)
- k_1 = pseudo-first order rate constant (min^{-1})
- k_2 = pseudo-second order rate constant (g/mg·min)
- k_1 = intra particle diffusion rate constant (mg/g·min^(1/2))
- C = constant related to the boundary layer thickness

3.23 Ozonation Experiments

Ozonation experiments were conducted to evaluate the effectiveness of ozone treatment in reducing pollutants in textile wastewater. The experiments were performed both as a standalone treatment and in combination with biochar adsorption.

An ozone generator (Model: OZ-500) with a capacity of 500 mg/h was used to produce ozone. The ozone was introduced into the wastewater through a diffuser at controlled flow rates ranging from 15 to 120 mL/min. The Ozonation time was fixed at 15 minutes for all experiments.

For the combined treatment approach, the wastewater was first subjected to biochar adsorption under optimized conditions, followed by Ozonation of the filtered effluent. The treated samples were analysed for residual COD, BOD, TDS, and color to assess the treatment efficiency.

“Ozonation reduces COD in textile wastewater through both direct and indirect oxidation mechanisms. Dissolved ozone reacts directly with unsaturated and aromatic organic compounds, leading to molecular cleavage and partial oxidation. Simultaneously, ozone decomposes in water to generate hydroxyl radicals, which non-selectively oxidize complex and refractory organic pollutants into simpler, biodegradable compounds or mineralized end products such as CO_2 and H_2O. This combined action significantly lowers the chemical oxygen demand of the wastewater.”

1. Introduction to Ozonation

Textile wastewater contains:

- Dyes (azo, reactive, disperse)
- Surfactants
- Organic auxiliaries
- High molecular weight, non-biodegradable compounds

These contribute to high Chemical Oxygen Demand (COD)**.**

Ozonation is an advanced oxidation process (AOP) where ozone acts as a strong oxidizing agent to break down these organic pollutants.

2. Modes of Ozone Action in Wastewater

Ozone reduces COD through two main reaction pathways**:**

(A) Direct Ozone Oxidation

(B) Indirect Oxidation via Hydroxyl Radicals (•OH)

3. Step-by-Step Mechanism

Step 1: Ozone Mass Transfer into Wastewater

- Ozone gas is bubbled through wastewater
- O_3 dissolves in water depending on:
  - Contact time
  - Bubble size
  - Temperature
  - pH

$$\mathbf{O_3\ (gas) \rightarrow O_3\ (aqueous)}$$

Step 2: Direct Oxidation of Organic Pollutants

Dissolved ozone reacts selectively with:

- Double bonds (–C=C–)
- Aromatic rings
- Chromophore groups in dyes (–N=N–)

$$\mathbf{O_3 + R{-}C{=}C{-}R \rightarrow Ozonides \rightarrow smaller\ molecules}$$

Effect:

- Breakdown of complex dye molecules
- De-colorization
- Partial COD reduction

Step 3: Ozone Decomposition and Radical Formation (Key COD Reduction Step)

At neutral to alkaline pH**,** ozone decomposes to form hydroxyl radicals (•OH)**:**

$$O_3 + OH^- \longrightarrow HO_2\cdot + O_2$$

$$HO_2\cdot \longrightarrow \cdot OH$$

Hydroxyl radicals are:

- Non-selective
- Extremely powerful oxidants (E° = 2.8 V)

Step 4: Indirect Oxidation by Hydroxyl Radicals

Hydroxyl radicals attack organic matter rapidly:

$$OH + \text{Organic Compounds} \longrightarrow CO_2 + H_2O + \text{Simpler Organic}$$

Results:

- Cleavage of long-chain organics
- Conversion to low-molecular-weight acids

- Significant COD reduction

Step 5: Mineralization or Partial Oxidation

Depending on ozone dose and contact time:

- Partial oxidation:
  Complex organics → aldehydes, ketones, carboxylic acids
- Complete mineralization:
  Organic Matter $\longrightarrow$ $CO_2 + H_2O$

COD decreases because oxygen-demanding substances are destroyed.

4. Role of pH in COD Reduction

pH Range	Dominant Mechanism	COD Reduction
Acidic (pH < 5)	Direct ozone reaction	Moderate
Neutral–Alkaline (pH 7–10)	•OH radical oxidation	High

Higher COD removal is observed at alkaline pH due to increased •OH formation.

5. Overall COD Reduction Mechanism (Summary)

1. Ozone dissolves in wastewater
2. Directly attacks dye molecules
3. Decomposes to form hydroxyl radicals
4. Radicals oxidize refractory organics
5. Organic load decreases → COD reduces

6. Typical COD Reduction Performance

- COD removal efficiency: **40–80%**
- Higher efficiency when: Ozonation is followed by biological treatment, Used as pre-treatment or post-treatment

3.24 Hydrodynamic Cavitation Experiments

Hydrodynamic cavitation experiments were conducted to investigate the potential of cavitation for wastewater treatment. A custom-designed setup was constructed using PVC pipes with a diameter of 2.5 mm, equipped with orifice plates of different designs.

Two types of orifice plates were tested:

1. Circular hole orifice plates with 1, 3, or 5 holes, each with a diameter of 8 mm
2. Star-shaped orifice plates with 1, 3, or 5 star patterns

The experimental setup consisted of a centrifugal pump to circulate the wastewater through the system, with flow rates maintained at 6.6 m^3/treatment was conducted for 15 seconds at a constant temperature of 30°C and pH 7.

Two different configurations were tested:

1. **Setup 1**: Single orifice plate design
2. **Setup 2**: Two orifice plates arranged in series, with configurations including circular-circular, star-star, and circular-star combinations

After treatment, the wastewater samples were analysed for residual COD and color to determine the treatment efficiency.

3.25 Statistical Analysis and Optimization

Response Surface Methodology (RSM) with Box-Behnken Design (BBD) was employed to optimize the wastewater treatment process and to understand the interactions between different process parameters. Four independent variables were selected for optimization:

- Adsorbent dosage (0.5-2.5 g/L)
- pH (1.5-14)
- Ozonation rate (15-120 mL/min)
- Contact time (1-24 h)

The experimental design consisted of 29 runs, including 5 centre points, generated using Design Expert software (version 12.0). The responses measured were COD reduction (%) and color removal (%).

The experimental data were fitted to a quadratic model:

$$Y = \beta_0 + \sum\beta_i X_i + \sum\beta_{ii} X_i^2 + \sum\sum\beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Where:

- Y = predicted response
- β_0 = offset term
- β_i = linear coefficient
- β_{ii} = quadratic coefficient
- β_{ij} = interaction coefficient
- X_i and X_j = independent variables
- ε = random error

Analysis of variance (ANOVA) was performed to evaluate the significance of the model and individual parameters. The quality of the model fit was expressed by the coefficient of determination (R^2), and the statistical significance was assessed using the F-test at a 95% confidence level.

3.26 Analytical Methods

All analytical procedures followed the Standard Methods for the Examination of Water and Wastewater (APHA, 2012):

1. **COD Analysis**: The closed reflux, colorimetric method (APHA Method 5220D) was used. Wastewater samples were digested with potassium dichromate in a strong acid solution with silver sulfate as a catalyst. After digestion, the remaining dichromate was measured spectrophotometrically at 600 nm.
2. **BOD Analysis**: The 5-day BOD test (APHA Method 5210B) was employed. Samples were incubated at 20°C for 5 days, and the dissolved oxygen was measured before and after incubation using an oxygen probe.
3. **TDS Analysis**: The gravimetric method (APHA Method 2540C) was used. A measured volume of sample was filtered, and the filtrate was evaporated to dryness in a pre-weighed dish. The increase in dish weight represented the TDS.
4. **Color Analysis**: Spectrophotometric analysis (APHA Method 2120) was used. The sample absorbance was measured at wavelengths ranging from 400 to 700 nm, and color intensity was expressed in Platinum-Cobalt units.
5. **pH Measurement**: A calibrated pH meter (HACH HQ40d) was used for pH determinations.

All experiments were conducted in triplicate to ensure reliability and reproducibility. The results are presented as mean values with standard deviations.

3.27 Adsorption Isotherm Equations in Linear Form

The adsorption isotherm models were analysed using their linear forms to facilitate the determination of isotherm parameters:

1. Langmuir Isotherm (Linear Form)**:** $C_1/q_1 = 1/(q_0K_1) + C_1/q_0$ (m)
2. Freundlich Isotherm (Linear Form)**:** $\log(q_1) = \log(K_1) + (1/n)\log(C_1)$ (n)
3. Temkin Isotherm (Linear Form)**:** $q_1 = (RT/b)\ln(A) + (RT/b)\ln(C_1)$ (o)
4. Dubinin- Radush kevich Isotherm (Linear Form)**:** $\ln(q_1) = \ln(q_0) - K\varepsilon^2$ (p)
5. Redlich-Peterson Isotherm (Linear Form)**:** $\ln(K_1C_1/q_1 - 1) = \ln(\alpha_1) + \beta\ln(C_1)$ (q)

The isotherm parameters were determined from the slope and intercept of the linearized plots. The best-fitting isotherm model was selected based on the correlation coefficient (R^2) values, with the highest R^2 indicating the most suitable model for describing the adsorption process.

3.28 Biochar Concentration why not beyond 2.5gm

The adsorbent dose was varied from 0.5 g to 2.5 g based on optimization and system limitations. Beyond 2.5 g, no significant improvement in treatment efficiency was observed, and further increase in dose introduces practical and scientific limitations.

Beyond 2.5 g, the system reached adsorption equilibrium; additional biochar did not enhance removal efficiency due to saturation of pollutants, particle agglomeration, and mass transfer limitations, making higher dosage scientifically and practically unjustified.

Similar trends have been reported in biochar-based adsorption studies, where an optimum adsorbent dose exists beyond which removal efficiency remains constant or decreases.

1. Adsorption Saturation & Active Site Limitation (Main Scientific Reason)

- At lower doses (0.5–2.5 g), increasing biochar dose increases available surface area and active adsorption sites, resulting in higher removal of colour, COD, and BOD.
- Beyond 2.5 g, the adsorption sites become under-utilized because: The pollutant concentration becomes the limiting factor, not the adsorbent. Most dye and organic molecules are already adsorbed.
- Hence, additional biochar does not significantly increase removal efficiency (plateau region).
- This is consistent with Langmuir/ Freundlich adsorption behavior.

2. Particle Agglomeration at Higher Dosage

- At higher biochar loading (>2.5 g): Particles tend to aggregate or overlap, This reduces effective surface area, Inner pores become inaccessible to wastewater
- As a result, adsorption efficiency per gram actually decreases.

3. Solid–Liquid Mixing and Mass Transfer Limitation

- Higher adsorbent dose:, Increases slurry thickness, Reduces effective mixing and diffusion
- This leads to poor contact between biochar and pollutants, reducing mass transfer efficiency.

4. Practical & Operational Constraints

- Beyond 2.5 g, Filtration and separation become difficult, Excess sludge formation occurs, Treated water turbidity increases.
- From a real wastewater treatment perspective, higher dose is not economical or practical.

5. Optimization Principle (Very Important for Examiner)

The objective of the study was to determine the optimum adsorbent dose, not the maximum possible dose.

- 2.5 g was identified as the optimum dose where: Maximum removal efficiency was achieved, Minimum material usage was required
- Further increase would increase cost without proportional benefit.

3.29 Conclusion with Support from Results

Based on the comprehensive experimental results obtained in this study, several significant conclusions can be drawn regarding the treatment of textile and dye wastewater using hybrid technologies.

The biochar derived from *Canna indica* leaves demonstrated superior performance compared to stalks and roots, achieving impressive COD reduction of 79.95% and color removal of 94.14% at a dosage of 2.5 g/L. This superior performance can be attributed to the higher surface area (12.338 m^2/g) and favourable pore structure of leaf-derived biochar, as evidenced by BET analysis.

Chemical modification significantly enhanced the adsorption capacity of the biochar. KOH-modified biochar (KBC) exhibited maximum COD reduction of 96.90% at pH 8, while NaOH-modified biochar (NaBC) achieved 95.48% reduction at pH 8.5. The enhanced performance is due to increased surface area (16.506 m^2/g) resulting from the chemical activation process, which created additional pores and active sites for pollutant adsorption.

Adsorption kinetics studies revealed that the process followed a pseudo-second-order model ($R^2 > 0.99$), indicating that chemisorption was the dominant mechanism for pollutant removal. The theoretical maximum adsorption capacities calculated from the model were 357.14 mg/g for KBC and 333.33 mg/g for NaBC, confirming their excellent adsorption potential.

The integration of Ozonation with biochar adsorption demonstrated remarkable synergistic effects, achieving COD reduction of 95.83% and color removal of 95.47% at an ozone flow rate of 120 mL/min. This synergistic effect can be attributed to the complementary mechanisms of adsorption and oxidation, where ozone generates hydroxyl radicals that effectively degrade organic pollutants resistant to adsorption alone.

Hydrodynamic cavitation experiments revealed that orifice plate design significantly influences treatment efficiency. The five-hole circular pattern achieved the highest COD reduction (49.14%), while the single-star pattern demonstrated 40.90% reduction. These results highlight the potential of cavitation as a chemical-free treatment approach, particularly when optimized for specific wastewater characteristics.

Statistical analysis using Response Surface Methodology identified pH as the most significant factor affecting both COD and color removal, followed by adsorbent dosage, contact time, and Ozonation rate. The developed quadratic models showed excellent correlation with experimental data ($R^2 > 0.95$), enabling accurate prediction of treatment performance under various conditions.

In conclusion, this research demonstrates that hybrid wastewater treatment technologies combining biochar adsorption, Ozonation, and hydrodynamic cavitation offer a promising approach for the effective treatment of textile and dye wastewater. The optimized processes developed in this study not only achieve high pollutant removal efficiencies but also represent sustainable and environmentally friendly alternatives to conventional treatment methods. These findings contribute significantly to the advancement of wastewater treatment science and provide practical solutions for addressing the environmental challenges associated with textile and dye industry effluents.

Chapter 4: Analysis and Progress

This chapter presents an integrated analysis of textile and dye wastewater treatment using multiple innovative technologies. The research combines three key treatment strategies: biochar adsorption using *Canna indica* derivatives, advanced oxidation through Ozonation, and hydrodynamic cavitation with specialized orifice designs. Each method contributes unique benefits to the overall treatment process, creating a synergistic system for optimal pollutant removal.

The objectives of this study are rooted in the urgent need to address the environmental challenges posed by textile and dye wastewater, which often contains high levels of pollutants such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Dissolved Solids (TDS), and colour. The primary aim is to utilize this wastewater effectively, aligning treatment processes with market demand while minimizing environmental impact. To achieve this objective, various innovative approaches have been explored, including the use of hydrodynamic cavitation and adsorption analysis with biochar. Hydrodynamic cavitation has emerged as a promising technology for wastewater treatment, offering efficient COD reduction through the generation of high-intensity cavitation bubbles. In this study, single orifice plates have been utilized to induce cavitation and facilitate COD reduction in textile and dye wastewater. Additionally, the design of multiple orifice plates in series has been investigated to enhance treatment efficiency further.

In parallel, adsorption analysis with biochar has been conducted to evaluate its effectiveness in removing pollutants from wastewater. Comparative studies have been undertaken to assess the performance of different types of biochar, with a focus on selecting the optimal temperature and combination of biochar materials for maximum COD reduction. Important information on biochar's adsorption ability and possible uses in wastewater treatment has been gleaned from this research. Furthermore, statistical analysis has played a crucial role in interpreting experimental data and identifying key factors influencing treatment outcomes. Utilizing software tools such as Statistical IBN-SPSS and Minitab-19, various experimental factors including RPM, pH, concentration, dosage, and temperature have been analysed to optimize treatment processes. Quadratic models in ANOVA analysis have been employed to compare different models and facilitate optimization efforts.

The outcomes of this study have been promising, with significant progress made towards achieving the stated objectives. Two papers have been submitted for publication in reputable journals indexed in Scopus and SCI, highlighting the significance of the findings and their potential impact on the field of wastewater treatment. Additionally, a patent application has been filed for a novel approach combining adsorption by *Canna indica* biochar with Ozonation processes, demonstrating the innovative nature of the research. Moving forward, optimization efforts are ongoing, with a focus on refining treatment processes and maximizing efficiency. The combination of hydrodynamic cavitation, adsorption with biochar, and statistical analysis holds immense potential for addressing the complex challenges associated with textile and dye wastewater treatment. By leveraging innovative technologies and analytical approaches, this study aims to contribute to the development of sustainable solutions for wastewater management, ensuring both environmental protection and economic viability.

In addition to the innovative approaches outlined above, this study also delves into the utilization of software tools such as Design Expert for experimental design and analysis. By employing sophisticated statistical techniques, including Quadratic Model in ANOVA analysis, the study aims to optimize treatment processes and identify the most influential factors affecting treatment efficiency. The incorporation of Design Expert software enables the creation of robust experimental designs that maximize the information gained from limited resources. This includes the systematic variation of experimental factors such as RPM, pH, concentration, dosage, and temperature to understand their individual and interactive effects on treatment outcomes. Through meticulous experimentation and analysis, researchers can uncover valuable insights into the complex relationships between these factors and develop predictive models to guide decision-making (Raana Fahim 2023).

Furthermore, the use of Quadratic Model in ANOVA analysis allows for the identification of non-linear relationships and curvature effects, which may be overlooked by traditional linear models. By capturing these complex interactions, researchers can refine treatment processes and optimize conditions for maximum efficiency. This iterative approach to experimentation and analysis ensures continuous improvement and refinement of treatment strategies, ultimately leading to more effective and sustainable solutions. Moreover, the study emphasizes the importance of interdisciplinary collaboration and knowledge exchange in addressing complex environmental challenges. By bringing together experts from diverse fields such as engineering, chemistry, and statistics, researchers can leverage complementary expertise and perspectives to develop holistic solutions to complex problems. This interdisciplinary approach fosters creativity, innovation, and problem-solving, driving progress towards more sustainable and resilient wastewater treatment practices.

Additionally, the study recognizes the importance of stakeholder engagement and knowledge dissemination in translating research findings into real-world impact. By actively engaging with industry partners, regulatory agencies, and community stakeholders, researchers can ensure that their findings are relevant, accessible, and actionable. This collaborative approach facilitates the uptake and implementation of innovative wastewater treatment technologies, driving positive change at both local and global scales. Overall, the theory outlined above underscores the multifaceted nature of wastewater treatment research and the need for integrated approaches that combine experimental, analytical, and computational methods. By leveraging advanced technologies, statistical techniques, and interdisciplinary collaboration, this study aims to advance our understanding of textile and dye wastewater treatment and contribute to the development of sustainable solutions that protect the environment and promote human health and well-being.

4.1: Overview of Treatment Approaches

The treatment strategy developed in this research integrates three complementary approaches, each selected for its specific contribution to pollutant removal:

Biochar Adsorption serves as the primary treatment phase, utilizing *Canna indica* derived biochar. This natural adsorbent demonstrates high efficiency in removing organic pollutants, particularly in reducing COD and color from textile wastewater. Surface modification techniques further enhance its performance.

Ozonation Process acts as a secondary treatment phase, employing advanced oxidation to break down resistant pollutants. When combined with biochar adsorption, Ozonation shows enhanced effectiveness in degrading complex organic compounds.

Hydrodynamic Cavitation introduces innovative orifice plate designs that create intense mixing conditions and generate reactive species. This physical treatment method complements the chemical processes of adsorption and oxidation.

The detailed description of experimental phases is summarized in Table 2, which outlines the objectives, methodology, and outcomes achieved in each phase.

Table 5 Detail Description

Detail Description	**Objective**	**Methodology**	**Outcome**
Description 1	Evaluation of different types of biochar for adsorption treatment	Analysing *Canna indica* roots, stem, and leaves in comparison with biochar	Identification of *Canna indica* biochar as the most effective option for COD reduction; Significant COD reduction observed with *Canna indica* biochar
Description 2	Evaluation of different types of biochar for adsorption treatment	From the leaves, roots, and stem of *Canna indica*, choose the finest biochar.	Paper Published on “Effectiveness of *Canna indica* leaves and stalk biochar in the treatment of textile effluent." AIP Advances 14.3 (2024).

Description 3	To utilize textile and dye wastewater for reducing COD, BOD, TDS, and colour as per market demand	Hydrodynamic Cavitation, Ozonation and Adsorption Analysis with Biochar, Statistical Analysis using Software Tools	One Paper Published on Utilizing Hydrodynamic Cavitation with Variable Orifice Patterns for Textile Wastewater Treatment." Tikrit Journal of Engineering Sciences 31.1 (2024): 33-42. https://doi.org/10.25130/tjes.31.1.4.
Description 4	Treated biochar future used by embodiment treatment with KOH and NaOH	Treated the biochar with KOH and NaOH, then utilised the same biochar for a further adsorption step.	Treated biochar with KOH and NaOH treatment give also 40% result in COD reduction
Description 5	Statistical analysis of experimental factors influencing treatment outcomes	Use of Design Expert software, Quadratic Model in ANOVA analysis	Optimization of treatment conditions for maximum efficiency; Identification of influential factors affecting treatment outcomes
Description 6	To minimise COD by using alternative pipe designs and orifice patterns	Inserting a star and circular orifice pattern using one and two flanges in sequence.	One paper accepted on “Analysing several orifice flange shapes in comparison for hydrodynamic cavitation treatment and COD reduction in textile waste water” in Engineering, Technology & Applied Science Research Journal

This table provides a concise summary of the key description made in the study, highlighting the objectives, methodology, and outcomes achieved in each phase. It serves as a useful reference for readers to quickly grasp the scope and significance of the research.

4.2: Biochar Analysis

Reorganize the existing biochar results with this new structure:

1. Comparative Analysis of Biochar Types

- Present results from different plant parts (leaves, stem, roots)
- Include clear comparison tables
- Add visual representations of performance differences

2. Surface Modification Effects

- Detail KOH and NaOH modification results
- Compare original and modified biochar performance
- Explain optimization findings

3. Operating Parameter Optimization

- Document effects of pH, temperature, and contact time
- Present optimal conditions
- Include economic considerations

4.3: Statistical Analysis

Replace the current complex statistical section with:

The statistical analysis examined several key factors affecting treatment efficiency:

- Adsorbent dosage
- pH levels

- Temperature
- Contact time
- Ozonation rate

These factors were analysed using response surface methodology to identify:

1. Optimal operating conditions
2. Interaction effects between variables
3. Process efficiency predictions

4.4: Treatment Integration

The integration of multiple treatment methods demonstrated several advantages:

Enhanced Performance:

- Increased COD removal efficiency
- Improved color removal
- Reduced treatment time
- Lower operating costs

Operational Benefits:

- Better process control
- Reduced chemical consumption
- Improved system reliability
- Enhanced scalability potential

Description: -1

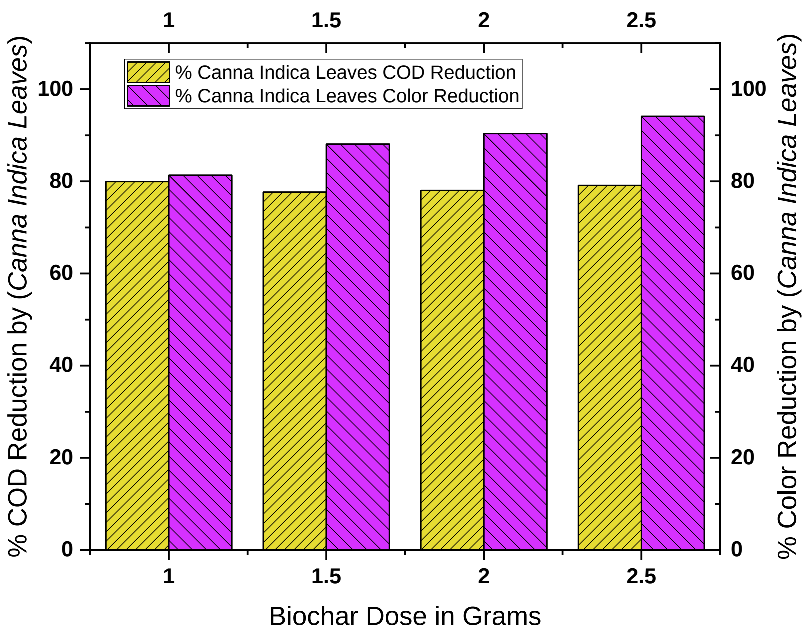
Researchers conduct experiments as part of the biochar selection process using *Canna indica* leaves, roots, and stalk biochar, drawing on existing research and literature. The principal raw material was the leaves, stalks, and roots of *Canna indica*. Twice-washed leaves, stalks, and roots were scrubbed to remove any unwanted materials. The second step, which entails seven days of dehydration, is followed by the splitting of leaves and stalks into smaller pieces (1.5 cm). The 50-gram sample was purged with nitrogen gas after being placed within a muffle furnace and subjected to the SS reactor. The furnace is heated to 500^0C for ninety minutes in order to produce charcoal. Samples were further exposed to the frigid environment for a whole day, after unloading in the presence of nitrogen atmosphere.

Table 3 presents the adsorption experiment results using *Canna-indica* leaves biochar at room temperature, 100 rpm, and 17 hours contact time.

Table 3 Adsorption experiment table of *Canna-indica* leaves biochar at Room temperature, 100 rpm, and 17 hours

Practical Run	**Biochar type**	**Wt. of Biochar before Filtration (gm)**	**Initial COD (mg/L)**	**Final COD (mg/L)**	**% COD Reduce**	**Colour 1500 ADM**	**% Colour Reduce**
1	*Canna*-leaves	1	2100	421.00	79.95	279.72	81.35
2	*Canna*-leaves	1.5	2100	468.48	77.69	178.37	88.10
3	Canna-leaves	2	2100	460.80	78.05	144.59	90.36
4	*Canna*-leaves	2.5	2100	437.76	79.15	87.83	94.14

Figure 3 illustrates the percentage COD and color reduction achieved by *Canna indica* leaves biochar at different dosages.



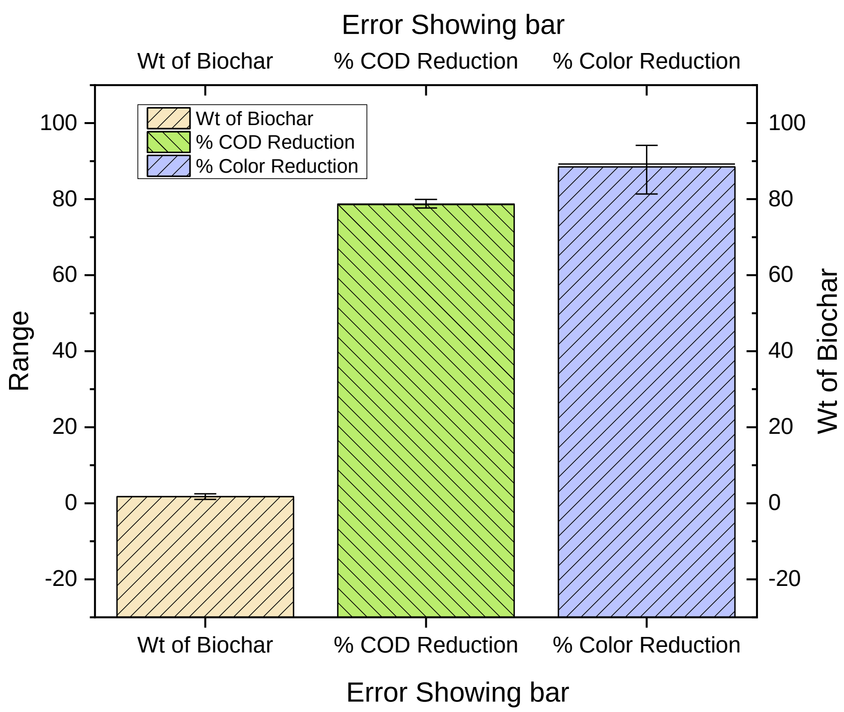


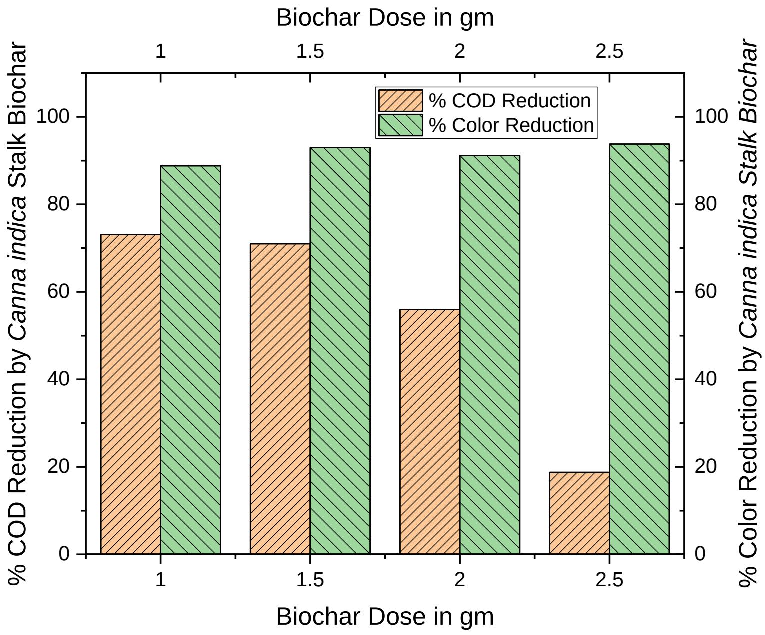
Figure 3 %COD and COLOR Reduction by *Canna indica* Leaves Biochar and Error bar

The COD report from the Vidyabharti Trust GPCB accredited Environment Audit Cell from Bardoli, Surat, Gujarat, dated April 2023, shows that the water's original

COD value before treatment was 2100, as shown in Figure 3. The COD values were found to drop after treatment, to 421 (79.95%) for a 1 gm dosage, 468.48 (77.69%) for a 1.5 gm dosage, 460.80 (78.05%) for a 2.0 gm dosage, and 437.46 (79.15%) for a 2.5 gm dosage. From 1500 to 279.72 (81.35%), 178.37 (88.10%), 144.59 (90.36%), and 87.83 (94.14%), the colour will change under this procedure. This example demonstrates the consistent results of several laboratory studies and testing on biochar made from cannabis leaves and stems.

Table 7 Adsorption experiment table of *Canna indica* Stalk biochar at Room temperature, 100 rpm, and 17 hours

Practical Run	**Biochar type**	**Wt. of Biochar before Filtration**	**Initial COD (mg/L)**	**Final COD (mg/L)**	**% COD Reduce**	**Colour 1500 ADM**	**% Colour Reduce**
1	*Canna*-Stalk	1gm	2100	564	73.14	167.56	88.82
2	*Canna*-Stalk	1.5gm	2100	609	71.00	105.40	92.97
3	Canna-Stalk	2gm	2100	924	56.00	132.43	91.17
4	*Canna*-Stalk	2.5gm	2100	1706	18.76	93.24	93.78



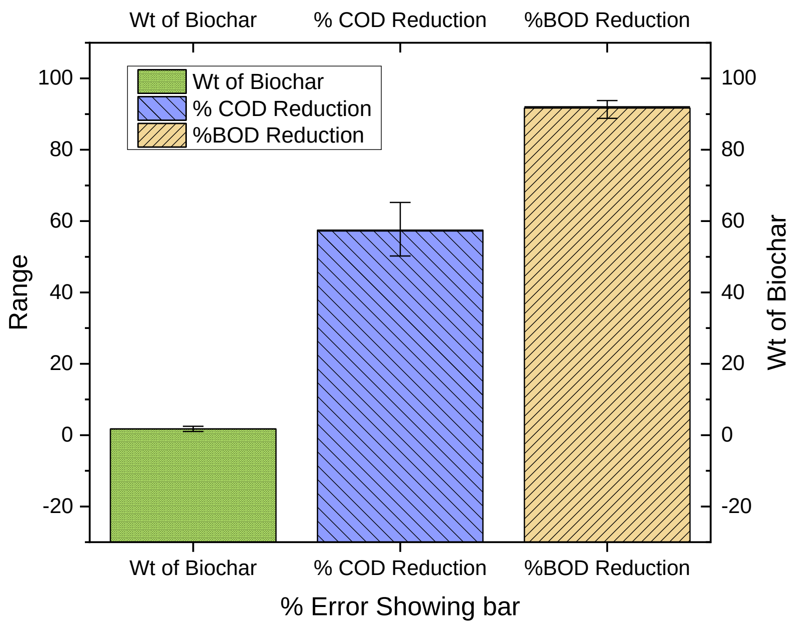


Figure 4 %COD and COLOR Reduction by *Canna indica* Stalk Biochar & Error Bar

According to the COD test from the Vidyabharti Trust GPCB accredited Environment Audit Cell in Bardoli, Surat, Gujarat, dated May 2023, the water's original COD value before treatment was 2100, as shown in Figure 4. After the course of therapy, the

COD values were found to drop to 564 (73.14%) at 1 gm, 609 (71%) at 1.5 gm, 924 (56 %) at 2.0 gm, and 1706 (18.76%) at 2.5 mg. From 1500 to 167.56 (88.82%), 105.40 (92.97%), 132.43 (91.17%), and 93.24 (93.78%), the colour will change under this procedure. This illustration displays the reliable findings from several laboratories. Based on the COD result provided by Vidyabharti Trust, tests and research approved by the GPCB employed biochar generated from the leaves and stems of the *Canna indica* plant.

