UNIVERSITI TEKNOLOGI MARA

CONVERSION OF CHICKEN BONE AND RICE WASTE INTO ACTIVATED CARBON BY PYROLYSIS AND MICROWAVE ASSISTED H_3PO_4: OPTIMIZATION FOR METHYL VIOLET DYE REMOVAL

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MSc

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ABSTRACT

In this study, food waste-derived activated carbon was synthesized from rice waste (RW) and chicken bone (CB) using H_3PO_4 activation via microwave-assisted and pyrolysis (P-RWCBAC), and microwave (M-RWCBAC)-induced methods. The resulting activated carbon (P-RWCBAC/M-RWCBAC) was evaluated for its efficiency in removing the cationic dye methyl violet (MV) from aqueous solutions. The physicochemical properties of the adsorbent were characterized using BET surface area analysis (P-RWCBAC: 369.3 m^2/g; M-RWCBAC: 83.3 m^2/g), XRD, pH_{pzc} (P-RWCBAC: 3.0; M-RWCBAC: 4.0), FTIR, and SEM-EDX analyses. The adsorption process was optimized using the Box-Behnken design (BBD), assessing the effects of adsorbent dose, solution pH and contact time yielded maximum MV removals of 90.4% for P-RWCBAC (0.1 g/100 mL dose, pH 7, 20 min) and 94.4% for M-RWCBAC (0.08 g/100 mL, pH 9.8, 105 min). Adsorption isotherm studies indicated that MV adsorption followed both the Langmuir and Freundlich models, while kinetic studies confirmed pseudo-second-order behaviour. The maximum adsorption capacity (q_{max}) of P-RWCBAC and M-RWCBAC was determined to be 88.4 mg/g and 126.8 mg/g, respectively. The adsorption mechanism was attributed to electrostatic interactions, π-π stacking, pore filling, and hydrogen bonding. These findings highlight the potential of food waste conversion into high-performance activated carbon for the removal of cationic dyes from contaminated water, contributing to sustainable wastewater treatment solutions.

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LIST OF SYMBOLS

Symbols

%	Percentage
°C	Degree Celcius
cm	Centimetre
cm^{-1}	Per Centimetre
g	Gram
g/L	Gram per litre
GHz	Gigahertz
L	Litre
M	Molarity
mg/g	Milligrams per Gram
mg/L	Milligrams per Litre
min	Minute
mL	Millilitre
mm	Millimetre
ppm	Parts Per Million
V	Volume
µm	Micrometre

LIST OF ABBREVIATIONS

Abbreviations

AC	Activated Carbon
ANOVA	Analysis of variance
AOP	Advances Oxidation Process
BBD	Box Behnken Design
BET	Brunauer-Emmet-Teller
CB	Chicken Bone
CO_2	Carbon Dioxide
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectrometer
H_3PO_4	Phosphoric Acid
IR	Infrared
KBr	Potassium Bromide
KOH	Potassium Hydroxide
KW	Kitchen Waste
M-RWCBAC	Microwave Rice Waste Chicken Bone Activated Carbon
M-RWCBAC-MV	Microwave Rice Waste Chicken Bone Activated Carbon Methyl Violet
MV2B	Methyl Violet 2B
MV	Methyl Violet

LIST OF ABBREVIATIONS

Abbreviations

NaCl	Sodium Chloride
NaOH	Sodium Hydroxide
N_2	Nitrogen
O_2	Oxygen
P-RWCBAC	Pyrolysis Rice Waste Chicken Bone Activated Carbon
P-RWCBAC-MV	Pyrolysis Rice Waste Chicken Bone Activated Carbon Methyl Violet
pH_{pzc}	Zero Point of Charge
RSM	Response Surface Methodology
RW	Rice Waste
RWCB	Rice Waste Chicken Bone
XRD	X-Ray Diffraction

CHAPTER 1
INTRODUCTION

1.1 Research Background

Amongst all the natural resources, water is the most essential and is thought to be the most necessary for life (Jayaswal et al., 2018). Its unique properties, including its ability to dissolve a wide variety of substances, make it indispensable for various biological and ecological processes. In the face of the world's growing industrialization, urbanization, and general lack of knowledge of the importance of water as a resource, around 80% of the world population are currently experiencing issues with water security and supply (Wang et al., 2024). This alarming situation emphasizes the urgent need for sustainable water management practices globally. Water pollution happens when harmful substances like chemicals or waste get into water sources like rivers, lakes, or oceans. This contamination can come from multiple sources such as agricultural runoff, untreated sewage, and industrial discharges. This pollution mostly comes from things people do, like factories dumping waste or farmers using too many chemicals on their crops. It is a big problem because it can harm animals and plants that live in the water and make it unsafe for people to drink or swim in. Furthermore, contaminated water can lead to the spread of waterborne diseases (Sharma et al., 2023), posing a significant public health risk. Additionally, a great deal of contamination in drinking water resources is a result of government, industrial, and human ignorance, which is making freshwater supplies more and more limited (Shah et al., 2023). The combined effect of these factors accelerates the degradation of water quality and poses challenges to achieving clean water access for all. Cleaning up water pollution is important to protect nature and keep people healthy, so scientists and governments are working together to find solutions. These efforts include introducing stricter regulations, developing innovative purification technologies, and raising public awareness about water conservation.

Dyes are chemical substances commonly used to impart colour to materials such as textiles, paper, and food. These dyes are carefully designed to attach firmly to the material, providing a lasting and vibrant coloration. Their complex molecular structures, typically consisting of aromatic rings linked with various functional groups,

enable them to absorb light within the visible spectrum (380-700 nm). This precise absorption gives rise to the range of colours observed in dyed products. Because of the presence of chromogens and chromophores, they produce colour (Brandner & Müller, 2023). Dye discharge has a detrimental effect on the environment since it has widespread applications and is present in the effluents of many industrial and processing facilities (Islam et al., 2025a). The persistence of dyes in water bodies also leads to the reduction of sunlight penetration, which negatively affects photosynthetic aquatic plants and disrupts the aquatic ecosystem balance. When dye gets into water, it can cause problems because of their high colour intensity and potential toxicity. The toxicity of certain dyes means they can be harmful or carcinogenic to aquatic and human life even at low concentrations. Sometimes, factories release dye into rivers or streams, which can change the water's colour and make it look unnatural (Hoque et al., 2024). This can be harmful to fish and other animals living in the water because it affects their habitat. The presence of dyes can also lead to oxygen depletion in water, impacting the survival of aquatic organisms. Also, if people drink water contaminated with dye, it could make them sick. Cleaning up dye pollution is important to keep water safe for both animals and people. Efforts to address this issue include developing advanced treatment methods such as adsorption, biological degradation, and chemical oxidation to remove dyes from wastewater effectively.

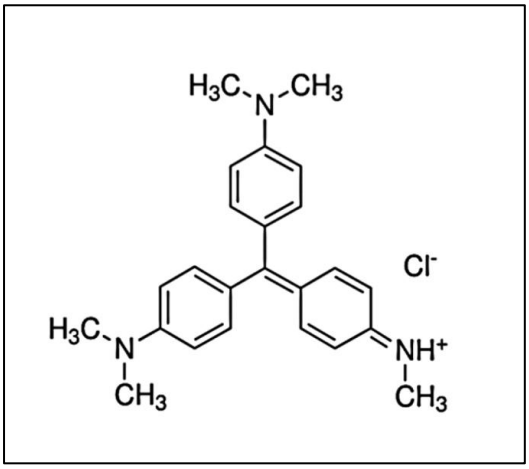


Figure 1.1 Methyl Violet 2B Dye (El-Ghobashy et al., 2022)

Adsorption is a widely used method for cleaning water by trapping harmful substances such as dye molecules. It has been effectively employed as a single treatment method, primarily because of its high efficiency in eliminating a wide variety of

contaminants, increased adaptability to different water treatment scenarios, affordability in terms of installation and operation, and the accessibility of a broad range of adsorbent materials (Lewoyehu, 2021). This versatility makes adsorption a preferred choice in many water treatment applications globally. When dye is present in water, it can be removed using specialized materials called adsorbents, which attract and hold onto the dye particles through physical or chemical interactions. These adsorbents can be natural materials like activated carbon or clay, or synthetic substances specially designed for this purpose with enhanced adsorption capacities. When water containing dye passes through these adsorbents, the dye molecules adhere to the surface of the adsorbent, effectively reducing the contamination level and leaving the water cleaner and safer. This technique plays a crucial role because it helps to make water safe for multiple uses such as drinking, swimming, and supporting aquatic life. Additionally, adsorption is favoured because it is relatively simple to operate, eco-friendly, and can often be carried out without the generation of harmful by-products (Aggour et al., 2025). Scientists are continuously working to improve adsorption methods with the goal of making them more effective, affordable, and scalable for widespread use in treating water pollution caused by dyes and other industrial contaminants. Advances in material science are leading to the development of novel adsorbents with higher surface areas, better selectivity, and improved regeneration capabilities, all of which contribute to a more sustainable approach to water purification.

Chemical and physical techniques play crucial roles in the production of activated carbon, particularly when utilizing advanced methods such as pyrolysis and microwave-assisted activation (He et al., 2023). Pyrolysis involves heating a carbonaceous precursor in an oxygen-free environment to create char, which can then be further processed to form activated carbon with a highly porous structure (He et al., 2023). In chemical activation methods employed during pyrolysis, activating agents like potassium hydroxide (KOH) or phosphoric acid (H_3PO_4) are often impregnated onto the precursor material before the heating process (Nandi et al., 2023). These chemical agents react with the carbon materials during pyrolysis, promoting the formation of pores and significantly increasing the surface area of the resulting activated carbon. Such enhancement of porosity is essential as it directly relates to the adsorbent's capacity to trap contaminants. Another innovative approach is microwave-assisted activation, where microwave energy is applied to rapidly and uniformly heat the precursor material, inducing pyrolysis and subsequent activation (He et al., 2023). This

physical technique is advantageous due to its quicker processing times and more precise control over heating compared to conventional thermal methods. While chemical activation agents can be used alongside microwave-assisted activation, the primary activation mechanism is the intense and uniform heating generated by microwaves (Lee et al., 2023). This method yields activated carbon with tailored properties, offering benefits such as shorter activation cycles, enhanced surface characteristics, and potentially higher yields. In conclusion, both pyrolysis and microwave-assisted activation incorporate a combination of chemical and physical methods to produce activated carbon with superior qualities. Chemical methods, including the impregnation of activating agents, increase pore formation and surface area during pyrolysis. Meanwhile, microwave-assisted activation mainly relies on physical heating to accelerate the activation process. Together, these techniques facilitate the efficient and controlled production of activated carbon with properties customized for diverse industrial and environmental applications.

Food waste is a significant global issue (Chen et al., 2020) with profound economic, environmental, and social implications. It refers to the discarding or loss of edible food at any stage of the food supply chain, from production and processing to distribution, consumption, and disposal. With approximately one-third of all food produced for human consumption being wasted annually (Conrad, 2020), according to estimates by the Food and Agriculture Organization of the United Nations, food waste not only represents a squandering of valuable resources such as water, energy, and labour but also contributes significantly to food insecurity by reducing the overall availability of nutritious food options (Balan et al., 2022). In addition to social consequences, food waste causes environmental degradation by contributing to the inefficient use of agricultural inputs, land, and water resources, exacerbating biodiversity loss, and releasing greenhouse gases during decomposition in landfills. The reasons for food waste are multifaceted and include inefficient agricultural practices such as overproduction and poor harvesting techniques, inadequate storage and transportation infrastructure leading to spoilage, consumer behaviour characterized by over-purchasing and improper food handling, and retail practices such as overstocking and stringent cosmetic standards. Addressing the challenge of food waste requires a comprehensive approach involving stakeholders across the entire food system, including policymakers, producers, retailers, consumers, and waste management organizations, to implement strategies aimed at reducing, redistributing, and recycling

food waste to create a more sustainable and resilient food system for future generations. Strategies such as improving supply chain efficiency, promoting consumer awareness, enacting policies to reduce waste, and developing technologies for food recovery and composting are critical in this regard.

Also, nowadays, waste management emerges as a significant problem in nations of both advanced and emerging economies. The rapid urbanization, population growth, and changing consumption patterns have led to substantial increases in the volume and complexity of waste generated. Organic waste materials, such as discarded rubber and plastic, serve as illustrative instances of waste goods that provide challenges in waste management, while simultaneously offering significant potential as valuable secondary resources. The effective management of such wastes requires the integration of technological, economic, and regulatory measures to promote resource recovery and minimize environmental harm. The deployment of suitable technology for resource recovery from non-conventional sources, such as organic waste, has emerged as a crucial measure to address a portion of our energy crisis and mitigate environmental degradation (Bian et al., 2024). Technologies such as anaerobic digestion, composting, and thermal conversion can transform organic wastes into bioenergy, fertilizers, and other useful products, promoting circular economy principles.

According to (Maalouf & Agamuthu, 2023), there is an annual production of billions of tonnes of waste globally, with a consistent upward trend in volume driven by increased industrial activities and consumer demand. Despite the notable success of the 3R strategy which encompasses the principles of waste reduction, recovery, and recycling a significant quantity of waste remains to be appropriately disposed of, posing ongoing challenges for waste management systems. Food waste generated in significant volumes globally, and its disposal is progressively causing challenges due to limited landfill capacity and potential environmental hazards. Biodegradable wastes are a notable category of waste materials that, when deposited in landfills, present substantial environmental hazards. Landfills are known to release methane, carbon dioxide, and other harmful gaseous substances as organic waste decomposes anaerobically. Methane is the main greenhouse gas produced by landfills and has a much higher global warming potential compared to carbon dioxide. Therefore, managing biodegradable waste properly can significantly contribute to climate change mitigation efforts. Biomass is a prospective feedstock for producing renewable chemicals, minerals, and fuels. Kitchen waste (KW) is a prevalent and readily available biomass resource, which falls under

various biomass resources accessible throughout the year. Households, institutions, and other food processing units create KW, which is a promising resource for bioenergy generation (Suriapparao & Vinu, 2021). Utilizing kitchen waste for bioenergy production not only addresses waste disposal issues but also helps in reducing dependence on fossil fuels and advancing sustainable energy goals. Moreover, converting KW into bioenergy or other value-added products supports waste valorization and promotes environmental sustainability.

The use of rice waste and chicken bones as combined raw materials for the manufacturing of activated carbon has not gotten much attention, despite the increasing number of studies on biomass-based activated carbon. Large amounts of food waste are produced by households (Hermanussen & Loy, 2024), eateries (Kanwal et al., 2024), and the food industry (Saba et al., 2023), and they are frequently thrown away without being put to good use. In addition to causing environmental issues, improper disposal results in the loss of potentially valuable resources. While rice waste is a plentiful biomass material that may be transformed into activated carbon with strong adsorption qualities (Meti et al., 2024), chicken bone contains mineral and carbon-rich components. As a result, using these wastes as precursor materials provides a sustainable way to cut waste production while creating a product with additional value. In this study, pyrolysis and microwave-assisted phosphoric acid (H_3PO_4) activation were used to turn rice waste and chicken bones into activated carbon. The capacity of the produced activated carbons to extract Methyl Violet 2B dye from aqueous solutions was then assessed. This research attempts to help waste valorization and resource recovery initiatives while advancing the development of inexpensive, environmentally friendly materials for wastewater treatment (Kumar et al., 2023) by converting often discarded food waste into an efficient adsorbent.

1.2 Problem Statement

The discharge of dye-containing wastewater from industries such as textiles, printing, paper, leather, and plastics has become a major environmental concern worldwide (Islam et al., 2025b). Synthetic dyes are often resistant to biodegradation and can remain in aquatic environments for a long period (Lin et al., 2023). The presence of these dyes in water bodies can reduce light penetration, disturb photosynthetic activity, affect aquatic ecosystems (Tang, 2024), and may pose potential risks to human health

due to their toxic and carcinogenic properties (Parida et al., 2025). Among these dyes, Methyl Violet 2B is widely used in industrial applications and is commonly found in wastewater streams (Agha et al., 2025). Therefore, effective treatment methods are needed to remove this contaminant before wastewater is discharged into the environment (Kooh et al., 2018).