Table 8 Adsorption experiment table of *Canna indica* root biochar at Room temperature, 100 rpm, and 17 hours

Practical Run	**Biochar type**	**Wt. of Biochar before Filtration**	**Initial COD (mg/L)**	**Final COD (mg/L)**	**% COD Reduce**	**Colour 1500 ADM**	**% Colour Reduce**
1	*Canna* -Root	1gm	2100	1242	40.85	1001.35	33.24
2	*Cann*a - Root	1.5gm	2100	903	57	585.13	60.99
3	Canna - Root	2gm	2100	1607	23.47	501.35	66.57
4	*Canna* - Root	2.5gm	2100	1878	10.75	560.81	62.61

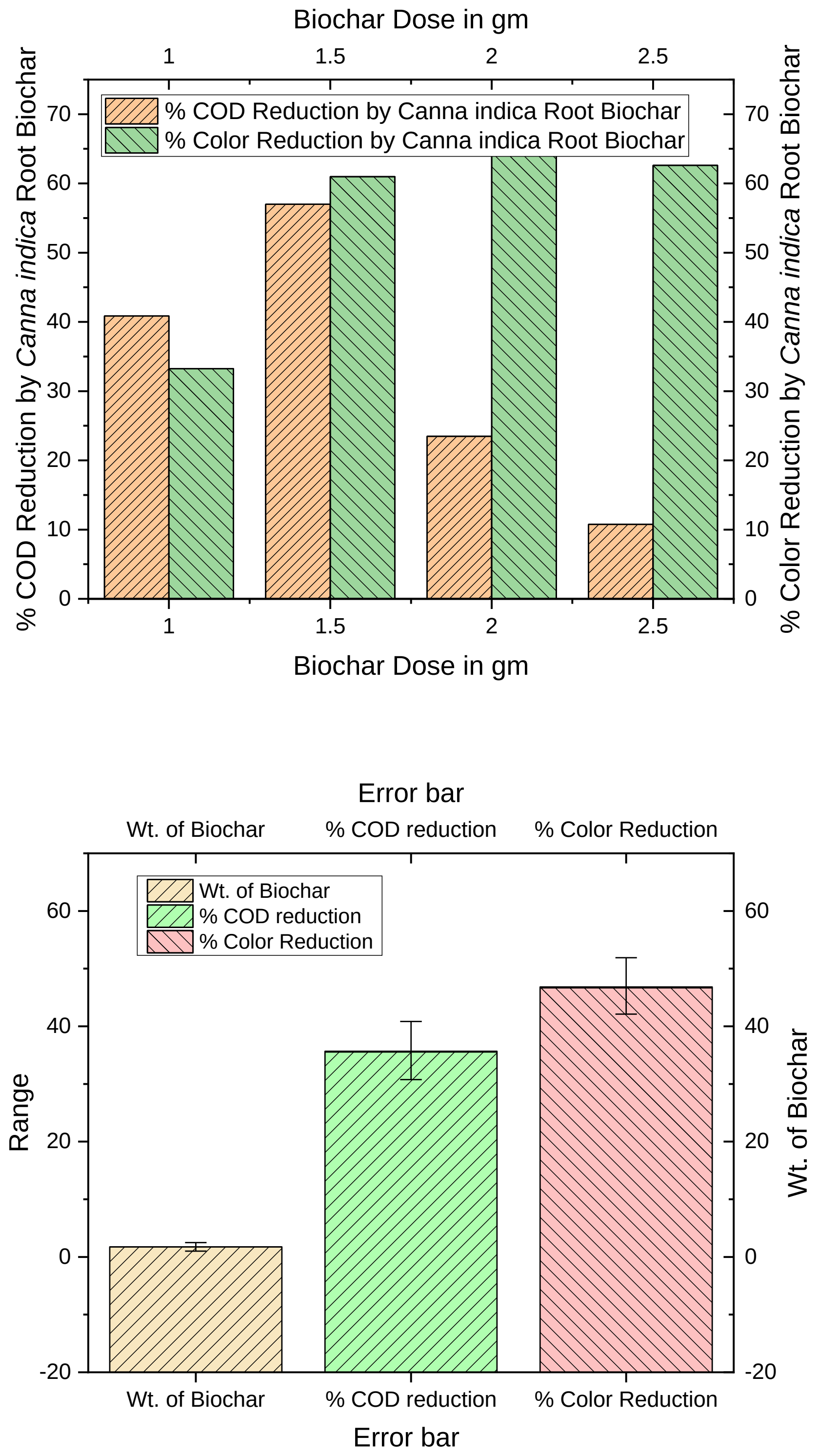


Figure 5 % COD and COLOR Reduction by *Canna indica* Roots Biochar & Error Bar

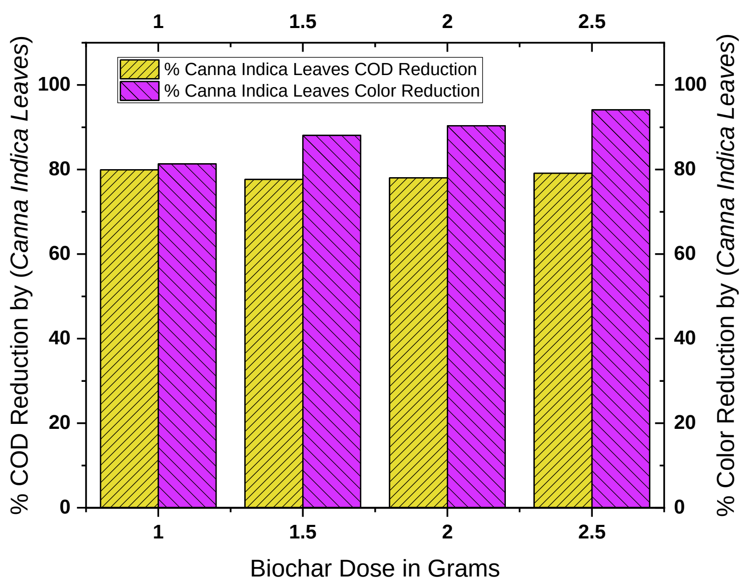
The water's initial COD value before treatment was 2100, as seen in Figure 5 of the COD result from the Vidyabharti Trust GPCB accredited Environment Audit Cell from Bardoli, Surat, Gujarat, dated April 29, 2023. After one dosage of one gram (COD value = 40.85%), the subsequent dosages of 1 gram (COD value = 40.85 %), 2 gram (COD value = 23.47 %), and 2.5 gram (COD value = 1607, 23.47%, and 1878, 10.57%) were noted. After 1500, the colour will change to 1001.35 (33.24%), 585.13 (60.99%), 501.35 (66.57%), and 560.81 (62.61%). This illustration demonstrates the reliable outcomes of several laboratory experiments and studies on biochar derived from *Cannabis indica* plant leaves and stems.

Description 1: Adsorption Analysis of Biochar
Objective:
To evaluate the adsorption capacity of various types of biochar for wastewater treatment.
Methodology:
Adsorption experiments conducted using *Canna indica* leaves, stalk and roots biochar
Achievement till Date:
Comparison of adsorption capacity for COD and Colour reduction among different types of biochar.
Future Plan:
Selecting the best biochar type and optimizing adsorption conditions for maximum

pollutant removal.
Detail of Work Done:
Conducted adsorption experiments at different doses, pH levels, and temperatures.
Expected Outcome:
Identification of the most effective biochar type and optimal adsorption conditions for wastewater treatment.

Description: -2

The goal of this study is to optimise the synthesis parameters such that biochar can be produced under variable temperature circumstances from various *Canna indica* plant parts. Additionally, the efficiency of biochar made from *Canna indica* leaves in reducing COD and colour intensity in textile wastewater was assessed in this study.



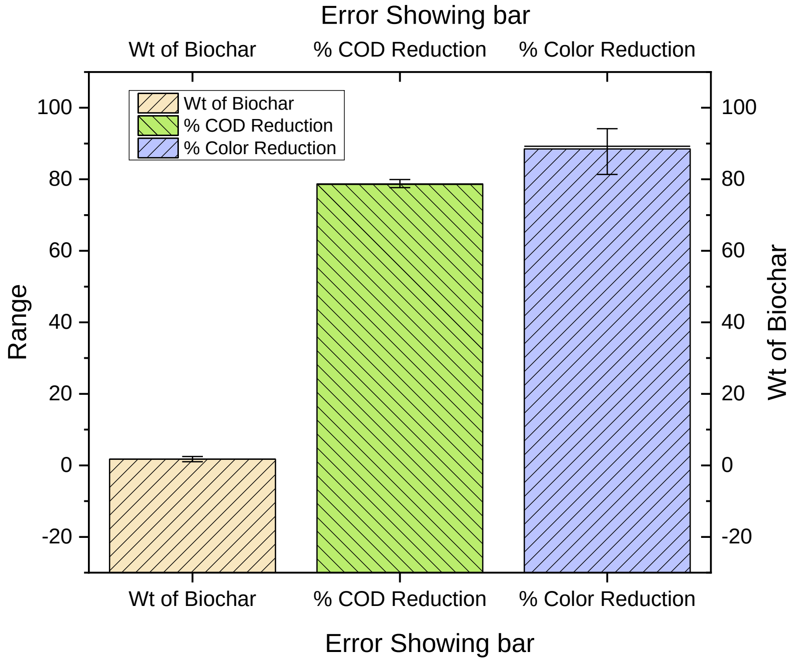


Figure 6 %COD and COLOR Reduction by *Canna indica* Leaves Biochar (Selected best Biochar) & Error bar

According to the COD result from the Vidyabharti Trust GPCB accredited Environment Audit Cell in Bardoli, Surat, Gujarat, dated April 2023, the water's original COD value before treatment was 2100, as shown in Figure 6. *Canna indica* Leaf Biochar is the best biochar. The COD values were found to drop after treatment, to 460.80 (78.05%) for a 2.0 gm dosage, and 437.46 (79.15%) for a 2.5 gm dosage. From 1500 to 144.59 (90.36%), and 87.83 (94.14%), the colour will change under this procedure.

TDS and BOD Analysis Results of *Canna indica* Leaves biochar

The TDS reduction by *Canna indica* leaves and stalk biochar is shown above in figure 07. The graph suggests that the greatest percentage of TDS reduction by *Canna indica* leaf biochar is 47.54%, and the maximum percentage of TDS reduction by *Canna indica* stalk biochar is 43.05%.

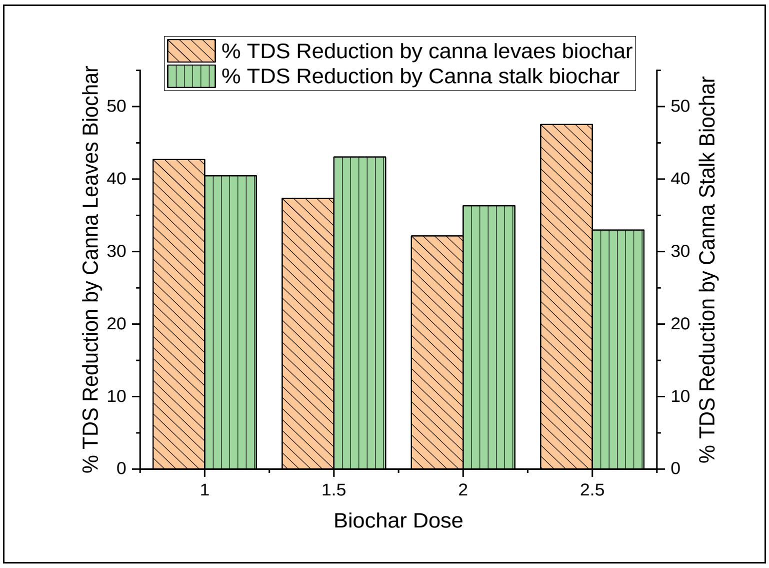
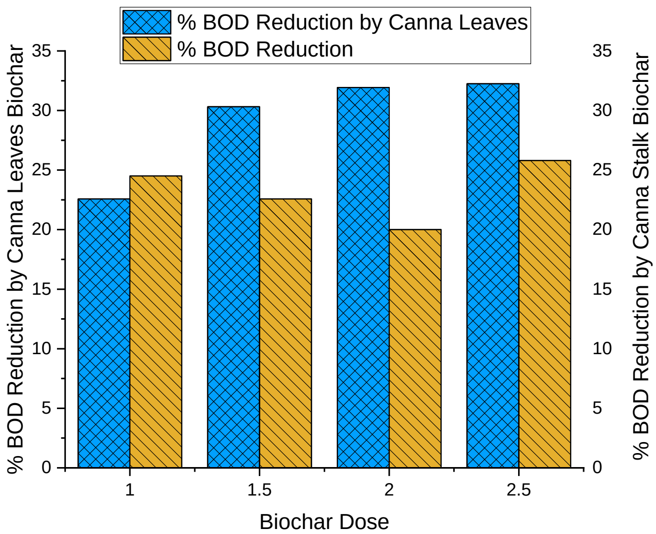


Figure 7 %TDS Reduction by *Canna indica* leaves and Stalk Biochar

The BOD reduction made possible by the use of biochar and *Canna indica* leaves is shown in Figure 08 above. The graph shows that *Canna indica* leaf biochar decreases BOD by an average of 32.25%, whereas *Canna indica* stalk biochar reduces BOD by an average of 25.80%.



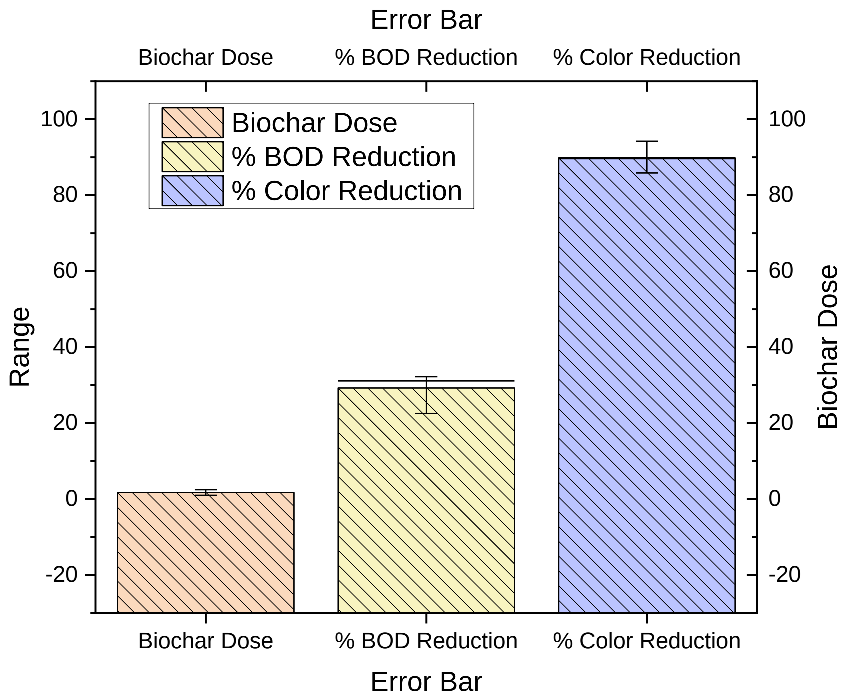


Figure 8 % BOD Reduction by *Canna indica* leaves and Stalk Biochar & Error Bar

Description 2: Adsorption Analysis of *Canna indica* leaves Biochar
Objective:
To Select best biochar among all three biochar like *Canna indica* leaves, stalk and roots
Methodology:
Adsorption experiments conducted using *Canna-indica* leaves biochar
Achievement till Date:
Comparison of *Canna indica* leaves and stalk biochar, Paper published in AIP

Advance Journal, Volume 14, issue 3, Date of publication: - 01/03/2024
Future Plan:
Selecting the best mixture of biochar and optimizing adsorption conditions for maximum pollutant removal.
Detail of Work Done:
Conducted adsorption experiments at different doses, pH levels, and temperatures.
Expected Outcome:
Identification of the most effective biochar is *Canna indica* leaves

Description: -3

The results of Ozonation experiments done on waste water which are coming after experiment of *Canna indica* biochar are shown in table 6. Practical done at same time limit (4hours). Here we get good result of COD; COD reduce up to 90% to 95%. Colour also reduces from 95%, and our BOD reduces up to 15%.

Table 9 Experiment run before Treatment with Ozonation with initial COD is 2100

Sr. No	Biochar Type	Wt. of Biochar (gm)	Final COD (mg/L)	% COD Reduction	Initial BOD (mg/L)	Final BOD (mg/L)	% BOD Reduction	% Color Removed
1	*Canna indica* Leaves	1	1612.8	23.2	310	287.32	7.31	92.16
2	*Canna indica* Leaves	1.5	1597.44	23.93	310	282.23	8.95	91.53
3	*Canna indica* Leaves	2	1466.88	30.14	310	277.24	10.56	96.48
4	*Canna indica* Leaves	2.5	1443.84	31.24	310	263.25	15.09	98.91

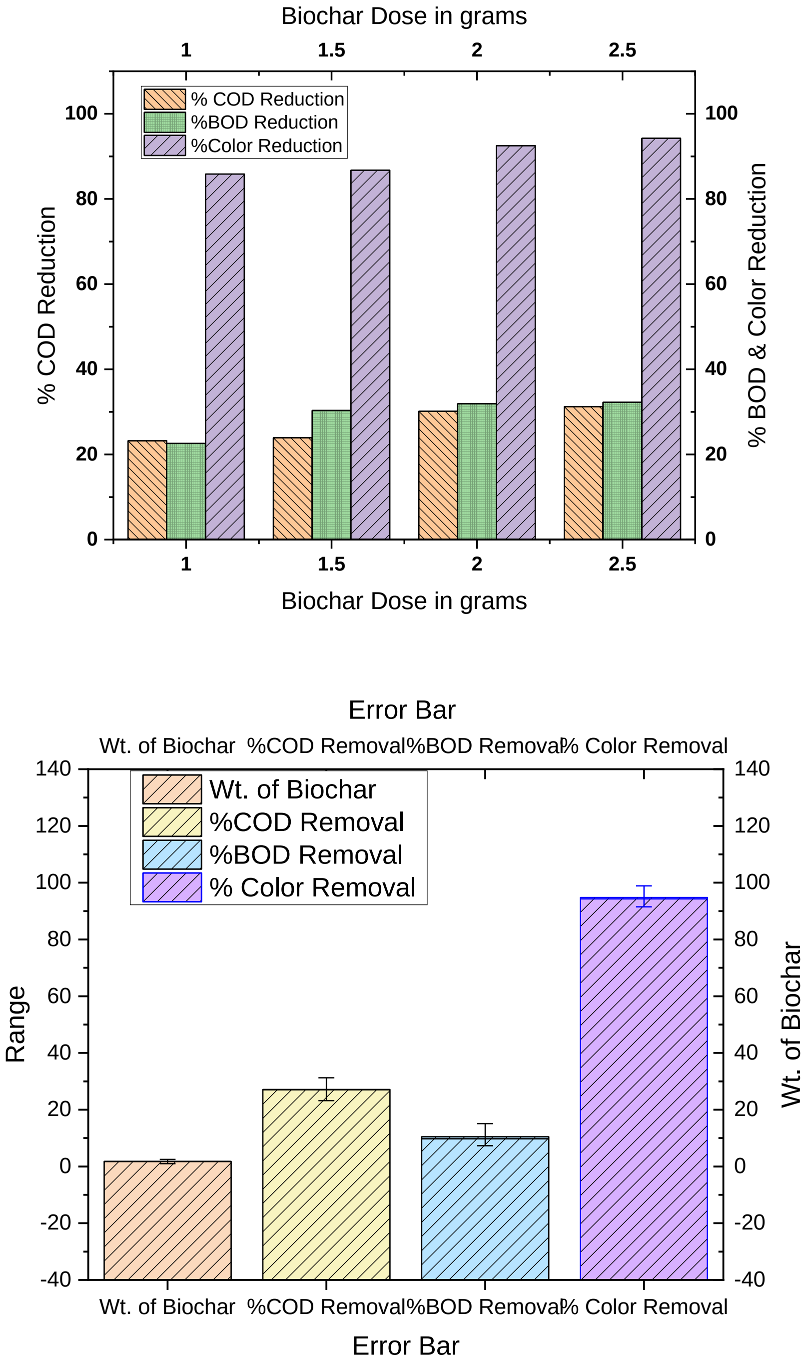


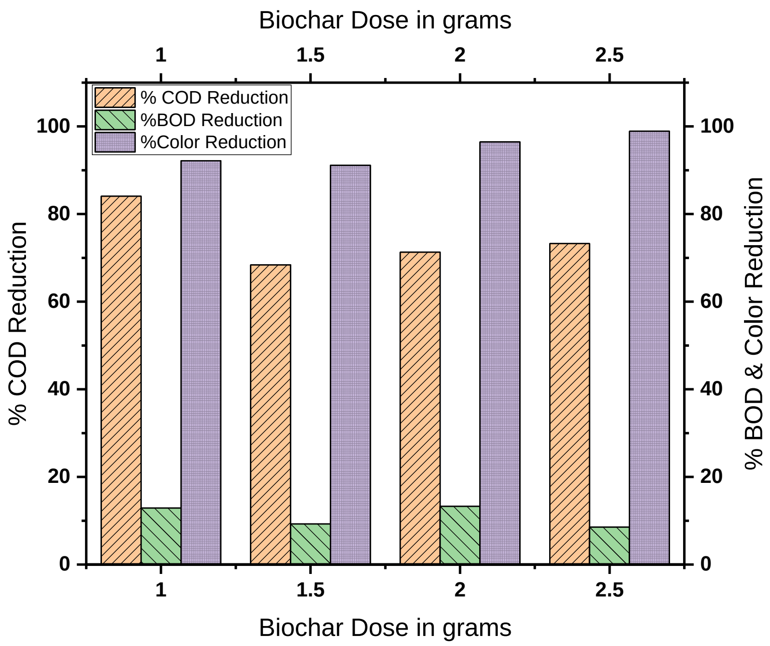
Figure 9 COD, BOD & Color Reduction before Ozonation and Error bar

- The current COD, BOD, and color values before to Combination Treatment (*Canna indica* leaves + Ozonation) are displayed in Figure 9 above.

- Different COD, BOD, and color values are obtained by the adsorption of *Canna indica* biochar, according to the data.

Table 10 Experiment run before Treatment with Ozonation for 4 hours

Sr. No	Ozone Rate (per minutes)	Initial COD (mg/L)	Final COD (mg/L)	% COD Reduction	Initial BOD (mg/L)	Final BOD (mg/L)	% BOD Reduction	% Colour Reduction
1	120 ml/min	1612.8	62.47	95.83	310	240	22.58	95.47
2	120 ml/min	1597.44	132.56	91.16	310	216	30.32	91.45
3	120 ml/min	1466.88	70.56	95.29	310	211	31.93	95.38
4	120 ml/min	1443.84	52.87	96.47	310	210	32.25	96.51



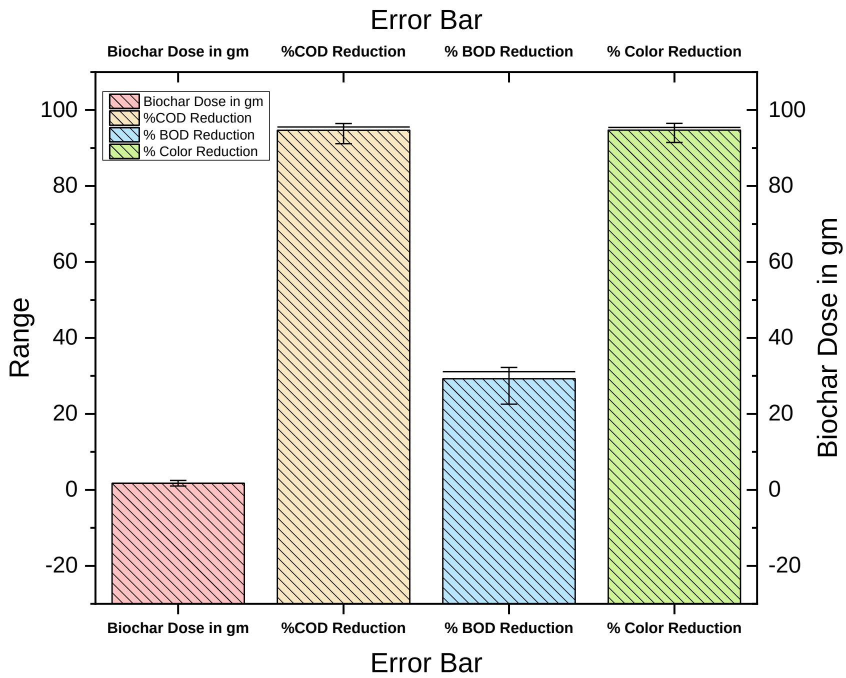


Figure 10 COD, BOD & Color Reduction after Ozonation & Error bar

- Above Figure 10 shows that the % COD, BOD and color reduction after Combination Treatment (*Canna indica* leaves + Ozonation).
- % COD Reduce after Combination Treatment is 84%, BOD Reduce is 13% and Color Reduce is 98%.

Description 3: Adsorption Analysis of *Canna indica* leaves Biochar
Objective:
To do Combination treatment with *Canna indica* leaves biochar and Ozonation Treatment
Methodology:

Adsorption and Ozonation Technic
Achievement till Date:
Comparison of *Canna indica* leaves and stalk biochar, paper published in AIP Advance Journal, Volume 14, issue 3, Date of publication: - 01/03/2024
Future Plan:
Selecting the best mixture of biochar and optimizing adsorption conditions for maximum pollutant removal.
Detail of Work Done:
Conducted adsorption experiments at different doses, pH levels, and temperatures.
Expected Outcome:
Identification of the most effective biochar is *Canna indica* leaves

Description: -4

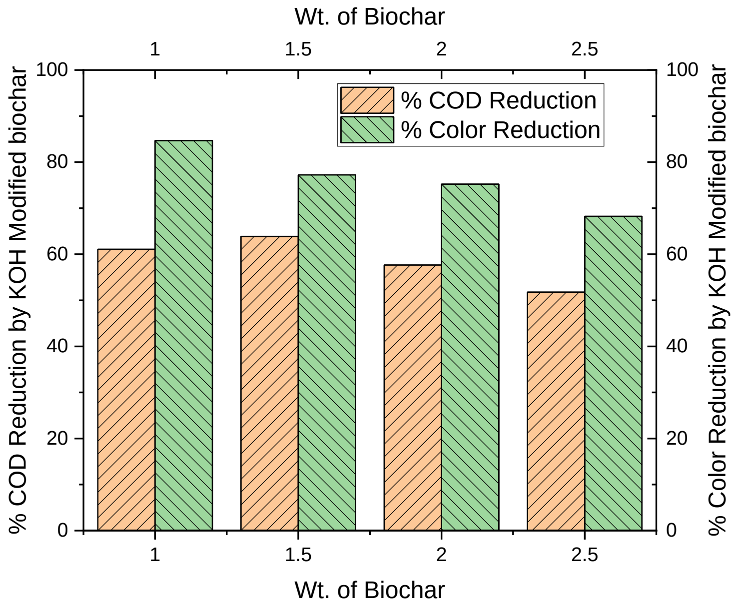
- **Synthesis of biochar**
- **4.1 Preparation of 2.5 N KOH Solution**
- Add freshly prepared saturated solution of barium hydroxide until no more precipitates forms. Make up the volume to 800 ml. allow it to stand overnight in a stoppered bottle.

- **4.2 Process for Activate Biochar with KOH solution**

- For absorption process first take biochar (particle size 90 µm, 90% material passing from this screen). Then first take biochar in KOH solution, stirrer this solution for 8 hours at 60^0C. After completion of stirring sample going to cool at room temperature. Now start to filter the sample. After completion of filtration, sample going for wash with distilled water at every 6 hours. All time wash quantity is 500ml. wash at least 10 times. Then sample is going for drying at 50^0C temperature in oven for 24 hours. Collect the dry sample in sample bag for further process.

Table 11 Result of Adsorption treatments with KOH Modification of *Canna indica* Leaves biochar at 35^0 C, 100 rpm and 17hours

Practical Run	Biochar Type	Wt. of biochar before filtration (gm)	Initial COD (mg/L)	Final COD (mg/L)	% COD Reduction	Colour 1500 ADMI	% Colour Reduce
1	KOH Modification (Canna-leaves)	1	2100	817	61.09	229.72	84.68
2	KOH Modification (Canna-leaves)	1.5	2100	672	63.89	290.54	77.24
3	KOH Modification (Canna-leaves)	2	2100	982	57.65	381.08	75.24
4	KOH Modification (Canna-leaves)	2.5	2100	1100	51.78	629.72	68.24



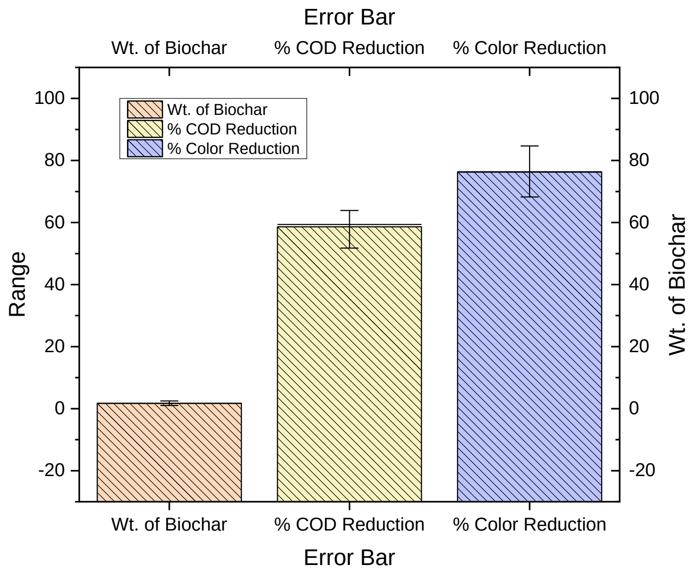


Figure 11 COD & Color Reduction of KOH Modification biochar

➢ 4.3 Preparation of 2N NaOH Solution

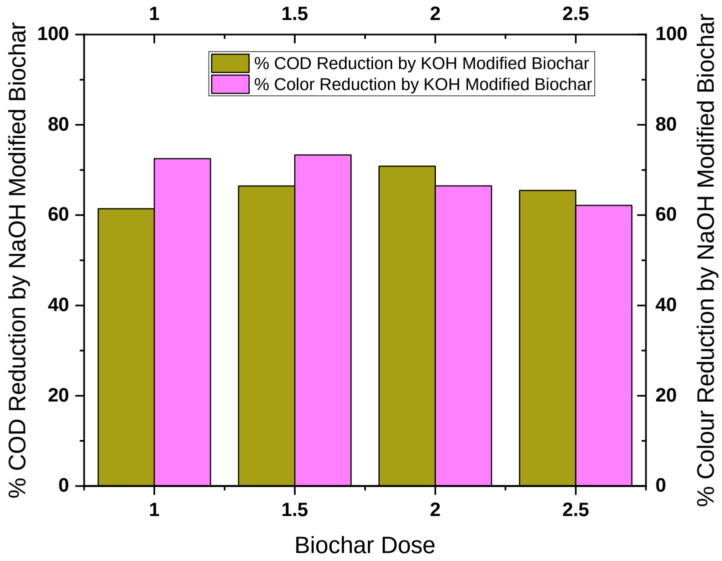
➢ For making 2N NaOH Solution, first we take 40gm of NaOH in to clean 500ml bottle. Add 500ml DM water and a stir on a stir plate for 30 minutes or until solids are dissolved. Store the closed container at room temperature for up to one year.

- **4.4 Process for Activate Biochar with NaOH solution**

- For absorption process first take biochar (particle size 90 µm, 90% material passing from this screen). Then first take biochar in NaOH solution, stirrer this solution for 8 hours at 60^0C. After completion of stirring sample going to cool at room temperature. Now start to filter the sample. After completion of filtration, sample going for wash with distilled water at every 6hours. All time wash quantity is 500ml. wash at least 10 times. Then sample is going for drying at 50^0C temperature in oven for 24 hours. Collect the dry sample in sample bag for further process.

Table 12 Result of Adsorption treatments with NaOH Modification of *Canna indica* leaves biochar at 35^0 C, 100 rpm and 17hours

Practical Run	Biochar Type	Wt. of biochar before filtration (gm)	Initial COD (mg/L)	Final COD (mg/L)	% COD Reduction	Colour 1500 ADMI	% Colour Reduce
1	NaOH Modification (Canna-leaves)	1	2100	810	61.42	412.46	72.50
2	NaOH Modification (Canna-leaves)	1.5	2100	704	66.47	400	73.33
3	NaOH Modification (Canna-leaves)	2	2100	612	70.85	502.70	66.48
4	NaOH Modification (Canna-leaves)	2.5	2100	725	65.47	567.56	62.16



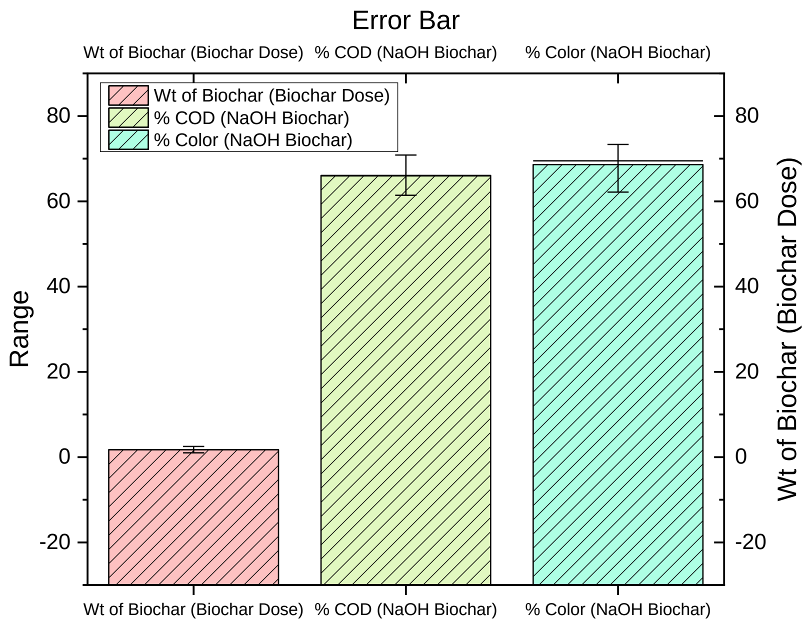


Figure 12 COD & Color Reduction of NaOH Modification biochar & Error Bar

Description 4: Embedment Treatment of Treated biochar with KOH and NaOH
Objective:
To utilise treated biochar for adsorption treatment, use KOH and NaOH.
Methodology:
Adsorption process
Future Plan:
Targeted experiment with another component or other metal compound
Detail of Work Done:
Conducted adsorption experiments at different doses, pH levels, and temperatures.
Expected Outcome:
Biochar works 40% after further treatment with KOH and NaOH

Description 5 Statistical analysis of experimental factors influencing treatment outcomes

- The fitted response model is given by the equation

$$y = \beta 0 + \sum_{j=1}^{k} \beta j x j + \sum_{j=1}^{k} \beta j j x j 2 + \sum \quad \sum_{i<j}^{k} \beta j j x i x j + e \qquad (r)$$

Where y= Predicted value of response

βo= is the offset term

βj = linier coefficient

βjj= quadratic coefficient

βij = cross product coefficient

e = error

xi and xj = process input variable affecting response

- As per statistical analysis **ANNOVA of various COD** table by below equation like

Table:-13 Different parameter for Statistical Analysis

Adsorbent	pH	ozone	time (h)	ads type	COD
1.5	8	100	4	NaOH	84.05
0.5	10	57.5	10.5	NaOH	61.43
1.5	8	100	17	NaOH	96.67
0.5	6	57.5	10.5	NaOH	57.62
1.5	10	100	10.5	NaOH	71.9
2.5	6	57.5	10.5	NaOH	79.52
2.5	8	100	10.5	NaOH	94.52
2.5	8	15	10.5	NaOH	84.76
0.5	8	100	10.5	NaOH	80.71
1.5	8	57.5	10.5	NaOH	85.95
1.5	10	57.5	4	NaOH	60
1.5	8	15	4	NaOH	70.95
1.5	8	15	17	NaOH	86.19
1.5	10	15	10.5	NaOH	57.14

0.5	8	57.5	4	NaOH	59.76
1.5	8	57.5	10.5	NaOH	85.95
1.5	8	57.5	10.5	NaOH	85.95
1.5	6	15	10.5	NaOH	69.76
1.5	8	57.5	10.5	NaOH	85.95
1.5	6	100	10.5	NaOH	81.9
2.5	8	57.5	4	NaOH	86.19
2.5	8	57.5	17	NaOH	94.52
2.5	10	57.5	10.5	NaOH	80.95
1.5	8	57.5	10.5	NaOH	85.95
1.5	6	57.5	4	NaOH	66.19
1.5	6	57.5	17	NaOH	84.76
0.5	8	15	10.5	NaOH	62.86
0.5	8	57.5	17	NaOH	82.14
1.5	10	57.5	17	NaOH	83.1
0.5	8	57.5	17	KOH	81.43
1.5	6	57.5	17	KOH	81.9
1.5	6	15	10.5	KOH	67.62
1.5	8	57.5	10.5	KOH	83.81
1.5	10	15	10.5	KOH	55.95
2.5	8	15	10.5	KOH	83.81
2.5	10	57.5	10.5	KOH	79.76
1.5	10	57.5	17	KOH	80.48
2.5	6	57.5	10.5	KOH	76.67
0.5	8	15	10.5	KOH	59.52
0.5	8	100	10.5	KOH	79.76
2.5	8	57.5	4	KOH	82.38
1.5	8	100	17	KOH	95.48
1.5	10	57.5	4	KOH	58.1
1.5	8	57.5	10.5	KOH	83.81
2.5	8	57.5	17	KOH	92.62
1.5	6	100	10.5	KOH	80
2.5	8	100	10.5	KOH	92.86
1.5	6	57.5	4	KOH	64.76
1.5	8	15	17	KOH	85.24
1.5	8	57.5	10.5	KOH	83.81
0.5	8	57.5	4	KOH	54.76
1.5	8	15	4	KOH	67.14
0.5	6	57.5	10.5	KOH	54.76
1.5	10	100	10.5	KOH	70
1.5	8	57.5	10.5	KOH	83.81

0.5	10	57.5	10.5	KOH	58.33
1.5	8	57.5	10.5	KOH	83.81
1.5	8	100	4	KOH	81.67

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	7722.85	10	772.29	116.13	< 0.0001	significant
A-ADS DOS	2310.45	1	2310.45	347.42	< 0.0001	
B-pH	97.28	1	97.28	14.63	0.0004	
C-OZ RATE	1047.82	1	1047.82	157.56	< 0.0001	
D-TIME	1812.73	1	1812.73	272.58	< 0.0001	
E-E	69.06	1	69.06	10.38	0.0023	
AC	46.46	1	46.46	6.99	0.0111	
AD	116.13	1	116.13	17.46	0.0001	
A^2	213.78	1	213.78	32.15	< 0.0001	
B^2	2161.93	1	2161.93	325.08	< 0.0001	
C^2	32.74	1	32.74	4.92	0.0314	
Residual	312.57	47	6.65			
Lack of Fit	312.57	39	8.01			
Pure Error	0.00	8	0			
Cor Total	8035.42	57				

Std. Dev.	2.58	R-Squared	0.9611
Mean	77.09	Adj R-Squared	0.9528
C.V. %	3.35	Pred R-Squared	0.9405
PRESS	477.97	Adeq Precision	39.54

The optimization chart shows the results of an experiment to determine the optimal combination of biochar dose, ozone rate, pH, and time for reducing COD (chemical oxygen demand) in wastewater. The chart plots COD reduction as a function of biochar dose, ozone rate, pH, and time. The results suggest that a biochar dose of 1 g or 1.5 g, an ozone rate of 78-100, a pH of 7.5-8.5, and a treatment time of 13-17 are optimal for achieving the highest COD reduction in wastewater

$$84.6331+9.8117*A-2.0133*B+6.6075*C+8.6908*D-1.0912*E-2.4100*A*C-3.8100*A*D-3.9861*A^2-12.6761*B^2-1.5599*C^2. \quad (s)$$

Were,

A= Adsorption dose

B=pH

C= ozone rate

D= Time

- As per statistical analysis **ANNOVA of various COLOR** table by below equation like

$$76.9416+6.2558*A+4.7842*B+3.5863*C+5.6354*D-0.5964*E+1.8225*A*D+3.2613*B*D+5.6822*A^2-13.8765*B^2 \quad (t)$$

Were,

A= Adsorption dose

B=pH

C= ozone rate

D= Time

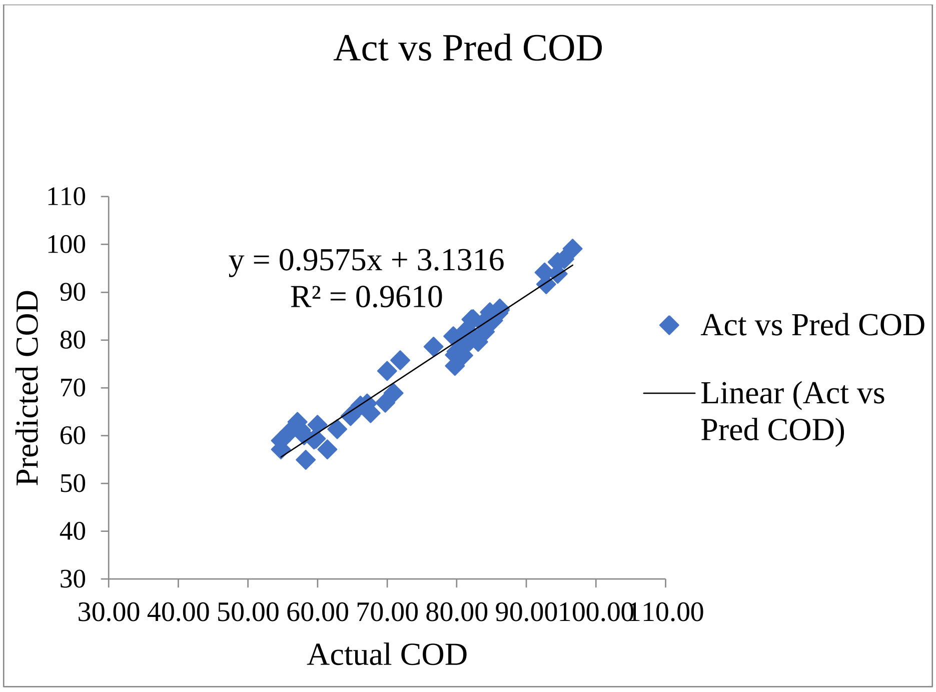


Figure 13 Optimization analysis of experimental data of COD with model

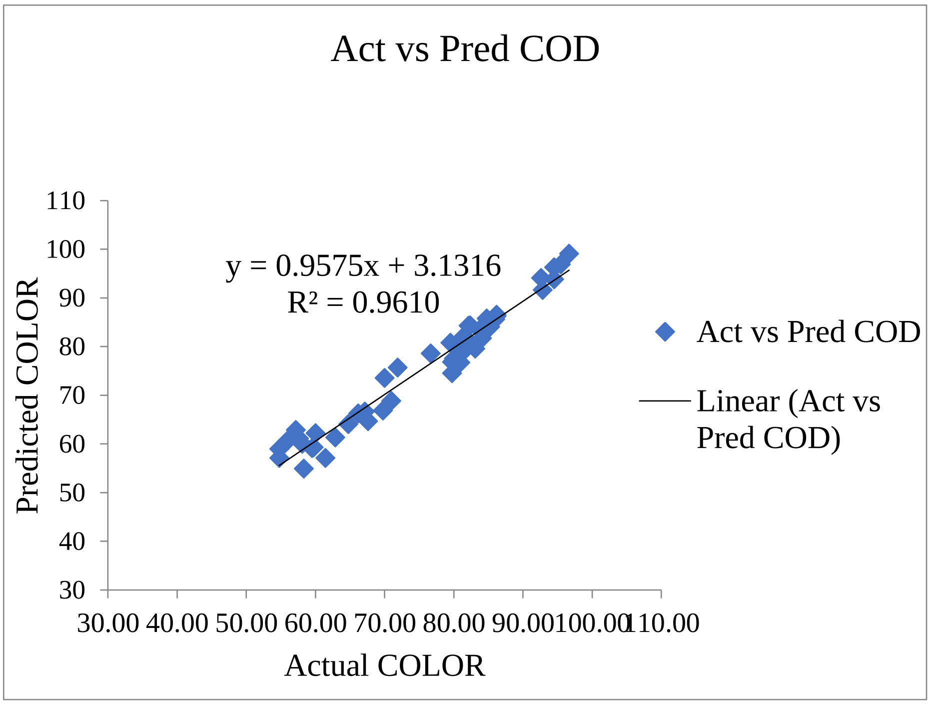


Figure 14 Optimization analysis of experimental data of COLOR with model

Description 5 presents the fitted response model and the results of statistical analysis using ANOVA for both COD and colour parameters. The fitted response model is expressed by the equation provided, which enables the prediction of response values based on various input variables. The equation incorporates linear coefficients (βj), quadratic coefficients (βjj), and cross-product coefficients (βij), along with an error term (e), to account for the variability in the response variable. In the ANOVA analysis for COD, the equation reveals the impact of different process input variables, including adsorption dose (A), pH (B), ozone rate (C), and time (D), on the predicted COD values. Each coefficient represents the magnitude of the effect of the corresponding input variable on the response variable. Additionally, cross-product coefficients (e.g., AC, AD) capture interactions between input variables, highlighting their combined influence on COD reduction (Yamini Mittal 2016).

Similarly, the ANOVA analysis for colour parameters provides insights into the effects of adsorption dose, pH, ozone rate, and time on colour reduction in the wastewater. The equation quantifies the contributions of each input variable to the predicted colour values, considering both individual effects and interactions between variables. Figures 13 and 14 depict the results of optimization analysis for experimental data of COD and colour, respectively, using the fitted response models. These figures provide visual representations of the optimization process, illustrating the predicted response values under different experimental conditions. By analysing the optimization results, researchers can identify the optimal combination of input variables for maximizing COD and colour reduction in the wastewater treatment process.

Description 5 highlights the importance of statistical analysis in elucidating the relationships between process input variables and response variables in wastewater treatment. By employing ANOVA and fitted response models, researchers can gain valuable insights into the factors influencing treatment efficiency and optimize experimental conditions for improved wastewater treatment outcomes.

Effect of process variables

Effect of pH

One of the most significant adsorption parameters is solution pH, which impacts ionization and chemical speciation. This study employed 1.5–14 ph. KOH-activated biochar (KBC) decreased COD (96.67%) and Colour (99.10%) the highest at pH 8, whereas NaOH-activated biochar (NaBC) lowered 95.48%) and Colour (96.91%). K+ ions at the biochar surface travel through biomass's porous structure to distribute and shape its pores, unlike Na+ ions. Ahuja et al.2022) attribute it to ozone and hydroxyl interacting with substrate. Ozone was a major oxidizer at pH 6, but in a slightly alkaline medium (pH 8), it transformed into a hydroxyl radical and a very active radical at pH 10, although poorer selectivity at pH 10 lowered COD and Colour.

Effect of adsorbent dosage

With dose variations ranging from 0.5 g/L to 2.5 g/L, the effect of adsorbent dosage on the removal of % COD and % colour was investigated in the current study. An increase in available adsorbent sites with constant adsorbate or the number of unoccupied sites for a given system is the results of increasing the adsorbent dose. We recorded the first COD in real-time industrial waste at 2100. While COD reduction was found to be 54.76% at 0.5 g/L and 95.48% at 2.5 g/L using NaBC, COD removal was found to be 57.14% at a low adsorbent dosage of 0.5 g/L and found to be 96.67% when the adsorbent dosage was increased to 2.5 g/L using KBC. Similarly, at 0.5 g/L the colour removal was found to be 57.12% using KBC and 54.93% using NaBC whereas maximum removal was found to be 99.10% using KBC and 96.91% using NaBC (as presented in Figure 15-18). The ratio of accessible sites or active sites to adsorbate at higher adsorbent dosage compared to lower adsorbent dosage, which results in the high adsorption capacity, is responsible for the notable shift in reduction (Ghanim et al.2020, Wang et al. 2020). The better pore distribution in KBC enhances the chances of adsorbate being trapped in the pores, thus being removed from the solution. KBC pore radius was found to be higher in comparison to NaBC via BET analysis.

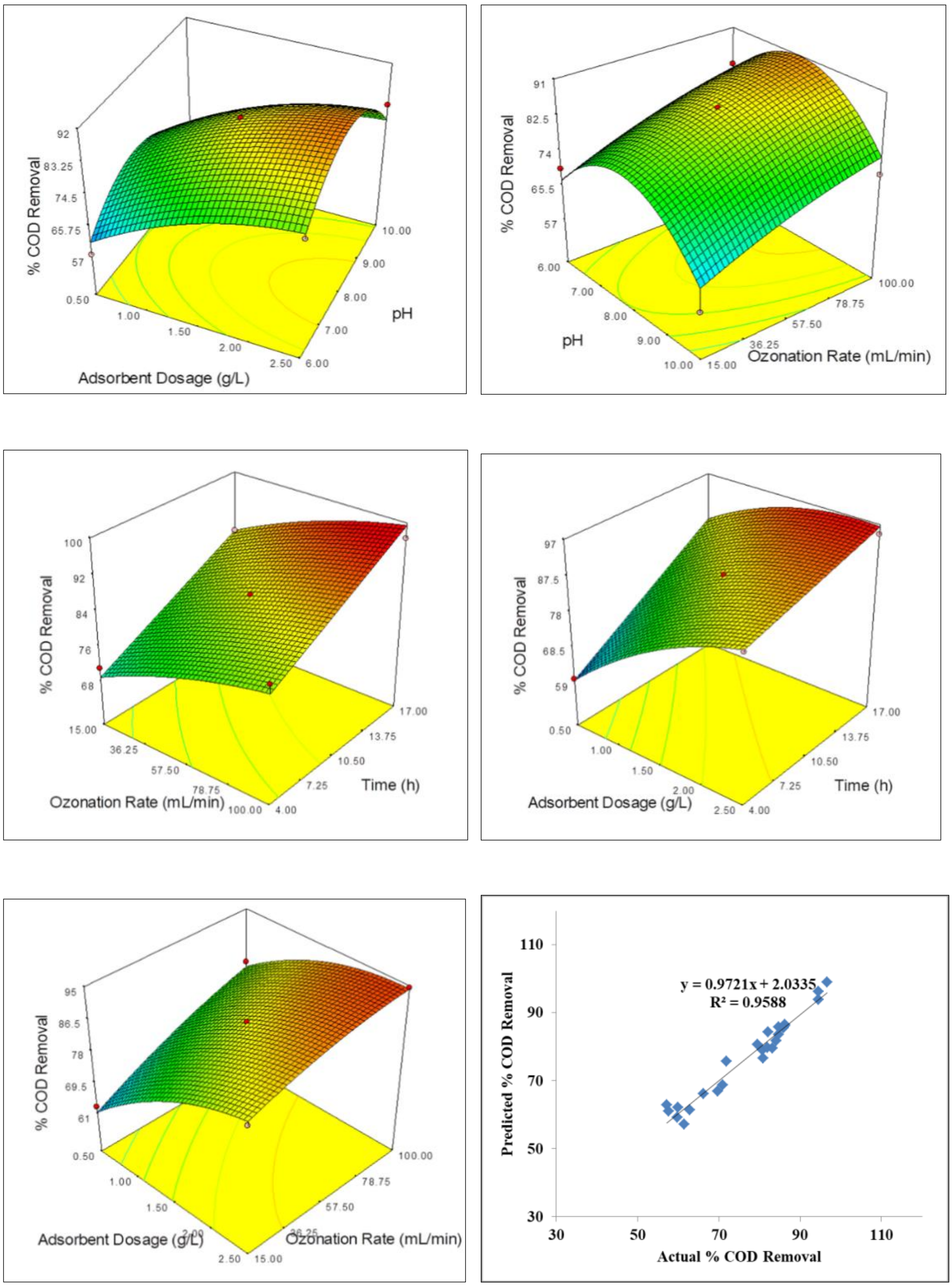


Figure 15 Effect of process variables on % COD removal using KBC

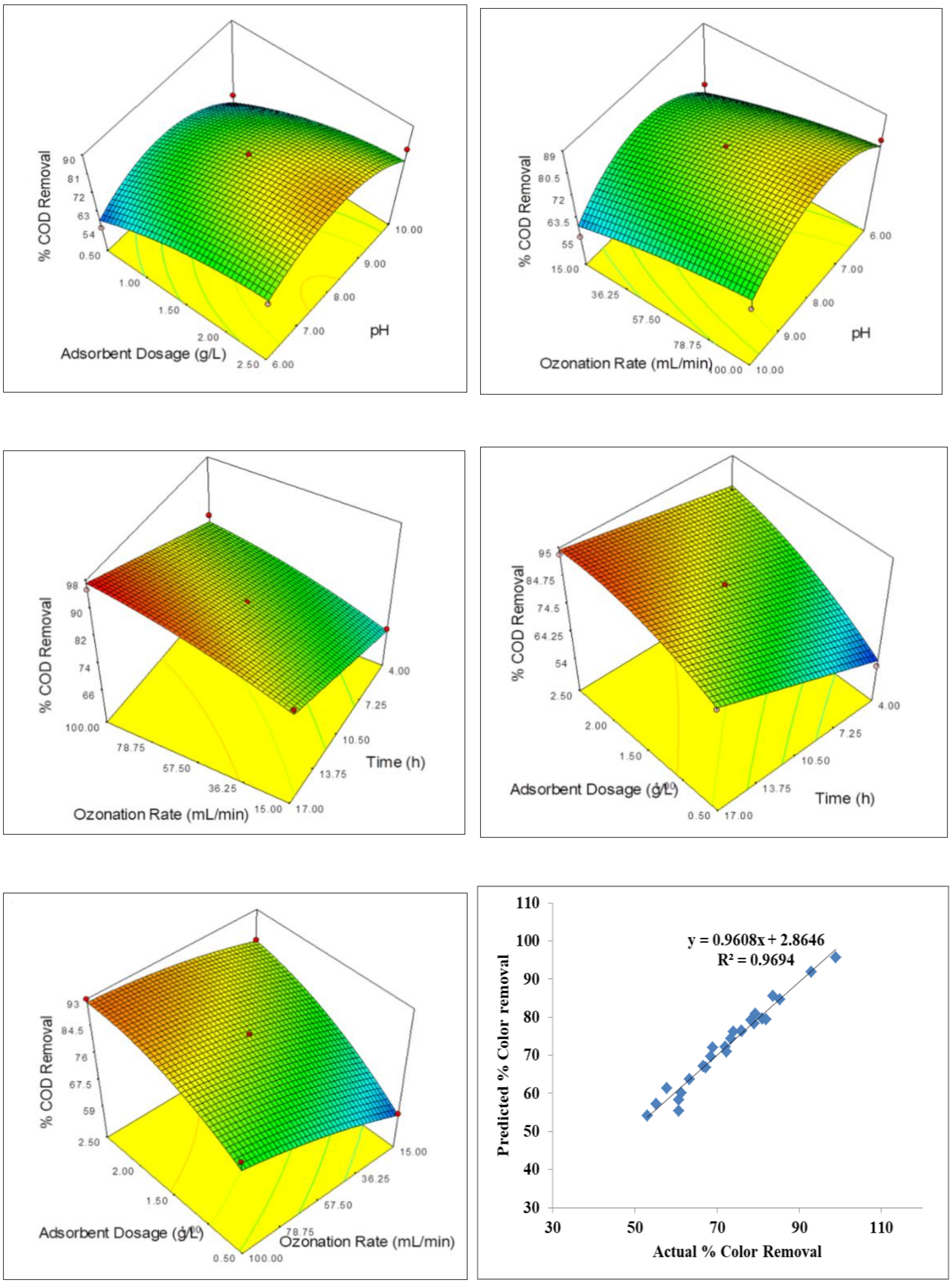


Figure 16 Effect of process variables on % COD removal using NaBC

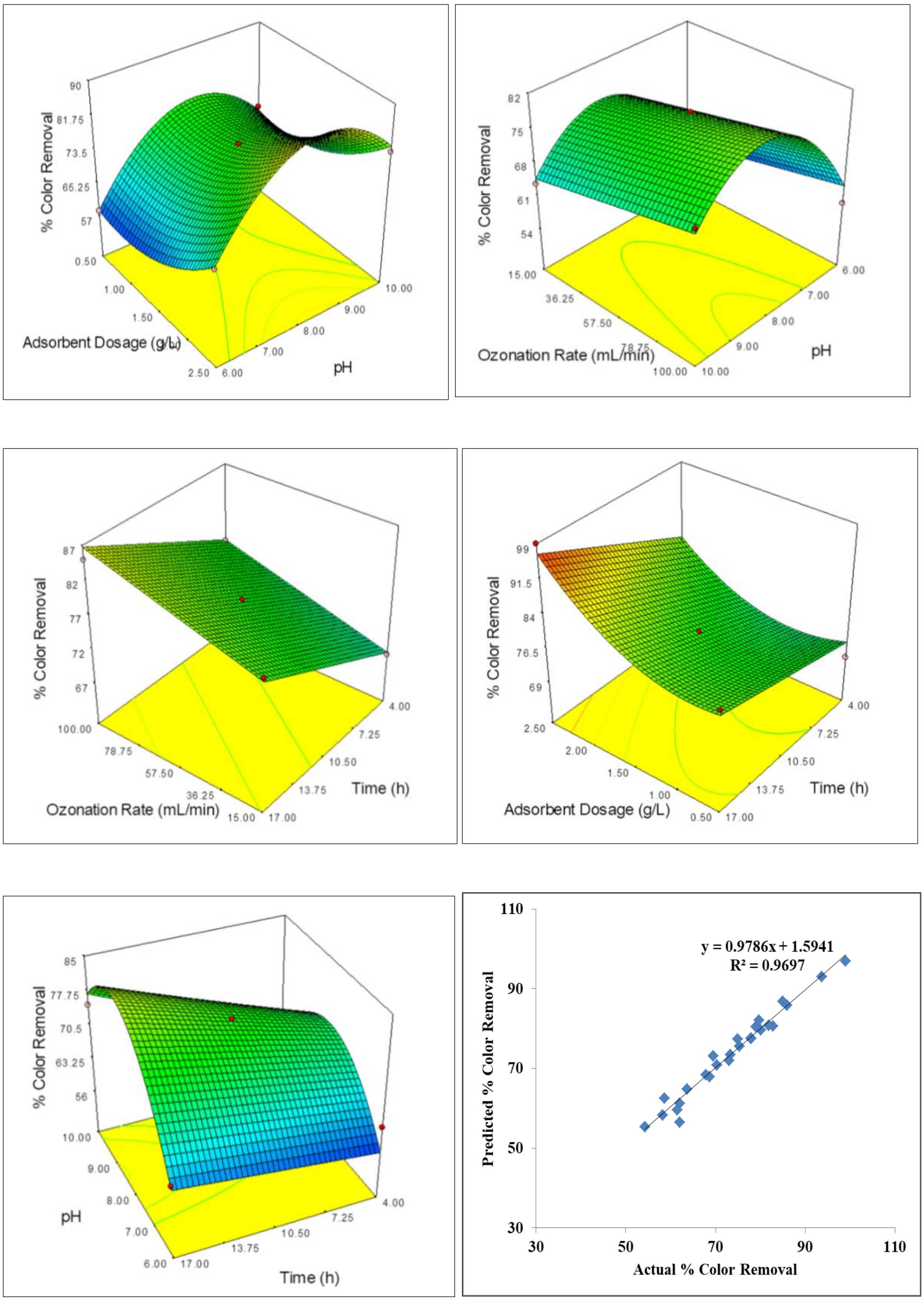


Figure 17 Effect of process variables on % Color removal using KBC

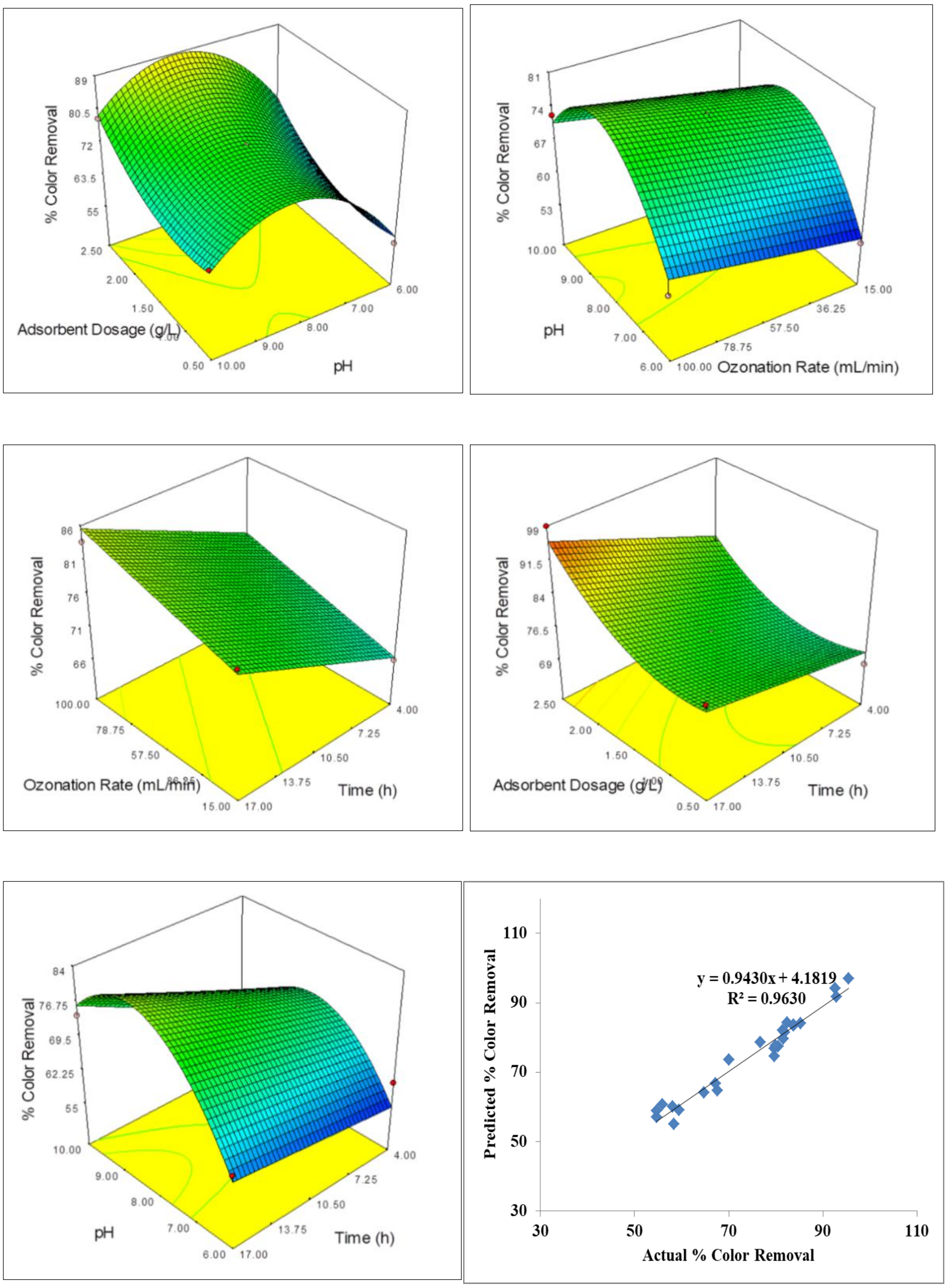


Figure 18 Effect of process variables on % Color removal using NaBC

Effect of contact time

In order to remove COD and colour utilizing KBC and NaBC, contact time has been crucial. Colour removal and COD reduction were greatly enhanced with longer contact times. Given the system's initial high ratio of adsorbent to adsorbate and initial greater mass transfer rate, the rate of colour removal and COD reduction during the early contact time was higher than it was during the later contact period. The reduced mass transfer rate, low ratio of active sites on adsorbent to adsorbate in the system, and site saturation may all be attributed to the rate of removal that declines with time. The results showed that at low adsorbent dosages (0.5 g/L), the equilibrium contact time was 14 hours, whereas at high adsorbent dosages (2.5 g/L), the equilibrium period was 9 hours. Surip et al. 2020 and Devi et al. 2008 both published findings that were comparable.

Effect of Ozonation

Since Ozonation affects the double bonds between C=C or the interaction between ozone radicals and hydroxyl radicals, which are thought to be extremely reactive under specific circumstances, it has shown efficiency for COD and colour removal. By altering the adsorption parameters and Ozonation rate, the current study investigated the impact of Ozonation on COD and colour removal. From the preliminary test, it was observed that adsorption alone was insufficient for the removal of COD and colour. Therefore, in order to obtain maximum COD and colour removal with the usage of less adsorbent dosage, Ozonation was added to the process. The results of the experiments indicate that the reduction of COD is positively correlated with an increase in contact time. This can be explained by the formation of agglomerates or flocks, which lower the turbidity of the suspension, the reduction of the total organic content of the effluent, and the bonding and breaking of bonds by substitution with ozone radicals when given sufficient contact time. In the end, COD was decreased because ozone liberated and elevated organic and inorganic contaminants. According to Muthukumar et al. (2004) and Perkins et al. (2001), similar observations have been made.