Chicken rice waste is one of the common organic food wastes in Malaysia. This is because there are many chicken rice shops and franchises in the country, which generate large amounts of waste such as chicken bones and rice. The main problem with the disposal of this waste is that it is usually collected and disposed of in landfills together with other municipal solid waste components, which remains one of the oldest and most common waste disposal methods (Kanwal et al., 2024). Landfilling requires a large land area, and its impact becomes more serious as land value increases. It can also cause environmental problems such as leachate production, gaseous emissions, dust generation, and very little value-added product, except for limited landfill gas recovery, making it less suitable as a sustainable solution (Mandal et al., 2017). More space is also needed to dispose of the increasing amount of food (Dobernig & Schanes, 2019). Another challenge in food waste treatment is that some wastes are acidic, making them difficult to manage using traditional methods such as incineration, anaerobic digestion, and composting (Taricska et al., 2017).

Even with the use of different waste management solutions, Malaysia still faces major challenges due to the rapid growth of solid waste. As shown in Table 1.1, the country continues to produce a large amount of waste, with daily generation often exceeding 39,000 tonnes. This situation places pressure on landfills and existing waste management systems. The information also shows that there is still a gap between the country's recycling goals and the current amount of waste generated. Although the 12th Malaysia Plan aims to achieve a 40% recycling rate by 2025, the gradual progress since 2022 suggests that the existing measures may still be insufficient. Therefore, improved waste characterization and more effective waste management strategies are needed to reduce dependence on conventional disposal methods.

Table 1.1
Annual Solid Waste Generation and National Recycling Rates in Malaysia (2022-2025)

Year	Total Annual Waste (Est. Tonnes)	Daily Generation (Tonnes)	National Recycling Rate	Reference
2022	14.5 million	39,936	33.17%	(Ahmad et al., 2025; Bernama, 2022; Foroutan, Mohammadi, et al., 2022; Selangor, 2022)
2023	14.3 million	39,078	35.38%	(GarGeon, 2026; Mail, 2025)
2024	15.2 million	39,078	36.5%	(GarGeon, 2026; Junaid Ibrahim, 2024; MIDA, 2025; Yang, 2025)
2025	15.38Million	39,000	40.00% (Target)	(Junaid Ibrahim, 2024; MIDA, 2025; Reccessary, 2024; Yang, 2025)

At the same time, adsorption using activated carbon is widely recognized as one of the most effective methods for dye removal due to its high efficiency and simplicity. However, the wider application of commercial activated carbon is often limited by its high production and regeneration costs. This has encouraged researchers to explore alternative low-cost precursor materials derived from agricultural and food wastes. Chicken bone and rice waste are generated in large quantities and are commonly disposed of as solid waste, creating additional environmental burdens. Although various biomass materials have been investigated for activated carbon production, studies on the utilization of chicken bone and rice waste as combined precursor materials remain limited.

In addition, the effectiveness of activated carbon is strongly influenced by its preparation method, surface characteristics, and pore structure. Microwave-assisted activation has emerged as a promising technique due to its rapid heating, energy efficiency, and ability to enhance pore development. However, limited information is available regarding the production of activated carbon from chicken bone and rice waste using microwave-assisted phosphoric acid activation and its application for Methyl Violet 2B dye removal. Additionally, few studies have used kinetic, isotherm, and thermodynamic analyses to investigate adsorption mechanisms and optimize adsorption conditions. Therefore, this study was conducted to develop activated carbon from chicken bone and rice waste, evaluate its physicochemical properties, optimize the adsorption process, and investigate its adsorption behaviour towards Methyl Violet 2B dye removal from aqueous solutions.

1.3 Research Objectives

a) To synthesize activated carbon from chicken bone and rice waste using pyrolysis and microwave-assisted H_3PO_4 activation.
b) To characterize the physicochemical properties of the activated carbons produced by using Field Emission Scanning Electron Microscopy (FESEM), Fourier Transform Infrared Spectroscopy (FTIR), Brunauer-Emmet-Teller (BET), X-Ray Diffraction (XRD), Organic Elemental Analysis (CHNS), and Point of Zero Charge (pH_{pzc}).
c) To optimize methyl violet dye removal using response surface methodology with a Box-Behnken design with three adsorption key parameters such as adsorbent dose, pH, and time.
d) To study the interaction between the adsorbents and adsorbate, as well as the adsorption mechanism and capacity of the adsorbents towards the target dye Methyl Violet 2B by performing kinetic, isotherm, and thermodynamic studies.

1.4 Significance of Study

The main significant of this study is to convert chicken rice waste with no economic value with problem of land fill disposal into activated carbon. This activated carbon can be used as a potential adsorbent for removal of toxic organic dyes from the contaminated water. Moreover, the significance of this study is to convert the chicken rice waste into activated carbon to minimize solid the waste disposal by using the pyrolysis and microwave technique. Char, often derived from biomass or waste materials, is not only cost-effective but also environmentally friendly, offering a sustainable alternative to conventional adsorbents. Its effectiveness in removing a wide range of dyes from wastewater makes it particularly valuable in addressing pollution caused by industrial dye effluents. activated carbon deserves to be considered a major key in wastewater treatment and at the same time decrease excessive food waste.

CHAPTER 2
LITERATURE REVIEW

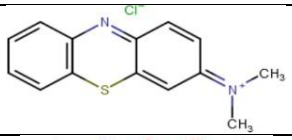
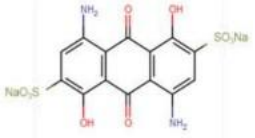
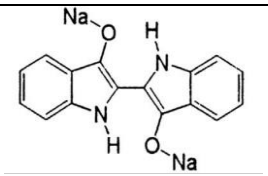
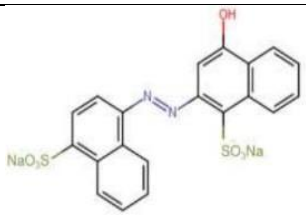
2.1 Introduction

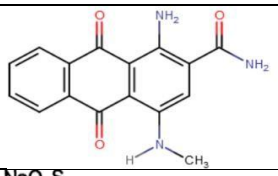
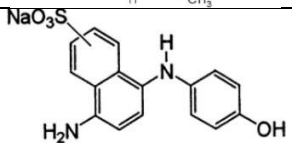
Dyes used in wastewater treatment are classified based on their chemical properties and interactions with water, reflecting the diverse nature of synthetic dyes found across various industries. These dyes are categorized according to their colour, application, and molecular structure (Samsami et al., 2020). One of the most important classification criteria is the chemical structure, which includes major groups such as azo, anthraquinone, and triphenylmethane dyes. This classification is essential as it helps determine the dye's chemical behaviour, environmental stability, and the most effective treatment strategies. The structural complexity of these dyes significantly influences their persistence in aquatic environments and their toxicity to living organisms. Methyl violet, a cationic dye belonging to the triphenylmethane category, holds particular significance due to its widespread use in paints, fabrics, and printing inks (Ali et al., 2022). Its vibrant purple colour (Zhang et al., 2021) is highly valued in these industries for aesthetic purposes but becomes a source of pollution when released into wastewater. Used extensively in textiles, paper, and leather industries (Ndoye et al., 2023), methyl violet's prevalence in industrial effluents poses major challenges for environmental management. This dye's complex molecular structure makes it highly resistant to conventional degradation processes, resulting in its persistence in water bodies, where even low concentrations can cause significant coloration and ecological harm. The presence of such dyes disrupts natural water systems by limiting sunlight penetration, altering oxygen levels, and introducing toxic substances that threaten aquatic life. Furthermore, once these dyes enter water bodies, they can bioaccumulate, posing risks to both wildlife and human health through contaminated water sources.

The environmental impact of dyes like methyl violet necessitates the use of diverse and often combined wastewater treatment methods to effectively remove them. Common treatment techniques include chemical coagulation, biological treatment, and advanced oxidation processes, each addressing different aspects of dye removal (Bahrodin et al., 2021; Khalidi-Idrissi et al., 2023; Ma et al., 2021). Chemical coagulation involves adding substances that cause dye molecules to clump together,

making them easier to separate from water. Biological treatments rely on microorganisms that can partially or fully degrade dye molecules, offering a sustainable and eco-friendly approach. Meanwhile, advanced oxidation processes utilize highly reactive chemical species to break down the complex dye structures into harmless compounds. Despite the availability of these technologies, complete removal of dyes remains technologically challenging due to their chemical stability and resistance to biodegradation (Safarzadeh et al., 2022). This often results in residual contamination in treated water, necessitating continuous innovation to improve treatment efficiency. Research is increasingly focused on synergistic treatment approaches that combine multiple methods, the development of highly efficient adsorbents, and refining process parameters to enhance dye degradation and removal. Additionally, there is growing emphasis on preventing dye pollution at the source by implementing stricter regulations and promoting sustainable industrial practices. In summary, methyl violet and similar synthetic dyes represent a prominent class of industrial pollutants with significant environmental and health hazards. Addressing their presence in wastewater requires comprehensive treatment solutions and vigilant regulatory oversight to protect aquatic ecosystems and ensure water safety for human use.

Table 2.1
Classification of Synthetic Dyes

Types of Dye	Chemical Structure	Description	Reference
Cationic (Basic dye)		These dyes are positively charged colored ions and more soluble in water.	(Ghosh & Rupanty, 2023)
Anionic (Acidic, Reactive, Direct dye)		These dyes are negatively charged colored ions with little fixation on the material surface, are brilliantly colored, hydrolyze simply, and are not liable to biological processes.	(Huang et al., 2023)
Vat Dyes		Vat dyes, a class of synthetic dyes, are characterized by their excellent colorfastness and commonly used in textile dyeing processes due to their ability to produce vibrant and durable colors.	(Alegbe & Uthman, 2024)
Azo dye		Consists of azo class compounds, which are completely stable and impenetrable to degradation. However, as dyes degrade, they may produce toxic and cancer-causing intermediates.	(Benkhaya et al., 2025)

Non-ionic (disperse dye)		They have a low water solubility, do not ionize in the aqueous phase, and are effectively removed by coagulation.	(Chemica, 2023; Zheng et al., 2023)
Sulphur Dyes		Type of synthetic dye, provides excellent colorfastness, and is commonly utilized in dyeing cellulose-based fibers due to their affordability and versatility.	(Chemica, 2023)

2.2 Wastewater Treatment Methods

In recent decades, surface and groundwater pollution has grown to be a serious environmental issue in many parts of the world (Jasechko et al., 2024). This growing concern threatens not only ecosystems but also public health as contaminated water becomes unsuitable for human consumption and agricultural use. Various pollutants, including organic and inorganic substances, heavy metals, pharmaceuticals, and emerging contaminants, have been detected in many water bodies, complicating remediation efforts. One of the biggest issues facing the world today is the shortage of water. Since clean water is essential for existence, new technologies are required to assist in supplying it (Diao & Ulanicki, 2025). The global increase in demand for freshwater resources, driven by population growth, urbanization, and industrial expansion, places unprecedented stress on limited water supplies. However, the world's current water resources are more contaminated than they were a generation ago because of the tremendous population growth and fast industrialization (Jasechko et al., 2024). This contamination exacerbates water scarcity issues by reducing the amount of safe, usable water available. Anthropogenic contaminations, which include sewage, fertilizers, and industrial waste, are the primary source of water pollution (Lin et al., 2022). These pollutants enter water ecosystems through various pathways such as agricultural runoff, untreated sewage discharge, and industrial effluents, leading to problems like eutrophication, toxicity to aquatic life, and the spread of waterborne diseases.

Wastewater treatment is important because it helps keep our water clean and safe for everyone (Singh et al., 2023). It serves as a critical barrier preventing harmful substances from re-entering natural water courses and causing widespread environmental damage. There are lots of different methods we use to clean up wastewater before it goes back into rivers or oceans. Primary treatment methods, such

as screening, sedimentation, and flotation, focus on the physical removal of large solids and organic matter (Nishat et al., 2023). These steps are effective in reducing the initial load of pollutants and preparing the water for further treatment. Secondary treatment, which often involves biological processes like activated sludge and trickling filters, uses microorganisms to decompose organic pollutants, converting them into less harmful substances like carbon dioxide and water (Shamshad & Rehman, 2025). This biological degradation is essential in lowering biochemical oxygen demand (BOD) and preventing oxygen depletion in receiving waters. Tertiary treatment methods, including filtration, chemical treatment, and disinfection, are employed to achieve advanced levels of purification, removing remaining pollutants to meet high quality requirements (Nishat et al., 2023). These methods help remove dissolved solids, pathogens, nutrients, and emerging contaminants that cannot be eliminated by secondary treatment, ensuring the discharged water complies with regulatory standards. Emerging technologies offer innovative approaches to wastewater treatment, such as membrane bioreactors, advanced oxidation processes, and constructed wetlands, which offer enhanced efficiency and pollutant removal capabilities. These novel technologies combine physical, chemical, and biological processes to address increasingly complex wastewater compositions and support sustainable water management. Despite these advancements, challenges persist, including the need to address emerging contaminants, optimize energy consumption, and promote sustainability in treatment processes (Singh et al., 2023). Achieving these goals requires multidisciplinary research, supportive policies, and investment in infrastructure to adapt to changing environmental and societal needs.

Ongoing research and innovation are essential to address these challenges and ensure the continued effectiveness and efficiency of wastewater treatment methods in protecting water resources and ecosystems (Satyam & Patra, 2024). In addition to improving treatment technologies, efforts are being made to integrate wastewater treatment with resource recovery initiatives, such as nutrient capture, biogas production, and water reuse, which contribute to circular economy goals and environmental sustainability. The implementation of smart monitoring systems and advanced data analytics is enhancing operational efficiency and enabling real-time management of treatment plants to respond promptly to fluctuations in wastewater quality. Moreover, public awareness and stakeholder engagement are increasingly recognized as crucial components of effective water management strategies, promoting responsible water use

and support for pollution prevention measures. As global water challenges intensify due to climate change and population pressures, wastewater treatment will continue to play a central role in safeguarding water security and environmental health. Continued investment in research, technology development, policy frameworks, and education is necessary to ensure that wastewater treatment evolves to meet future demands and contributes to the overall resilience of water systems worldwide.

Table 2.2
The Environmental Dataset Infomation

Category	Process	Description	Advantages	Disadvantages	References
Physicochemical	Coagulation & Floculation	To coagulate the dyestuffs, a chemical is applied to the effluent. After that, the coagulated dyestuff is eliminated as sludge.	• Low capital and operational cost • Easy to operate	• High sludge production (hazardous waste) • Potential of colour reappearance	(Aragaw & Bogale, 2023; Iloamaeke et al., 2025)
	Adsorption	Wastewater is streamed through an adsorption agent (usually activated carbon) to remove the colour and other substances (volatile compounds that can have a smell, organic residue, etc.). Requires periodic generation	• Low capital cost • High performance and flexibility	• Does not degrade the substance. • Requires constant maintenance since saturated adsorbent dramatically reduces the performance	(El Meziani et al., 2025; Kuppusamy et al., 2026)
	Membrane Filtratrion	Similar to adsorption, in which pollutant is filtered through the membrane pores. Requires periodic regeneration.	• Very high removal percentage	• High capital and cost • Low operational flow rate • Perform the best as the last process in the	(Dehingia et al., 2024; Khan et al., 2025)

				sequences	
Advanced oxidation process	Ozone	Oxidation of dyes involves hydroxyl radical species formed by ozone	• High performance • Suitable for all type of dyes	• Very expensive • Treated water may still be toxic to aquatic life	(Benjelloun et al., 2023; Hutagalung et al., 2023)
	Fenton	Oxidation of dyes by using peroxide (H_2O_2) through formation of hydroxyl radical ion.	• High colour removal rate • Suitable for all types of dyes	• Excessive chemical use • Only works under acidic conditions • Performs better as a tertiary treatment	(Maezono et al., 2011; Mansoorian et al., 2014)
	Photocatalytic	Heterogenous oxidation of dyes via photoreaction in the presence of a catalyst, usually titanium oxide (TiO_2)	• Little to zero chemical use	• Generally, has low performance • High initial cost (precious metal catalysts are generally expensive)	(Das et al., 2022; Nayak, 2022)
	Photo-Fenton	Homogenous oxidation of dyes via photoreaction in the presence of ferrous (Fe^{2+}) iron	• Very high colour removal rate for most dyes. • Low chemical usage due to continuous cycle of reagent • Small to zero sludge production	• Works best under acidic conditions (requires pH adjustments)	(Xiao et al., 2024)

			• No toxic by products		
Biological	Biological Process	Degradation of dyes under anaerobic conditions through the breaking of the chemical bond. mostly applied to azo dyes. The aromatic amine molecule is further broken down by an aerobic mechanism.	• Environmentally and cost-efficient • Widely applied in textile wastewater treatment plants (WWTPs)	• Both processes are necessary for color deterioration • Biological processes are complex by nature. • Restricted use for specific dye types only	(Alzain et al., 2023)
	Fungi-Based process	The wastewater's dyestuff is broken down and demineralized using fungus culture.	• More dye types can be used than in microbiological systems • Can be used in conditions that fluctuate	• Prolonged reaction time, potentially compromising process stability • Unreliable performance	(Latif et al., 2023; Pundir et al., 2024)

2.3 Methyl Violet 2B Dye

Methyl Violet 2B (MV2B) is a cationic triphenylmethane dye widely used in various industrial processes such as colouring biological materials, dying textiles, and manufacturing ink (Alsuhybani et al., 2024). Its strong affinity for negatively charged surfaces allows it to effectively colour bacterial cells and tissue samples, making it valuable in microbiology and histology applications. The dye is characterized by its distinctive violet colour, exhibiting its strongest wavelength of absorption in water between 590 and 600 nm (Goudjil et al., 2024). Being a synthetic dye, MV2B readily dissolves in both water and organic solvents, which contributes to its persistence in industrial wastewater if not properly treated. This widespread industrial usage combined with its solubility increases the likelihood of MV2B contaminating water bodies, especially where wastewater treatment facilities are inadequate or inefficient. The dye's ease of dissolution also facilitates its transport through aquatic systems, potentially spreading contamination over large areas and making remediation efforts more complex and costly (Ndoye et al., 2023).