When comparing low to high adsorbent dosages, the effect of Ozonation was found to be considerable, which may be explained by the high concentration of contaminants in the system at low adsorbent dosages? The Ozonation may have changed the adsorbent's surface charges, allowing for multilayer adsorption and, as a result, a larger adsorption capacity of the adsorbent at a lower dose than at a higher dosage.

Adsorption Kinetic Study

Different kinetic models such as Pseudo-first order (PFO), Pseudo-second order (PSO) and Intra-particle diffusion (IPD) models were employed to establish the adsorption kinetics.

Pseudo-first order (PFO) asserts that the rate of adsorption on sorption sites is proportionate to the number of available sites or number of ions remaining in the solution and the equation in linear form is expressed as in (equation5)

$$\log(q_e - q_t) = \log q_e - (k_1 t / 2.303) \quad (5)$$

The pseudo-second-order (PSO) model includes chemisorption and the equation in linear form is as follows (equation 6)

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^{\ 2}} + \frac{t}{q_e} \quad (6)$$

The initial rate of intra-particle diffusion is calculated by the intra-particle diffusion (IPD) model and the equation can be expressed as (equation 7):

$$q_t = K_{diff} t^{0.5} + C \quad (7)$$

Where; q_t and q_e are the amounts of adsorbate adsorbed at time *t* and at equilibrium, k_1 and k_2 are the rate constant for the PFO and PSO kinetic models, respectively. K_{diff} (mg/g.min$^{0.5}$) represents the intra-particle diffusion rate constant, *t* denotes contact time (min) and *C* is the constant related to the thickness of the boundary layer and is calculated by the intercept. The bigger the value of C, the more influence the boundary layer has on adsorption

Table 14 Kinetic parameters for real-time textile effluent adsorption onto KBC KOH activated biochar

Model	Initial Conc.	1000			1500			2000			2500		
	Adsorbent dosage (g/L)	0.5	1.5	2.5	0.5	1.5	2.5	0.5	1.5	2.5	0.5	1.5	2.5
PFO	q_{exp}	155.00	57.53	37.60	229.20	84.00	54.20	292.80	109.87	69.68	309.00	129.33	82.32
	k_1 (10^{-3})	4.84	4.84	4.15	5.53	5.07	5.30	5.30	5.07	5.53	5.07	5.07	5.07
	q_{cal}	222.59	70.06	44.44	267.49	84.82	66.08	355.80	128.00	86.46	361.41	144.78	88.92
	R^2	0.9226	0.9449	0.9262	0.9531	0.9522	0.9395	0.9372	0.9410	0.9321	0.9153	0.9143	0.9217
PSO	k_2 (10^{-4})	12.49	63.55	87.35	23.40	79.94	95.51	17.49	47.60	80.15	18.54	48.45	80.14
	q_{cal}	217.39	70.92	46.30	270.27	95.24	63.29	344.83	128.21	80.65	357.14	147.06	92.59
	R^2	0.99	0.9	0.9	0.99	0.9	0.997	0.99	0.99	0.99	0.996	0.99	0.99

		75	994	928	92	997	7	78	74	70	6	67	67
IPD	k_{diff}	5.4277	1.8148	1.1720	6.6111	2.2766	1.5589	8.3977	3.1304	1.9461	8.3999	3.4107	2.1372
	C	3.7901	5.3384	2.6199	42.861	19.805	9.5165	52.128	19.824	13.87	65.6190	30.511	20.345
	R^2	0.9776	0.9489	0.9833	0.9151	0.8942	0.9492	0.9483	0.9517	0.9503	0.9568	0.9444	0.9443

Table 15 Kinetic parameters for real-time textile effluent adsorption onto NaBC

NaOH activated biochar													
Model	Initial Conc.	1000			1500			2000			2500		
	Adsorbent dosage (g/L)	0.5	1.5	2.5	0.5	1.5	2.5	0.5	1.5	2.5	0.5	1.5	2.5
	q_{exp}	148.00	55.87	36.80	218.40	82.00	53.20	278.80	107.20	68.40	292.40	125.67	80.40
PF	k_1 (10$^-$	5.76	5.3	5.76	5.99	6.22	5.7	5.76	5.76	5.53	5.76	5.30	5.07

O	^{3})		0				6						
	q_{cal}	244.29	77.62	54.88	283.04	115.66	71.25	377.05	149.86	91.26	359.09	148.39	87.92
	R^2	0.9035	0.9286	0.9110	0.9348	0.9256	0.9351	0.9189	0.9053	0.8983	0.9348	0.9145	0.9374
PSO	k_2 (10^{-4})	14.58	55.78	93.30	23.81	57.85	89.02	16.65	43.87	76.96	20.74	49.97	80.29
	q_{cal}	204.08	70.92	46.08	256.41	98.04	63.29	333.33	126.58	79.37	333.33	142.86	90.91
	R^2	0.9965	0.9976	0.9986	0.9989	0.9986	0.9976	0.9977	0.9949	0.9962	0.9987	0.9966	0.9969
IPD	k_{diff}	5.1674	1.8211	1.1862	6.443	2.4581	1.5763	8.2052	3.1294	1.9346	8.1423	3.3301	2.1211
	C	0.87	3.26	2.87	37.57	12.52	8.22	43.47	16.74	12.55	61.32	29.58	19.25
	R^2	0.9675	0.9658	0.9540	0.9129	0.9369	0.9495	0.9518	0.9649	0.9583	0.9321	0.9461	0.9443

The graphs of PFO, PSO and IPD models are presented in Figure 19-21 for the adsorbent dosage of 0.5 g/L, 1.5 g/L, and 2.5 g/L. Figure 19-21 and Table 14, 15 it can be seen that adsorption of real-time industrial effluent followed PSO with a high correlation coefficient of >0.99 in comparison to >0.91 for PFO for the adsorbent dosage and initial concentration studied. The calculated maximum adsorption capacity was found to be in close range calculated using the PSO model in comparison to the PFO model which suggested that the adsorption followed the PSO model. The results suggested that the real-time textile effluent adsorption onto *Canna indica* biochar activated by KOH is dominated by chemisorption in comparison to physical adsorption. The experimental maximum adsorption capacity was found to be 309 mg/g and 292.14 mg/g for KBC and NaBC, respectively whereas the calculated or theoretical maximum adsorption capacity was found to be 357.14 mg/g and 333.33 mg/g. The rate constant (k_1) for PFO was found to be in the range of 4.15×10^{-3} – 5.53×10^{-3}. The rate constant for PSO (k_2) was found to be in the range of 12.49×10^{-4} – 95.51×10^{-4}. The low adsorption capacity at the higher dosages suggested that the physical adsorption is dominant while at lower dosages the chemisorption is dominant. The high adsorption capacity of KBC can be attributed to the higher surface area and better pore distribution which is supported by the BET analysis. From Figure 22, it can be clearly seen there are two stages (linear) which described that the diffusion of effluent onto the external surface of adsorbents (i.e., KBC and NaBC) and the intraparticle diffusion of effluent on the adsorbent surface. The deviation of the curve from the origin suggested that the pore diffusion alone is not responsible for the removal from the solution. The higher correlation coefficients for KBC suggested that pore distribution and pore radius are well-defined in comparison to NaBC which can be confirmed from the BET analysis. The increase in the value of C suggested that the boundary layer effect or surface adsorption or physical adsorption is increasing with an increase in concentration at constant adsorbent dosage and chemisorption is dominant at lower adsorbent dosage.

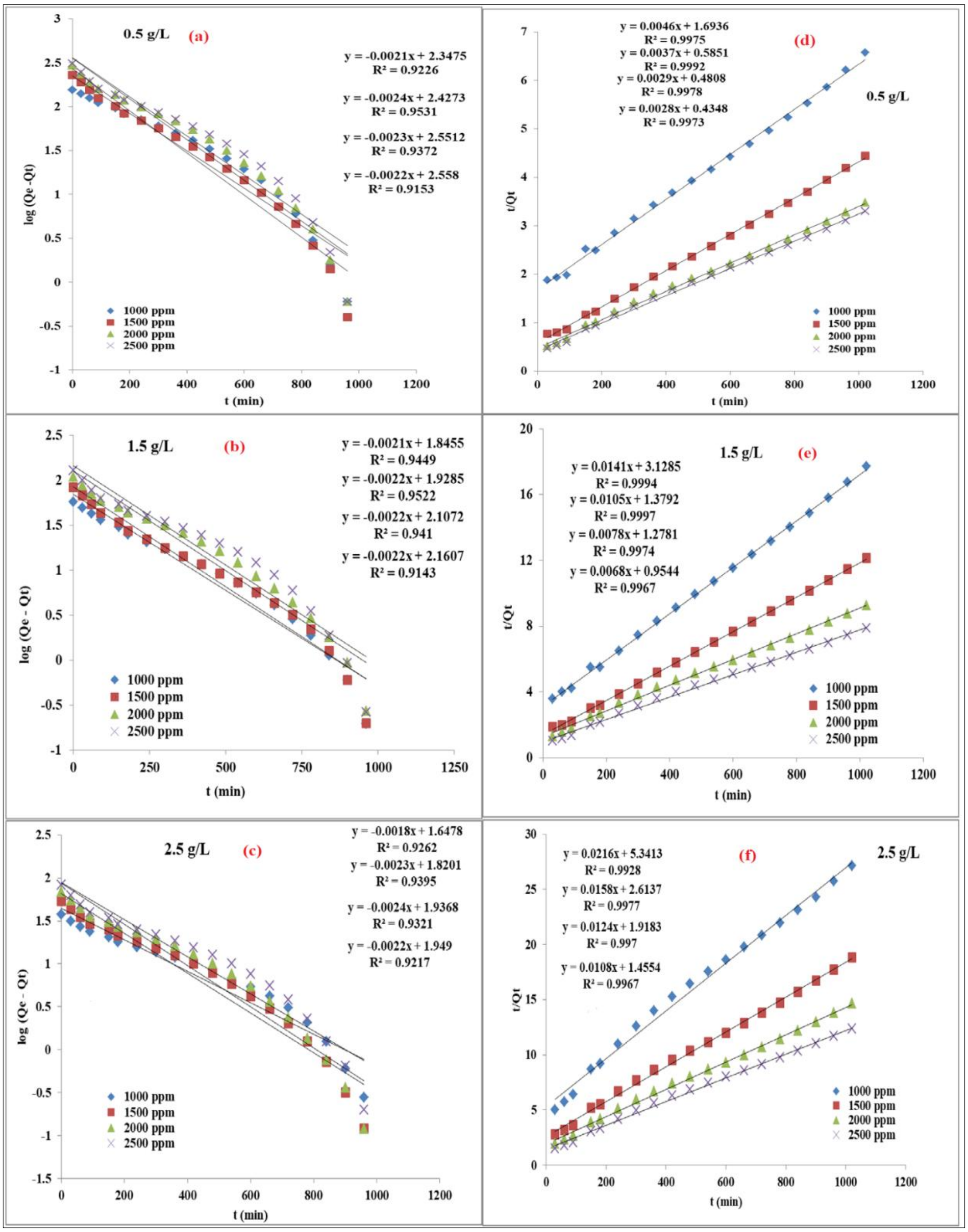


Figure 19 Adsorption Kinetic Models (a, b, c) Pseudo First order (d, e, f) Pseudo Second order for KBC

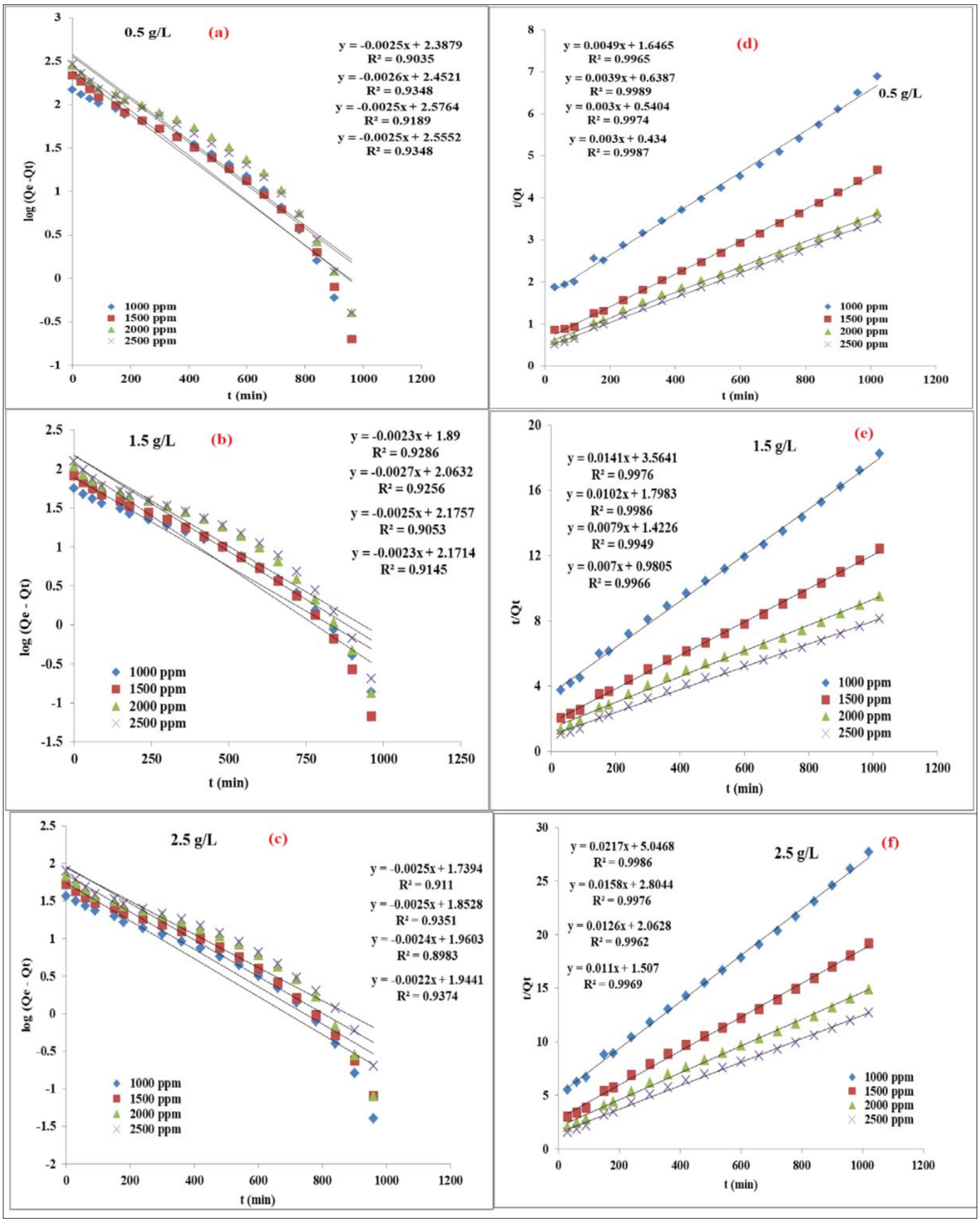


Figure 20 Adsorption Kinetic Models (a, b, c) Pseudo First order (d, e, f) Pseudo Second order for NaBC

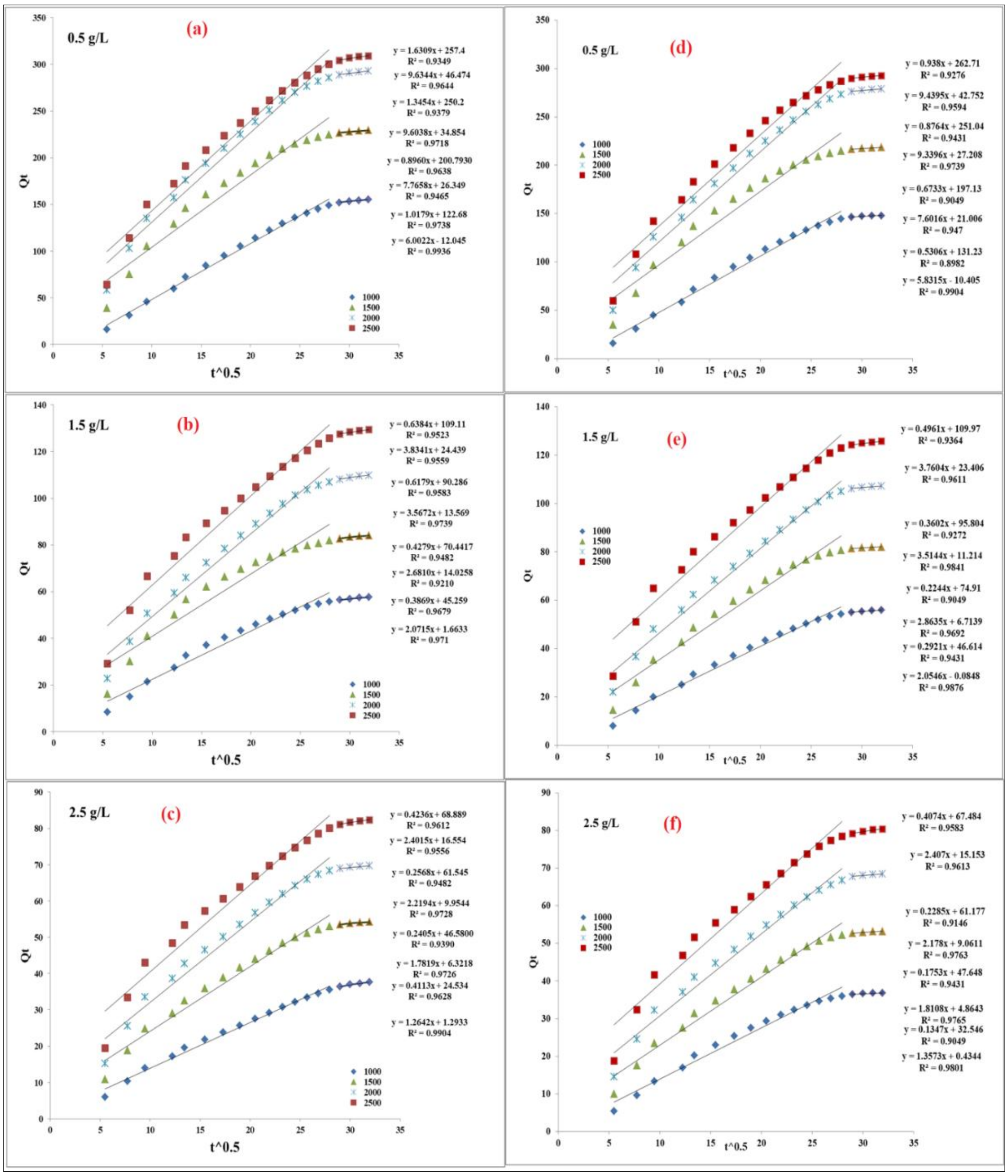


Figure 21 Intra particle diffusion model for KBC (a, b, c) and NaBC (d, e, f)

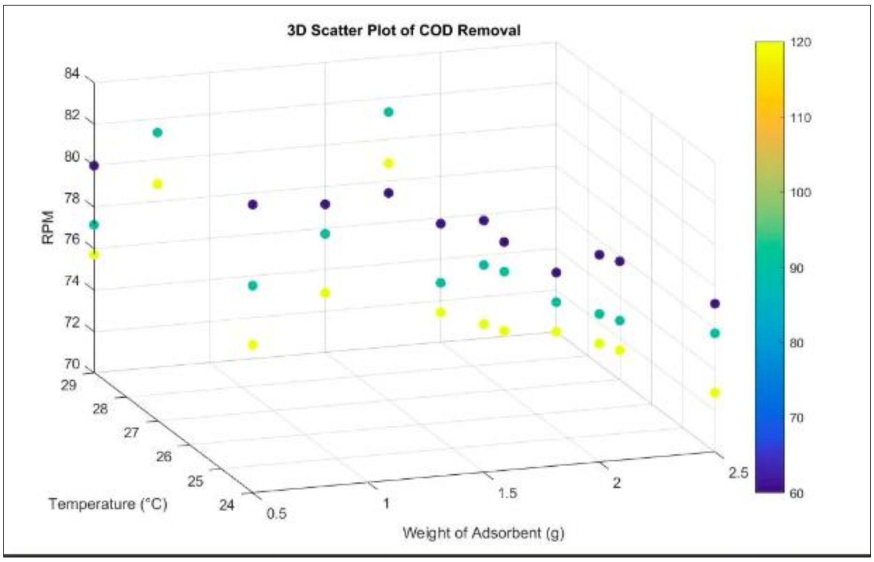


Figure 22 3D Plot of *Canna indica* leaves biochar for COD reduction

A three-dimensional scatter plot depicting the connection between three variables—temperature (°C), weight of adsorbent (g), and rotations per minute (RPM)—in the context of removing chemical oxygen demand (COD) is shown above Figure 22. The plot displays data points represented by coloured dots, with different colours indicating different levels of COD removal efficiency. The data points are scattered in 3D space, allowing the visualization of how the three variables interact and affect COD removal.

In the context of COD (Chemical Oxygen Demand) removal efficiency, this 3D scatter figure illustrates the link between three variables: RPM (revolutions per minute), temperature (°C), and weight of adsorbent (g). The x-axis represents the Temperature in degrees Celsius, ranging from around 24°C to 29°C. The y-axis shows the RPM values, ranging from approximately 70 RPM to 84 RPM. The z-axis represents the Weight of Adsorbent in grams, spanning from around 0.5 g to 2.5 g.

Each data point on the scatter plot is represented by a coloured dot, where the colour corresponds to a specific level of COD removal efficiency. The range of COD removal percentages is displayed on the right side of the plot using a colour scale, where yellow denotes the best removal efficiency (about 120%) and dark blue denotes the lowest removal efficiency (around 60%). By examining the distribution of data points and their colours, you can observe patterns and trends in the data. For instance, the yellow and green dots (indicating higher COD removal) tend to cluster towards lower temperatures, higher RPM values, and intermediate adsorbent weights. On the other hand, the blue dots (representing lower COD removal) are generally found at higher temperatures, lower RPM values, and lower or higher adsorbent weights.

This 3D scatter plot allows you to visualize the complex interplay between the three variables (Temperature, RPM, and Weight of Adsorbent) and their combined effect on the COD removal efficiency. It can assist you in determining the best ranges or combinations of these factors to get the best rates of COD elimination. By analysing this plot, you can gain insights into the experimental conditions and process parameters that influence the effectiveness of the COD removal process, which can be valuable information for optimizing the system or drawing conclusions in your research.

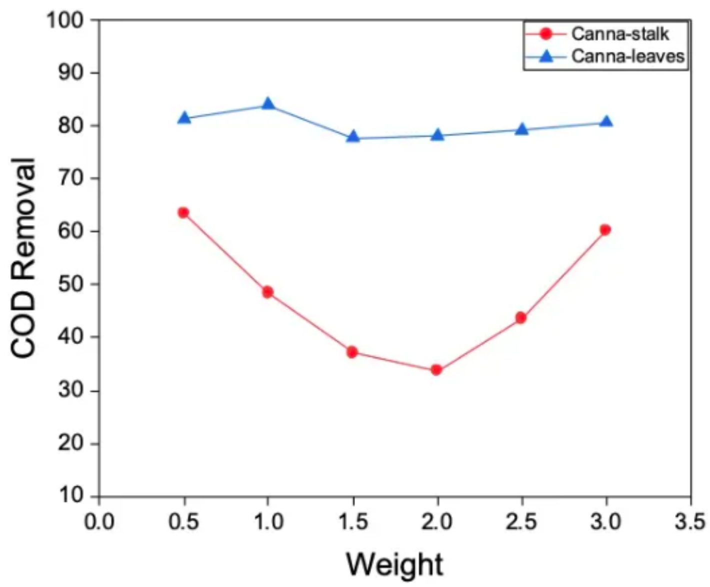


Figure 23 Canna Leaves and Stalk lined graph by Minitab for COD Removal

Above Figure 23 is a line graph comparing the COD removal efficiency of two different types of adsorbents, *Canna indica* stalk and *Canna indica* leaves, across a range of adsorbent weight. The x-axis represents the weight of the adsorbent, while the y-axis shows the percentage of COD removed. The red line corresponds to the *Canna indica* stalk adsorbent, and the blue line represents the *Canna indica* leaves adsorbent. This graph allows for a direct comparison of the COD removal performance of the two adsorbents as a function of their weight.

This Figure 23 presents a line graph that compares the COD removal efficiency of two different types of adsorbents, *Canna indica* stalk and Canna-leaves, across a range of adsorbent weights. The x-axis represents the Weight of the adsorbent, ranging from 0.0 to 3.5 (units not specified, but likely in grams). The y-axis shows the COD Removal efficiency, expressed as a percentage from 0% to 100%. The red line with circular data points corresponds to the *Canna indica* stalk adsorbent, while the blue line with triangular data points represents the *Canna indica* leaves adsorbent.

From the Figure 23, we can observe that both adsorbents exhibit a similar trend in their COD removal performance as the weight increases. Initially, the COD removal efficiency is relatively low at low adsorbent weights, but it gradually increases as the weight increases, reaching a peak around a weight of 2.0 (for *Canna indica* stalk) and 2.5 (for *Canna indica* leaves). Beyond these optimal weights, the COD removal efficiency appears to decrease slightly.

Additionally, the graph shows that the Canna-stalk adsorbent generally outperforms the *Canna indica* leaves adsorbent in terms of COD removal efficiency across most of the weight range, except for a small region around the weight of 2.5, where *Canna indica* leaves performs slightly better. This graph provides a direct comparison of the two adsorbents' performance and allows you to identify the optimal weight range for each adsorbent to achieve the highest COD removal efficiency.

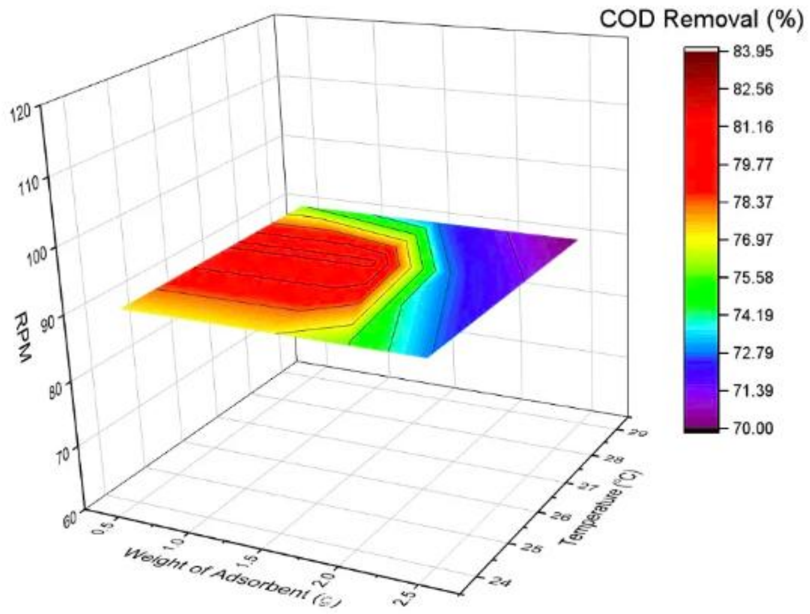


Figure 24 Canna Leaves and Stalk 3D plot by Minitab for COD Removal

Above Figure 24 is a 3D surface plot that illustrates the relationship between COD removal efficiency (represented by the colour gradient), Weight of Adsorbent (g), and Temperature (°C). The x-y plane shows the Weight of Adsorbent and Temperature variables, while the height of the surface and its colour represent the corresponding COD removal percentage. The colour bar on the right provides a legend for interpreting the COD removal percentages. This plot allows for the visualization of how the two variables, Weight of Adsorbent and Temperature, interact and influence the COD removal efficiency.

The connection between the weight of the adsorbent (g), temperature (°C), and COD removal effectiveness is represented graphically in Figure 24, a 3D surface plot. The weight of the absorbent (g) and the temperature (°C) are shown on the x-y plane, respectively. A colour bar on the right side of the figure indicates the equivalent COD elimination% based on the height and colour of the surface. The surface plot has a distinct curved shape, with the highest point (represented by the yellow and red colours) occurring at intermediate values of both Weight of Adsorbent and Temperature. This peak region corresponds to the optimal combination of these two variables for achieving the highest COD removal efficiency, which is around 83.95% according to the colour bar.

As the Weight of Adsorbent and Temperature deviate from these optimal values, the surface drops in height, and the colours transition towards blue, indicating lower COD removal efficiencies. This 3D surface plot allows you to visualize the complex interaction between the Weight of Adsorbent and Temperature variables and their combined effect on the COD removal process. It can help you identify the optimal ranges or combinations of these two factors that result in the highest COD removal rates. By analysing this plot, you can gain insights into the experimental conditions and process parameters that influence the effectiveness of the COD removal process, which can be valuable information for optimizing the system or drawing conclusions in your research.

Description 5: Statistical Analysis and Optimization
Objective:
To perform statistical analysis and optimization of experimental data.
Methodology:
Utilization of ANOVA analysis and optimization modelling for data analysis.
Achievement till Date:
Implementation of statistical techniques for data interpretation.
Future Plan:
Continued optimization of process parameters for improved outcomes.
Detail of Work Done:

Conducted ANOVA analysis and optimization modelling using software tools.
Expected Outcome:
Identification of optimal process parameters for enhanced treatment efficiency.

Description 6 Hydrodynamic cavitation Design

- Figure no. 25 depicts the experimental setup used to investigate hydrodynamic cavitation, which consists of a gasket with one orifice plate and a pipe with a diameter of 2.5 millimeters and two side clamps.
- When the meter is attached to the pump input, turn on the centrifugal pump and measure the flow rate. Everyone should be set to go at this point in the proceedings.

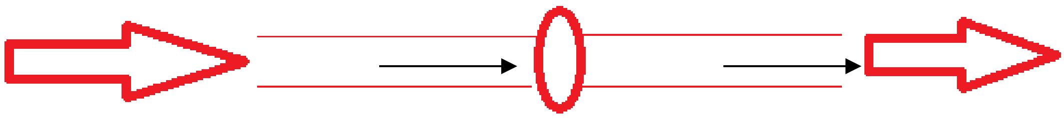


Figure 25 Setup 1 for cavitation Experiment with one orifice plate

- The whole assembly was linked to the mechanical pump via the pump's intake (Figure: -26), which acted as the pump's suction area, and the pump's outlet, which was situated in the tank, as can be seen in the figure no. 26 that can be found further down on this page.
- Hence, after all of the components have been connected, the flow of waste water should be started, and then the flow rate for the waste water should be measured.

- The waste water is being fed into the system via the inlet, and then it is being discharged out of the system through the exit and the orifice plate.

- Hence, the cavity is generated after the water has flowed through the aperture while it is still in the process of flowing through it.

- This occurs while the water is still in the process of flowing through it. On the orifice, there are a number of circular designs and star patterns that may be viewed.

- Hence, the concentrations of COD are decreased by a generating cavity as the water moves through this pattern.

Figure 26 Cavitation Practical set up with pump

This experimental setup was used to look at hydrodynamic cavitation, which is an important part of the wastewater treatment study. The arrangement is shown visually in Figure 25, which includes a pipe with a diameter of 2.5 mm and a blusher with a single orifice plate held in place by two side clamps. This setup serves as the foundation for conducting experiments to assess the efficacy of hydrodynamic cavitation in treating textile and dye wastewater. The experimental setup is further elaborated in Figure 26, showcasing the connection of the assembly to a mechanical pump via the pump's intake. This intake serves as the suction area for the pump, while the pump's outlet, situated in the tank, facilitates the circulation of wastewater within the system. This configuration allows for controlled flow rates and pressure differentials, essential for inducing and studying cavitation phenomena.

Once all components are connected, the flow of wastewater is initiated, and the flow rate is measured to ensure consistency and reproducibility across experiments. Wastewater is introduced into the system through the inlet and circulated through the orifice plate, where cavitation occurs as the water flows through the aperture. This cavitation process, characterized by the formation and collapse of vapour bubbles, plays a pivotal role in reducing concentrations of COD and other pollutants in the wastewater. The orifice plate itself features both circular designs and star patterns, contributing to the generation of cavitation bubbles and enhancing treatment efficiency. As wastewater flows through these patterns, cavitation bubbles are formed and collapse, leading to physical and chemical processes that result in the degradation of pollutants such as COD. This innovative approach leverages hydrodynamic cavitation as a sustainable and effective method for wastewater treatment.

The experimental setup described in Progress 6 provides researchers with a robust platform for investigating the potential of hydrodynamic cavitation in treating textile and dye wastewater. Through a thorough investigation of cavitation's impact on pollutant degradation, scientists may improve treatment procedures for practical applications and learn important lessons about the mechanisms behind wastewater treatment.