However, despite its industrial importance, MV2B poses significant environmental and health risks. The compound is highly resistant to natural degradation processes, resulting in long-term persistence in aquatic environments. Studies have demonstrated that MV2B is toxic to marine life and poses carcinogenic and mutagenic risks to human health (Alsuhybani et al., 2024). Its accumulation in ecosystems can obstruct sunlight penetration in water bodies, hindering photosynthetic activity and disrupting the ecological balance of marine habitats. The inhibitory effects on photosynthesis can lead to oxygen depletion, negatively affecting aquatic organisms dependent on balanced oxygen levels. In addition, the bioaccumulation of MV2B and its metabolites in aquatic organisms raises concerns about biomagnification through the food chain, potentially affecting higher trophic levels, including humans. Given these serious implications, developing effective and sustainable methods for the removal of MV2B from wastewater remains an important focus of environmental research (Oros, 2025). The urgent need to mitigate its harmful impacts has spurred investigations into both conventional and advanced treatment technologies, emphasizing the necessity of integrating multiple approaches for comprehensive remediation.

Several treatment methods have been explored for MV2B removal, with adsorption standing out as one of the most effective and environmentally friendly

approaches. Activated carbon, biochar, and other adsorbents derived from agricultural and food waste have demonstrated high adsorption capacities for MV2B from aqueous solutions. These materials provide an economical and sustainable alternative to commercial adsorbents, contributing to waste valorization efforts (Tyagi & Anand, 2024). Additionally, advanced oxidation processes (AOPs), such as photocatalysis and the Fenton reaction, have been employed to degrade MV2B into less harmful byproducts through the generation of reactive oxygen species. Such AOPs offer efficient dye breakdown but may require optimization for large-scale use due to energy and chemical input considerations. Combining adsorption with AOPs has also been studied, enhancing removal efficiency and reducing operational limitations associated with single methods. In line with sustainable waste management goals, producing activated carbon from chicken bones and rice husks presents a promising low-cost strategy for MV2B removal. This approach not only addresses industrial dye pollution but also promotes recycling of agricultural residues, aligning with circular economy principles and environmental protection efforts (Yoğun & Yıldırım, 2025). Ongoing innovations focus on enhancing adsorbent regeneration, reducing treatment costs, and minimizing secondary pollution, thereby supporting the broader application of these techniques in industrial wastewater management.

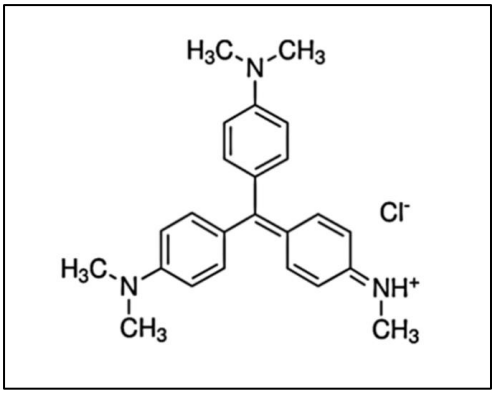


Figure 2.1 Methyl Violet 2B Dye (El-Ghobashy et al., 2022)

2.4 Adsorption Process

The adsorption process in wastewater treatment reveals its significance as a highly efficient (Rashid et al., 2021) and widely used (Rathi & Kumar, 2021) method for pollutant removal. This method's versatility allows it to be applied across a wide spectrum of contaminants, ranging from organic compounds and heavy metals to dyes and emerging pollutants. The use of several adsorbent materials, such as activated carbon, zeolites, clay minerals, and biochar, in the removal of pollutants such as organic compounds, heavy metals, and colours from wastewater streams has been the subject of numerous studies. Each type of adsorbent offers unique surface properties, pore structures, and chemical functionalities that influence its adsorption capacity and selectivity. Researchers have focused on optimizing adsorption parameters such as adsorbent dosage, contact time, pH, temperature, and initial concentration to enhance the efficiency of the process (Jawad & Abdulhameed, 2020). These parameters critically affect the interaction between adsorbate and adsorbent, influencing adsorption kinetics and equilibrium. Additionally, studies have explored the mechanisms of adsorption, including physical adsorption (van der Waals forces) and chemical adsorption (ionic interactions, complexation), to understand the factors influencing pollutant adsorption onto the surface of adsorbent materials. Understanding these mechanisms is vital for designing tailored adsorbents with improved affinity for target contaminants and for modelling adsorption processes under various operational conditions. Furthermore, advancements in materials science and engineering have led to the development of new adsorbents with specific characteristics to target specific pollutants (Ateia et al., 2020) and improve adsorption performance in wastewater treatment applications (Bukva et al., 2023). Novel materials such as functionalized biochar, magnetic nanocomposites, and hybrid organic-inorganic frameworks are increasingly being engineered to enhance adsorption capacity, regeneration ability, and selectivity towards complex wastewater matrices.

Moreover, this field highlights the importance of considering the economic feasibility and practical implementation of adsorption processes in wastewater treatment systems (Ahmad, 2023). While lab-scale studies demonstrate promising adsorption capacities, scaling up these processes requires thorough cost-benefit analyses, including material costs, regeneration frequency, and process integration. Cost-effectiveness analyses, life cycle assessments, and techno-economic evaluations

have been conducted to assess the overall viability and sustainability of adsorption-based treatment methods compared to conventional treatment approaches (Ngeno et al., 2022). These evaluations consider factors such as energy consumption, carbon footprint, and waste generation associated with adsorbent production and disposal, informing sustainable decision-making. Furthermore, studies have explored innovative techniques such as hybrid processes combining adsorption with other treatment methods such as membrane filtration (Alardhi et al., 2023) and electrochemical processes to enhance pollutant removal efficiency and reduce operational costs (Ensano et al., 2016). These hybrid systems aim to overcome limitations inherent in single treatments by leveraging synergistic effects, improving overall water quality and enabling the treatment of complex effluents with mixed contaminants. The integration of adsorption with advanced oxidation processes or biological treatments is also being investigated to achieve deeper pollutant removal and to facilitate adsorbent regeneration (Adeoye et al., 2024). Overall, this shows how very promising adsorption methods might be in wastewater treatment for addressing water pollution challenges and achieving environmental sustainability goals, while also emphasizing the need for further research to optimize process performance, overcome limitations, and facilitate practical implementation at larger scales. Continued innovation in adsorbent design, process optimization, and system integration will be essential for transitioning adsorption technologies from pilot studies to full-scale applications that contribute effectively to global water resource management.

2.5 Chicken Bone and Rice Waste Generation in Malaysia

Malaysia is among the top consumers of poultry meat globally, with Malaysians consuming approximately 48.2 kg of chicken per capita annually, placing the country among the highest consumers in Asia (Alfred et al., 2022). This high consumption rate reflects not only cultural dietary preferences but also the affordability and accessibility of poultry meat as a primary protein source in Malaysian households. The increasing demand has driven growth in the poultry industry, making it a significant contributor to the nation's agricultural economy. However, this surge in consumption simultaneously generates a substantial amount of chicken bone waste, which often ends up in landfills due to limited recycling and valorization options (El-Khateeb et al., 2022). Chicken bones consist mainly of organic and inorganic components, including a significant

amount of hydroxyapatite and protein (Abd Rahman et al., 2024). These components present a valuable opportunity for reuse and recycling, yet the lack of efficient processing technologies and awareness limits practical applications. In Malaysia, chicken bones make up a sizable amount of food waste and are frequently thrown away without being properly reused or recycled, which exacerbates solid waste management issues and pollutes the environment (SAHARUDDIN et al., 2025). The improper disposal not only contributes to landfill overflow but also risks environmental contamination through leachate and greenhouse gas emissions. Although chicken bones are rich in calcium and can be valorized, such as being converted into catalysts for biodiesel production or adsorbents, these applications remain underdeveloped and not widely implemented, leading to inefficiencies in waste utilization (Andas & Jusoh, 2022). Expanding the utilization of chicken bone waste into functional materials could pave the way for innovative, eco-friendly solutions that align with Malaysia's environmental sustainability goals.

Rice is the primary staple food in Malaysia and is consumed 86.9% to 97.3% daily by most of the population (Noraida Binti et al., 2018). Due to its widespread consumption, a significant amount of cooked rice is wasted every day from households, restaurants, cafeterias, and other food service establishments. In many cases, rice is prepared in excess and discarded when it is no longer suitable for consumption (Angeles-Agdeppa et al., 2023). As the population continues to grow and food demand increases, the amount of rice waste generated has also risen. This contributes to the growing issue of food waste in Malaysia, where large quantities of edible food are disposed of in landfills each year (Yatoo et al., 2024). The accumulation of rice waste not only increases the burden on waste management systems but also contributes to environmental problems such as greenhouse gas emissions during decomposition (Mohammad Sabri et al., 2024). Consequently, there is increasing interest in finding sustainable ways to utilize rice waste rather than treating it solely as a disposal problem.

Leftover rice mainly consists of starch, which is composed of amylose and amylopectin (Shen et al., 2025), along with smaller amounts of proteins, fats, and minerals. These components contain functional groups that can interact with pollutants such as hydroxyl, carboxyl, carbonyl, amine, and phosphate groups making rice waste a potential raw material for adsorbent production (Shen et al., 2025). It can be converted into activated carbon or biochar through thermal treatment processes (Bakari et al., 2024). Such treatments enhance the surface area and porosity of the material, improving

its adsorption performance. As a result, rice waste has attracted attention as a low-cost and environmentally friendly alternative to commercial adsorbents.

Several studies have reported the successful use of rice waste-derived materials for removing contaminants from wastewater (Sahoo et al., 2023). After undergoing suitable treatment and activation, rice waste can develop a porous structure capable of adsorbing dyes, heavy metals, and other pollutants (Leng et al., 2021). The adsorption process occurs through interactions between the pollutant molecules, and the functional groups present on the adsorbent surface. Rice waste-based adsorbents have shown promising performance in the removal of synthetic dyes (Awang et al., 2024) commonly found in industrial effluents. The abundance and low cost of rice waste make it an attractive option for wastewater treatment applications (Sahoo et al., 2023). At the same time, its utilization helps reduce food waste generation and promotes the conversion of waste materials into value-added products, supporting sustainable waste management and circular economy practices.

Both chicken bone and rice waste generation in Malaysia present a pressing need for sustainable waste management strategies. Their continuous generation in large quantities not only creates disposal challenges but also offers opportunities for conversion into valuable materials such as activated carbon. Activated carbon derived from such biomass waste has wide-ranging applications in adsorption and pollution control, contributing significantly to environmental remediation efforts (Adegoke et al., 2025). This valorization can reduce environmental impacts and produce functional materials for applications in adsorption and pollution control, supporting Malaysia's goals for a circular economy and sustainable resource utilization. Encouraging collaboration between academia, industry, and government agencies is essential to realize the full potential of these waste streams and to develop scalable, cost-effective waste-to-resource technologies.

2.6 Activated Carbon as an Adsorbent

Activated carbon (AC) is widely recognized as a highly effective adsorbent for water treatment (Jawad et al., 2021) due to its porous structure and large surface area. These structural properties enable AC to provide numerous active sites that facilitate the binding and removal of contaminants from water. A significant amount of research has examined how well AC works to remove different types of contaminants from water

sources (Hasan & Muhammad, 2020). These contaminants include organic compounds, heavy metals, dyes, and emerging pollutants like pharmaceuticals and pesticides. Research studies have explored factors influencing AC's adsorption capacity, including its pore size distribution, surface chemistry, and the characteristics of target pollutants. The interplay between pore size and contaminant molecular size plays a critical role in determining the adsorption efficiency, as it affects the accessibility of adsorption sites. Additionally, optimization of operational parameters such as contact time, adsorbent dosage, pH, temperature, and flow rate has been extensively studied (Awang et al., 2023) to enhance the efficiency of the adsorption process (Othmani et al., 2021). Fine-tuning these parameters helps in maximizing the removal capacity while reducing treatment costs and time (Mohd Radhuwan et al., 2024), which is essential for practical applications in water treatment plants.

Furthermore, researchers have studied the mechanisms on AC surfaces that cause the adsorption of things. Physical mechanisms such as van der Waals forces and chemical interactions such as electrostatic attraction play crucial roles in the adsorption process (Tomul et al., 2021). These mechanisms enable the trapping of diverse contaminants through weak intermolecular forces and stronger chemical bonds, facilitating both reversible and irreversible adsorption. Understanding these mechanisms is essential for optimizing AC's performance and developing specialized adsorption systems for specific water treatment applications. For example, tuning the surface chemistry of AC through functionalization can enhance selective adsorption of heavy metals or organic dyes (Wang et al., 2023). New AC-based adsorbents with improved adsorption capabilities and selectivity toward target pollutants have been developed because of recent developments in material science. These advanced materials often involve the incorporation of nanoparticles or chemical modification to boost adsorption kinetics and capacity. Additionally, researchers have explored the incorporation of AC into hybrid adsorption systems (Othmani et al., 2021), combining it with other treatment processes such as membrane filtration and electrochemical treatment, to achieve synergistic pollutant removal and overall process efficiency (Othmani et al., 2021).The integration of such hybrid systems aims to overcome limitations associated with single treatment methods by combining their advantages. This literature study highlights the versatility and effectiveness of AC as an adsorbent in water treatment, with ongoing research aimed at further improving its performance, understanding its mechanisms, and expanding its practical applications in addressing

emerging water quality challenges. The surface areas of the current study and different waste products that are being used to absorb dye pollutants are compared in Table 2.3.

Table 2.3
Comparison Study of Biomass Waste

Adsorbent employed for dye removal	**Activation Method**	**Surface Area (m^2/g)**	**Reference**
Chicken Rice Waste	Pyrolysis	369.32	(Awang et al., 2023)
Banana Peel	Microwave	263.006	(Soleimani et al., 2022)
Sawdust	Microwave	367	(Kazmierczak-Razna et al., 2015)
Date Stones	Microwave	315.5	(Shamsabadi et al., 2021)
Date Pit	Pyrolysis	278.18	(Al-Onazi et al., 2021)
Pomegranate Peel	Pyrolysis	115	(Hessien, 2022)

2.7 Method for Preparing Activated Carbon

The methods for preparing activated carbon (AC) reveal a diverse array of techniques aimed at optimizing its properties for effective adsorption in water treatment and other applications. Common methods include physical activation, chemical activation, and thermal activation (Bandani et al., 2026). Physical activation involves the pyrolysis of carbon-derived precursors (Contescu et al., 2018), such as chicken rice waste, which consists of chicken bone and rice grain, at high temperatures in an inert atmosphere, followed by steam or carbon dioxide activation to create porosity (Alvarez et al., 2015).

Chemical activation, on the other hand, involves impregnating the precursor material with a chemical agent, such as potassium hydroxide (KOH) or phosphoric acid (H_3PO_4), before subjecting it to pyrolysis (Heidarinejad et al., 2020). This method yields AC with well-developed porosity and high surface area due to the activation of pores during carbonization (Heidarinejad et al., 2020). Thermal activation, also known as gasification, utilizes oxidizing gases like air or steam to react with the precursor material at elevated temperatures (Jenkins, 2020), resulting in the formation of porous AC.

Numerous investigations have investigated alterations to these conventional techniques to improve the quality and consistency of the resulting activated carbon. For instance, researchers have explored the use of new precursors (Hossen et al., 2024), such as agricultural residues, industrial waste materials, and biomass-derived sources, to produce sustainable and cost-effective AC (Heidarinejad et al., 2020). These alternative materials not only repurpose waste, thereby reducing environmental burden, but also help reduce production costs compared to conventional coal- or wood-based precursors. Additionally, efforts have been made to optimize activation conditions, including temperature, activation time, impregnation ratio, and heating rate, to achieve pore structures and surface chemistry tailored to specific adsorption applications (Godoy Bautista et al., 2025). Advanced experimental designs such as Response Surface Methodology (RSM) have been employed to efficiently optimize these parameters, balancing yield, surface area, and pore distribution to maximize adsorption performance. Furthermore, advancements in process engineering, such as pyrolysis-assisted activation, the use of fluidized bed reactors, microwave-assisted activation, and electrochemical activation, have been explored to improve the efficiency, uniformity, and scalability of AC production (Al-Ghurabi et al., 2025). These innovative

technologies facilitate better temperature control, reduce processing times, lower energy consumption, and allow the production of AC with desirable properties for a range of industrial applications.

It emphasizes the importance of methodological advancements in preparing activated carbon with tailored properties suitable for various applications, including water treatment, gas purification, energy storage, and catalysis. The continued research in this field aims not only to enhance adsorption performance and product quality but also to promote sustainability using renewable precursors and energy-efficient processes (Moghaddam & Esfandyari, 2025). The integration of green chemistry principles with technological innovation has the potential to revolutionize AC production (Escobar & Laibach, 2021), meeting rising demand while minimizing environmental impact.

2.8 Physical Activation

The development of a pore structure in carbon is termed activation, which is categorised into physical and chemical mechanisms. Physical activation methods were established earlier and are more prevalent in industry; they can produce activated carbon at a reduced cost due to the lower prices of activating agents for example steam (Ojo et al., 2025), carbon dioxide (CO_2), or air and the absence of requirements for further treatment and specialised equipment. Physical activation is a bifurcated process comprising a carbonisation phase in the presence of an inert gas such as Nitrogen (N_2) or Argon (Ar), succeeded by an activation phase utilising an oxidising gas Oxygen (O_2), Carbon Dioxide (CO_2), Water steam (H_2O steam) within a temperature range of 800-1200 °C. The primary advantages of physical activation are its environmentally friendly manufacture and the absence of secondary waste management, in contrast to chemical activation. Nonetheless, the drawbacks of physical activation include to its elevated activation temperature, long processing time, comparatively low carbon output, and inadequate specific surface area. The primary elements influencing physical activation encompass the nature of carbon precursors, their particle dimensions, gas flow rate, heating velocity, carbonisation duration, and carbonisation temperature (Stavropoulos & Zabaniotou, 2009). Chemical activation, referred to as "wet oxidation," is a singular process wherein carbonisation and activation occur concurrently within a temperature range of 450–850 °C (Gao et al., 2020).

2.8.1 Pyrolysis-Assisted Activated Carbon Preparation

Pyrolysis-assisted activated carbon preparation is an advanced method of making useful stuff from waste (Januszewicz et al., 2020). Do you know how, when you burn wood, it turns into charcoal? Well, for pyrolysis, it is like that, but instead of wood, we use things like old tires, agricultural waste, or even sewage sludge. This process heats up these materials in a unique way, without burning them completely, and turns them into activated carbon. Activated carbon is like a sponge for pollutants (Allgayer et al., 2020), it can soak up all kinds of yucky stuff from water or air, making them cleaner and safer for us to use. Scientists have found that using pyrolysis to make activated carbon is not only a clever way to recycle waste (J. L. Yang et al., 2022), but it also produces high-quality carbon (Wang et al., 2021) that's really good at cleaning up our environments.

Pyrolysis is a thermal decomposition technique that involves heating a material in the absence of oxygen (Zaman et al., 2017) to break it down into smaller molecules and chemical compounds. The tube furnace is a common equipment used in pyrolysis (Xue et al., 2021). It is a cylindrical chamber that is heated by an external heat source, such as electric heating elements or gas burners. In the tube furnace, the substance to be pyrolyzed is heated to the appropriate temperature. A tube furnace's pyrolysis procedure can be broken down into multiple steps:

1. Preheating: The tube furnace is heated to the desired temperature before the sample is introduced. Normally, it will be pre-heated one day before the use of the actual sample. This is to ensure that the sample is heated evenly and quickly.
2. Pyrolysis/Ramping up: The sample is introduced into the tube furnace and heated to the desired temperature at a rate of 10 °C/min to 600 °C, 700 °C, and 800 °C for 1- or 2-hours during heating. The decomposition of the material occurs as the temperature increases.
3. Retaining: The temperature will be retained at a consistent level for a specific time limit, and it all depend on our settings. It is crucial to retain the temperature to obtain the desired product and to prevent overheating or under heating of the sample.

4. Cooling: Once the desired temperature is reached, the sample is cooled to prevent further decomposition or oxidation.

5. Analysis: The products of the pyrolysis are analyzed to determine the chemical composition and properties.

Pyrolysis using a tube furnace is a versatile technique that can be used to study a wide variety of materials (Escalante et al., 2022), such as plastics, biomass, and organic compounds. It can also be used to recover valuable chemicals and fuels from waste materials. However, this process requires careful monitoring and control to ensure that the products of the pyrolysis are safe and of high quality.

What's good about pyrolysis-assisted activated carbon preparation is that it's like turning trash into treasure (J. L. Yang et al., 2022). By using materials that might otherwise end up in landfills or pollute our environment, we are creating something valuable and useful. Plus, activated carbon made this way has lots of applications, like purifying water, removing pollutants from air, or even storing energy. This method is effective and sustainable, offering a smart solution to waste management and environmental protection. Therefore, researchers continue to explore and improve pyrolysis-assisted activated carbon preparation, we're getting closer to a cleaner and greener future.

Figure 2.2 illustrates the general overview of the pyrolysis process involved in the preparation of activated carbon from carbonaceous precursor materials. Pyrolysis is a thermochemical conversion process that involves the thermal decomposition of organic materials under an oxygen-limited or oxygen-free environment (Tan et al., 2024). During the pyrolysis process, the precursor material undergoes gradual heating (Pan et al., 2022), resulting in the breakdown of complex organic compounds and the release of volatile components in the form of gases and vapours, leaving behind a carbon-rich solid residue known as char (Ungureanu et al., 2025). This process promotes the rearrangement of carbon structures and creates initial pores within the carbon matrix. When combined with chemical activation using agents such as phosphoric acid (H_3PO_4), further development of the pore structure occurs through dehydration and oxidation reactions, which enhance the surface area and adsorption properties of the activated carbon. The pyrolysis conditions, including temperature, heating rate, residence time, and type of precursor material, significantly influence the

physicochemical characteristics of the produced activated carbon (Jerzak et al., 2024). Therefore, pyrolysis-assisted activation is considered an effective method for converting biomass waste into porous carbon materials with desirable adsorption capacity for wastewater treatment applications.

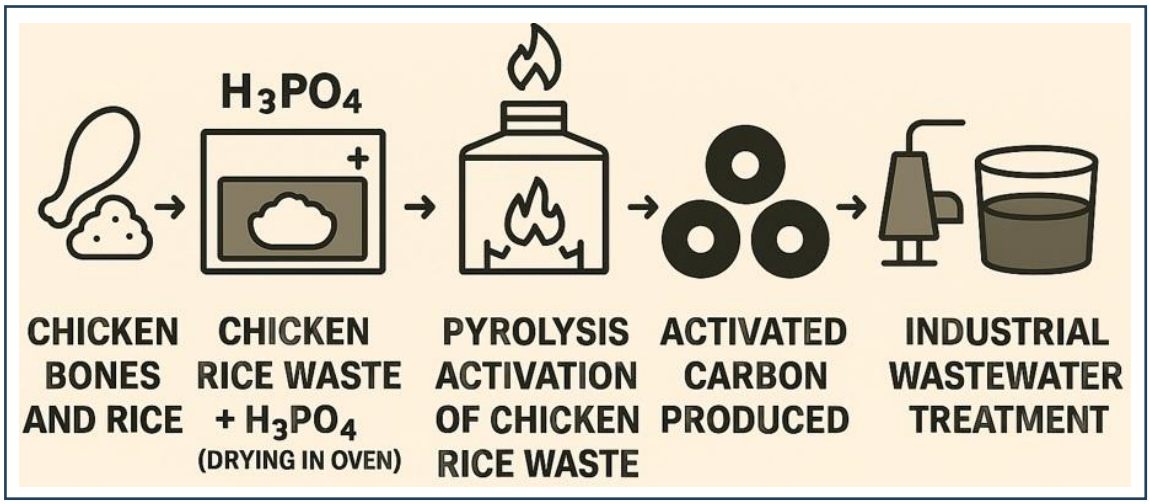


Figure 2.2 Overview of Pyrolysis Testing

2.8.2 Microwave-Assisted Activated Carbon Preparation

Microwave-assisted activated carbon preparation involves several key steps to convert carbonaceous precursors into highly porous activated carbon using microwave energy (Iwanow et al., 2020). Initially, the precursor material, such as biomass or waste materials, is selected and processed to ensure uniformity and proper size distribution. Next, the precursor is impregnated with a suitable activating agent (Heidarinejad et al., 2020), typically KOH or H_3PO_4, which enhances the porosity and surface area of the final activated carbon product (Gayathiri et al., 2022). The impregnated precursor is then subjected to microwave irradiation in a specially designed reactor. It must operate on electromagnetic radiation with wavelengths ranging from 1 mm to 1 m and frequencies between 0.3 to 300 GHz.

To prevent interference, these ranges must be controlled and tailored for a variety of applications, such as industrial, scientific, and medical ones. Different frequencies are used for business and residential purposes (Escobar & Laibach, 2021). For instance, industrial applications can benefit from frequencies like 2.45 GHz, which is widely used in household and industrial microwave ovens, 5.8 GHz is used in some industrial applications and 0.915 GHz is used in large-scale industrial processes where

deeper penetration is needed (Stavropoulos & Zabaniotou, 2009). Wavelengths between 12 and 33 cm are chosen for household applications because they provide high efficiency and less penetrative heating. Most household microwave ovens operate specifically at 2.45 GHz, which is a wavelength of about 12.24 cm. Microwave radiation rapidly heats the sample (Amini et al., 2021), causing the activation agent to react with the carbonaceous material. This leads to the release of volatile gases and the formation of a highly porous structure within the material, producing activated carbon (Alharbi et al., 2022).

One of the main advantages of microwave-assisted activated carbon preparation is its rapid and efficient activation process (Zhou et al., 2021). Microwave heating provides uniform and intense heat distribution throughout the sample (Dinani et al., 2020), leading to faster reaction kinetics and shorter activation times compared to conventional heating methods. Additionally, microwave irradiation offers better control over the activation process parameters (Yang et al., 2022), such as temperature and heating rate, allowing for fine-tuning of the final activated carbon properties. This method also enables the use of a wide range of carbonaceous precursors, including biomass and waste materials, making it a versatile and sustainable approach for producing high-quality activated carbon for various applications (Heidarinejad et al., 2020), including environmental remediation, water treatment, and energy storage.

Figure 2.3 illustrates the general overview of the microwave-assisted activation process for activated carbon preparation. Microwave heating is based on the conversion of electromagnetic energy into thermal energy through molecular interactions within the precursor material (Qiuchen et al., 2025). Unlike conventional heating methods, where heat is transferred from the outer surface towards the inner part of the material, microwave irradiation enables direct and volumetric heating through dipole rotation and ionic conduction, resulting in rapid and uniform temperature distribution. During the microwave-assisted activation process, the applied microwave energy promotes the decomposition of volatile components, accelerates carbonization, and enhances the development of porous structures within the carbon framework (Ren et al., 2024). When combined with chemical activating agents such as phosphoric acid (H_3PO_4), microwave irradiation facilitates dehydration reactions, improves pore formation, and reduces carbon loss by minimizing excessive structural collapse (Villota et al., 2018). These effects contribute to the production of activated carbon with enhanced surface characteristics and adsorption performance. Therefore, microwave-assisted activation

is considered an efficient alternative technique due to its shorter processing time, improved energy efficiency, and better control over the physicochemical properties of activated carbon, making it suitable for the conversion of biomass waste into effective adsorbent materials for wastewater treatment applications (Olugbenga et al., 2024).

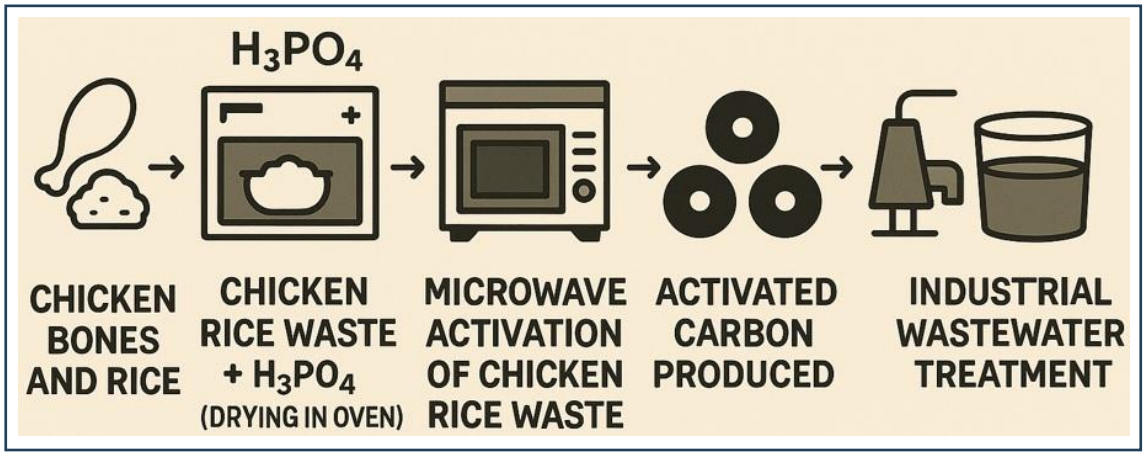


Figure 2.3 Overview of Microwave Testing

2.9 Response Surface Methodology (RSM) for Process Optimization

Response Surface Methodology (RSM) for process optimization of dye involves examining numerous studies and research related to the application of RSM in optimizing dyeing processes. Researchers typically begin by exploring the fundamentals of RSM, including its mathematical principles and experimental design techniques, such as factorial designs and central composite designs. they examine previous applications of RSM in dyeing processes, across different dye types (e.g., natural dyes, synthetic dyes) and substrates (e.g., textiles, polymers). This involves analysing how RSM has been used to optimize dyeing parameters (Abdelileh et al., 2023) such as dye concentration, temperature, pH, time, and the coating process to improve colour yield, fastness properties, and overall dyeing efficiency. Additionally, these may highlight advancements in RSM methodologies specific to dyeing processes, including the incorporation of eco-friendly dyeing techniques, such as enzymatic or microwave-assisted dyeing, and the use of novel statistical tools for model validation and optimization.