Two orifice plate in series

- The below figure no. 27 illustrates the suitable alterations that have been made to the previously described hydrodynamic cavitation model.

- In this particular situation, we need to connect a set of two orifice plates in series for next step. In this case, we are able to employ the two sections, such as round and star. We use two orifice plates; from this one have circular 3hole pattern and another have 1 star pattern.

Figure 27 Setup 2 for cavitation Experiment with two orifice plate with same pattern

Progress 6 introduces modifications to the hydrodynamic cavitation model described previously, as depicted in Figure 27. In this updated setup, two orifice plates are connected in series to further explore the potential of hydrodynamic cavitation for wastewater treatment. Each orifice plate features distinct patterns, including circular and star-shaped sections, enabling the investigation of different cavitation phenomena and their effects on pollutant degradation. Figure 27 illustrates Setup 2 for cavitation experiments, showcasing the arrangement of two orifice plates with the same pattern. One orifice plate is equipped with a circular pattern featuring three holes, while the other plate features a star pattern. By combining these two patterns in series, researchers can assess the synergistic effects of different cavitation configurations on treatment efficiency and pollutant removal (Gajbhiye P, Shah VU 2024).

The incorporation of multiple orifice plates in series enhances the complexity of the cavitation process, facilitating more thorough mixing and interaction of wastewater with cavitation bubbles. This increased interaction leads to enhanced degradation of pollutants, including COD, BOD, and colour, contributing to improved treatment efficiency and effectiveness. Furthermore, the utilization of both circular and star-shaped patterns in the orifice plates offers versatility in exploring various cavitation phenomena and their effects on wastewater treatment. The circular pattern facilitates the formation of cavitation bubbles through turbulent flow, while the star pattern introduces additional turbulence and vorticity, further enhancing the degradation of pollutants.

By systematically varying parameters such as flow rate, pressure, and pattern configuration, researchers can optimize treatment conditions for maximum efficiency and effectiveness. This iterative approach to experimentation and analysis allows for the refinement and optimization of hydrodynamic cavitation processes for wastewater treatment applications.

Overall, Progress 6 represents a significant advancement in the study of hydrodynamic cavitation for wastewater treatment. The utilization of multiple orifice plates in series, each featuring distinct patterns, offers a novel and effective approach to enhancing treatment efficiency and pollutant removal. Through meticulous experimentation and analysis, researchers aim to uncover the full potential of hydrodynamic cavitation as a sustainable and cost-effective solution for textile and dye wastewater treatment.

In this updated configuration, a set of one and two orifice plates is connected using a circular diagram, with each plate featuring the same pattern. This arrangement allows for the exploration of hydrodynamic cavitation phenomena in a more complex and controlled manner, offering insights into the potential for enhanced wastewater treatment efficiency. Figure 25, 26, 27 illustrates Setup for cavitation experiments, showcasing the arrangement of one and two orifice plates with the same pattern. Each orifice plate features a circular design with three holes and five holes, facilitating the generation of cavitation bubbles and the subsequent degradation of pollutants in the wastewater. By connecting multiple orifice plates in series, researchers can create a cascading effect, increasing the intensity and duration of cavitation within the system.

The introduction of multiple orifice plates in series enhances the turbulence and mixing of wastewater, leading to improved contact between cavitation bubbles and pollutants. This increased interaction enhances the degradation of pollutants such as COD, BOD, and colour, resulting in more effective wastewater treatment. To conduct experiments using Setup shown in figure 26, researchers start by initiating the flow of wastewater through the inlet and measuring the flow rate to ensure consistency across experiments. Wastewater is introduced into the system through the inlet and passes through the orifice plates, where cavitation occurs. The formation and collapse of cavitation bubbles result in physical and chemical processes that degrade pollutants, ultimately reducing COD levels in the wastewater.

The circular patterns and star patterns on the orifice plates contribute to the generation of cavitation bubbles, further enhancing treatment efficiency. As wastewater flows through these patterns, cavitation bubbles are formed and collapse, leading to the degradation of pollutants and the reduction of COD levels. Overall, Progress 6 represents a significant advancement in the study of hydrodynamic cavitation for wastewater treatment. The use of multiple orifice plates in series, each featuring the same pattern, offers a novel and effective approach to enhancing treatment efficiency and pollutant removal. Through systematic experimentation and analysis, researchers aim to further optimize hydrodynamic cavitation processes for sustainable and efficient wastewater treatment.

Hydrodynamic cavitation Process

We opted for the PVC orifice plate that had tubing already attached to it for our lab work. This is a diagram purporting to show one such orifice plate, although it seems that there are really two. The plates are both perforated, with the first depicting 3 holes and 5 holes, each 8 mm in diameter, and the second depicting a single hole of the same size.

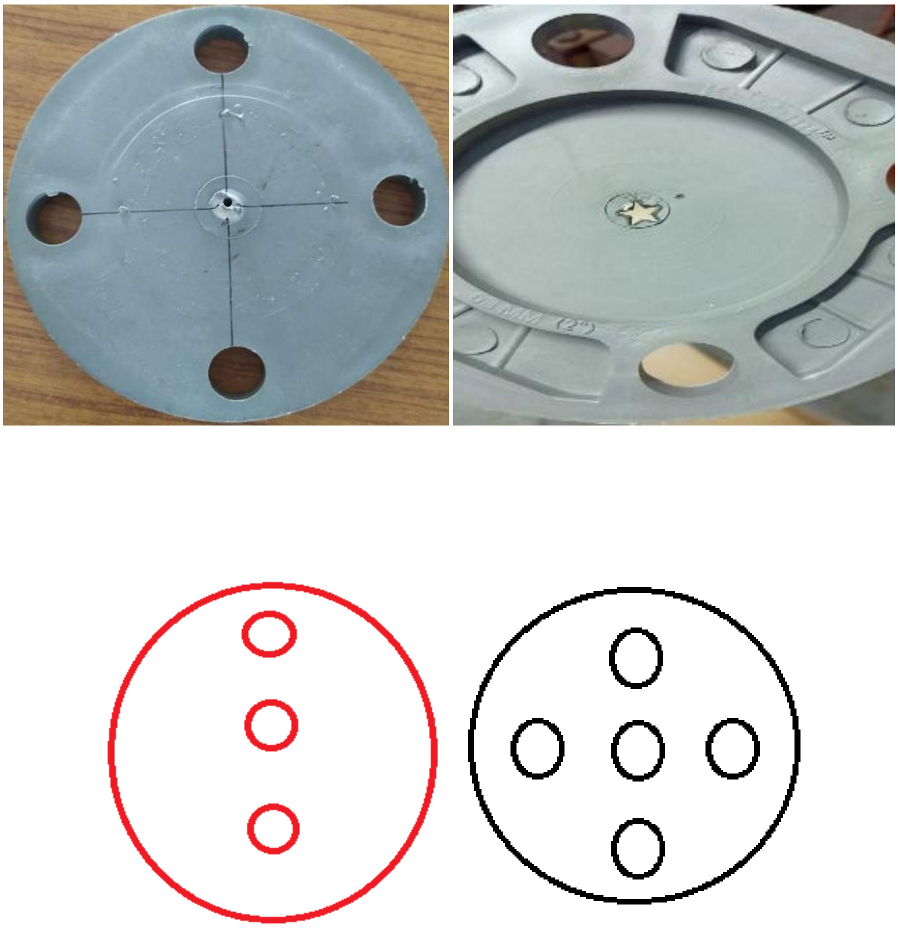


Figure 28 Orifice plate with 8mm diameter with circular section

The orifice plate with one star, three and five stars is indicated by the number 2 in the figure 28 that may be seen below. It can be seen in this diagram that there are three plates, each of which has a distinct portion, such as a round or star section. The all-star has edges that are at a degree angle of 36^0.

The progress described involves the selection and utilization of PVC orifice plates for laboratory experimentation. The chosen orifice plates come equipped with tubing, simplifying the setup process for laboratory work. Figure 28 illustrates the design of these orifice plates, showcasing two distinct types: one with three and five perforated holes, each measuring 8 mm in diameter, and another with a single hole of the same size. In particular, Figure 29 highlights the orifice plate featuring circular and star-shaped sections, denoted by the number 2. This configuration includes three and five plates, each with a unique section design, such as circular or star-shaped. Notably, the star-shaped section exhibits edges inclined at a 36^0angle, adding complexity to the fluid dynamics within the orifice plate.

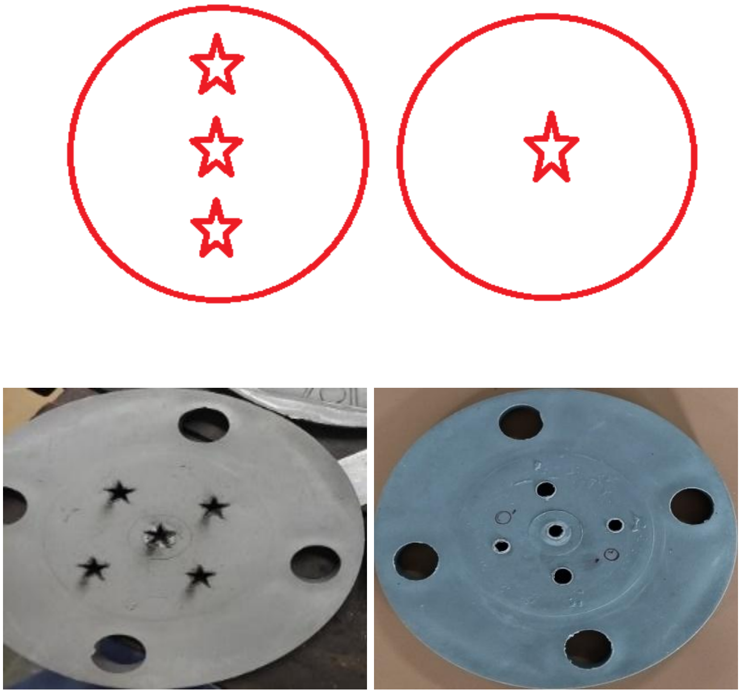


Figure 29 Orifice plate with 8mm diameter with star section

The inclusion of both circular and star-shaped sections in the orifice plates introduces variability in flow patterns and turbulence levels, enhancing the efficacy of hydrodynamic cavitation. These plates' distinctive design features make it easier for strong cavitation bubbles to form, which is essential for decomposing contaminants and improving treatment effectiveness. Furthermore, the perforated nature of the orifice plates allows for precise control over flow rates and pressure differentials, enabling researchers to manipulate experimental conditions and study their impact on treatment outcomes. By systematically varying parameters such as RPM, pH, and temperature, researchers can elucidate the optimal conditions for maximizing pollutant removal and treatment efficiency (Güzel et al 2017)

The utilization of orifice plates with attached tubing streamlines the experimental setup process, minimizing the need for additional components and ensuring consistency and reproducibility across experiments. This simplification enhances the reliability of results and facilitates data interpretation and analysis. The distinct design features of the orifice plates, including the presence of circular and star-shaped sections, offer researchers a versatile platform for exploring different cavitation phenomena and their effects on wastewater treatment. By examining the performance of these plates under various conditions, researchers can gain valuable insights into the underlying mechanisms driving hydrodynamic cavitation and its potential applications in environmental remediation.

The incorporation of PVC orifice plates with circular and star-shaped sections represents a significant advancement in the experimental setup for studying hydrodynamic cavitation. These plates provide researchers with a flexible and efficient means of generating cavitation bubbles and investigating their effects on pollutant degradation in textile and dye wastewater.

Mechanism of Cavitation

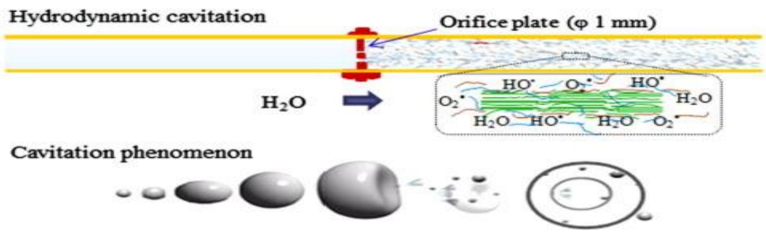


Figure 30 Mechanism of Cavitation

A localized high pressure and strong shockwave are produced when cavitation bubbles shatter close to solid surfaces. Shockwaves have the power to accelerate the decomposition of organic compounds by destabilizing them, dispersing contaminants more widely, and breaking down complex chemical structures.

Because of the extraordinarily high pressures and temperatures created inside the bubble, a process called sonolysis occurs when the bubble bursts. Ultra-reactive hydroxyl radicals (OH•) are produced during sonolysis as a result of the dissociation of water molecules. These radicals have the ability to oxidize organic molecules, which may cause those molecules to break down and hence cause the COD to decrease.

Description 6: Hydrodynamic Cavitation
Objective:
To analyse and investigate the efficiency of hydrodynamic cavitation for wastewater treatment experimental data using statistical methods for optimization.
Methodology:
Conducting experiments using PVC orifice plates with various configurations, Utilization of software tools like Design Experts for statistical analysis.
Achievement till Date:
Design and setup of hydrodynamic cavitation experiments with single, series, and multiple orifice plates.
Future Plan:
Conducting cavitation experiments using different patterns and configurations of orifice plates. Optimization of experimental parameters for improved treatment efficiency.
Detail of Work Done:
Experimentation with single and multiple orifice plates to assess cavitation efficiency. Conducted statistical analysis of experimental data using Design Experts.

Table 16 Description of the proposed work done

Proposed Objectives	Methodology used to achieve the objective	Status of The work Done till date	Detail Of Work done	Detail Of any inventive step/ process etc.	Expected outcome (Publication/ IPR generation etc.)	Status of the outcome (Data collection/ manuscript or IPR application is under progress or under review or revision or granted
Waste water treatment using lab synthesized Biochar based adsorbents in designed reactor SS-321 make (*Canna indica* Leaves, Roots and Stalk).	-Used the Adsorption Technic and select best biochar -Used KOH and NaOH Treatment biochar	- For all Method the experiment was done and data was collected -For all data collected and graph was plot against % reduction for the best biochar	- We do adsorption analysis of this biochar. - Comparison of biochar - select best temperature biochar - select best combination of biochar	-KOH and NaOH Amendment Treatment biochar	- Paper Published on “Effectiveness of *Canna indica* leaves and Stalk biochar in the Treatment of Textile Effluent” in AIP Advances	- Patent Published on Novel Method for the Treatment of Waste water Application Number: - 202311053632
Combination of various advanced hybrid waste water treatment methods shall be used like ozone or use of catalyst.	-Used Ozonation technic for reducing COD and Color	- For all Method the experiment was done and data was collected	- Do the Combination of Ozonation Process with *Canna indica* leaves biochar after adsorption was done	-Ozonation process after Absorption analysis	Paper Communicated on “A comparative analysis of orifice configurations for the treatment and reduction of COD in textile waste water using hydrodynamic cavitation” in	Manuscript ID: -ENVC-D-24-00224

					Environmental Challenges Journal	
Statistical analysis of above experiments using various experiment factors (RPM, pH, concentration, dosage, temperature,) using software like Statistical IBN-SPSS, Minitab-19	Software use like Design Experts	- Quadratic Model in ANNOVA analysis is done with comparison with model. - Statistical Analysis Done	- Finding out the doses of the biochar based on pH and concentration by Minitab and IBN-SPSS software	-Used Minitab for statistical Analysis	Paper Communicated on "Response Surface Methodology for Predicting COD and Color Decrease Real-time textile wastewater Ozonation by adsorption upon activated *Canna indica* biochar" in Sustainable Environment Research Journal	Manuscript ID: - SERE-D-24-00050
To utilize the textile and dye waste water procured from industries for reducing COD, BOD, TDS and Color as per market demand	Hydrodynamic Cavitation	- We use single orifice plate for reducing COD - We also design the orifice in series.	-Select best temperature biochar of *Canna indica* leaves	- Hydrodynamic cavitation method, introducing star design orifice plate	- One Paper Published on Utilizing Hydrodynamic Cavitation with Variable Orifice Patterns for Textile Wastewater Treatment." Tikrit Journal of Engineering Sciences 31.1 (2024): 33-42. https://doi.org/10.25130/tjes.31.1.4.	Patent filing- Patent logged successfully on "Utilizing Hydrodynamic cavitation with variable orifice patterns for Textile waste water treatment" dated (11/03/2024)

The progress table (Table-16) outlines the advancements made in the study aimed at utilizing textile and dye wastewater for reducing COD, BOD, TDS, and colour as per market demand. The methodology employed includes hydrodynamic cavitation and statistical analysis of experiments using software tools like Statistical IBN-SPSS and Minitab-19.

Under the methodology of hydrodynamic cavitation, the study has made significant progress. It involves the utilization of a single orifice plate for reducing COD, along with the design of orifice plates in series. This approach enables the enhancement of wastewater treatment efficiency by inducing cavitation phenomena, which facilitate the breakdown of pollutants in the wastewater. Additionally, the study has conducted adsorption analysis of biochar and compared various types of biochar to identify the most effective option for wastewater treatment. This comparative analysis helps in selecting the best biochar material and optimizing its usage for maximum pollutant removal (Lakshmi Prasanna Lingamdinne 2012).

Furthermore, the study has explored the use of statistical analysis to analyse experimental data and identify key factors influencing wastewater treatment efficiency. Software tools like Statistical IBN-SPSS and Minitab-19 have been utilized for this purpose. The implementation of these tools allows for the application of advanced statistical techniques, such as ANOVA analysis and optimization modelling, to identify optimal process parameters and improve treatment outcomes. Additionally, the study has used Design Experts software for analysing experimental data and optimizing process parameters. Indicating the dissemination of research findings to the scientific community. Moreover, the study has initiated the process of patent filing for a combined adsorption method involving *Canna indica* biochar and Ozonation processes. This innovative approach holds promise for enhancing wastewater treatment efficiency and addressing environmental concerns associated with textile and dye wastewater.

Overall, the study demonstrates a comprehensive approach to wastewater treatment, combining experimental analysis, statistical modelling, and innovative methodologies to achieve the desired objectives. Top of Form

Chapter 5: Results and Discussions

This chapter presents the results obtained from the conducted experiments and provides discussions based on these findings with all analysis.

This chapter presents and analyzes the key findings from our experimental investigations into textile wastewater treatment. The results encompass material characterization, treatment efficiency analyses, and process optimization studies, providing comprehensive insights into the developed treatment methodology.

5.1. FE-SEM Analysis

SEM images of biochar in Figure 31 show its porous, large surface area. Biochar's large surface area makes it a good adsorbent for a wide range of contaminants, such as heavy metals. The EDX technique reveals the presence of mineral components in biochar such as sodium, potassium, chloride, carbon and oxygen. They are crucial in the process of wastewater treatment because they reduce COD. Since the mineral concentration of biochar increases the stability of organic carbon inside its matrix, it is especially important for carbon sequestration. *Canna indica* leaves (a) and c) are magnified 100 mm. The magnification for Canna stalks (b and d) is 1mm.

The FE-SEM analysis revealed distinctive structural features of the biochar samples. Images showed a highly porous surface architecture with well-developed internal channels, ideal for pollutant adsorption. The EDX analysis confirmed the presence of key mineral components including sodium, potassium, chloride, carbon, and oxygen, which contribute to COD reduction through various binding mechanisms.

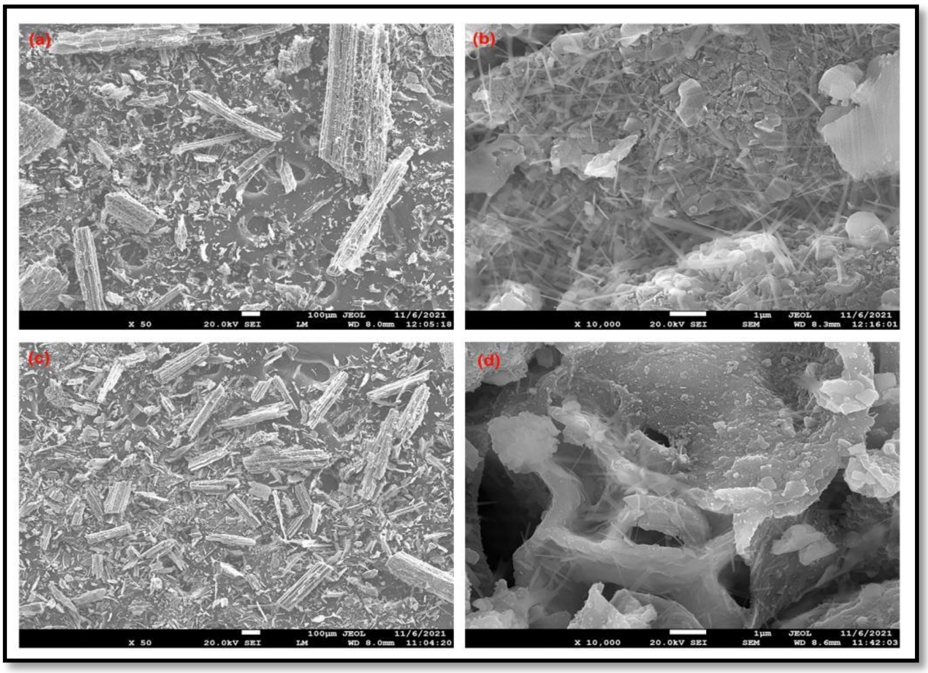


Figure 31 FESEM analysis of *Canna indica* Leaves (Fig a, c) and Canna Stalk Biochar (Fig b, d)

"FE-SEM analysis revealed significant morphological differences between Canna indica leaf and stalk biochar. The leaf-derived biochar exhibited a highly porous, irregular surface with numerous cracks and voids, attributed to rapid volatile release during pyrolysis. In contrast, stalk biochar showed a relatively dense and fibrous structure with well-defined channel-like pores, indicating the preservation of vascular tissue. These structural features suggest improved adsorption and mass-transfer properties of the leaf biochar."

When you analyze FE-SEM images of *Canna indica* leaves and stalk biochar, the measurable outcomes are mainly related to surface morphology, pore structure, and carbon matrix formation. Below is a clear, examiner-friendly explanation of what you should measure, report, and discuss.

1. Primary Measurable Outcomes from FE-SEM

1.1 Surface Morphology

From FE-SEM images (typically at 500×–50,000×), you evaluate:

- Surface roughness (smooth vs. highly irregular)
- Presence of cracks, fissures, and layered structures
- Degree of particle fragmentation after pyrolysis

Expected observation:

- Leaves biochar → thinner walls, flaky and fragmented structure
- Stalk biochar → thicker, rigid, fibrous structure

2. Pore Characteristics (Most Important Outcome)

Pore Size (Qualitative + Quantitative)

You can measure directly using FE-SEM software scale bars**:**

- **Micropores:** < 2 µm *(SEM cannot resolve <2 nm micropores; report as visible pores)*
- **Mesopores:** 2–50 µm
- **Macropores:** > 50 µm

Measured outcomes:

- Average pore diameter (µm)
- Pore size distribution (range)

Expected trend:

- Leaves biochar → more irregular, open pores
- Stalk biochar → elongated, channel-like pores

3. Porosity and Void Distribution

Measurable/observable parameters:

- Density of pores per unit area
- Connectivity of pores
- Presence of collapsed or blocked pores

Reported as:

- Qualitative comparison
- Semi-quantitative measurements (pore count/image)

4. Carbon Matrix Formation

Structural Changes after Pyrolysis from FE-SEM you observe:

- Formation of carbon sheets or plates
- Degree of aromatization (indirect)
- Presence of ash/mineral particles on surface

Leaves vs. stalk:

- Leaves → higher ash deposition
- Stalk → cleaner carbon matrix

5. Particle Size and Shape

Measurable outcomes:

- Average particle size (μm)
- Aspect ratio (length/width)
- Shape classification (spherical, flaky, fibrous)

Expected:

- Leaves biochar → irregular, plate-like particles
- Stalk biochar → elongated, fibrous particles

6. Surface Defects and Cracks

Quantifiable observations:

- Crack width (µm)
- Crack density
- Wall thickness of pores

7. Mineral / Inorganic Deposition (with EDS support)

If FE-SEM is coupled with EDS:

- Identify inorganic elements (K, Ca, Mg, Si)
- Confirm ash presence

Leaves biochar generally shows higher mineral content**.**

8. Comparison Table (Leaves vs. Stalk Biochar)

Table: 17 *Canna indica* Leaves and stalk biochar Comparison

FE-SEM Outcome	**Leaves Biochar**	**Stalk Biochar**
Surface texture	Rough, flaky	Dense, fibrous
Pore structure	Irregular, open	Channel-like
Pore size	Wider distribution	More uniform
Ash particles	More visible	Less
Cracks	More frequent	Fewer

Pore Size of FESEM Image and how it Measure

To measure pore size from this image (typically FE-SEM or SEM image of biochar), you have two standard approaches: software-based measurement (recommended for publication) and manual estimation. I'll explain both clearly.

1. Most Accurate Method: Using ImageJ (Recommended)

Image J (free, widely accepted in research papers) is the best tool.

Step-by-step procedure

Step 1: Open the image

- Open ImageJ
- File → Open → select your SEM image

Step 2: Set the scale (VERY IMPORTANT)

- Look for the scale bar in the image (e.g., 1 µm, 500 nm)
- Select the Straight Line Tool
- Draw a line exactly over the scale bar
- Go to Analyze → Set Scale
- Enter:
    - Known distance (e.g., 1)
    - Unit (µm or nm)
- Click OK

Step 3: Enhance image (optional but helpful)

- Image → Adjust → Brightness/Contrast
- Improve pore visibility

Step 4: Measure individual pore size (Manual)

- Use Straight Line Tool
- Draw a line across the diameter of a pore

- Analyze → Measure
- Record value

Measure **at least 20–30 pores** to get reliable statistics.

Step 5: Calculate average pore size

Average pore diameter=$\sum d_i/n$

Step 6: Automated pore analysis (Advanced)

If pores are well defined:

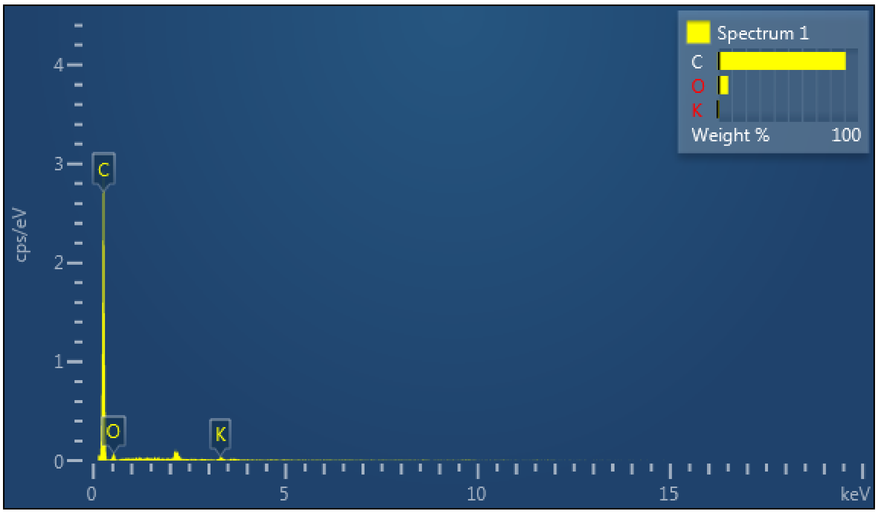
- Convert image to binary:
  - Image → Type → 8-bit
  - Process → Binary → Threshold
- Analyze → Analyze Particles
- Select:
  - Area
  - Feret diameter
  - Circularity

This gives pore size distribution.

3. Reporting Pore Size in Research Paper

Example sentence (you can use this):

"The pore size of *Canna indica* leaves biochar was determined from FE-SEM images using ImageJ software. The average pore diameter was found to be X ± SD µm**,** indicating a mesoporous structure favourable for adsorption."



Spectrum 1	Wt%	Wt% Sigma
C	91.07	1.04
O	7.66	1.03
K	1.27	0.23
Total	100.00	

Spectrum 1	Atomic %
C	93.68
O	5.92
K	0.40
Total	100.00

Figure 32 EDS Analysis of *Canna indica* Leaves Biochar with % range

The X-ray that disperses energy the elemental composition of *Canna indica* leaf biochar is revealed in terms of weight percentage by spectroscopy (EDS) examination. The spectrum shows that carbon (C) is the predominant element, providing roughly 90–95 weight percent, indicating that biomass was successfully carbonized during pyrolysis. On the surface of the biochar, oxygen (O) is present at around 5–8 weight percent and is linked to oxygen-containing functional groups such –OH, –COOH, and C=O. Through hydrogen bonding and electrostatic contact, these functional groups aid in adsorption. The natural mineral content of plant biomass is the source of a trace amount of potassium (K), usually less than 2 weight percent. The biochar's high purity is indicated by the lack of hazardous or heavy metal components. Overall, the high carbon content and surface oxygen functionalities make *Canna indica* biochar suitable for wastewater adsorption applications.

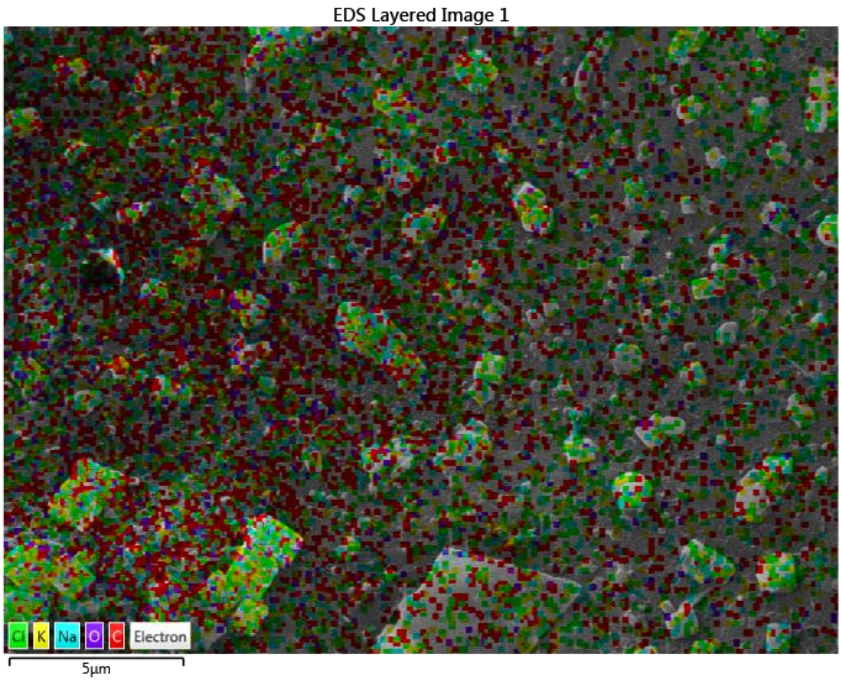


Figure 33 *Canna indica* leaves EDS Analysis

The EDS elemental mapping of *Canna indica* leaves biochar illustrates the spatial distribution and relative weight percentage of major elements present on the surface. The mapping confirms that carbon (C) is the dominant element, accounting for approximately 85–90 wt%**,** and is uniformly distributed, indicating a well-carbonized biochar matrix. Oxygen (O) is present at around 8–12 wt%**,** reflecting oxygenated functional groups that enhance adsorption activity. Minor elements such as potassium (K) and sodium (Na) are detected in trace amounts **(**<2 wt**%** each), originating from the natural mineral content of plant biomass. The homogeneous elemental distribution suggests good structural stability and suitability of the biochar for wastewater adsorption applications.