Researchers may discuss challenges and limitations associated with applying RSM to dyeing processes, such as the complexity of dye-substrate interactions, the need for accurate measurement techniques, and the consideration of environmental and sustainability factors. All things considered, it offers a thorough summary of the state-

of-the-art in employing RSM to optimize dyeing procedures, highlighting patterns, weaknesses, and prospects for further study and use in the dye sector. The application system for response surface methodology (RSM) consists of the following:

1. Planning a series of investigations that will produce accurate and trustworthy measurements of the relevant response
2. Selecting a mathematical model and testing model variable assumptions to determine which model best fits the data from the design selected in (1).
3. Determining the ideal experimental factor values that result in the greatest (or smallest) response value. If response surface approaches are the best, they seek to enhance the understanding of the system as a whole or at the very least make it possible to determine the ideal condition (stages) of the elements to optimize a desired output. Figure 2.2, on the other hand, focuses more on the optimization and simulation of the physicochemical RSM process, which entails six sequential steps:

    1) Selecting the appropriate answers after screening independent variables.
    2) Selecting the methodology for the experimental design.
    3) Conduct experimentation and obtain data.
    4) Matching experimental results to the developed mathematical model.
    5) Using graphs and analysis of variance to validate the model.
    6) Determining the ideal conditions.

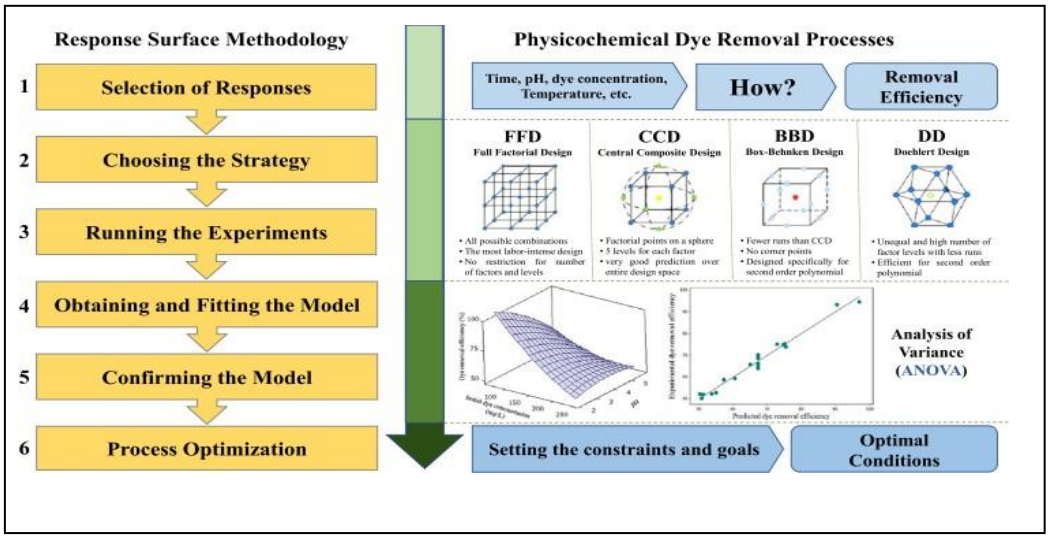


Figure 2.4 The General Concepts of RSM in Physicochemical Dye Removal Processes (Karimifard & Moghaddam, 2018)

RSM physicochemical may be useful when multiple factors influence a set of responses of interest (Karimifard & Moghaddam, 2018). For quadratic response surfaces, one can use the Box-Behnken, central composite, Doehlert, and three-level factorial designs. The number of runs, blocks, and experimental points, as well as the number of factors levels, varies among these symmetrical designs. Numerous computer programs are available to facilitate the completion of these steps. Notable DOE tools for physicochemical dye removal include Minitab (Minitab Inc.), Design Expert (State-Ease Inc.), Statistica (Stat Soft), and MATLAB (Mathworks) (Karimifard & Moghaddam, 2018). The table illustrates how RSM is used in analytical chemistry in conjunction with different optimization methods.

2.10 Characterization of Activated Carbon

2.10.1 X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is a characterization method used to study the structural arrangement of atoms and molecules in a material (Khan et al., 2020). In this technique, a sample is exposed to X-rays, and the diffracted beams are recorded based on their angles and intensities. The resulting diffraction pattern provides insights into the sample's crystal lattice, atomic arrangement, and overall composition. XRD is widely utilized in chemistry, materials science, and mineralogy to characterize the structural and physical properties of solid materials (A. Ali et al., 2022; Bunaciu et al., 2015; Khan

et al., 2020). In the context of producing rice waste-derived chicken bone (RWCB) particles, assessing crystallinity is essential. The degree of crystallinity and the presence of amorphous phases serve as indicators of the synthesis quality of RWCB particles, with optimal crystallinity and amorphous characteristics considered favourable for further development. The underlying principle of XRD analysis is based on the interference of monochromatic X-rays with the periodic atomic arrangement in a crystalline sample. During analysis, the diffraction angle (2θ) is varied, typically between 10° and 90°, to generate a comprehensive diffraction profile.

2.10.2 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is a technique used to identify and analyze the chemical composition of a sample by measuring its infrared (IR) absorption spectrum (Guerrero-Pérez & Patience, 2020). IR radiation is passed through the sample, and the amount of radiation absorbed at each wavelength is measured. This information is then used to create a spectrum, which shows the absorption (or transmittance) of the sample as a function of wavelength. The FTIR method uses a mathematical process called a Fourier transform to convert the measured IR absorption data into a spectrum (Dutta, 2017).

The chemical compounds included in a sample can be identified and measured using its absorption spectrum, which is specific to those chemicals (Fiore & Pellerito, 2021). Many scientific disciplines, including materials science, chemistry, biology, and environmental science, employ FTIR extensively to study a variety of samples, including gases, liquids, and solids. FTIR is a crucial analytical technique in many commercial and research applications, and it may be used to identify and quantify the chemical composition of a wide range of materials (Workman Jr, 2026), including biological molecules, minerals, and polymers. The sample's infrared spectra are acquired using FTIR at room temperature, covering a spectral range of 4000 to 500 cm-1 (Perkin Elmer, Spectrum One, FT-IR Spectrometer). Prior to being compressed using translucent pellets, the samples are first ground and combined with potassium bromide (KBr) at a mass ratio of 1:100.

2.10.3 Field Emission Scanning Electron Microscopy (FESEM)

FESEM represents one of the advanced analytical tools that enable ultra-high-resolution imaging of the sample surface, based on a focused electron beam (Moteallemi et al., 2024). Before analysis, the sample adsorbent would be crushed into a powder for sample preparation. Afterwards, the sample's surface would be covered with gold by using gold sputtering for observational factors. The major difference between FESEM and other SEMs is the source of electrons, since it uses an FEG to produce a finer, more coherent electron beam (Lewczuk & Szyryńska, 2021). This provides much larger magnification-up to several millions of times-and sharper images with a larger depth of field. Because of this, FESEM is especially useful in the investigation of microstructure and nanoscale surface features in materials. It can visualize features as small as 1-2 nanometres. Therefore, this technique has immense importance in materials science, nanotechnology, and semiconductor-related research.

Moreover, FESEM has the advantage of low acceleration voltages that minimize sample damage, especially in sensitive and non-conductive materials (Riedel et al., 2026). Besides, it provides imaging by secondary and backscattered electrons, offering contrast mechanisms related to surface topography and material composition. The accelerating voltage within 5-20 kV. If higher than that it will cause the sample to burn. The versatility extends in FESEM, being applicable across an enormously wide range of industries, from the study of biological tissues and cellular structure right through to the analysis of industrial coatings, thin films, and nanoparticles. With the ability to produce three-dimensional-like detailed images, it is a very useful tool in both the research and quality control aspects concerning advanced scientific applications.

2.10.4 Organic Elemental Analysis (CHNS/O)

Here, the CHNS/O Analyzer (Flash 2000, Organic Elemental Analyzer, ThermoScientific) was used to analyze the sample adsorbent by measuring its carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) content at 925 °C for combustion and 640 °C for reduction. Their difference would be used to compute the oxygen contents. To guarantee that there were no errors made during the weighing process, samples would be ground and dried at 100 °C in the oven the night before analysis. Pure oxygen and helium gas would be combined to purge this equipment. Acetanilide was used as

the calibration reference, and the results' precision and accuracy were within two to three percent.

2.10.5 Brunauer -Emmet-Teller (BET)

Brunauer-Emmett-Teller (BET) analysis is a technique used to determine the specific surface area of a material by measuring the adsorption of gas molecules on its surface (Osterrieth et al., 2022). The process begins with sample preparation through degassing to eliminate any pre-adsorbed gases or contaminants. The sample is then placed inside a sample cell within the BET instrument, where a known adsorbate gas, commonly nitrogen, is introduced at controlled low pressures. As the gas molecules adsorb onto the surface of the sample, the volume adsorbed is recorded at different pressure points. This adsorption data is applied to the BET equation, which correlates the amount of gas adsorbed with the surface area of the material, enabling calculation of the specific surface area. BET analysis provides critical insights into the porosity and surface properties of materials, making it a valuable tool in applications including catalysis, materials science, and nanotechnology (Irwansyah et al., 2024).

2.10.6 Zero Point of Charge (pH_{pzc})

The point of zero charge (pH_{pzc}) refers to the pH at which a material's surface carries no net electrical charge. It reflects the acid–base characteristics of the material and is typically determined through zeta potential measurements, which evaluate electrophoretic mobility as a function of pH. Zeta potential indicates the surface charge resulting from the balance between positively and negatively charged functional groups. At the pH_{pzc}, these charges are equal, resulting in a neutral surface. This parameter is crucial for understanding the behaviour of colloids, clay minerals, and other adsorptive materials in both natural and engineered systems.

For the experimental determination, 250 mL of 0.01 M Sodium Chloride (NaCl) solution at different initial pH values was prepared. The pH of the NaCl solution was adjusted between 3 and 11 using 0.1 M HCl or 0.1 M NaOH. A weighed amount of 0.1 g of the adsorbent sample was then added into a 250 mL conical flask, which was placed on a shaker operated at one rotation per minute for 48 hours at room temperature (27 ± 2 °C). After equilibration, the final pH of each solution was measured, and the

difference between the initial pH (pHi) and the final pH (pH_f) was calculated. A plot of ΔpH (pH_i - pH_f) versus pHi was constructed, and the point at which ΔpH equals zero was taken as the pH_{pzc} of the material.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Materials

The raw material is Rice Waste (RW) and Chicken Bone (CB) which is being used in this project. The Rice Waste Chicken Bone (RWCB) was collected at the chicken rice shop of Faculty of Applied Science, UiTM Shah Alam, Selangor. The bones were collected by the basin then were washed by tap water to remove any meat, fat or other contaminants. Next the bones were placed inside an oven for drying before being crashed into powder. After it been crushed properly, the bones were mixed with rice and the mixture of it would be called RWCB. The raw RWCB was prepared in the form of dust particle before combined with the activator which is H_3PO_4 to form activated carbon.

3.2 Chemicals

Table 3.1
Chemicals and Its Formula

No	Materials and Chemicals	Chemical formula	Company
1	Methyl Violet 2B	$C_{24}H_{28}N_2Cl$, 393.95 g/mol, λ_{maz} = 575nm	Kermel
2	Phosphoric Acid	H_3PO_4, 97.994 g/mol	R&M Chemicals
4	Acetone	CH_3COCH_3, 58.08 g/mol	R&M Chemicals
5	Sodium Hydroxide	NaOH, 40.0 g/mol	R&M Chemicals
6	Hydrochloric Acid	HCL, 36.46 g/mol	Bendosen
7	Bleach	NaClO, 74.44 g/mol	Clorox

3.3 Equipment and Apparatus

The equipment and apparatus that would be used in the preparation of the adsorbent and adsorption study are 1100C Tube Furnace w/ Vacuum Flange (12" Heat Zone) & Programmable TempController-GSL-1100X-LD, modified microwave oven (model Panasonic NNJ- 993), glass rod, beakers (25mL-2000mL), hot plate and stirrer,

oven, mortar and pestle, 250 µm sieve , analytical balance (0.0000 g), 250 mL conical flask, 1-mL and 25-mL micropipettes, 10mL pipette filler, pH meter, syringe filter, thermometer, water bath shaker, Erlenmeyer flask, filter paper, filter paper, graduated cylinder, volumetric flask (5mL-2000mL), test tube.

3.4 Instruments

Instruments that were used in this experiment to identify the physical and chemical properties of the adsorbent are Micromeritics ASAP 2060 Analyzer, X'Pert PRO, Hitachi 38 TM3030Plus (SEM-EDX), Organic Elemental Analyzer, PANalytical (XRD), CHNS-O Analyzer (Flash 2000, Thermo-scientific), Perkin-Elmer, Spectrum RX1 (FTIR).

3.5 Preparation of RWCB with H_3PO_4 using Microwave

To obtain activated carbon with the best adsorption property, the coal made from chicken rice waste would go through several preparatory steps. Firstly, the powder of RWCB was mixed with H_3PO_4 using 1:1 impregnation ratio. The impregnation ratio 1:1 was chosen to ensure a balanced activation process where enough H_3PO_4 is available to interact thoroughly with the carbon precursor without over activating it. At this level, the acid can properly penetrate the structure of the raw material and help break down the biomass matrix, which encourages the development of pores during microwave treatment. After the mixing process the sample was put into the oven for almost one day at 100°C to dry any leftover moisture and improve the stability of it. Next, the sample then would then be put into the quartz glass reactor with a 7.5 cm diameter and 8.5 cm length. The quartz glass needs to be sealed properly grease in order to not make any gas leakage because the gas need to flow properly inside the quartz using the air canal that already made on top of the quartz glass and in order to activate it, the specific condition for the microwave are 600 Watts, 15 min time and in the presence of nitrogen gas.

After the sample was cooled down, the sample would then be crushed and washed by the hot water and a few drops of base was added into the hot water which is 0.1M NaOH since the sample was in the acidic condition. This step was called washing because the sample need to be in the range of pH 7 since the sample was already mixed with the H_3PO_4 which is acidic. After the pH of the sample turned neutral, the sample

was then drying again in the oven at 100°C because after the sample had been dried it need to be crushed using the mortar and pestle. After that the AC would be sieved to achieve a particle size range of 0.5 mm to 0.8 mm. The size need of AC needs to be in that range to guarantee consistency and ease of handling. The sample was labelled as M-RWCBAC. Next, the particle of the M-RWCBAC would be put into a small yellow airtight container. In this experiment a modified microwave model (Panasonic NNJ-993) would be used to perform the pyrolysis process with a fixed irradiation power and activation time in the presence of nitrogen gas.



Figure 3.1 Microwave Setup

3.6 Preparation of RWCB via Tube-Furnace Pyrolysis System

To obtain activated carbon with the best adsorption property, the coal made from chicken rice waste would go through several preparatory steps. Firstly, the powder of RWCB was mixed with H_3PO_4 using 1:1 impregnation ratio. After the mixing process the sample was put into the oven for almost one day to drying it. After the sample already dry, the sample then put inside the tube furnace to burn it in the specific condition which is 600˚C, 90 minutes time and in the presence of nitrogen gas. The pyrolysis conditions of 600°C for 90 min under N_2 atmosphere were selected to ensure

complete carbonisation of the biomass while maintaining a stable carbon framework suitable for subsequent activation. At around 600 °C, most lignocellulosic components such as cellulose, hemicellulose, and lignin undergo thorough thermal decomposition, resulting in the formation of a carbon-rich char with a relatively stable pore precursor structure. During the heating process, they were many waters vapour and oil produce. Nitrogen gas was used to remove this excess oil and water vapour and make sure the pore produces nicely during the heating process. After the sample was cooled down, the sample would then be crushed and washed by the hot water and a few drops of base was added into the hot water which is 0.1M NaOH since the sample was in the acidic condition. This step was called washing because the sample need to be in the range of pH 7 since the sample was already mixed with the H_3PO_4 which is acidic. After the pH of the sample turned neutral, the sample was then drying again in the oven at 100°C because after the sample had been dried it need to be crushed using the mortar and pestle.