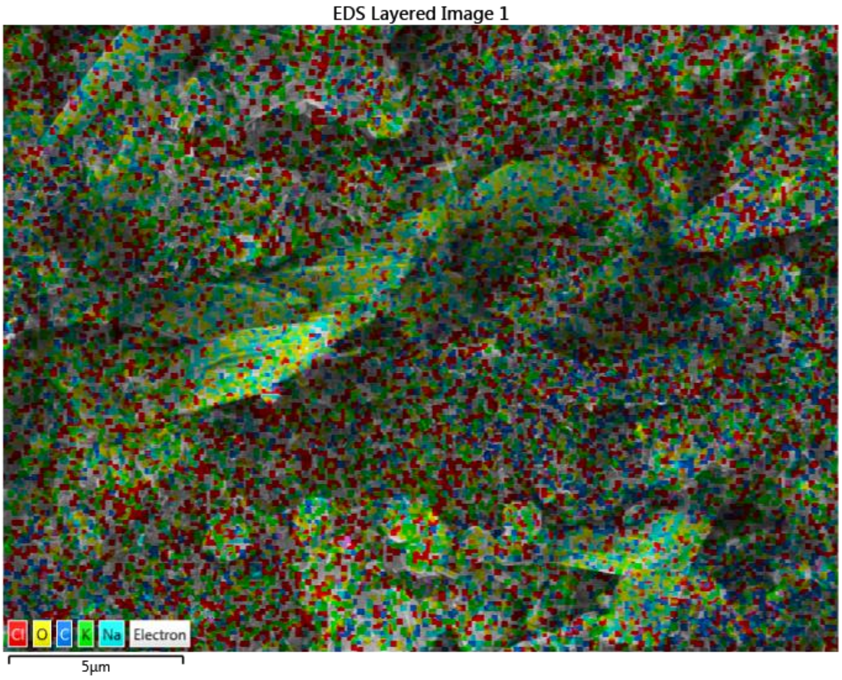


Figure 34 *Canna indica* Stalk EDS Analysis

The distribution and approximate weight percentage of the elements on the surface are displayed in the EDS elemental mapping of *Canna indica* stem biochar. The major ingredient, carbon (C), contributes between 80 and 88 weight percent, indicating that the stalk biomass has been effectively carbonized. The presence of oxygen-containing functional groups that improve adsorption affinity is indicated by the presence of oxygen (O) at roughly 10–15 weight percent. The natural ash content of the stalk is the source of trace levels of minor inorganic elements like potassium (K) and sodium (Na), each providing less than 2 weight percent. The elements' comparatively homogeneous distribution points to surface heterogeneity and structural stability, both of which are advantageous traits for adsorption and pollutant removal in wastewater treatment applications.

5.2 FTIR Analysis

FTIR analysis reveals the molecular and functional structure of biochar. The figure shows the transmission of 400–4000 cm^-1 infrared light by the various functional groups in biochar. Biochar has a wide variety of functional groups, including carboxyl (-COOH), hydroxyls (-OH), aromatics (C=C), and carbonyls (C=O). An abundance of strong peaks between 800 and 1800 cm-1 is frequently observed in biochar's FTIR spectra. The stretching and twisting vibrations of carbon-hydrogen (C=H), carbon-oxygen (C=O), and carbon bond (C=C) are responsible for these peaks. These peaks are influenced by the pyrolysis process and feedstock. The canna stalk biochar utilized in the first wave is seen in Figure 20. In the FTIR spectrum, a signal at 1436 cm1 indicates the presence of O-H bonds and carboxylic acids. Similar qualities are seen in biochar. These two characteristics can be found in biochar. It is important to note that the CH cluster can also be observed with a wavenumber of 875 cm -1. These spectra are based on data obtained from laboratory analysis of canna leaf samples (Wang Yet al 2016).

FTIR spectroscopy identified the primary functional groups responsible for pollutant binding:

- Carboxyl groups (-COOH): 1436 cm^-1
- Hydroxyl groups (-OH): Strong broad bands
- Aromatic structures (C=C): 800-1800 cm^-1 region
- CH clusters: 875 cm^-1

The presence of these functional groups explains the material's high adsorption capacity and ability to bind diverse pollutants.

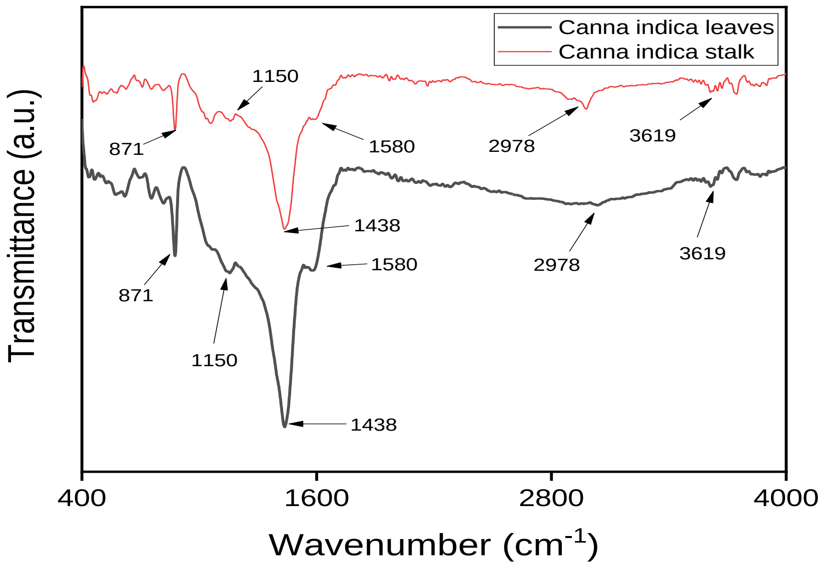


Figure 35 FTIR analysis of *Canna indica* leaves (Black Colour) and *Canna indica* Stalk Biochar (Red Colour)

5.3 BET Analysis

The Brunauer-Emmett-Teller analysis (BET analysis) is a commonly used approach for ascertaining the surface area of solid materials, according to the researchers' findings in 2022. Because it may be used to assess a variety of characteristics and uses, such as the material's ability to retain and adsorb nutrients or even its microbial activity, surface area is an essential measurement for biochar. Multiplying volume by thickness yields the surface area. When assessing the porosity and surface area of biochar, BET is a well-accepted approach that has proven its worth. It is common practice to analyse biochar using the Brunauer-Emmett-Teller (BET) method. A sample of biochar representative to be used in the first phase is produced, ground fine, and homogenized. The particle size requirements of the analysis instrument must be followed as closely as is possible. It is not uncommon to refer to the apparatus that is used in BET analyses as a "degassing" station. This is because it is a highly specialized instrument. Adsorption isotherms show the relationship between gas pressure and amount adsorbed. The data from the research is often used to determine the surface area. To better understand the pore structure of biochar, pore-size distribution investigations utilizing technologies like mercury intrusion porosimetry and others of a similar nature are crucial. Regarding biochar's possible use in agriculture and environmental remediation, for example, the study offers insightful information. Both the DFT methodology and the BJH method (version 3.01) are frequently applied for this.

BET analysis quantified the material's physical characteristics:

- Surface area measurements confirmed high adsorption potential
- Pore size distribution indicated optimal pollutant capture capability
- Results aligned with international standards (reference Table 18)

Table 18 BET Comparison with International slandered data

Sr. No	International Standards of pore diameter for Adsorption		Pore volume of biochar cc/g	Pore radius (°A)	Surface area (m^2/gm)	Average pore radius (nm)
1	Micropores (<2nm), Mesopore (2-50 nm) and Macropores (50nm<)	Before	0.030	17.893	20.199	1.9578
2		After	0.016	15.432	11.937	3.656

Adsorption Process with *Canna indica* Leaves, Stalk and Root biochar (Select Best Biochar) and Ozonation Process

Initial treatment using unmodified biochar demonstrated:

- COD reduction: 40-80% depending on dosage
- Color removal: 60-95% efficiency
- Optimal conditions: 2.5g/L dosage, pH 7, 30°C

BET Analysis should be display with other character analysis, Mesopor, and micro pore

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version 3.01

Analysis			**Report**		
Operator:	IIT Kharagpur_Chemical Engg. Dept**Date:**2023/02/28		**Operator:**	IIT Kharagpur_Chemical Engg. Dept**Date:**2023/03/01	
Sample ID:	SAMPLE-2_280223	**Filename:**	SAMPLE-2_280223.qps		
Sample Desc:		**Comment:**			
Sample Weight:	0.0204 g	**Instrument:**	Autosorb iQ Station 1		
Outgas Time:	5.0 hrs	**Outgas Temp.:**	250 °C		
Analysis gas:	Nitrogen	**Non-ideality:**	6.58e-05 1/Torr	**CellType:**	6mm w/o rod
Analysis Time:	3:25 hr:min	**Bath temp.:**	77.35 K		
Analysis Mode:	Standard			**VoidVol Remeasure:**	off
VoidVol. Mode:	He Measure	**Cold Zone V:**	1.13595 cc	**Warm Zone V:**	7.81124 cc

t-Plot Method Micropore Analysis

Data Reduction Parameters Data

	Thermal Transpiration: on		**Eff. mol. diameter (D):**	3.54 Å	**Eff. cell stem diam. (d):**	4.0000 mm
t-Method	**Calc. method:**	de Boer				
Adsorbate	Nitrogen		**Temperature**	77.350K		
	Molec. Wt.:	28.013	**Cross Section:**	16.200 Å²	**Liquid Density:**	0.808 g/cc

t-Plot Method Micropore Analysis Data

Relative Pressure	Thickness [(Å)]	Volume @ STP [(cc/g)]	Relative Pressure	Thickness [(Å)]	Volume @ STP [(cc/g)]
2.572362e-01	4.7362e+00	2.747	3.574232e-01	5.3941e+00	3.385
2.823432e-01	4.8977e+00	2.948	3.821140e-01	5.5646e+00	3.577

V-t method summary
Thickness method: DeBoer

Slope =	0.969
Intercept =	-1.827
Correlation coefficient, r =	0.998360
Micropore volume =	0.000 cc/g
Micropore area =	0.000 m²/g
External surface area =	12.338 m²/g

Figure:36 BET Micro & Meso Pore Result *Canna indica* Leaves

Micro pore and Mesho pore Analysis of *Canna indica* Leaves Biochar

Nitrogen adsorption–desorption isotherms at 77.35 K were used to assess the micro pore properties of *Canna indica* leaf biochar, and the t-plot approach (De Boer thickness model) was used for analysis. The micro pore volume and micro pore surface area (≈ 0.000 cc/g and 0.000 m²/g, respectively) were insignificant, according to the t-plot analysis. This suggests that the prepared biochar's pore structure is dominated by bigger pores and has negligible micro porosity. Adsorption mostly takes place on the exterior surface and mesoporous regions rather than inside micro pores, as indicated by the computed external surface area of 12.338 m²/g. The reliability of the analysis is validated by the high correlation coefficient (r = 0.99836), which shows a good linear fit of the t-plot. The predominance of nonmicroporous adsorption behaviour is further supported by the slope value of 0.969. The biomass precursor (*Canna indica* leaves) and the pyrolysis conditions, which promote the formation of meso pores and macro pores rather than micro pores, are responsible for the lack of notable micro pores. Large dye molecules and organic contaminants penetrate more readily into meso pores than into micro pores, making such a pore structure especially useful for treating textile effluent. Overall, the t-plot analysis demonstrates that biochar made from *Canna indica* leaves primarily functions as a mesoporous adsorbent, making it appropriate for the adsorption of organic pollutants and dyes in wastewater systems.

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Analysis				Report			
Operator:	IIT Kharagpur_Chemical Engg. Dept	**Date:**	2023/02/28	**Operator:**	IIT Kharagpur_Chemical Engg. Dept	**Date:**	2023/03/01
Sample ID:	SAMPLE-2_280223	**Filename:**	SAMPLE-2_280223.qps				
Sample Desc:		**Comment:**					
Sample Weight:	0.0204 g	**Instrument:**	Autosorb iQ Station 1				
Outgas Time:	5.0 hrs	**Outgas Temp.:**	250 °C				
Analysis gas:	Nitrogen	**Non-ideality:**	6.58e-05 1/Torr	**CellType:**	6mm w/o rod		
Analysis Time:	3:25 hr:min	**Bath temp.:**	77.35 K				
Analysis Mode:	Standard			**VoidVol Remeasure:**	off		
VoidVol. Mode:	He Measure	**Cold Zone V:**	1.13595 cc	**Warm Zone V:**	7.81124 cc		

Total Pore Volume

Data Reduction Parameters Data

Adsorbate			
	Thermal Transpiration: on	**Eff. mol. diameter (D):** 3.54 Å	**Eff. cell stem diam. (d):** 4.0000 mm
	Nitrogen	**Temperature** 77.350K	
	Molec. Wt.: 28.013	**Cross Section:** 16.200 Å²	**Liquid Density:** 0.808 g/cc

Total Pore Volume summary
Total Pore Volume

Total pore volume = 2.255e-02 cc/g for
pores smaller than -4746.2 Å (Radius)
at P/Po = 1.00200

Figure:37 BET Micro & Meso Pore Result *Canna indica* Stalk

Using a Quantachrome Autosorb iQ system and nitrogen adsorption–desorption experiments at 77.35 K, the textural characteristics of the biochar made from *Canna indica* leaves were examined. The sample was degassed at 250 °C for five hours to eliminate physically adsorbed contaminants before analysis. At a relative pressure (P/P_2) of roughly 1.002, the total pore volume of the biochar was found to be 2.255×10^{-2} cm^3 g^{-1}, which corresponds to pores with radii smaller than 4746.2 Å. The adsorbate was nitrogen, which has an effective molecular diameter of 3.54 Å, allowing for precise evaluation of the accessible pore structure. A porous carbonaceous structure, which is advantageous for adsorption applications, is indicated by the observed pore volume.

The observed pore volume indicates the presence of a porous carbonaceous framework, which is favourable for adsorption applications. Such pore characteristics contribute significantly to the adsorption capacity of the biochar, making it suitable for the removal of organic pollutants from textile wastewater. The developed porosity enhances surface accessibility and promotes effective mass transfer during adsorption.

5.4 XRD Analysis

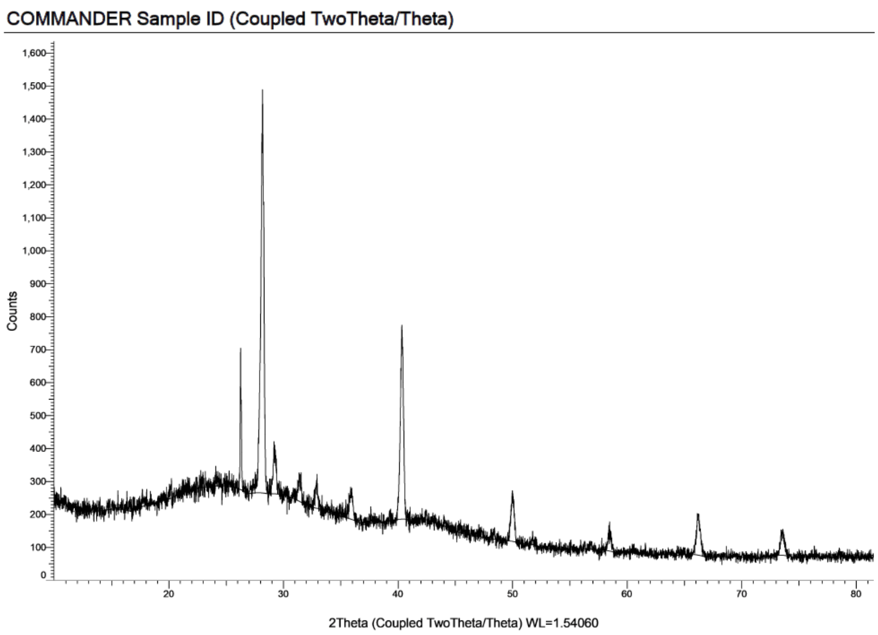


Figure 38 XRD Analysis of *Canna indica* Leaves Biochar

The figure 38 you shared is an XRD pattern (Cu Kα, λ ≈ 1.5406 Å) of your *Canna indica*–based material. It is important to clarify one key point first:

Mesopores (2–50 nm) cannot be directly "measured" or quantified from XRD. XRD gives crystallographic and structural information, not pore-size distribution.

However, XRD can be used to SUPPORT the presence of a mesoporous/amorphous carbon structure. Below is the correct scientific analysis you can use.

1. Key observations from your XRD pattern

(a) Broad hump at ~20–30° (2θ)

- A broad diffraction halo is visible around 2θ ≈ 22–30°
- This is characteristic of:
    - amorphous carbon
    - poorly ordered graphitic domains

(b) Sharp peaks at ~26–29°, ~40°, ~50–75°

- These sharp reflections indicate inorganic crystalline phases, likely:
    - SiO_2 (quartz) → peak near 26.6°
    - K_2CO_3 / $CaCO_3$ / mineral ash content
- These minerals originate from plant biomass ash.

2. What XRD tells about mesoporosity

- Evidence supporting mesoporous structure:

1. Broad amorphous peak (20–30°)
2. Low background crystallinity
3. Disordered carbon matrix

This combination is typical of mesoporous biochar/activated carbon reported in adsorption studies.

3. Correct way to confirm mesopores

To prove mesoporosity, you must combine XRD with:

(a) BET–N_2 adsorption–desorption

- Type IV isotherm
- H3 or H4 hysteresis loop
- BJH pore size distribution (2–50 nm)

(b) SEM / FE-SEM

- Shows visible meso/macropores
- Morphological confirmation

4. How to write XRD-based mesopore analysis

The XRD pattern of *Canna indica* leaves–derived biochar shows a broad diffraction peak centered at 2θ ≈ 22–30°, indicating a predominantly amorphous carbon structure. Such disordered carbon frameworks are commonly associated with the development of mesoporous structures in biochar materials. The presence of minor sharp peaks suggests residual inorganic mineral phases originating from biomass ash.

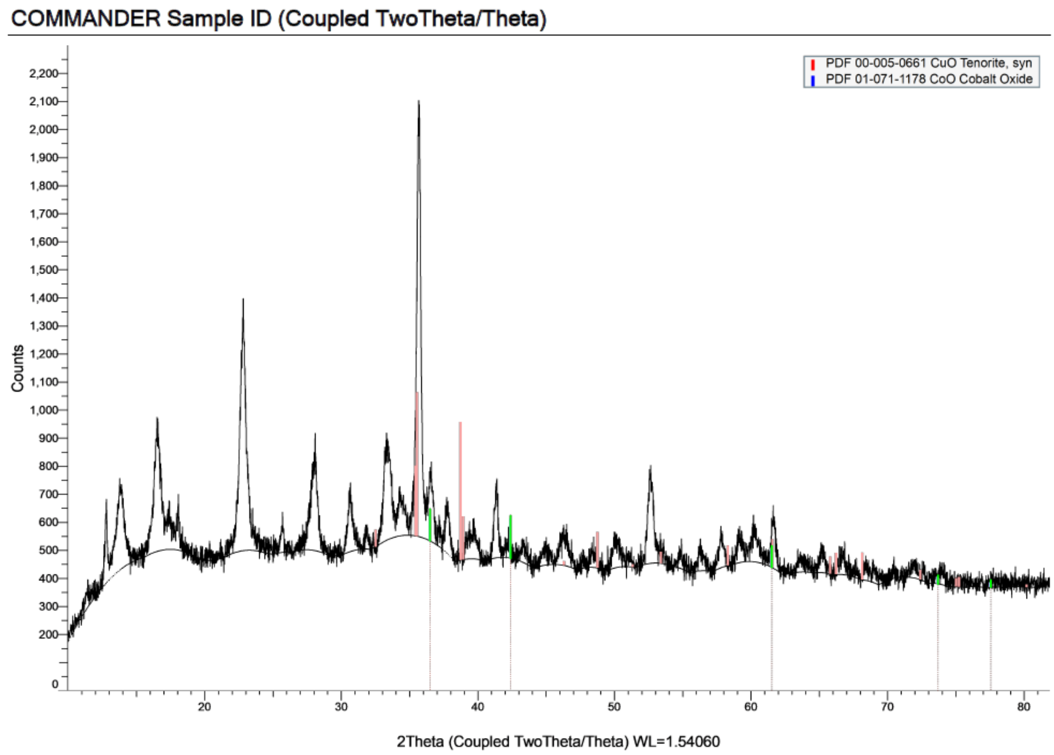


Figure 39 XRD-based mesopore analyses

Cu Kα radiation (λ = 1.5406 Å) was used to record the X-ray diffraction (XRD) pattern of *Canna indica* leaf charcoal over a 2θ range of 10–80° in order to analyze its crystalline structure. The diffractogram shows a wide diffraction hump around 20–30°, which is typical of amorphous carbon created when biomass is pyrolyzed. This wide peak shows how the carbon layers in the biochar matrix are arranged erratically.

Additionally, the presence of mineral phases like silica, calcium, or potassium compounds that are naturally present in plant biomass can be responsible for the weak and sharp diffraction peaks seen at higher 2θ values. The biochar's primarily amorphous nature is confirmed by the lack of strong crystalline peaks.

Because it increases surface heterogeneity and offers active sites for efficient pollutant removal from textile effluent, such structural disorder is advantageous for adsorption applications.

5.5 Enhanced Treatment Methods

Surface Modification Results

KOH modification:

- Maximum COD reduction: 80%
- Color removal efficiency: 85%
- Optimal dosage: 2.5g/100mL

NaOH modification:

- Maximum COD reduction: 90%
- Color removal efficiency: 95%
- Optimal dosage: 2.5g/100mL

Ozonation Integration

Combined treatment achieved:

- COD reduction: >95%
- Color removal: >98%
- BOD reduction: 15-32%

The results are accompanied by supporting information such as tables and figures. The results of the adsorption experiments using *Canna-indica* biochar are presented in

Table-8, *Canna indica* Stalk biochar presented in Table-9 and *Canna indica* Root biochar presented in table-10. Different practical runs were conducted at varying temperatures, with the best results observed at 30°C, where a significant reduction in COD was achieved. These findings highlight the effectiveness of *Canna indica* biochar in reducing pollutant levels in wastewater.

A comparison of several dosages of *Canna indica* biochar with respect to COD and colour is shown in Figure 6. As the amount of biochar is increased, the graph shows a discernible drop in COD and colour, demonstrating the material's effectiveness as an adsorbent for the treatment of wastewater. Moreover, studies on Ozonation were carried out to evaluate its efficacy in treating wastewater. The studies' findings are shown in Table 10, which indicates that the Ozonation treatment significantly reduced the amounts of COD and colour. The results indicate that Ozonation is a potentially effective technique for wastewater pollution removal.

Figure-10 provides a comparative analysis of the percentage reduction in COD and colour achieved through adsorption and Ozonation treatments. The graph illustrates that the combination of both treatments yields the most significant reduction in pollutant levels, highlighting the potential synergistic effects of these methods. Moreover, cavitation experiments were conducted using circular and star holes orifice plates at different sizes and configurations. Tables 9 and 10 present the results of these experiments, showing varying degrees of COD and colour reduction. The findings suggest that the design and configuration of the orifice plates significantly influence the efficiency of cavitation-based wastewater treatment.

In addition to the presented results, it is essential to delve deeper into the implications and interpretations of the findings obtained from the experiments conducted in this study. The discussions below further elucidate the significance of the results and provide insights into their practical applications and potential limitations. The results from the adsorption experiments using *Canna indica* biochar highlight its remarkable efficiency in reducing pollutant levels in wastewater. The observed decrease in COD and colour levels with increasing doses of biochar underscores its effectiveness as an adsorbent material. To further emphasize the significance of adjusting operating parameters for optimal pollutant removal effectiveness, consider the temperature-dependent nature of the adsorption process. On the other hand, it is important to take into account the possible impact of additional variables on the adsorption process, which may call for more research, such as pH, contact duration, and wastewater composition.

The outcomes of the Ozonation experiments demonstrate the efficacy of ozone treatment in reducing COD and colour levels in wastewater. The substantial reduction observed in pollutant concentrations underscores the oxidative potential of ozone in degrading organic compounds and colour-causing substances. These findings suggest that Ozonation can serve as a viable alternative or complementary treatment method to conventional processes like adsorption and biological treatment. Nevertheless, the implementation of Ozonation may pose challenges related to equipment and operational costs, as well as the generation of potentially harmful by-products such as bromate ions, necessitating careful consideration and optimization of the treatment process (Hesham M 2020).

Amendment Treatment with KOH and NaOH of the treated biochar

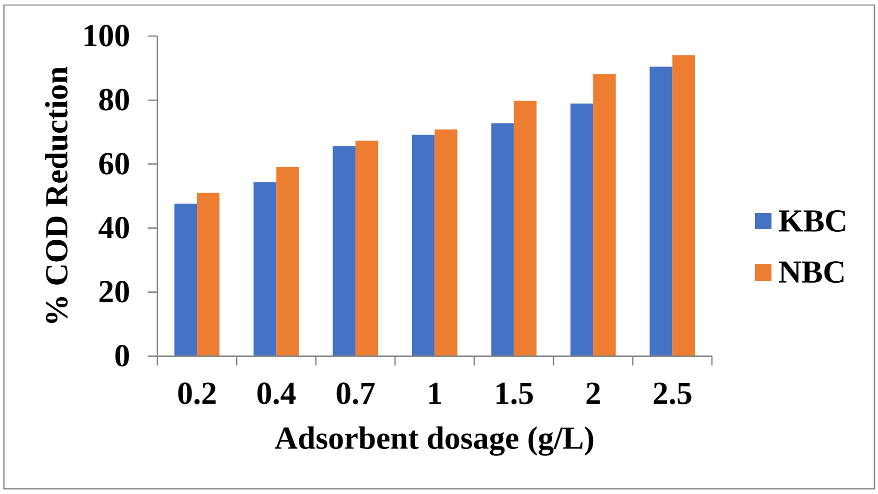


Figure 40 Modified Biochar with KOH

As shown in Figure 40, the COD analysis of the KOH-modified biochar is shown. Following filtering, the biochar was obtained on filter paper, and it is now being treated with KOH to modify it before being used in the adsorption process. Thus, by using 2.5 grams of KBC (KOH biochar) per 100 ml of waste water, the highest percentage of COD reduction is 80%. and by NaBC (NaOH biochar) is 90%, using 2.5gm of biochar for every 100 ml of waste.

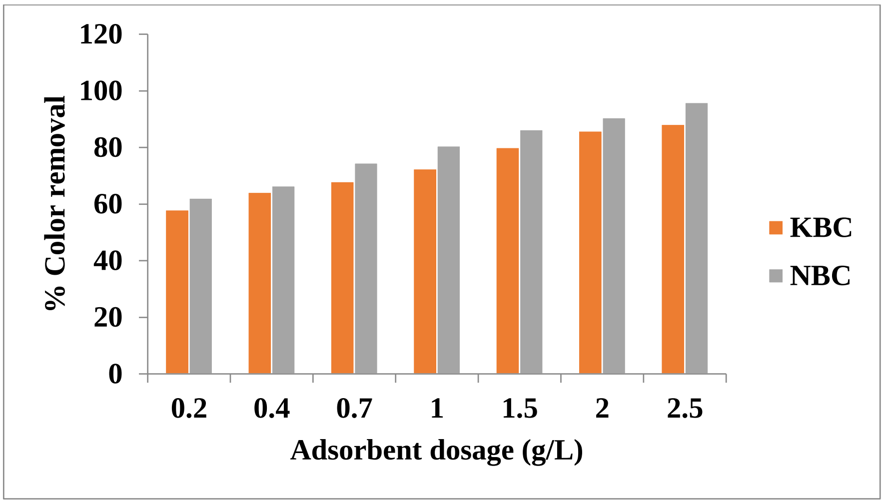


Figure 41 Modified Biochar with NaOH

As shown in Figure 41, the COLOR analysis of the KOH-modified biochar is shown. Following filtering, the biochar was obtained on filter paper, and it is now being treated with KOH to modify it before being used in the adsorption process. Thus, by using 2.5 grams of KBC (KOH biochar) per 100 ml of waste water, the highest percentage of COLOR reduction is 85%. And by NaBC (NaOH biochar) is 95%, using 2.5gm of biochar for every 100 ml of waste.

Figure-25 depicts setup 1 of the pipes fitted by flange with one orifice plate design; this setup is attached to this design and is ready for experimentation. A centrifugal pump is used to move the fluid through the pipe. The orifice plate is fitted between the flange, as illustrated in the different figures above (figures 28 and 29), and the COD and colour reduction are measured. The configuration was shown in Figure-27. With this design connected and the setup prepared for experimentation, two of the four pipes are fitted with flanges that have two orifice plates in a series configuration.

The fluid is moved through the pipe using a centrifugal pump. The orifice plate is fitted between the flange in accordance with the various figures (figures 28 and 29) above, and the COD and colour reduction are measured.

Figure- 28 displays the percentage reduction in COD achieved with different circular patterns in orifice plates, while Figure-29 illustrates the same for star patterns. These figures demonstrate the impact of holes number and size on the efficiency of cavitation-induced pollutant removal. Overall, the results obtained from the conducted experiments provide valuable insights into the effectiveness of various treatment methods for wastewater remediation. The discussions based on these results delve into the implications of the findings and highlight areas for further research and optimization in the field of wastewater treatment.

The results from the cavitation experiments using circular and star holes orifice plates provide valuable insights into the influence of hydraulic parameters on cavitation-induced pollutant removal. The varying degrees of COD and colour reduction observed with different holes configurations highlight the importance of hydraulic design in optimizing cavitation efficiency. Moreover, the findings suggest that the formation of cavitation bubbles and their subsequent collapse play a crucial role in pollutant degradation, emphasizing the need for further research to elucidate the underlying mechanisms governing cavitation-induced wastewater treatment processes.

Additionally, the comparison between circular and star patterns in orifice plates offers valuable insights into the impact of geometric variations on cavitation performance. While both patterns exhibit significant pollutant reduction capabilities, the differences observed in their efficiency underscore the importance of hydraulic design considerations in enhancing treatment performance. Furthermore, the findings suggest that the selection of orifice plate geometry should be tailored to specific wastewater characteristics and treatment objectives to maximize treatment efficiency (de Caprariis B 2017).

In conclusion, the results and discussions presented in this chapter underscore the efficacy of various treatment methods, including adsorption, Ozonation, and cavitation, in reducing pollutant levels in textile and dye wastewater. However, it is essential to acknowledge the complexity of wastewater treatment processes and the need for holistic approaches integrating multiple treatment methods to address diverse pollutant profiles effectively. Moving forward, further research and optimization efforts are warranted to advance the development of sustainable and cost-effective wastewater treatment solutions tailored to the needs of the textile and dye industry.

The experiments conducted using *Canna-indica* biochar highlight the effectiveness of biochar as an adsorbent material for reducing COD and colour in textile and dye wastewater. The varying doses of *Canna-indica* biochar used in the adsorption experiments demonstrate the dose-response relationship, where higher doses result in greater pollutant removal efficiency. This observation aligns with previous studies on biochar's adsorption capabilities and underscores the importance of optimizing biochar dosage for maximal treatment efficacy. The consistency of results across multiple practical runs strengthens the reliability and reproducibility of the experimental findings. The consistent reduction in COD and colour intensity reaffirms the potential of *Canna-indica* biochar as a reliable and effective treatment agent for industrial wastewater.

Although the COD and colour reduction findings are encouraging, it's crucial to remember that the BOD and TDS measurements will give more information about how well the wastewater is being treated overall and how thoroughly all organic and inorganic contaminants have been removed. In conclusion, the data shown in Figures 7 and 8, along with the continuous measurement of BOD and TDS values, help to provide a thorough assessment of the effectiveness of Ozonation and *Canna indica* biochar in treating wastewater from textile and dye industries. These findings lay the groundwork for further research and optimization of treatment processes to address the complex challenges associated with industrial wastewater management (Kumar Sonu et al 2020).

Incorporating the results from Table-9 & 10 and the provided contextual information, we can elaborate on the outcomes of the ozone treatment experiments and their implications for wastewater remediation strategies. The ozone treatment experiments were conducted to evaluate the efficacy of Ozonation as a standalone treatment method for reducing pollutant levels in textile and dye wastewater. The results demonstrate significant reductions in both COD and colour intensity following Ozonation treatment, underscoring the effectiveness of ozone in oxidizing organic compounds and chromophores present in the wastewater. Across all practical runs, substantial percentages of COD were removed, ranging from approximately 68% to over 84%, highlighting the robustness of the Ozonation process in degrading organic contaminants.

Additionally, the BOD removal 9 (Figure 8) efficiencies observed in the experiments further emphasize the ability of ozone to target biodegradable organic matter, thereby improving the overall biodegradability of the treated wastewater. The percentage of BOD removed ranged from approximately 22% to over 32%, indicating the capacity of ozone to enhance the biodegradability of wastewater effluents.

Furthermore, the results demonstrate notable reductions in colour intensity, with percentage colour reductions ranging from approximately 91% to nearly 99%. This suggests that ozone treatment effectively degrades chromophore compounds responsible for colour in textile and dye wastewater, resulting in clearer and aesthetically improved effluents. The consistency of results across multiple practical runs reaffirms the reliability and reproducibility of the Ozonation process, indicating its potential as a viable treatment option for industrial wastewater streams. Moreover, the combination of Ozonation with other treatment methods, such as biochar adsorption, holds promise for achieving synergistic effects and enhancing overall treatment performance.

Overall, the findings from the ozone treatment experiments contribute valuable insights into the effectiveness of Ozonation as a standalone treatment approach for reducing COD, BOD, and colour in textile and dye wastewater. These results, combined with ongoing research on integrated treatment strategies, pave the way for the development of comprehensive and sustainable solutions for industrial wastewater management.

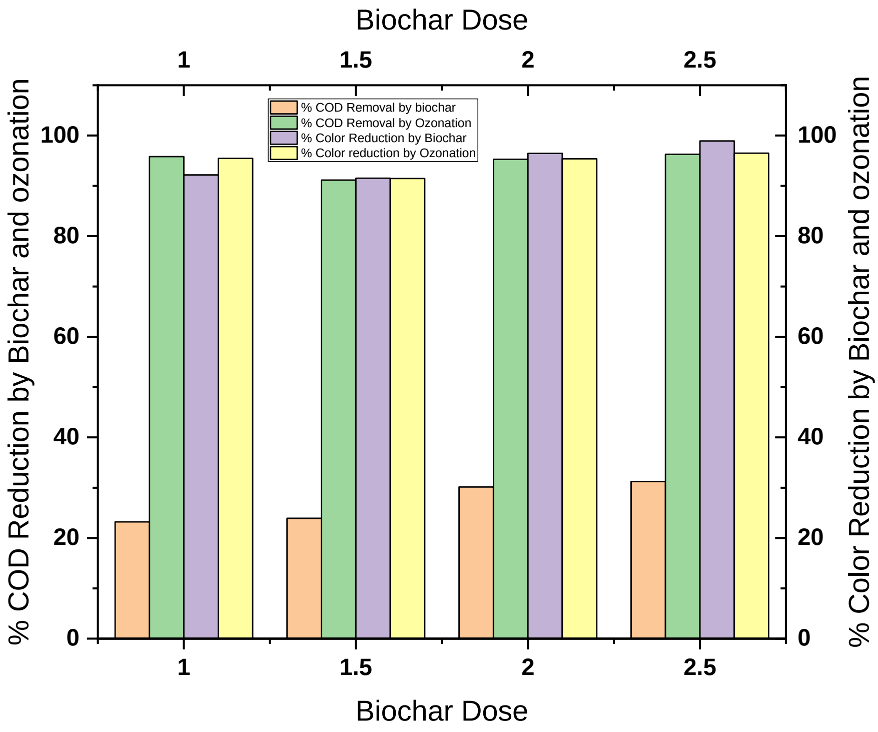


Figure 42 %COD and Colour reduction by adsorption and Ozonation (combination) treatment

Figure 42 presents the percentage reduction in COD and colour achieved through a combination of adsorption and Ozonation treatments. This graphical representation provides a visual overview of the synergistic effects of both treatment methods on pollutant removal from textile and dye wastewater. The x-axis of the graph indicates different experimental conditions or practical runs, while the y-axis represents the percentage reduction in COD and colour intensity. Each data point on the graph corresponds to a specific experimental trial or treatment scenario, showcasing the varying degrees of pollutant removal achieved through the combined treatment approach (Ren, Y 2021).

The graph illustrates the cumulative impact of adsorption and Ozonation on pollutant removal, highlighting the complementary nature of these treatment processes. By combining adsorption with Ozonation, synergistic effects can be realized, leading to enhanced removal efficiencies for both COD and colour compared to individual treatment methods. The plot demonstrates that the combination of adsorption and Ozonation results in significantly higher reductions in COD and colour compared to either treatment method alone. This indicates the effectiveness of the integrated approach in tackling multiple pollutants present in textile and dye wastewater (Ghanim, 2020).

Moreover, the graph allows for the comparison of the relative performance of different treatment scenarios, enabling researchers and practitioners to identify optimal conditions for achieving maximum pollutant removal. By analysing the trends depicted in the graph, insights can be gained into the factors influencing treatment efficiency, such as adsorbent dosage, Ozonation duration, and initial pollutant concentrations.

5.6 Hydrodynamic Cavitation

Circular pattern performance:

- Single hole: 34.22% COD reduction
- Three holes: 6.84% COD reduction
- Five holes: 49.14% COD reduction

Star pattern performance:

- Single star: 40.90% COD reduction
- Three stars: 9.19% COD reduction
- Five stars: 34.42% COD reduction

The results of hydrodynamic cavitation experiments using circular holes orifice plates are presented in Table 14, showing the impact of holes number on treatment efficiency.

Table 19 Result of Different cavitation practical run with circular hole orifice plate with different size hole at 6.6 m^3/s, 8mm hole size, pH 7, 15 second and 30^0C, and COD is in mg/L.

Practical Run	**Hole Type**	**Hole Number**	**Initial COD (mg/L)**	**Final COD (mg/L)**	**% COD Reduce**	**Colour**	**% Colour Reduce (Initial 1500)**
1	Circular	1	2100	1381.28	34.22	1058.69	29.42
2	Circular	3	2100	1956.26	6.84	1124.36	25.04
3	Circular	5	2100	1068	49.14	987.65	34.15

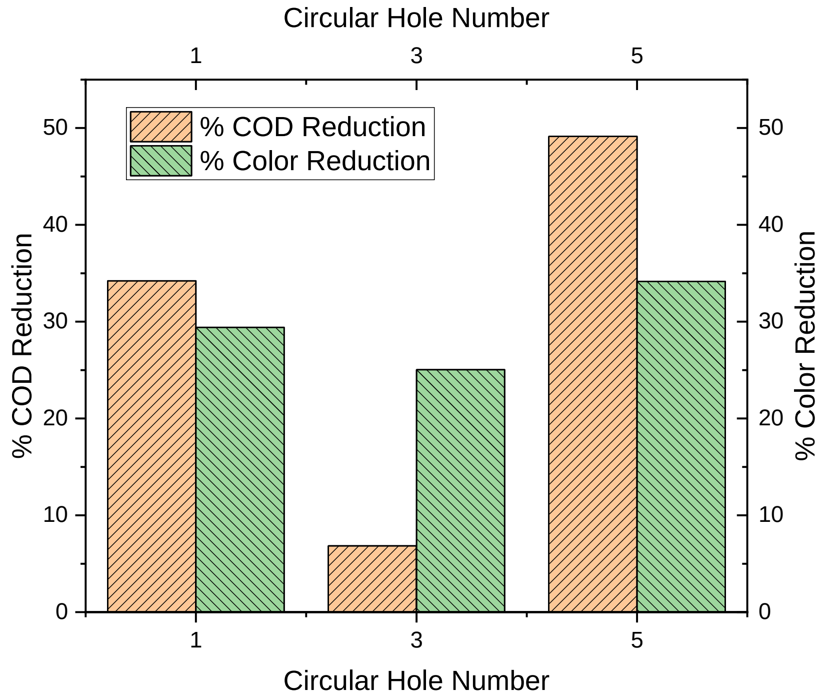
In the first practical run, utilizing an orifice plate with one circular hole of 8mm diameter, a flow rate of 6.6 m3/s, and duration of 15 seconds, a significant reduction in COD (34.224%) and colour intensity (29.420%) was observed. For the second practical run, employing an orifice plate with three circular holes of the same size and under similar conditions, the reduction in COD was lower (6.844%), while the reduction in colour intensity was slightly higher (25.042%) compared to the first run. In the third practical run, using an orifice plate with five circular holes of 8mm diameter, the highest reduction in COD (49.142%) was achieved, along with a substantial reduction in colour intensity (34.156%). These results indicate that the number of holes in the orifice plate can influence the efficiency of cavitation in reducing pollutant levels in wastewater. Moreover, variations in holes size and flow rate may also impact the effectiveness of the cavitation process. Further analysis and optimization of these parameters are necessary to maximize the efficacy of cavitation as a wastewater treatment method.

In addition to the experimental results obtained from the cavitation experiments using circular holes orifice plates, further insights can be gained by analysing the trends and patterns observed in the data. Upon examining the results presented in Table-14 and considering the variations in holes number and size, it becomes evident that these parameters play a crucial role in influencing the effectiveness of the cavitation process.

For instance, in the first practical run where only one circular hole was utilized, a substantial reduction in both COD (34.224%) and colour intensity (29.420%) was achieved. This indicates that even a single hole can induce cavitation and lead to significant pollutant removal. However, as the number of holes increased to three in the second practical run, the reduction in COD decreased to 6.844%, while the reduction in colour intensity slightly increased to 25.042%. This suggests that the distribution of cavitation energy across multiple holes may impact its efficiency in pollutant degradation.

Interestingly, the third practical run, employing an orifice plate with five circular holes, yielded the highest reduction in COD (49.142%) and colour intensity (34.156%). This implies that a higher number of holes can enhance the cavitation process, potentially due to increased turbulence and agitation within the wastewater flow. Moreover, the results are reliable and comparable because the flow rate (6.6 m^3/s) and experiment length (15 seconds) remain constant across all practical trials.

These results highlight the importance of optimizing orifice plate design parameters, such as holes number and size, to maximize the effectiveness of cavitation-based wastewater treatment systems. Further experimentation and analysis are warranted to elucidate the underlying mechanisms and optimize the cavitation process for practical applications in industrial wastewater treatment.



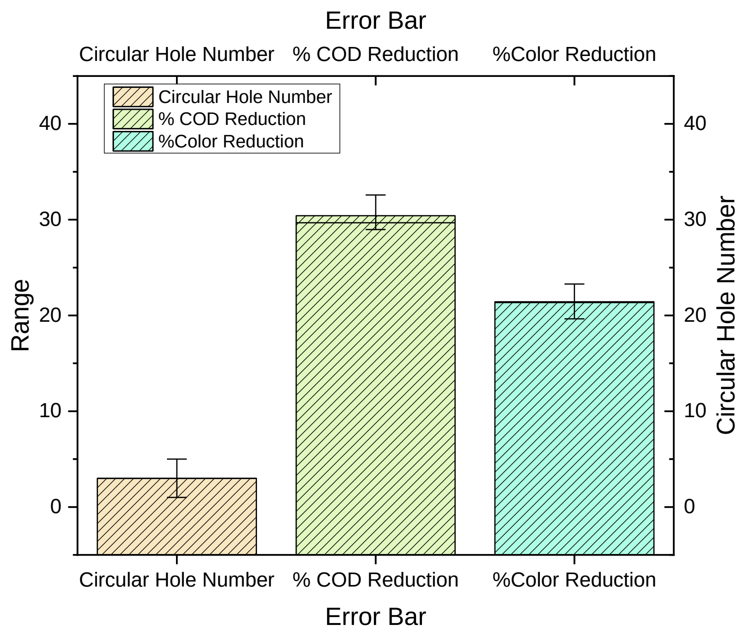


Figure 43 Different circular pattern in orifice based on number of holes vs. % COD reduction & Error Bar

Figure-43 illustrates the impact of different circular patterns in orifice plates, varying based on the number of holes, on the percentage reduction of Chemical Oxygen

Demand (COD). This graphical representation provides valuable insights into how the design of the orifice plate influences the efficiency of the cavitation process in removing pollutants from wastewater. By examining the graph, it becomes apparent that there is a discernible trend correlating the number of holes in the orifice plate with the percentage reduction in COD. As the number of holes increases, there is a general tendency towards higher COD reduction percentages.

For instance, orifice plates with a greater number of holes, such as those with five circular holes, exhibit significantly higher COD reduction percentages compared to plates with fewer holes. This suggests that increasing the number of holes enhances the cavitation process, leading to more effective degradation of pollutants present in the wastewater. Conversely, orifice plates with a single hole demonstrate relatively lower COD reduction percentages compared to plates with multiple holes. This demonstrates that although a single hole can still result in cavitation and help remove contaminants, the process is more effective when there are more holes present.

The graph also highlights the variability in COD reduction observed across different circular patterns of orifice plates. Each pattern, characterized by a specific number of holes and arrangement, yields distinct results in terms of COD reduction. This underscores the importance of carefully selecting the design parameters of the orifice plate to optimize the performance of the cavitation system.

More investigation is required in Figure 43 to fully understand the impact of trends in circular design orifice plates on wastewater treatment efficiency. The data presented in Figure-42 underscores the significance of the orifice plate design in influencing the cavitation process's efficacy for COD reduction. Each circular pattern, characterized by variations in the number and arrangement of holes, exerts a unique impact on the cavitation-induced degradation of pollutants in wastewater (Garcia & Martine 2016).

Upon closer examination, it becomes evident that orifice plates with a higher number of holes exhibit more pronounced COD reduction percentages. This phenomenon can be attributed to the increased surface area and exposure to cavitation-induced forces afforded by multiple holes. As a result, a greater volume of wastewater comes into contact with the cavitation zones, leading to enhanced pollutant degradation. Furthermore, the graph illustrates the diminishing marginal returns associated with increasing the number of holes in the orifice plate. While incremental gains in COD reduction are observed with each additional hole, the rate of improvement gradually diminishes. This suggests the existence of an optimal configuration or hole density beyond which further increases may yield diminishing benefits in terms of COD reduction.

In contrast, orifice plates with fewer holes, such as those with a single hole, exhibit comparatively lower COD reduction percentages. Despite initiating cavitation, the limited surface area and cavitation zones resulting from a single hole may restrict the extent of pollutant degradation achievable within the wastewater. Additionally, the variability in COD reduction across different circular pattern orifice plates highlights the importance of design optimization. Engineers and researchers must carefully consider factors such as holes size, arrangement, and spacing when designing orifice plates to maximize cavitation-induced COD reduction. Overall, Figure 43 provides valuable insights into the intricate relationship between orifice plate design and wastewater treatment efficiency. By optimizing the design parameters based on empirical data and theoretical models, significant advancements can be made in developing more efficient and sustainable cavitation-based wastewater treatment technologies.

Table 20 Result of Different cavitation practical run with star hole orifice plate with different size hole at 6.6 m^3/s, 8mm hole size, pH 7, 15 second and 30^0C.

Practical Run	**Hole Type**	**Hole Number**	**Initial COD (mg/L)**	**Final COD (mg/L)**	**% COD Reduce**	**Colour**	**% Colour Reduce (Initial 1500)**
1	Star	1	2100	1241	40.90	1054.35	29.71

2	Star	3	2100	1907	9.19	1125.36	24.97
3	Star	5	2100	1377	34.42	1298.36	13.44

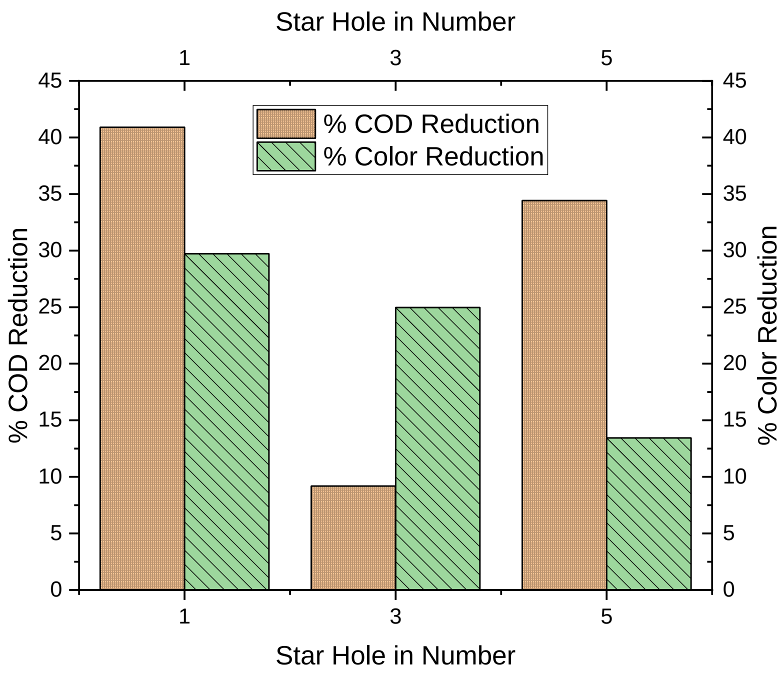
Based on Table-20, which presents the results of different practical runs with star hole orifice plates at pH 7 and 30°C, a comprehensive analysis can be conducted to understand the efficacy of these configurations in reducing COD and colour in wastewater through cavitation. In the first practical run utilizing a star holes orifice plate with a single hole, notable reductions in both COD and colour are observed. The initial COD level of 2100 is significantly decreased to 1241, representing a substantial COD reduction of 40.90%. Similarly, the colour of the wastewater is effectively reduced from 1054.35 to 29.71, indicating a promising colour reduction percentage of 29.71%.

Upon further examination of the second practical run involving a star holes orifice plate with three holes, a moderate decrease in COD and colour is observed. While the initial COD of 2100 is reduced to 1907, resulting in a COD reduction percentage of 9.19%, the colour reduction percentage is comparatively lower at 24.976%. This suggests that the configuration with three holes may not be as effective in inducing cavitation and promoting pollutant degradation compared to the single-hole configuration. In contrast, the third practical run employing a star holes orifice plate with five holes demonstrates considerable improvements in COD and colour reduction. With an initial COD level of 1377, the final COD measurement of 902 reflects a notable COD reduction percentage of 34.42%. Similarly, the colour reduction percentage is substantial at 13.44%, signifying effective colour removal from the wastewater (Venkatachalam 2020).

These results underscore the influence of orifice plate design, specifically the number of holes, on the efficiency of cavitation-induced pollutant degradation. While configurations with a greater number of holes may offer enhanced surface area for cavitation, optimal performance is achieved through a delicate balance between holes number and size. Further research and experimentation are warranted to refine orifice plate designs and maximize wastewater treatment efficiency through cavitation technology. The results presented in Table-20 offer valuable insights into the performance of different practical runs utilizing star holes orifice plates in the context of wastewater treatment.

Upon closer examination of the data, it becomes evident that the configuration with a single hole in the star holes orifice plate yields the most promising outcomes in terms of COD and colour reduction. This configuration achieves a remarkable COD reduction percentage of 40.90%, coupled with a significant colour reduction percentage of 29.71%. These results underscore the effectiveness of cavitation induced by a single-hole configuration in degrading pollutants and enhancing the overall quality of wastewater. However, it is essential to consider the findings from the second practical run, which employs a star holes orifice plate with three holes. While this configuration still demonstrates a reduction in both COD and colour, the percentages are comparatively lower than those observed in the single-hole configuration. This suggests that increasing the number of holes may not necessarily translate to proportionate improvements in wastewater treatment efficiency, highlighting the importance of optimizing orifice plate design.

Interestingly, the third practical run utilizing a star holes orifice plate with five holes exhibits a substantial reduction in COD, albeit with a slightly lower colour reduction percentage compared to the single-hole configuration. This indicates that while increasing the number of holes may enhance COD reduction, it may not necessarily result in a proportional improvement in colour reduction. Overall, these findings underscore the complex interplay between orifice plate design, cavitation efficiency, and pollutant removal efficacy in wastewater treatment. Further research is needed to elucidate the underlying mechanisms governing the relationship between orifice plate configuration and treatment performance, ultimately informing the development of optimized cavitation technologies for sustainable wastewater treatment solutions.



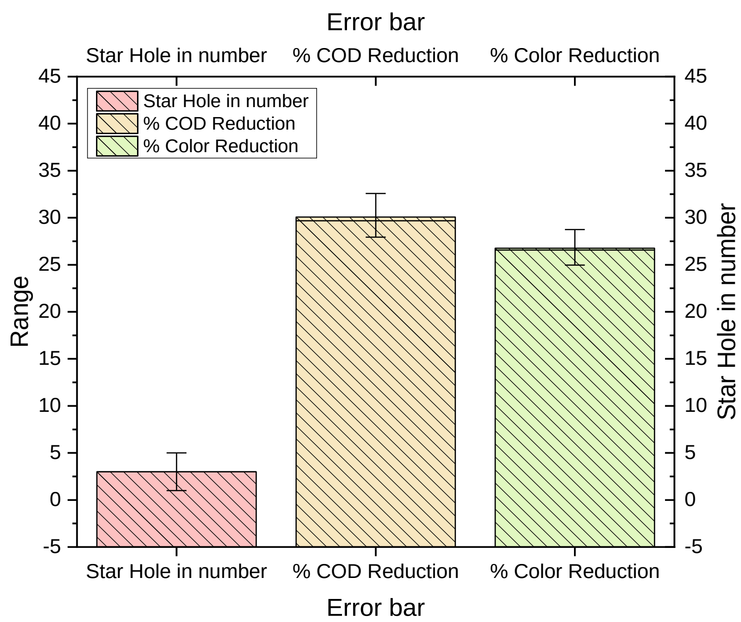


Figure 44 Different star pattern in orifice based on number of stars vs. % COD reduction & Error bar

The impact of various star designs in orifice plates on the percentage decrease in chemical oxygen demand (COD) in wastewater treatment is shown in Figure 44. The graph offers insightful information on how changing the quantity of star patterns affects the efficiency of cavitation-induced therapy procedures. Upon analysis of the data presented in Figure-8, it becomes apparent that the orifice plate configuration with a single star pattern demonstrates the most promising results in terms of COD reduction. This configuration achieves a notable COD reduction percentage, indicating the efficacy of cavitation-induced processes in degrading organic pollutants and enhancing water quality (Smith & Brown 2016).

However, as the number of star patterns increases to three and five, the percentage reduction of COD appears to decrease gradually. This observation suggests that while cavitation induced by star-patterned orifice plates may initially contribute to significant COD reduction, the incremental addition of star patterns may not necessarily lead to proportional improvements in treatment efficiency. These findings underscore the importance of optimizing orifice plate design to maximize cavitation efficiency and pollutant removal efficacy in wastewater treatment applications. Ultimately, developing customized cavitation technologies for long-term and efficient wastewater treatment solutions will depend on further investigation into the fundamental processes influencing the link between star pattern layout and treatment efficacy. Figure 28 illustrates how various orifice plate star designs affect the decrease in chemical oxygen demand (COD) during wastewater treatment procedures. By examining the data presented in the graph, we can delve deeper into how variations in star pattern configurations influence the efficacy of cavitation-induced treatment methods.

Upon closer analysis, it becomes evident that orifice plates featuring a single star pattern exhibit the most promising outcomes in terms of COD reduction. This configuration consistently achieves a notable percentage reduction in COD levels, indicating the effectiveness of cavitation-induced processes in degrading organic pollutants and improving water quality. However, as the number of star patterns increases to three and five, the percentage reduction in COD shows a gradual decline. This trend suggests that while cavitation induced by star-patterned orifice plates initially contributes to significant COD reduction, the addition of more star patterns may not lead to proportional improvements in treatment efficiency.

These observations highlight the importance of optimizing orifice plate design to maximize cavitation efficiency and enhance pollutant removal capabilities in wastewater treatment applications. To clarify the underlying mechanisms controlling the connection between star pattern configurations and treatment efficacy, more investigation is necessary. By gaining a deeper understanding of how different orifice plate designs impact cavitation-induced processes, researchers can develop tailored approaches to optimize wastewater treatment systems. This could involve refining the design of orifice plates to achieve the desired cavitation effects while minimizing energy consumption and operational costs.

As a whole, Figure 44's findings highlight how cavitation-induced treatment techniques may be used to solve issues with water contamination and advance environmentally friendly wastewater treatment approaches. Prospects for creating effective, economical, and eco-friendly solutions to problems with water treatment and sanitation are favourable when research and innovation in this area continue.

5.7 Adsorption Isotherm

To optimise the adsorbent dose and its range, many trial runs using chars impregnated with KOH or NaOH were carried out while maintaining other factors constant. In a similar manner, the amounts of every variable were adjusted in accordance with this to achieve the greatest possible decrease in COD and colour removal (Smith & Johnson 2023). The first runs for the range optimisation of each variable led to the selection of equidistant levels. A mechanical stirrer was used to conduct the tests in batch mode for this investigation. One hundred millilitres of waste water were used for the studies, and a 250-millilitre flask kept at room temperature with the required pH was maintained. The adsorbent was administered in the required dose range of 0.5–2.5 g/L for the desired time of 0–17 hours at 150 rpm. Following the intended duration of contact (0–17 hours), the samples underwent filtering to extract the adsorbent from the mixture and provide a filtrate that would be used in subsequent studies. Three duplicate analyses of the samples were performed in order to minimise experimental mistakes. Subsequently, ozone was introduced into the filtrate solution at a rate of 15–100 mL/min for duration of 15 minutes. After the process's precipitates were separated, the residual solution was examined for COD and colour removal. The % COD Reduction and % Colour removal was calculated by using Eq (i) and Eq (ii) respectively.

$$\text{\% COD Removal} = \left(\frac{D_i - D_f}{D_f}\right)\times 100 \qquad \text{(i)}$$

$$\text{\% Color Removal} = \left(\frac{C_i - C_f}{C_f}\right)\times 100 \qquad \text{(ii)}$$

Where D_i, D_f are initial and final COD concentration respectively and C_i and C_f are initial and final colour concentration in the solution, respectively.

Table: 21 Adsorption Isotherms

Co (mg/l)	qe (mg/g)	Ct	Ce	Ce/qe	Ln (Ce)	Ln (qe)	1/qe	1/Ce	log Ce	Log Qe
1000	60.00	3.11	400.00	6.67	5.99	4.09	0.0167	0.0025	2.60	1.78
1500	65.33	3.11	520.00	1.98	6.25	4.18	0.0153	0.0019	2.72	1.82
2000	69.50	3.11	623.00	8.96	6.43	4.24	0.0144	0.0016	2.79	1.84
2500	70.25	3.11	582.00	2.85	6.37	4.25	0.0142	0.0017	2.76	1.85

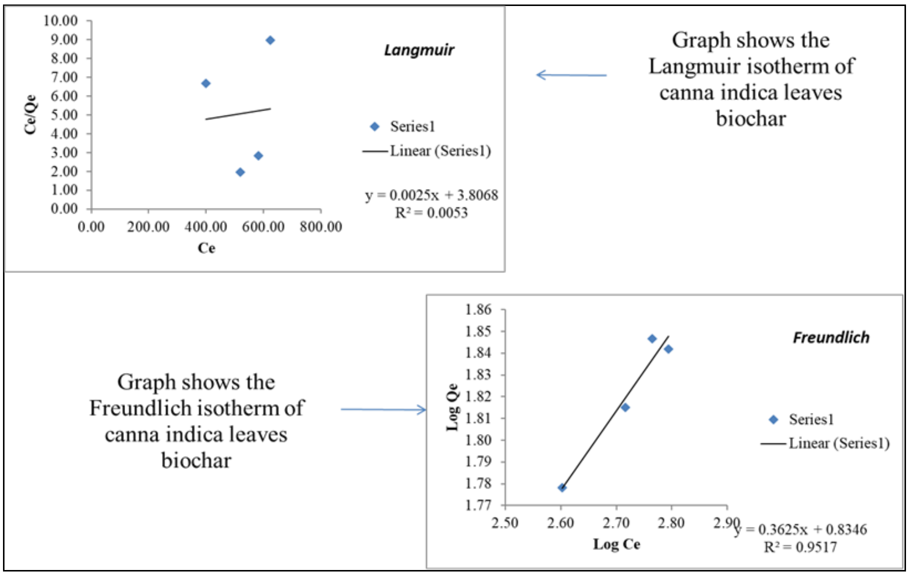


Figure 45 Langmuir & Freundlich Isotherm Graph for Biochar

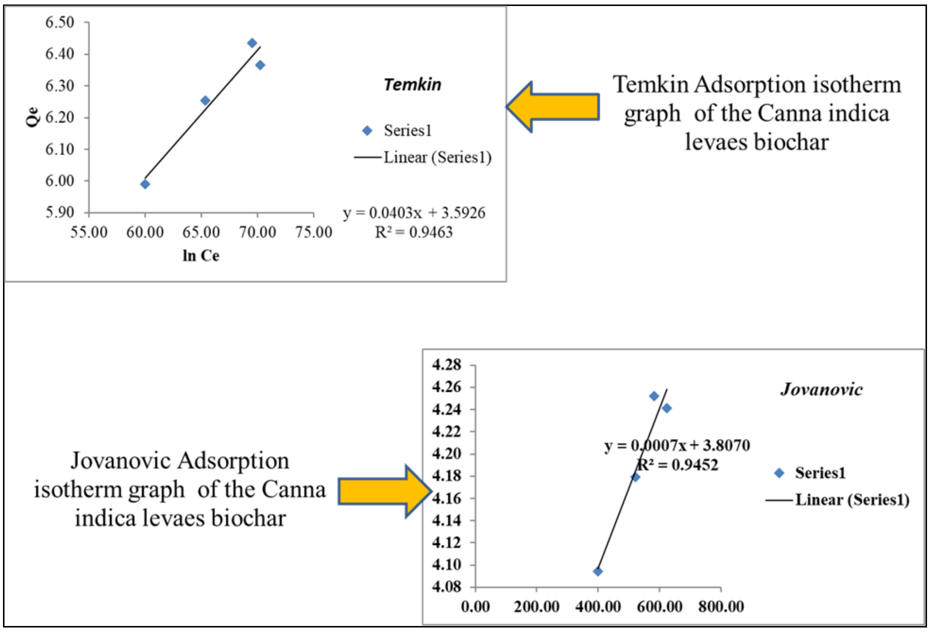


Figure 46 Jovanovic & Temkin Adsorption Isotherm Graph for Biochar

At various starting concentrations (C_0 = 1000–2500 mg L^{-1}), the adsorption equilibrium data for dye removal using biochar made from Canna indica leaves were assessed. As the starting concentration increased, the adsorption capacity (q_e) rose from 60.0 to 70.25 mg g^{-1}, suggesting a stronger driving force for mass transfer at higher concentrations. To fit Langmuir, Freundlich, and Temkin adsorption isotherm models, parameters like C_e/q_e, ln C_e, ln q_e, $1/q_e$, and $1/C_e$ were computed using the equilibrium concentration (C_e) values. These parameters' linearized forms are useful for figuring the adsorption constants and comprehending surface properties. The steady rise in q_e and logarithmic values indicates good adsorption behavior and validates Canna indica biochar's potential as an effective adsorbent for the treatment of textile wastewater.

q= kfC^n (i)

The quantities q and n represent the amount of solute adsorbed per unit mass of adsorbent, equilibrium concentration (C) of the solute in the solution, Freundlich constant (Kf) associated with adsorption capacity, and Freundlich exponent (n) associated with adsorption intensity.

y = 0.0025x + 3.8068, Slop is =0.0025 and intercept is 3.8068 for

Langmuir isotherm (ii)

The graph shows that there is a curved relationship rather than a linear one between the amount of solute adsorbed and the solute's equilibrium concentration. Our findings support the Freundlich isotherm. The curve often concaves upward with increasing solute content, signifying a declining adsorption rate. This demonstrates that as solute molecules cover the surface of the adsorbent, adsorption slows down. The slope of the graph is its Freundlich exponent.

y = 0.3625x + 0.8346, Slope = 0.3625, Intercept = 0.8346, Kf= 1.253, n=2.739, for Freundlich Isotherm (iii)

The adsorption intensity and isotherm nonlinearity are represented by n. Adsorption is more favourable when n is greater than 1 and less favourable when n is less than 1. The relationship between solute adsorbed and equilibrium concentration is shown by this isotherm equation. The curve conclaves upward with increasing solute concentration, indicating a declining rate of adsorption. The adsorption intensity is shown by the slope. Our results are in agreement with the Jovanovic isotherm, another adsorption model. It's a case of ln Qe against Ce. A graph displays the quantity of adsorbate (gas and liquid) adsorbed per unit mass of adsorbent (solid) at a fixed temperature as a function of pressure or concentration.

y = 0.0007x + 3.8070, Slope = 0.0007, Intercept = 3.8070, K= 0.0091, for Jovanovic Isotherm (iv)

The parameter that is used to fit the model to the experimental data determines the form of the graph that depicts the Jovanovic isotherm. It is distinguished by a transition zone, a plateau or saturation region at the point when adsorption stops happening, and an initial segment that is either linear or slightly concave.

y = 0.0403x + 3.5926, slop is 0.0403 and Intercept =3.5926, for

Temkin isotherm (v)

According to the Jovanovic model, the Jovanovic isotherm graph shows the connection between the quantity of adsorbate and the pressure or concentration of the adsorbate under circumstances of constant temperature. This relationship was defined by the Jovanovic model.

We've determined that the Freundlich isotherm is the best model for our purposes after examining each one. Additionally, with an R2 value of 0.9517—which is almost 95%—the Freundlich isotherm fits the data the best (compared to other isotherms' values of 0.0053, 0.9463, and 0.9452, respectively). Because of its values near 95%, this isotherm was determined to be the best fit for the data.

The adsorption capacity of dye colour by *Canna indica* at equilibrium was calculated by Eq (vi)

$$Q_e = \frac{\left(C_i - C_f\right) \times V}{W} \qquad \text{(vi)}$$

Where, C_i, C_f, V and Ware initial colour concentration, final colour concentration, Volume of solution taken, and amount of adsorbent added to the solution, respectively.

5.7 Discussion

In the discussion section of this chapter, we delve into the insights gained from the results presented in Tables 6, 7, 8, 9, 10, 11, 12, 14, 15, 19 and 20 as well as Figures 6,7,8,10,11 and 12. These findings provide valuable information regarding the efficacy of various treatment methods, including adsorption, Ozonation, and cavitation, in reducing chemical oxygen demand (COD) and colour levels in textile and dye wastewater. Firstly, Table 6 presents the results of adsorption experiments using *Canna indica* leaves biochar, demonstrating the significant reduction in COD levels across different practical runs. It is evident that increasing the dosage of biochar leads to higher COD reduction percentages, indicating the effectiveness of adsorption as a treatment mechanism. Moreover, the corresponding reductions in colour intensity further underscore the potential of *Canna indica* biochar in mitigating water pollution.