After that the AC would be sieved to achieve a particle size range of 0.5 mm to 0.8 mm. This size range was chosen to achieve a good balance between adsorption performance and ease of handling. At this size, the activated carbon has enough surface area for the adsorbate to interact with the pores, while still being stable and easy to separate during experiments. Smaller particles give faster adsorption because the molecules do not need to travel far to reach the inside pores, so the process happens quicker. However, if the particles are too small, they can stick together and become difficult to handle during filtration or testing. Larger particles, on the other hand, slow down adsorption because the molecules take more time to move into the inner structure. Even though particle size does not greatly change the total adsorption capacity, it affects how fast the adsorption happens. Therefore, 0.5-0.8 mm is a suitable range that gives fast adsorption, good contact with pollutants, and easy experimental handling. The sample was labelled as P-RWCBAC and put into a small yellow container.



Figure 3.2 Pyrolysis Setup

3.7 Experimental Design and Parameters

The adsorption study was conducted using a batch adsorption method to evaluate the performance of the prepared activated carbon for methyl violet (MV) removal from aqueous solution. All experiments were performed under laboratory conditions to ensure consistency and comparability of results. The MV dye solutions were prepared by diluting a 1000 ppm stock solution with distilled water to obtain working concentrations ranging from 20 to 250 ppm. In each experiment, a fixed volume of 100 mL dye solution was transferred into a 250 mL conical flask, followed by the addition of activated carbon with different dosages ranging from 0.02 to 0.10 g. The experimental design was developed using Box-Behnken Design (BBD), in which all experimental runs were statistically generated to evaluate the interaction effects between variables. The selected independent variables were initial dye concentration, adsorbent dosage, solution pH, and contact time. The ranges for each parameter were set as follows: pH 4 to 10, adsorbent dosage 0.02-0.10 g, and initial dye concentration 20-250 ppm. The mixture was agitated using a mechanical shaker to ensure proper contact between the adsorbent and adsorbate. The contact time was fixed according to the BBD experimental matrix, ranging from 5 to 20 minutes for P-RWCBAC and 10 to 200 minutes for M-RWCBAC, under the same operating conditions. All experiments were carried out at room temperature (25 ± 2 °C) with constant shaking speed to

maintain uniform mixing. After the adsorption process, the mixture was filtered to separate the adsorbent from the solution. The concentration of residual methyl violet was determined using a UV-Visible spectrophotometer at a maximum wavelength of 584 nm.

3.8 Characterization Methods

3.8.1 X-ray Diffraction (XRD) Analysis

Different crystalline components in mixtures can be identified using the X-ray diffraction (XRD) technique (Bergslien, 2022). The X-Ray diffraction model X'Pert PRO, PA Nalytica X-Ray diffractometer was used to evaluate the materials. The CB, RW, P-RWCBAC, and M-RWCBAC were ground into powder for sample preparation prior to analysis. The samples' surfaces were then covered with gold for imaging and observation to differentiate the crystallinity based on the identified peaks. Powder samples were exposed to X-ray radiation, which has a characteristic wavelength (λ) of 1.5418 Å, to get diffraction data. Cu-K_α X-rays were produced by applying 40 kV of voltage and 40 mA of current to a Cu anode.

3.8.2 Fourier Transform Infrared Spectrometer (FTIR)

To assess the interaction between the adsorbent and adsorbate during the adsorption process, functional group identification is necessary (Moges et al., 2022; Pellenz et al., 2023). The existence of functional groups in CB, RW, P-RWCBAC, and M-RWCBAC was examined using FTIR analysis both before and after the MV2B dye solution was adsorbed. An FTIR spectrometer (Perkin-Elmer, RX I) was used to analyze the materials. To create an extremely fine powder, the materials were ground in a 1:10 ratio with potassium bromide, KBr (spectrophotometric grade). Next, a hydraulic press was used to compress this powder into a thin pellet. After that, the translucent, thin pellet was put in the cell holder and put into the FTIR spectrophotometer for analysis. Every spectrum was captured in the 4000/450 cm^{-1} wavenumber band.

3.8.3 Field Emission Scanning Electron Microscopy (FESEM)

The composition of the elements was determined using Energy Dispersive X-ray Spectroscopy (EDS), and the surface morphology, topography, and chemical content of the samples were investigated using Field Emission Scanning Electron Microscopy (FESEM). The materials were analyzed both before and after the MV2B dye was adsorbed. Before being made electrically conductive by applying a thin layer of gold-palladium using an Agar Sputter Coater in an argon atmosphere, the sample was protected on carbon tapes. To examine the surface morphologies of each sample, they were all magnified 3000 times.

3.8.4 Organic Elemental Analysis (CHNS/O)

The CHNS/O Analyser (Flash 2000, Organic Elemental Analyser, Thermo-Scientific) is commonly used to measure the amounts of carbon (C), hydrogen (H), nitrogen (N), sulphur (S), and oxygen (O) in combustible materials (Torres-Herrador et al., 2022) using the Organic Elemental Analysis (OEA or CHNS/O) method. The generated CO_2 and H_2O molecules contain the elements C and H. Additionally, N_2, which is created when NO_2 is reduced, can be used to measure N. Since no other elements were expected to be present in significant amounts in the sample, the amount of oxygen was calculated by subtraction (Torres-Herrador et al., 2022). Prior to analysis, the materials were thoroughly ground and airdried overnight to guarantee that no mistakes would be made during the weighing process. The instrument was cleaned using a mixture of helium gas and pure oxygen. Acetanilide served as the calibration reference, and the results were accurate to within two to three percent.

3.8.5 Brunauer-Emmet-Teller (BET)

The distribution of pore sizes and total surface area (López-Pérez et al., 2021) were calculated using the Brunauer-Emmet-Teller (BET) method. In this work, the activated carbon sample was assessed using a surface area analyser that was compatible with the BET equation to obtain information under BET analysis at 77K.

3.8.6 Zero Point of Charge (pH_{pzc})

The adsorption capacity of an adsorbent and the kind of surface-active sites on it are ascertained using a particular property called the point of zero charge (pH_{pzc}). The electrokinetic characteristics of a surface are described by the point of zero charge (pHpzc) (Hamzezadeh et al., 2022), which is the point at which surface charge is zero. The An and Dultz method was used to calculate the samples' pH_{pzc} values (An & Dultz, 2007). During this process, 100 mL of 0.01 M NaCl was mixed with 0.1 g of each sample. The pH of NaCl was then adjusted between pH 3 and pH 11 using 0.1 M HCl and 0.1 M NaOH. The mixture was then agitated on a revolving shaker for a full day. The solution was collected using filter paper. To ascertain the final pH, the collected solution was analysed using a pH metre (Metrohm, 827 pH lab).

3.9 Optimization of Adsorption key parameters by BBD-RSM

The optimization of adsorption key parameters using Box-Behnken Design (BBD) coupled with Response Surface Methodology (RSM) involves several steps. Initially, key parameters influencing the adsorption process, such as pH, temperature, initial concentration, and contact time, are identified based on prior knowledge or preliminary experiments. A BBD experimental design is then employed to systematically vary these parameters at various levels while minimizing the number of experiments required. The adsorption experiments are conducted according to the designed matrix, and the responses, such as adsorption capacity or efficiency, are measured. The obtained data are then fitted to a mathematical model using RSM to establish the relationship between the key parameters and the response. Next, the optimal conditions for maximum adsorption performance are determined by solving the established mathematical model, enabling efficient utilization of resources and enhanced adsorption efficiency for various applications such as wastewater treatment, pollutant removal, and purification processes. The adsorbent dose (A), solution pH (B), temperature (C), and time (D) would all be studied in the design of the experiment for RWCB. Box–Behnken design (BBD) in response surface methodology (RSM) would be used to optimize the methyl violet dye adsorption. Table 3.2 displays the independent variables' levels, ranges, and codes.

Table 3.2
Terms used in Evaluating Model Adequacy

Cod	Variables	Units	Low	High
A	Adsorbent Dose	gram (g)	DPTR	DPTR
B	pH		DPTR	DPTR
C	Time	minute	DPTR	DPTR

Note (DPTR= depends on the preliminary test result)

Equation (3.1) is a second-order polynomial model that would be used to estimate the elimination of Methyl Violet dye.

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \sum \beta_{ij} X_i X_j \quad (3.1)$$

Where Y is the response (dye removal), β_0 is the model constant, β_i is the input parameter's linear coefficient, β_{ii} is its quadratic coefficient, and β_{ii} is the input parameter's interaction coefficient. Meanwhile, the independent variables are represented by X_i and X_j. Depending on the results of the preliminary test, BBD would create a series number of tests to optimize and analyze the three independent variables: adsorbent dose (g), pH, and time (minute). The MV 2B dye's removal efficacy (R, %) was calculated using the following mathematical formula (3.2):

$$R\ (\%) = \frac{C_o - C_e}{C_o}\ x\ 100 \quad (1.2)$$

The abbreviations C_o (mg/L) and C_e (mg/L), respectively, indicate the concentrations of MV 2B in the initial and equilibrium phases.

3.10 Preparation of Methyl Violet

One litre of distilled water would be used to dissolve 1.0 g of $C_{24}H_{28}N_3Cl$ powder to create the Standard Aqueous Solution of Methyl Violet stock solution. By dilution to the required concentrations, the MV stock solution was made into the MV standard solution and followed the standardized wavelength which is 575nm.

3.11 Batch of Adsorption Study

A series of 250 mL dye solutions were used for the batch adsorption tests of MV2B dye onto P-RWCBAC and M-RWCBAC. Each held 250 mL of an unadjusted pH 50 mg/L MV2B dye solution. Following that, the sample was stirred at a speed of 150 rpm at room temperature (RT = 27 ± 2°C) until equilibrium was reached. A double beam UV-Vis spectrophotometer with a maximum wavelength of 575 nm was used to measure the variations in the concentration of the MV2B dyes at time t = 0 and equilibrium. Twenty-four hours was the suggested period to achieve equilibrium. The ideal adsorbent dosage for the following studies was determined to be the one that fulfilled the requirement of obtaining good and maximum color removal. Equations (3.3) and (3.4) were used to get the equilibrium adsorption capacity, qe (mg/g), and the percentage of color removal.

$$Adsorption\ capacity, q_e = \frac{(C_o - C_e)\,V}{W} \tag{3.3}$$

$$Dye\ Removal\ (\%) = \frac{C_o - C_e}{C_o}\ x\ 100 \tag{3.4}$$

Where the initial and equilibrium dye concentrations in the aqueous solution are represented by C_o (mg/L) and C_e (mg/L). W is the mass of the quantity of P-RWCBAC and M-RWCBAC (g), while V is the volume of the dye solution (L).

3.12 Effect of Initial Dye Concentration and Contact Time

The impact of the initial MV2B dye concentration was assessed at various dye solution concentrations (20-250 mg/L) and contact times (0-250 min). For both P-RWCBAC and M-RWCBAC activated carbon, the best adsorbent was created. The sample was put in the rotating device container, which was adjusted to the ideal pH of various MV2B solution concentrations. It was then stirred at room temperature (RT = 27 ± 2°C) until equilibrium was attained. A double beam UV-Vis spectrophotometer with a maximum wavelength of 575 nm was then used to analyze the concentration fluctuations of the MV2B dyes. The following activated carbon was used to repeat the same process.

3.13 Adsorption Kinetics

Adsorption kinetics involves studying the rate at which adsorption occurs over time onto a solid surface from a liquid or gas phase. Typically, this process is analysed using experimental data obtained from batch adsorption experiments. In these experiments, a known quantity of adsorbate solution or gas is brought into contact with a fixed amount of adsorbent material under controlled conditions. Samples are withdrawn at regular intervals, and the concentration of the adsorbate remaining in the solution or gas phase is measured. The amount of adsorbate adsorbed onto the adsorbent at each time interval is calculated, and various kinetic models, such as pseudo-first-order, pseudo-second-order, or intraparticle diffusion models, are applied to fit the experimental data. The model choice depends on the adsorption mechanism and the experimental conditions. The rate constants and other kinetic parameters obtained from the model fitting are then used to interpret the adsorption mechanism, determine the rate-controlling step, and predict the adsorption behaviour under different conditions. Overall, adsorption kinetics provides insights into the dynamic nature of the adsorption process, which is essential for optimizing adsorption systems in various practical applications, including environmental remediation, separation processes, and adsorbent material design.

3.13.1 Pseudo-First Order (PFO)

The pseudo-first-order kinetic equation was initially introduced by (Lagergren, 1898). This model is widely applied in the form later presented by (Ho & McKay, 1999), with its nonlinear expression shown in Equation (3.5):

$$q_t = q_e \left(1 - exp^{-k1^t}\right) \tag{3.5}$$

In this equation, q_e (mg/g) represents the adsorption capacity at equilibrium, while qt (mg/g) refers to the adsorption capacity at a specific time, t. Meanwhile, k1 (1/min) denotes the rate constant for pseudo-first-order adsorption. At room temperature, a linear plot of ln (q_e-q_t) against t is constructed. From this plot, the values of k1 and q_e can be obtained, while the correlation coefficient (R^2) is used to assess how well the pseudo-first-order kinetic model fits the experimental data (Ali et al., 2016).

3.13.2 Pseudo -Second Order (PSO)

The adsorption performance of the adsorbent was evaluated using the pseudo-second-order kinetic model (Vega et al., 2024). The nonlinear form of this model was introduced by (Ho & McKay, 1999), as presented in Equation (3.6):

$$q_t = \frac{q_e^2 k_2^t}{1 + q_e k_2^t} \tag{3.6}$$

In this model, qe (mg/g) and qt (mg/g) represent the sorption capacities of the adsorbent at equilibrium and at a given time, t, respectively. Meanwhile, k2 (1/min) refers to the rate constant of pseudo-second-order adsorption. A linear plot of t/qt against t is generated at room temperature, and the correlation coefficient (R^2) obtained from the plotted graph is used to determine the suitability of the pseudo-second-order kinetic model in describing the adsorption process (Ali et al., 2016).

3.14 Adsorption Isotherm

The adsorption isotherm analysis involves studying the equilibrium relationship between the concentration of adsorbate molecules in the fluid phase and the amount adsorbed onto the solid adsorbent at a constant temperature. This is typically achieved through batch adsorption experiments, where a series of solutions or gases with varying concentrations of the adsorbate are brought into contact with a fixed amount of adsorbent material. After reaching equilibrium, the concentration of the adsorbate remaining in the solution or gas phase is measured, allowing calculation of the amount adsorbed onto the adsorbent. By plotting the equilibrium adsorption data against the equilibrium concentration, various adsorption isotherm models such as Langmuir, Freundlich, or Temkin models are fitted to the experimental data to describe the adsorption behaviour and infer key parameters such as adsorption capacity, surface coverage, and affinity between adsorbate and adsorbent. The choice of model depends on the specific characteristics of the adsorption system, including the nature of the adsorbate and adsorbent, as well as the experimental conditions. Ultimately, the methodology for adsorption isotherm analysis provides valuable insights into the

adsorption mechanism and helps optimize adsorption processes in diverse applications such as wastewater treatment, gas separation, and purification processes

Isotherm Models	**Equations**	
Langmuir	$q_e = \frac{q_{max} K_a C_e}{1 + K_a C_e}$	(3.7)
Freundlich	$q_e = K_f C_e^{\frac{1}{n}}$	(3.8)
Temkin	$q_e = \frac{RT}{b_T} \ln(K_T C_e)$	(3.9)

3.15 Thermodynamic Studies

The methodology for conducting thermodynamic studies involves investigating the energy changes and relationships within a system undergoing a physical or chemical process. This typically begins with defining the system and its surroundings, establishing the initial and final states, and identifying the relevant variables such as temperature, pressure, volume, and entropy. Various thermodynamic properties such as heat capacity, enthalpy, entropy, and Gibbs free energy are determined through experimental measurements or theoretical calculations. These properties provide valuable insights into the process's spontaneity, feasibility, and equilibrium. Additionally, thermodynamic equations and principles, such as the laws of thermodynamics and equations of state, are applied to analyze the system's behaviour and predict how it responds to changes in conditions. By systematically analysing thermodynamic properties and relationships, researchers gain a deeper understanding of the underlying mechanisms governing physical and chemical processes, aiding in designing and optimizing processes in fields ranging from chemical engineering to environmental science.

$$\Delta G^\circ = -RT \ln K_d \tag{3.10}$$

$$k_d = \frac{q_e}{C_e} \tag{3.11}$$

$$\ln k_d = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \tag{3.12}$$

CHAPTER 4
RESULTS AND DISCUSSION FOR PYROLYSIS AND MICROWAVE OF CHICKEN RICE WASTE INTO ACTIVATED CARBON ASSISTED BY H_3PO_4: OPTIMIZATION FOR METHYL VIOLET DYE REMOVAL

4.1 Introduction

This study utilized food wastes, specifically rice waste (RW) and chicken bones (CB), as eco-friendly precursors to synthesize activated carbon (RWCBAC) by a pyrolysis-assisted H_3PO_4 activation technique and microwave-assisted H_3PO_4 activation technique. The analysis emphasizes the substantial differences in surface morphology, pore structure, surface functional groups, and overall adsorption capacity between the two forms of activated carbon. The elimination of the organic colour methyl violet (MV) from aqueous solutions has been thoroughly investigated utilizing P-RWCBAC and M-RWCBAC as an adsorbent. The adsorption properties, for pyrolysis comprising A: P-RWCBAC dosage (0.02-0.1 g), B: pH (4-10), and C: time (5-20 min) while for microwave A: M-RWCBAC dosage (0.02-0.1 g), B: pH (4-10), and C: time (10-200 min), were assessed utilizing the established Box-Behnken statistical method. The results of the adsorption isotherms indicated that the MV adsorption aligns closely with the Langmuir model. At the same time, the kinetic data may be sufficiently described by the pseudo-second-order model. The adsorption capacity of P-RWCBAC was determined to be 88.4 mg/g while for M-RWCBAC was determined to be 126.8 mg/g. Electrostatic forces, π-π stacking, and hydrogen bonding are the potential mechanisms that may govern the adsorption of MV by P-RWCBAC and M-RWCBAC. This study demonstrates that P-RWCBAC and M-RWCBAC, derived from RW and CB, can serve as an effective adsorbent for wastewater treatment. This chapter analyzes the adsorption capability of chicken rice waste during pyrolysis experiment and microwave experiment. This experiment can be characterized by many analytical methods, including pH_{pzc}, XRD, FTIR, TGA, BET, FESEM, and CHNS. The influence of adsorption process parameters was optimized utilizing Box-Behnken Design (BBD) within Response Surface Methodology (RSM). Furthermore, a plausible method for the adsorption of Methyl Violet dye by the P-RWCBAC and M-RWCBAC.

4.2 Characterization

4.2.1 Physiochemical Properties P-RWCBAC

The physicochemical features of P-RWCBAC, including its constituent composition, average pore diameter, total pore volume, and surface area characteristics, were presented in Table 4.1.

Table 4.1
Physiochemical Characteristics of P-RWCBAC

Parameters(s)	**P-RWCBAC**
BET surface area (m^2/g)	369.3
Langmuir surface area (m^2/g)	691.8
Total volume in pores (cm^3/g)	0.31
Pore diameter (nm)	4.76
C (%)	45.2
H (%)	2.90
N (%)	1.75
O (by the difference) (%)	50.2

The physico-chemical characteristics of P-RWCBAC, such as surface area, pore volume, and average pore size, are summarized in Table 4.1. Elemental composition analysis indicated that the material contains 45.15% carbon, 50.2% oxygen, 2.90% hydrogen, and 1.75% nitrogen. The specific surface area was determined to be 369.32 m^2/g, with a total pore volume of 0.3105 cm^3/g. The mean pore diameter measured 4.759 nm, which, based on the IUPAC classification (Sing, 1985), places the pores within the mesoporous range of 2–50 nm. The BET parameters derived from the investigation of the N_2 adsorption-desorption isotherm for P-RWCBAC clarify the adsorbent's porous structure (Figure 4.1). This adsorbent is classified as a Type IV (Sing, 1985) system with an H3-type hysteresis loop, indicating that the P-RWCBAC structure features slit-like pores (Hu et al., 2020). The evidence indicates that the generated P-RWCBAC possesses distinctive characteristics, including elevated porosity, substantial pore size, and a high specific surface area, rendering its surface ideal for MV dye adsorption.

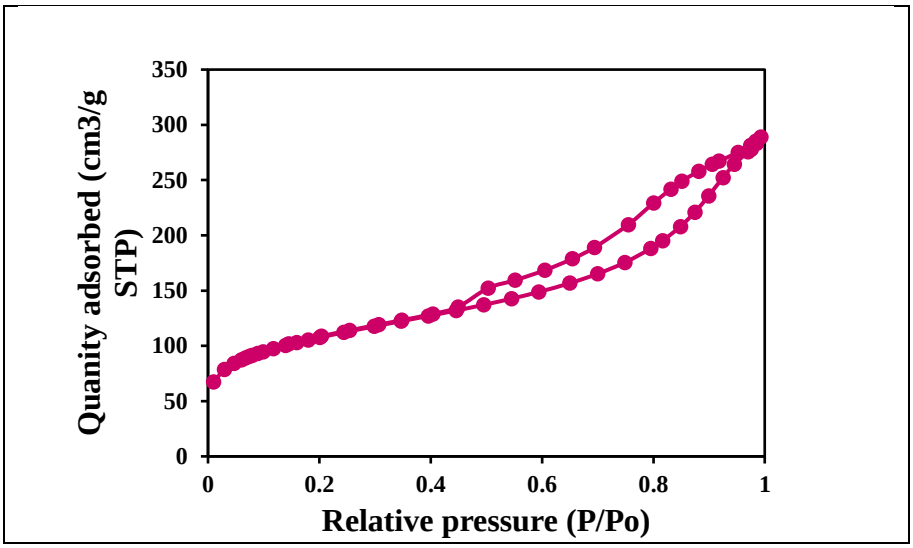


Figure 4.1 The N_2 Adsorption-Desorption Isotherms of P-RWCBAC

4.2.2 Physiochemical Properties M-RWCBAC

Table 4.2 provides a comprehensive overview of the physico-chemical properties of the (M-RWCBAC), detailing key parameters such as total pore volume, mean pore diameter, and specific surface area. These properties are critical in evaluating the material's potential as an effective adsorbent for pollutants. Elemental analysis of M-RWCBAC reveals the composition by weight percentages of its primary elements: carbon constitutes 71.03%, oxygen 22.12%, hydrogen 5.09%, and nitrogen 1.76%. This elemental distribution suggests a predominantly carbonaceous structure with significant oxygen-containing functional groups, which may enhance the adsorbent's affinity for various contaminants, including dyes.

Further investigation into the surface characteristics shows that the M-RWCBAC possesses a specific surface area of 83.3 m^2/g, signifying a substantial amount of available surface for adsorption processes. Additionally, the total pore volume is measured at 0.16 cm^3/g, indicating a considerable volume of internal voids within the adsorbent matrix, which contributes to increased adsorption capacity. The average pore diameter is found to be 6.57 nm. Based on the International Union of Pure and Applied Chemistry (IUPAC) classification (Sing, 1985), pores within the size range of 2 nm to 50 nm are categorized as mesopores or medium-sized pores (Kim et al., 2016), which are particularly effective for adsorbing larger molecules such as methyl violet (MV) dye.

Table 4.2
Physiochemical Characteristics of M-RWCBAC

Parameters(s)	**M-RWCBAC**
BET surface area (m^2/g)	83.3
Langmuir surface area (m^2/g)	192
Pore volume (cm^3/g)	0.16
Total volume in pores (cm^3/g)	0.11
Pore diameter (nm)	6.57
C (%)	71.03
H (%)	5.09
N (%)	1.76
O (by the difference) (%)	22.12

The nitrogen adsorption-desorption isotherm analysis was conducted to further characterize the porous structure of M-RWCBAC. Figure 4.2 illustrates the isotherm pattern, which corresponds to a Type IV isotherm as defined by IUPAC. This type of isotherm is indicative of mesoporous materials and is accompanied by an H3-type hysteresis loop (Sing & Williams, 2004). The presence of this hysteresis loop suggests that the pores within the M-RWCBAC have slit-like shapes, a morphology consistent with the findings of Reichenbach et al. (2013). This unique pore geometry enhances the material's ability to capture and retain dye molecules by providing an extended surface interaction area and facilitating diffusion into the pore network (Jiang et al., 2026).

Taken together, these physicochemical properties demonstrate that the synthesized M-RWCBAC exhibits a combination of elevated porosity, moderate yet effective pore sizes, and a high surface area. These features collectively contribute to the material's excellent potential as an adsorbent. The structural characteristics of M-RWCBAC render its surface highly suitable for the efficient adsorption of methyl violet (MV) dye from aqueous solutions, suggesting its promising application in wastewater treatment and pollutant removal.

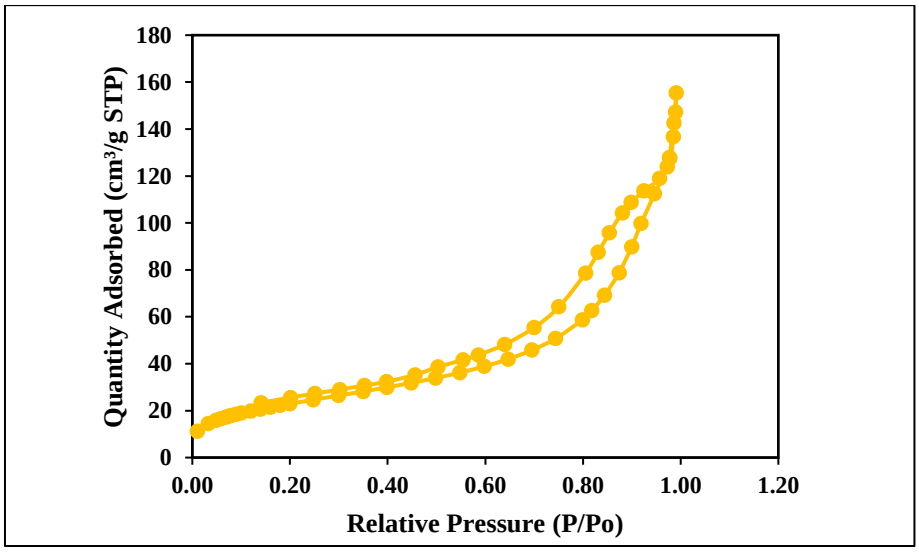


Figure 4.2 The N_2 Adsorption-Desorption Isotherm of M-RWCBAC

4.2.3 Point of Zero Charge (pH_{pzc}) Analysis P-RWCBAC

The Point of Zero Charge (pH_{pzc}) is the pH at which the surface charge of a material (such as an adsorbent or catalyst) is neutral, meaning the number of positive and negative surface charges is balanced. It plays a critical role in adsorption, electrochemistry, and colloidal stability. The point of zero charge must be identified to comprehend the adsorption action (pH_{pzc}). The pH_{pzc} value of P-RWCBAC value is 3 as shown in Figure 4.3. This relatively low value is due to the presence of more acidic functional groups on its surface such as carboxyl and hydroxyl groups, which increase the negative surface charge at lower pH. This condition is commonly reported in activated carbon derived from biomass where oxidation during preparation increases oxygen-containing groups The P-RWCBAC have negative surface charges above the pH_{pzc}. Above pH_{pzc}, dye ion adsorption increases. Cationic MV dye is a positively charge and attract the adsorbents and is drawn to the negatively charged surface of P-RWCBAC. From an electrostatic point of view, when the solution pH is below the pH_{pzc}, the composite surface acquires a positive charge. Under acidic conditions, the higher concentration of protons compared to hydroxide ions facilitates the attraction of negatively charged anions to the adsorbent surface. Accordingly, the surface of P-RWCBAC was identified as positively charged since the experimental pH values were lower than the measured pHpzc.

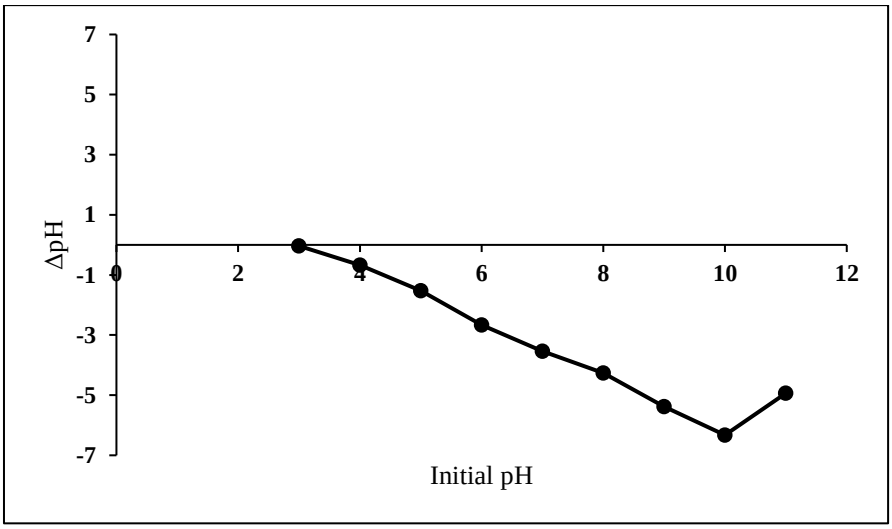


Figure 4.3 pH_{pzc} of P-RWCBAC

4.2.4 Point of Zero Charge (pH_{pzc}) Analysis M-RWCBAC

The Point of Zero Charge (pH_{pzc}) is the pH at which the surface charge of a material (such as an adsorbent or catalyst) is neutral, meaning the number of positive and negative surface charges is balanced. It plays a critical role in adsorption, electrochemistry, and colloidal stability. The point of zero charge must be identified to comprehend the adsorption action (pH_{pzc}). The pH_{pzc} value of M-RWCBAC is 4, as shown in Figure 4.4. It shows a slightly higher pHpzc value of 4. This shift may be due to differences in the modification or activation process, which can reduce acidic surface groups or introduce more basic sites on the carbon surface. According to previous studies, changes in activation conditions such as temperature and chemical treatment can significantly alter surface functional groups and shift pHpzc values. The M-RWCBAC has negative surface charges above the pH_{pzc}. Above pH_{pzc}, dye ion adsorption increases. Cationic MV dye is a positively charged and attracts the adsorbents and is drawn to the negatively charged surface of M-RWCBAC. Electrostatically, when the solution pH falls below the pH_{pzc}, the composite surface develops a positive charge. Under acidic conditions, the excess of protons over hydroxide ions promotes the adsorption of negatively charged anions onto the adsorbent surface. Hence, M-RWCBAC was determined to carry a positive surface charge, as the experimental pH values were lower than the obtained pH_{pzc}. In this regard (Wu et al., 2022) reported similar findings on $pH_{pzc.}$

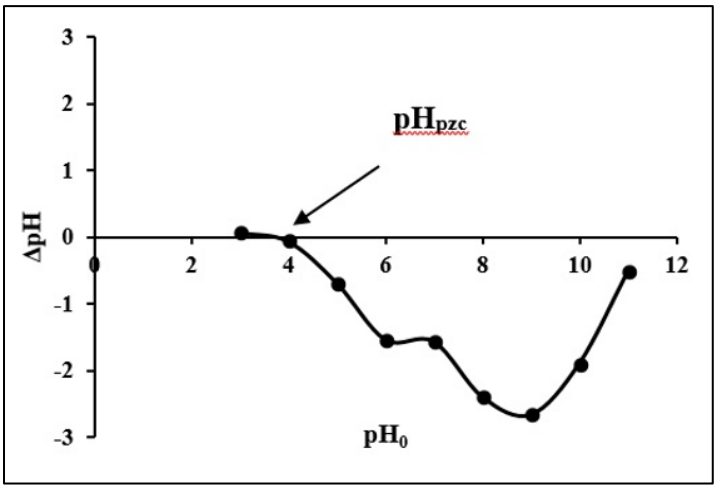


Figure 4.4 pH_{pzc} of M-RWCBAC

4.2.5 X-ray Diffraction (XRD) Analysis P-RWCBAC

The XRD patterns provide essential information about the structural properties of the three samples: Figure 4.5 (a) chicken bone, Figure 4.5 (b) rice, and Figure 4.5 (c) activated carbon derived from chicken bone and rice. Figure 4.5 (a), chicken bone, displays pronounced and intense diffraction peaks, signifying a highly crystalline substance. The notable peaks represent hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), the principal inorganic constituent of bone, characterised by an organised crystalline structure. The lack of a significant baseline indicates that the amorphous fraction in this sample is minimal, rendering it primarily crystalline.