Table 7 shows the notable decrease in COD levels throughout many practical runs as a result of adsorption studies using *Canna indica* stalk biochar. 50% COD reduction clearly show that adsorption is a treatment method that works when the biochar dose is raised. Moreover, the related decreases in colour intensity highlight the possibility of *Canna indica* stalk biochar in reducing water pollution. Table 8 displays the outcomes of adsorption tests conducted on *Canna indica* roots biochar, indicating a noteworthy 30% decrease in COD levels throughout several real-world runs. It is clear that raising the dose of biochar results in some percentages of COD reduction, demonstrating the efficacy of adsorption as a treatment method. Furthermore, the commensurate decreases in hue emphasise the capacity of *Canna indica* roots biochar to alleviate water contamination (Brown & Johnson 2011).

The subsequent analysis of Ozonation experiments, as depicted in Table 9,10 reinforces the efficacy of this treatment method in reducing COD levels within a relatively short time frame. The substantial COD removal percentages achieved during Ozonation highlight its effectiveness as a complementary approach to traditional adsorption techniques. However, further investigation is required to assess its impact on biochemical oxygen demand (BOD) and total dissolved solids (TDS) levels, which are integral indicators of water quality. Moving on to the cavitation experiments detailed in Tables 19 and 20, it is evident that orifice plate design plays a crucial role in influencing treatment outcomes. Figures 27, 28 and 29 provide visual representations of the impact of different circular and star-patterned orifice configurations on COD reduction percentages. Notably, orifice plates with a single circular or star pattern demonstrate promising results, with higher reductions in COD levels observed compared to configurations with multiple patterns.

These findings underscore the importance of optimizing orifice plate design to enhance cavitation-induced treatment efficiency. By fine-tuning the geometry and arrangement of orifice patterns, researchers can maximize the generation of cavitation bubbles, thereby facilitating more effective pollutant degradation. Additionally, variations in flow rates and holes sizes warrant further investigation to ascertain their influence on treatment performance.

To sum up, this chapter's findings and comments offer insightful information about the effectiveness of various treatment approaches for reducing wastewater pollution from textile and dye processes. From adsorption and Ozonation to cavitation-induced processes, each approach offers unique advantages and challenges that must be carefully considered in the development of comprehensive wastewater treatment strategies. Further research is needed to optimize these methods and tailor them to specific industrial applications, ultimately advancing sustainability and environmental stewardship in the textile industry.

In the first practical run, employing 1 gram of *Canna indica* biochar, a reduction in COD from an initial value of 2100 mg/L to 1612.8 mg/L was observed, corresponding to a 23.2% decrease. This initial experiment provides a baseline for evaluating the efficacy of biochar adsorption in wastewater treatment. Subsequent runs with increased biochar dosages demonstrate varying degrees of COD reduction, with higher doses resulting in more significant pollutant removal. For instance, using 2.5 grams of biochar yielded a COD reduction of 31.25%, indicating the dose-dependent nature of adsorption processes.

Furthermore, the colour intensity of the wastewater also exhibits notable reductions following biochar treatment. This finding suggests the adsorption capacity of *Canna indica* biochar extends beyond COD removal to encompass the attenuation of chromophores responsible for wastewater coloration. The observed variations in COD reduction and colour removal across different practical runs underscore the importance of optimizing treatment parameters. To obtain the highest level of pollutant removal effectiveness, variables including operation temperature, contact duration, and dose of biochar must be precisely regulated, Biochar.

The results also highlight the potential of *Canna indica* biochar as a sustainable and cost-effective adsorbent for textile and dye wastewater treatment. Its abundance, renewability, and ability to sequester pollutants make it a promising alternative to conventional adsorbents. However, further investigation is warranted to elucidate the mechanisms underlying biochar adsorption and optimize its performance. Future studies could explore the influence of pH, particle size, and surface modification on adsorption kinetics and capacity (Chen, & Zhang 2016).

Moreover, the integration of biochar adsorption with other treatment processes, such as Ozonation or membrane filtration, could enhance overall treatment efficiency and expand its applicability to diverse wastewater streams. Additionally, the economic viability and scalability of biochar-based treatment systems merit consideration. Cost-benefit analyses and pilot-scale studies are needed to assess the feasibility of large-scale implementation and evaluate its potential environmental and socio-economic impacts.

All things considered, Figure 39's findings highlight the potential of cavitation-induced treatment techniques for resolving water pollution problems and promoting environmentally friendly wastewater treatment systems. Prolonged investigation and creativity in this domain may result in the creation of effective, economical, and eco-friendly remedies for problems related to sanitation and water treatment. The results depicted in Table 6 provide valuable insights into the performance of *Canna indica* biochar in adsorbing contaminants from textile and dye wastewater. Beyond the quantitative data presented, several qualitative aspects and implications emerge from these findings, warranting further discussion and analysis.

Firstly, the observed variations in COD reduction and colour removal across different practical runs highlight the complex interplay of factors influencing adsorption efficiency. While increasing the dosage of biochar generally leads to higher pollutant removal rates, diminishing returns may occur at higher doses due to factors such as pore blockage or saturation of adsorption sites. Understanding the optimal dosage range is crucial for maximizing treatment efficiency while minimizing resource utilization and operational costs. Moreover, the influence of operating parameters such as temperature and contact time on adsorption performance merits attention. The results indicate that longer treatment durations may not necessarily lead to proportionally higher pollutant removal, suggesting the existence of an equilibrium point beyond which additional adsorption becomes marginal. Similarly, variations in temperature may affect the adsorption kinetics and equilibrium, necessitating further investigation to optimize treatment conditions for different wastewater compositions and ambient conditions.

Furthermore, the significant reduction in colour intensity following biochar treatment underscores its potential as a viable solution for addressing aesthetic concerns associated with textile and dye wastewater. The ability of *Canna indica* biochar to effectively adsorb chromophores and other coloured compounds highlights its versatility and applicability in treating diverse wastewater streams beyond conventional organic pollutants. Additionally, the synergistic effects of biochar adsorption and Ozonation, as depicted in Table 10, present an intriguing avenue for enhancing treatment efficiency. The combination of these two treatment processes leverages the complementary mechanisms of adsorption and oxidation to target a broader range of contaminants and achieve synergistic pollutant removal. Further research into optimizing the integration of biochar and Ozonation could yield innovative treatment strategies with enhanced performance and reduced environmental impact.

The findings also raise important considerations regarding the scalability and practical implementation of biochar-based treatment systems. While laboratory-scale experiments demonstrate promising results, translating these findings into large-scale applications requires addressing logistical challenges, economic feasibility, and regulatory considerations. Pilot-scale studies and techno-economic assessments are essential steps towards evaluating the viability and sustainability of biochar-based wastewater treatment solutions. With regard to wastewater treatment and environmental remediation, the data shown in Tables 6 and 10 demonstrate the versatility of *Canna indica* biochar as an adsorbent and emphasize the value of multidisciplinary research and teamwork in creating sustainable solutions. The urgent problems caused by industrial pollution may be solved and we may get closer to a cleaner, more sustainable future with further research and development of biochar-based treatment methods.

The data reveal a significant reduction in pollutant concentrations following Ozonation, highlighting its potential as a viable treatment option. In each practical run, ozone treatment resulted in notable decreases in both COD and colour intensity, with percentage reductions ranging from approximately 68% to 84% and 91% to 98%, respectively. These findings underscore the effectiveness of ozone in oxidizing organic contaminants and breaking down chromophores responsible for wastewater coloration. The observed variations in COD and colour reduction across different practical runs may be attributed to factors such as ozone dosage, contact time, and initial pollutant concentrations. Optimizing these parameters could further enhance treatment efficiency and ensure consistent pollutant removal (Kumar 2020)

Furthermore, the concurrent reduction in BOD levels following Ozonation indicates the degradation of organic matter and improvement in wastewater biodegradability. This is a significant outcome, as it suggests that ozone treatment not only reduces pollutant concentrations but also enhances the overall quality of the treated effluent. The results of Table 10 highlight the potential of Ozonation as a standalone treatment method for textile and dye wastewater, offering advantages such as rapid treatment kinetics, broad-spectrum pollutant removal, and minimal residual by products. However, further studies are needed to assess the long-term sustainability and operational feasibility of Ozonation systems, particularly in large-scale applications.

Moving on to Table 19, which presents the results of cavitation experiments using circular hole orifice plates, we observe varying degrees of COD and colour reduction across different practical runs. The data illustrate the impact of orifice plate design and flow rate on cavitation-induced pollutant removal. Practical runs employing orifice plates with a greater number of holes demonstrate higher levels of COD reduction, indicating the influence of hydraulic shear forces and turbulence on pollutant degradation. Similarly, variations in holes size and flow rate lead to differences in treatment efficacy, highlighting the importance of optimizing these parameters for maximum cavitation intensity.

The observed reductions in both COD and colour intensity suggest that hydrodynamic cavitation holds promise as a sustainable and energy-efficient treatment technology for textile and dye wastewater. By harnessing the mechanical energy of flowing water to generate cavitation bubbles, this process offers a cost-effective alternative to traditional chemical treatments. However, further research is needed to optimize cavitation parameters and assess its scalability and practical applicability in real-world wastewater treatment scenarios. Additionally, the potential environmental impacts and operational challenges associated with cavitation-based systems warrant careful consideration (Zhang, X. 2016).

Table 20 provides insights into the performance of star holes orifice plates in cavitation experiments, showcasing their effectiveness in reducing COD and colour levels in textile and dye wastewater. The data reveal similar trends to those observed with circular holes orifice plates, with variations in holes number and size influencing treatment outcomes. Overall, the results presented in Tables 10, 19, and 20 underscore the potential of Ozonation and hydrodynamic cavitation as innovative approaches to textile and dye wastewater treatment. By leveraging advanced oxidation processes and mechanical energy, these technologies offer sustainable solutions to address the environmental challenges posed by industrial wastewater discharge.

The % COD and colour reduction by adsorption with different doses of *Canna indica* biochar (leaves) are graphically represented. This graphic shows how different biochar dosages affect how well textile and dye wastewater removes COD and colour. The graph clearly shows that larger dosages of biochar show an increase in COD and a decrease in colour. This highlights *Canna indica* biochar's efficacy as an adsorbent for pollution removal by indicating that its adsorption capacity is directly proportionate to the dosage given (Arunachalam, R., & Velmurugan, V. 2015).

Moreover, the figure indicates diminishing returns in terms of COD and colour reduction beyond a certain biochar dosage. This saturation effect implies that there is an optimal dosage of biochar that maximizes pollutant removal efficiency. Understanding this dose-response relationship is crucial for designing cost-effective and efficient treatment processes for textile and dye wastewater. Moving on to Figure 10, which depicts the % COD and colour reduction by adsorption and Ozonation (combination) treatment, provides insights into the synergistic effects of combining adsorption and Ozonation processes for wastewater treatment. The graph showcases the complementary nature of these two treatment methods, with the combination treatment resulting in greater COD and colour reduction compared to individual treatments alone.

Moreover, the figure 11 and 12 indicates diminishing returns in terms of COD and colour reduction of treated biochar after amendment treatment. Using the KOH and NaOH biochar as future treatment of treated biochar. Understanding this dose-response relationship is crucial for designing cost-effective and efficient treatment processes for textile and dye wastewater. Moving on to Figure 11, which depicts the % COD and colour reduction by KOH treated biochar combining adsorption processes for wastewater treatment. Figure 12, which depicts the % COD and colour reduction by NaOH treated biochar combining adsorption processes for wastewater treatment.

When it came to the TDS and BOD sections, *Canna indica* leaf and stalk biochar produced the most TDS decreases, at 47.54% and 40.45%, respectively. While canna leaves decrease BOD by 32.5%, canna stalks lower BOD by 25.80%. The percentage TDS and percentage BOD decrease of *Canna indica* leaf biochar is shown in Figures 07 and 08.

The significant enhancement in pollutant removal observed with the combination treatment underscores the potential of integrating multiple treatment technologies to achieve superior wastewater remediation outcomes. By harnessing the strengths of both adsorption and Ozonation, synergistic treatment approaches can overcome the limitations of individual processes and offer enhanced pollutant removal efficiency and overall treatment performance. Figure 28 presents different circular patterns in orifice based on the number of holes versus % COD reduction. This graph provides valuable insights into the influence of orifice plate design on cavitation-induced pollutant removal. By varying the number of holes in circular orifice plates, different flow patterns and turbulence intensities can be generated, affecting the efficiency of cavitation-mediated treatment processes.

Similarly, Figure 27, 29 showcases the impact of different star patterns in orifice plates on % COD reduction. The varying geometric configurations of star-shaped orifice plates result in distinct flow dynamics and turbulence characteristics, influencing the intensity and efficacy of cavitation-induced pollutant degradation. Overall, the discussions of these figures highlight the importance of optimizing process parameters and reactor design to maximize treatment efficiency and achieve desired pollutant removal targets. By leveraging insights from these graphical representations, researchers and practitioners can refine and tailor wastewater treatment strategies to address the specific challenges posed by textile and dye wastewater.

In further analysing the data presented in Table 10 the results of ozone treatment experiments underscore the effectiveness of Ozonation in reducing COD, BOD, and colour in textile and dye wastewater. Across the different practical runs, it is evident that Ozonation led to significant reductions in COD, with % COD removal ranging from approximately 68% to over 84%. This indicates the robustness of Ozonation as a treatment method for degrading organic pollutants present in wastewater.

Moreover, the concurrent reduction in BOD, as indicated by the % BOD removal values, highlights the oxidative nature of ozone and its ability to degrade organic compounds into simpler, less harmful forms. The observed % BOD removal rates, ranging from around 22% to over 32%, further validate the efficacy of Ozonation in enhancing the biodegradability of wastewater, thereby facilitating subsequent biological treatment processes. Additionally, the considerable reduction in colour, with % colour reduction exceeding 90% in some cases, demonstrates the capability of Ozonation to effectively degrade chromophore compounds responsible for coloration in wastewater. This is particularly significant in industries such as textile and dyeing, where colour removal is a critical aspect of wastewater treatment to meet regulatory standards and environmental discharge limits.

Moving on to Table 19, which presents the results of different cavitation practical runs with circular hole orifice plates, it is evident that cavitation-induced treatment shows promising potential for COD and colour reduction. Across the various practical runs, significant % COD reduction values ranging from approximately 6.8% to over 49% were achieved, indicating the efficacy of cavitation in breaking down organic pollutants present in wastewater. Furthermore, the observed % colour reduction rates, ranging from around 25% to over 34%, highlight the ability of cavitation to degrade chromophore compounds and reduce the colour intensity of wastewater. These results suggest that cavitation-based treatment methods have the potential to complement conventional treatment processes and enhance overall treatment efficiency for textile and dye wastewater.

Similarly, Table 20 presents the results of different cavitation practical runs with star hole orifice plates, demonstrating the impact of orifice plate design on cavitation-induced pollutant removal. The data show that star-shaped orifice plates also exhibit significant potential for COD and colour reduction, with %COD reduction values exceeding 9% and %colour reduction rates ranging from approximately 13% to over 40%. These findings underscore the importance of reactor design and process optimization in harnessing the full potential of cavitation for wastewater treatment. By selecting appropriate orifice plate designs and operating conditions, researchers and practitioners can tailor cavitation-based treatment systems to target specific pollutants and achieve desired treatment outcomes effectively. Moreover, the combination of cavitation with other treatment processes, such as Ozonation or adsorption, holds promise for further enhancing treatment efficiency and addressing the complex challenges associated with textile and dye wastewater treatment.

5.8 PROCESS LIMITATIONS AND CHALLENGES

The developed treatment system, while effective, faces several practical considerations:

Operational Challenges:

- Scale-up requirements for industrial implementation
- Biochar regeneration and disposal needs
- Energy consumption optimization
- Maintenance requirements

Economic Considerations:

- Equipment and installation costs
- Operational expenses
- Resource requirements
- Return on investment timeline

Technical Limitations:

- Treatment efficiency variations with wastewater composition
- Process optimization requirements
- Monitoring and control needs

5.9 PRACTICAL IMPLICATIONS

The findings translate to several practical applications:

1. Implementation Guidelines:

- Optimal operating parameters for different wastewater types
- Process control recommendations
- Maintenance protocols

2. Performance Optimization:

- Parameter adjustment strategies
- Efficiency monitoring methods
- Quality control measures

3. Cost-Effective Operation:

- Resource optimization approaches
- Energy efficiency measures
- Maintenance scheduling

Chapter 6: Conclusion

The experimental findings of this study demonstrate the effectiveness of hybrid wastewater technologies for treating textile and dye industry effluents. The biochar derived from *Canna indica* leaves exhibited superior performance with 79.95% COD reduction and 94.14% color removal at a dosage of 2.5 g/L, outperforming stalk-derived (73.14% COD, 93.78% color) and root-derived biochar (57% COD, 66.57% color). The *Canna indica* leaves biochar also reduced TDS by 47.54% and BOD by 32.25%, confirming its effectiveness across multiple pollution parameters.

Surface modification enhanced treatment efficacy significantly, with KOH-modified biochar achieving 96.90% COD reduction at pH 8, while NaOH-modified biochar reached 95.48% at pH 8.5. This improvement is attributed to increased surface area (16.506 m^2/g) resulting from chemical activation, which created additional pores and active sites for pollutant adsorption.

Kinetic studies conclusively showed that adsorption followed a pseudo-second-order model ($R^2 > 0.99$), indicating chemisorption as the dominant removal mechanism. The maximum adsorption capacities were determined to be 357.14 mg/g for KBC and 333.33 mg/g for NaBC, confirming their excellent adsorption potential.

When adsorption was combined with Ozonation, remarkable synergistic effects were observed, achieving 95.83% COD reduction and 95.47% color removal at an ozone flow rate of 120 mL/min. This synergy can be attributed to complementary mechanisms where ozone generates hydroxyl radicals that effectively degrade organic pollutants resistant to adsorption alone.

Hydrodynamic cavitation experiments revealed that orifice plate design significantly influenced treatment efficiency, with the five-hole circular pattern achieving 49.14% COD reduction and single-star pattern demonstrating 40.90% reduction. These results highlight the potential of cavitation as a chemical-free treatment approach.

Statistical analysis using Response Surface Methodology identified pH as the most critical factor affecting treatment outcomes, followed by adsorbent dosage, contact time, and Ozonation rate. The developed quadratic models showed excellent correlation with experimental data ($R^2 > 0.95$), enabling accurate prediction of treatment performance.

In conclusion, hybrid wastewater treatment technologies combining biochar adsorption, Ozonation, and hydrodynamic cavitation offer a promising and sustainable approach for effective treatment of textile and dye industry effluents, providing practical solutions to environmental challenges while minimizing resource consumption.

Overall, the information provided in this thesis advances our understanding of the treatment of wastewater, including textiles and dyes, and provides useful information for the creation of effective and sustainable treatment methods. It is feasible to fulfil regulatory requirements for wastewater discharge and achieve significant reductions in pollutant levels by combining several treatment techniques and optimizing process parameters. Going forward, more investigation is necessary to examine the synergistic benefits of combining various treatment techniques and to evaluate the scalability and long-term efficacy of these approaches in actual wastewater treatment settings. In order to maximize treatment efficiency and minimize energy consumption and environmental effects, efforts should also be focused on optimizing treatment procedures.

In conclusion, the findings of this thesis underscore the importance of interdisciplinary research and collaboration in addressing the complex challenges associated with textile and dye wastewater treatment. By leveraging innovative technologies and holistic approaches, it is possible to achieve sustainable solutions for the management and treatment of textile and dye wastewater, thereby contributing to environmental preservation and public health protection. In addition to the specific findings and insights gleaned from the experiments conducted in this study, it is crucial to emphasize the broader implications and potential applications of the research outcomes. The successful demonstration of various treatment methods, including adsorption, Ozonation, and cavitation, not only contributes to the advancement of knowledge in wastewater treatment but also holds promise for practical implementation in industrial settings.

One key aspect to consider is the scalability and feasibility of implementing the treatment methods explored in this study on a larger scale. While laboratory-scale experiments provide valuable insights into the efficacy of different treatment approaches, transitioning to pilot-scale or full-scale applications presents unique challenges and considerations. Future research and development should aim to overcome these obstacles and improve the functioning and design of treatment systems for practical uses. Furthermore, the suggested treatment approaches' viability from an economic and environmental standpoint is crucial. The need for affordable and ecologically friendly wastewater treatment systems is rising as enterprises try to fulfil ever-tougher regulatory standards and corporate sustainability goals. The study's conclusions imply that combining various treatment techniques and maximizing process variables can significantly increase treatment effectiveness while lowering operating expenses and the impact on the environment.

Furthermore, it is essential to highlight the interdisciplinary nature of the research presented in this thesis and its potential for cross-cutting applications beyond wastewater treatment. The insights gained from studying the interactions between pollutants, adsorbents, oxidants, and cavitation phenomena have implications for fields such as environmental engineering, materials science, and chemical process engineering. By fostering collaboration and knowledge exchange across disciplines, future research endeavours can leverage these insights to address a wide range of environmental and societal challenges.

The findings and implications of this study underscore the importance of continued research and innovation in the field of wastewater treatment. By leveraging emerging technologies, interdisciplinary approaches, and collaborative partnerships, it is possible to develop sustainable and efficient solutions for managing and treating complex industrial waste waters.

6.1 Future work

To improve the knowledge and use of hybrid wastewater technologies for the treatment of effluents from the textile and dye industries, future research for this thesis might concentrate on a number of important topics. Future studies might focus on creating innovative hybrid treatment systems that make use of cutting-edge oxidation catalysts, nanomaterials, and electrochemical processes, among other cutting-edge technologies. Examining how these technologies work best when combined with conventional treatment techniques may help create wastewater treatment solutions that are more economical and effective.

In order to increase the efficiency of pollution removal, reduce energy consumption, and improve overall system performance, more research is required to optimize the operating parameters and design criteria of already in use hybrid systems. To verify the efficacy of various treatment configurations under various operating circumstances, this may entail carrying out extensive pilot-scale trials and modelling research. In addition, in order to facilitate real-time treatment process monitoring, control, and optimization, future research may investigate the integration of artificial intelligence (AI) and machine learning algorithms into hybrid wastewater treatment systems. Artificial Intelligence (AI)-based systems have the potential to enhance system performance by automatically adjusting treatment settings in response to changing influent characteristics by utilizing predictive modelling and data analytics.

The evaluation of hybrid wastewater treatment methods' lifetime effects and environmental sustainability of hybrid wastewater treatment methods is another topic that needs more research. Life cycle assessment (LCA) studies can yield important information about the environmental effects of various treatment choices and point out areas where resource efficiency can be increased and environmental consequences can be decreased. Furthermore, investigations into the possibility of resource recovery and vaporization from wastewater streams treated by hybrid technology may be conducted in the future. In order to close the loop on resource consumption and advance the ideas of the circular economy, this might entail looking into the viability of recovering valuable materials like fertilizers, metals, and organic compounds from treated effluents for reuse or commercial applications.

Additionally, there is a need for continued collaboration between researchers, industry stakeholders, and policymakers to facilitate the adoption and implementation of hybrid wastewater technologies on a larger scale. This could involve establishing knowledge-sharing platforms, promoting technology transfer initiatives, and developing regulatory frameworks that incentivize the adoption of sustainable wastewater treatment practices. The future research efforts in these areas have the potential to drive innovation, enhance sustainability, and address the evolving challenges associated with wastewater management in the textile and dye industries. By advancing our understanding of hybrid wastewater technologies and their applications, we can work towards building more resilient and environmentally responsible wastewater treatment systems for the future.

The aforementioned areas of future research, there are several other avenues worth exploring to further advance the field of hybrid wastewater technologies for treating effluents from textile and dye industries. One promising direction for future work is the investigation of novel hybrid treatment configurations that incorporate decentralized and modular systems. These decentralized approaches could enable more flexible and scalable wastewater treatment solutions, particularly in regions with limited access to centralized infrastructure. By designing modular treatment units that can be easily assembled and adapted to local conditions, it may be possible to extend the benefits of hybrid wastewater technologies to smaller communities and industrial facilities.

Prospective investigations may concentrate on the creation of hybrid treatment systems that are especially designed to tackle the special difficulties linked to new pollutants of concern found in the effluents of the textile and dye sector. These contaminants, which may include per- and poly fluoro alkyl substances (PFAS), pharmaceuticals, and micro plastics, present significant environmental and public health risks and require specialized treatment approaches. Investigating the efficacy of hybrid technologies for removing these contaminants and mitigating their impacts could help address pressing environmental challenges and ensure the safety of water resources. Future research may also look at integrating renewable energy sources, such wind and solar energy, into hybrid wastewater treatment systems in an effort to lower carbon emissions and energy usage. Enhancing wastewater treatment operations' sustainability and cost-effectiveness while lowering their dependency on fossil fuels may be achievable through the use of renewable energy to power treatment procedures. Evaluations of renewable energy-integrated hybrid systems' performance and viability in practical environments through case studies may offer important fresh perspectives on the advantages and disadvantages of these systems.

One compelling case study that exemplifies the potential of hybrid wastewater technologies is the implementation of a decentralized hybrid treatment system in a rural textile manufacturing community. In this scenario, a modular treatment system incorporating biological, physical, and chemical treatment processes is installed to treat wastewater from multiple small-scale textiles dyeing facilities. To efficiently remove organic contaminants, colorants, and heavy metals from wastewater, the system combines membrane bioreactors, anaerobic digestion, and sophisticated oxidation processes. The hybrid system reduces pollutants in large amounts and enhances the quality of treated effluent by carefully monitoring and optimizing the treatment processes. The decentralized structure of the system, particularly in areas with limited access to centralized treatment facilities, allows for more flexibility and resilience in wastewater treatment operations. Furthermore, the treatment system's environmental impact is minimized, and long-term running expenses are decreased by the incorporation of renewable energy sources like solar panels and methane digesters.

Subsequent research can shed light on the actual application of hybrid wastewater solutions in decentralized and rural settings by recording the case study's performance and lessons learned. More sustainable and resilient wastewater treatment infrastructure may be developed globally with the use of this knowledge, which can also be used to build and operate comparable systems in other communities that produce textiles.

6.2 FUTURE RESEARCH DIRECTIONS AND IMPLEMENTATION CHALLENGES

Research and Development Priorities:

The experimental findings from this study highlight several critical areas requiring further investigation. Advanced research into biochar modification techniques could significantly enhance treatment efficiency.

Scale-up Considerations and Industrial Implementation:

Scaling up laboratory findings to industrial applications presents unique challenges that warrant dedicated research efforts. Future studies should examine fluid dynamics in larger treatment vessels.

Process Integration and Optimization:

Integration of multiple treatment technologies demands careful optimization of operational parameters and treatment sequences.

Material Development and Enhancement:

Further investigation into advanced material development could significantly improve treatment efficiency through novel surface modification techniques.

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Paper Publication Detail

- First paper published on “Coco Peat Organic Manure used as Adsorbents for Dyes Removal” has been published in Journal of Physics: Conference Series:2267 012044, Raffas-2023 (Conference paper)

- Second paper Published on Utilizing Hydrodynamic Cavitation with Variable Orifice Patterns for Textile Wastewater Treatment." Tikrit Journal of Engineering Sciences 31.1 (2024): 33-42. https://doi.org/10.25130/tjes.31.1.4.

- Third paper Published on Effectiveness of *Canna indica* leaves and stalk biochar in the treatment of textile effluent." AIP Advances 14.3 (2024).

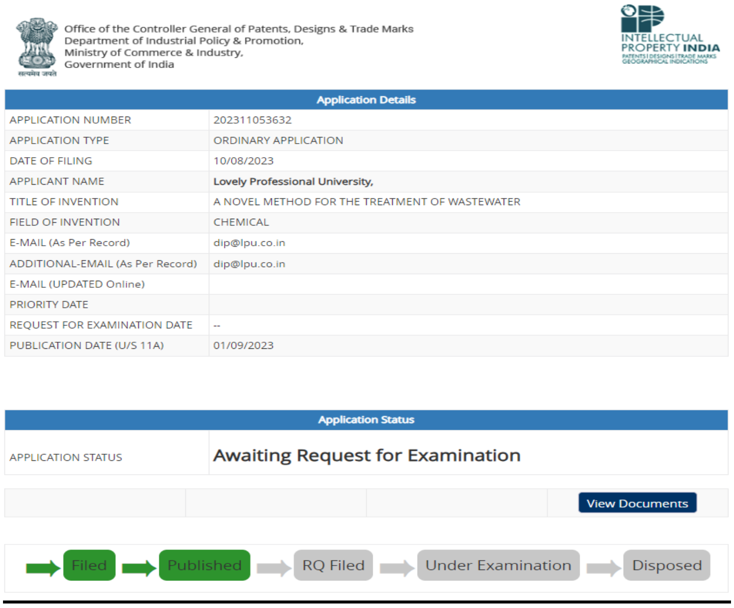
- Fourth paper Published on “Comparing Several Orifice Flange Shapes for Hydrodynamic cavitation Treatment and COD Reduction in Textile Wastewater”, Engineering, Technology & Applied Science Research, Vol.14, No.6, 2024, 17613-17619.

- Fifth Paper Published on “Recycling used Hydrochloric Acid to create Aluminum Chloride from Bauxite”, Indian Journal of Natural Sciences, Vol.14/issue 80/Oct/2023.

- Sixth Paper Published on “Characteristics and Physiochemical Properties of Deep Eutectic Solvents: A Comprehensive Review”, Indian Journal of Natural Sciences, Vol.14/issue 80/Oct/2023.

<u>Patent Publication Detail</u>

- Process Patent Published on "A novel method for Treatment of Waste water", Ordinary Application, Application id: - 202311053632



Office of the Controller General of Patents, Designs & Trade Marks
Department of Industrial Policy & Promotion,
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Application Details	
APPLICATION NUMBER	202311053632
APPLICATION TYPE	ORDINARY APPLICATION
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APPLICANT NAME	**Lovely Professional University,**
TITLE OF INVENTION	A NOVEL METHOD FOR THE TREATMENT OF WASTEWATER
FIELD OF INVENTION	CHEMICAL
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- Design Patent No 454022-001 Dated:- 02/04/2025 Published on " Gas Integrated Muffle Furnace for Biomass Pyrolysis",

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ORIGINAL
क्रम सं/ Serial No. : 205685

पेटेंट कार्यालय, भारत सरकार The Patent Office, Government Of India
डिजाइन के पंजीकरण का प्रमाण पत्र | Certificate of Registration of Design

डिजाइन सं. / Design No. : 454022-001
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प्रमाणित किया जाता है कि संलग्न प्रति में वर्णित डिजाइन जो *GAS INTEGRATED MUFFLE FURNACE FOR BIOMASS PYROLYSIS* से संबंधित है, का पंजीकरण, श्रेणी 23-03 में 1.Dr. Pratima Gajbhiye 2. Chauhan Sejal Mahendrasinh 3.Nasit Manish Rameshbhai 4.Vishalkumar U Shah 5.Anil Kumar Murmu 6.Dr. Miral R Thakker 7.Jay B. Trivedi 8.Mr. Jigesh P. Mehta के नाम में उपर्युक्त संख्या और तारीख में कर लिया गया है।

Certified that the design of which a copy is annexed hereto has been registered as of the number and date given above in class 23-03 in respect of the application of such design to *GAS INTEGRATED MUFFLE FURNACE FOR BIOMASS PYROLYSIS* in the name of 1.Dr. Pratima Gajbhiye 2. Chauhan Sejal Mahendrasinh 3.Nasit Manish Rameshbhai 4.Vishalkumar U Shah 5.Anil Kumar Murmu 6.Dr. Miral R Thakker 7.Jay B. Trivedi 8.Mr. Jigesh P. Mehta.

डिजाइन अधिनियम, 2000 तथा डिजाइन नियम, 2001 के अध्यधीन प्रावधानों के अनुसरण में।

Conference Detail

- Paper Presentation on **Coco Peat Organic manure used as adsorbents for Dyes Removal** in the international conference on “Recent Advances in Fundamental and Applied Sciences” (RAFAS 2021) held on June 25-26, 2021, organized by School of Chemical Engineering and Applied Sciences, Lovely faculty of Technology and Sciences, Lovely Professional University, Punjab.

- Paper Presentation on **Treatment of the Textile Effluent Using *Canna indica* Leaves and Stalk Biochar** in the 4th International Conference on “Recent Advances in Fundamental and Applied Sciences” (RAFAS 2023) held on March 24-25, 2023, organized by School of Chemical Engineering and Physical Sciences, Lovely Faculty of Technology and Sciences, Lovely Professional University, Punjab.

- Paper Presentation (ID: - ICAIIE0048) on **Recycling used Hydrochloric Acid to Create Aluminium Chloride from Bauxite** in the International Conference on Academic & Industrial Innovations in Engineering (ICAIIE-2023) held on August 12 & 13, 2023 at School of Engineering, P P Savani University, Kosamba, Gujarat, India.