Figure 4.5 (b) shows rice with wider peaks than chicken bone, indicating a substantial amorphous component. This pattern is characteristic of materials such as rice, which comprises biopolymers like cellulose and amylopectin. The pronounced peaks observed in the graph may indicate the presence of crystalline materials, such as silica (SiO_2), commonly found in rice husks or other constituents of rice grains. The prominent peaks in the graph indicate disordered or amorphous regions, possibly derived from organic macromolecules and the polymeric composition of rice.

Figure 4.5 (c), activated carbon sourced from chicken bone and rice, has a mixture of pronounced peaks and an extensive background. The pronounced peaks probably arise from leftover hydroxyapatite or silica that maintained crystallinity during activation. The comprehensive baseline, however, is characteristic of an amorphous carbonaceous substance that develops throughout the carbonisation process. This

signifies that the sample possesses a heterogeneous structure, comprising both amorphous carbon and certain crystalline phases. The total structure exhibits greater heterogeneity than the individual precursors due to the activation process, which introduces flaws, disordered regions, and novel structural configurations.

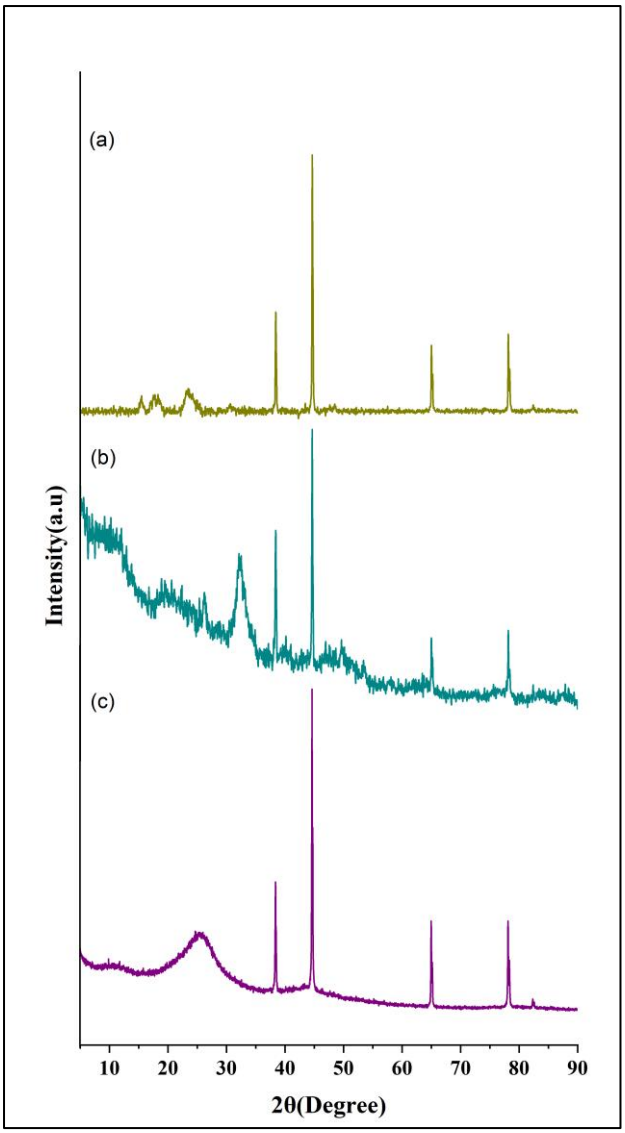


Figure 4.5 XRD Profile of (a) CB, (b) RW, and (c) P-RWCBAC

4.2.6 X-ray Diffraction (XRD) Analysis M-RWCBAC

X-ray diffraction (XRD) analysis was carried out to examine the crystalline and amorphous characteristics of chicken bones (CB), rice waste (RW), and M-RWCBAC samples. As shown in Figure 4.6 (a), the CB sample exhibits distinct diffraction peaks at 2θ values of 23.6°, 38.48°, 44.6°, 65.7°, and 78.2°, which are consistent with the

crystal planes of hydroxyapatite (Méndez-Lozano et al., 2025). The XRD profile of RW, presented in Figure 4.6 (b), demonstrates the crystalline nature of cellulose originating from rice waste, with characteristic reflections at 2θ = 15.5°, 26.2°, and 32.4°, confirming the presence of cellulose (Vu et al., 2024). Meanwhile, the M-RWCBAC diffractogram in Figure 4.6 (c) shows reflections corresponding to the (002) and (100) Bragg planes. A broad peak at 2θ = 24.1° is attributed to the (002) reflection, while a sharper peak at 2θ = 44.6° corresponds to the (100) reflection, indicative of a graphitic structure. Furthermore, the additional distinct peaks observed in Figure 4.6 (c) confirm the presence of hydroxyapatite within the M-RWCBAC sample (Côrtes et al., 2019).

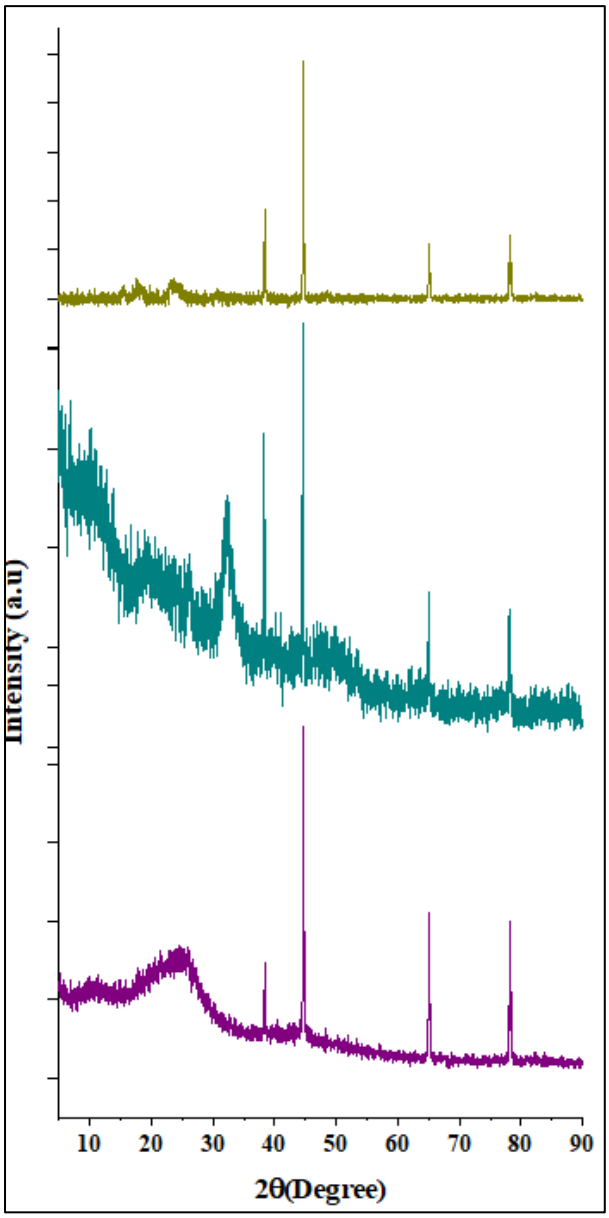


Figure 4.6 XRD Profile of (a) CB, (b) RW, and (c) M-RWCBAC

4.2.7 Fourier Transform Infrared (FTIR) Analysis M-RWCBAC

FTIR analysis was conducted to better understand the interaction between P-RWCBAC and MV, particularly in relation to the chemical structure of P-RWCBAC. The FTIR spectra of both (a) P-RWCBAC and (b) P-RWCBAC-MV are shown in Figure 4.7. For P-RWCBAC (Figure 4.7a), a broad absorption band at 3450 cm^{-1} was attributed to O-H stretching of hydroxyl groups. Additional characteristic peaks appeared at 2890 cm^{-1} (C-H stretching), 2331 cm^{-1} (C≡C bond), 1640 cm^{-1} (C=O stretching), 1500 cm^{-1} (aromatic C=C), 1250 cm^{-1} (O-C-O), and 1032 cm^{-1} (C-O)

(Côrtes et al., 2019). After MV adsorption (Figure 4.7b), noticeable shifts and changes in peak intensities were observed, indicating that the main functional groups of P-RWCBAC were actively involved in the adsorption of MV.

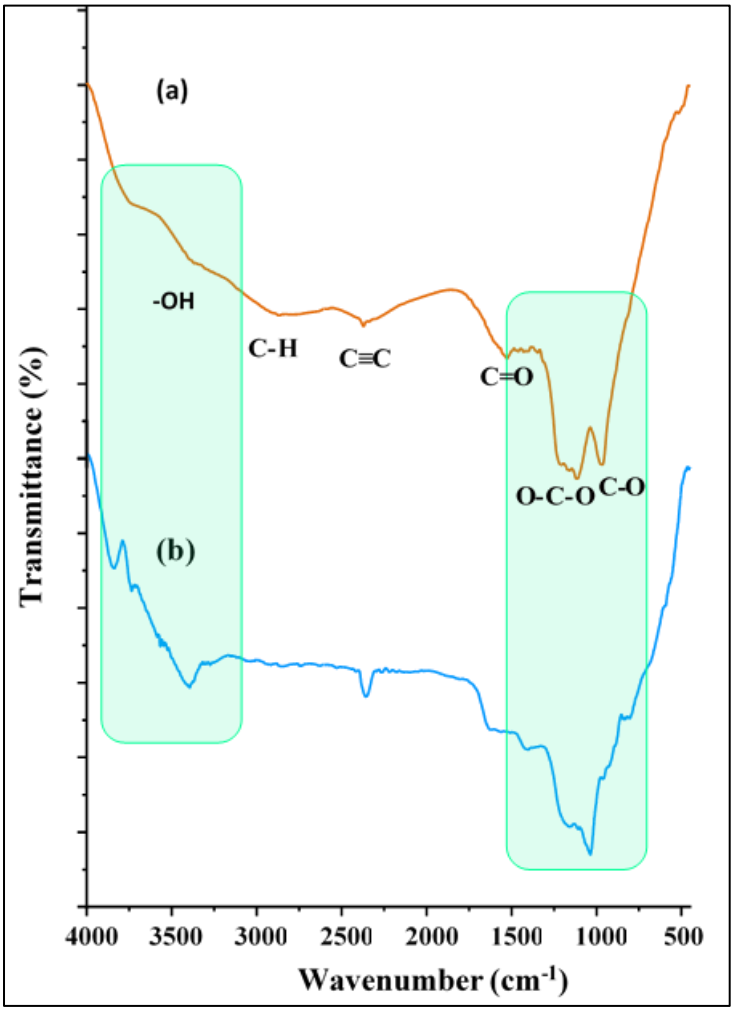


Figure 4.7 FTIR Analyses of (a) P-RWCBAC, and (b) P-RWCBAC-MV

4.2.8 Fourier Transform Infrared (FTIR) Analysis M-RWCBAC

Figure 4.8 illustrates the FTIR spectra used to identify the functional groups present in CB, RW, CBRW, M-RWCBAC, and M-RWCBAC-MV. The spectra of the precursor materials (CB, RW, and CBRW) exhibited similar features, as shown in Figures 4.8(a-c). The spectra show a broad band in the 3200-3500 cm^{-1} range, attributed to O-H stretching vibrations. The C-H stretching vibrations are observed in the 2850-2950 cm^{-1} range, while the weak band in the 2100-2400 cm^{-1} range is associated with C≡C groups. The carbonyl (C=O) functional group appears in the 1650-1750 cm^{-1}

range, while aromatic C=C vibrations are observed in the 1500-1600 cm^{-1} range. The C-O-C stretching is in the 1100-1200 cm^{-1} range, and the C-O stretching appears in the 1000-1100 cm^{-1} range. After the activation process using H_3PO_4 (Figure 4.8(d)), slight changes in peak intensity within these ranges indicate surface modification during carbonization. These changes suggest the development of a more activated surface with available functional sites.

For the FTIR spectrum after MV adsorption (Figure 4.8(e)), changes in intensity and slight shifts within the same wavelength ranges are observed compared to M-RWCBAC before adsorption. The reduction in intensity in the 3200–3500 cm^{-1} and 1650-1750 cm^{-1} ranges suggest the involvement of O-H and C=O groups in adsorption. Changes in the 1500-1600 cm^{-1} range indicate possible π-π interactions between the carbon surface and MV dye molecules. These results confirm that adsorption occurs through interactions between MV and surface functional groups.

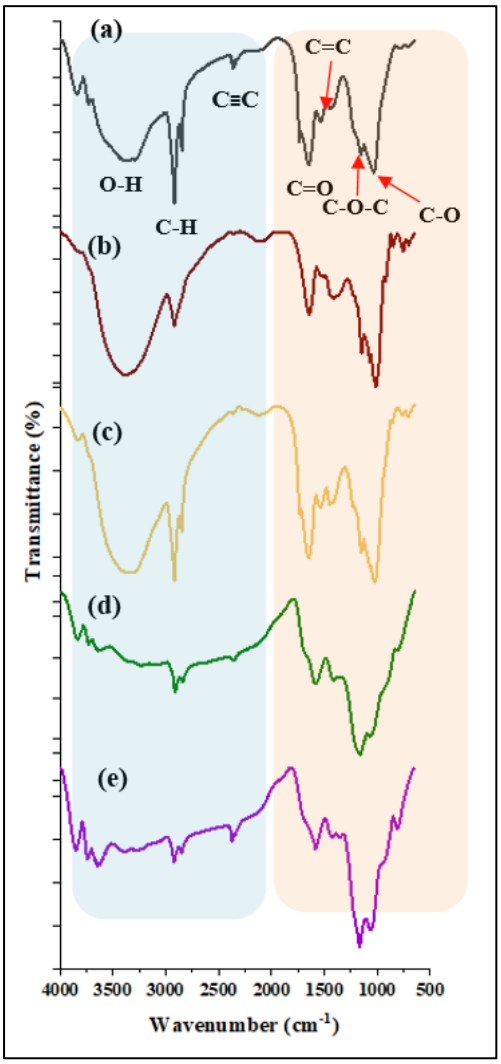


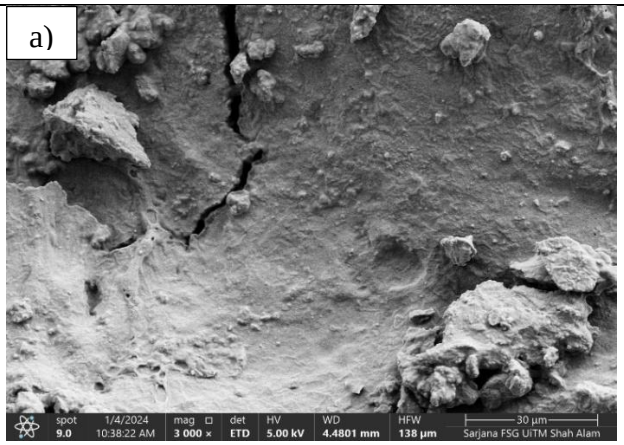
Figure 4.8 FTIR Spectra of (a) CB, (b) RW, (c) RWCB, (d) M-RWCBAC, and (e) M-RWCBAC-MV

4.2.9 Field Emission Scanning Electron Microscopy (FESEM) P-RWCBAC

The provided data and image obtained from a Field Emission Scanning Electron Microscope (FESEM) reveal the surface morphology, topography, and chemical composition of chicken bone biomaterials. Figure 4.9 (a) and (b) shows the FESEM analysis highlights a porous structure with interconnected pores, which is characteristic of rice waste and chicken bone. This porous morphology is crucial for biomedical applications, such as bone scaffolds, as it facilitates cell adhesion, proliferation, and nutrient transport. The elemental composition derived from Energy Dispersive X-ray Spectroscopy (EDS) shows a dominance of carbon (58.15% by mass), indicating the presence of organic components such as collagen, which forms the bone matrix. Oxygen

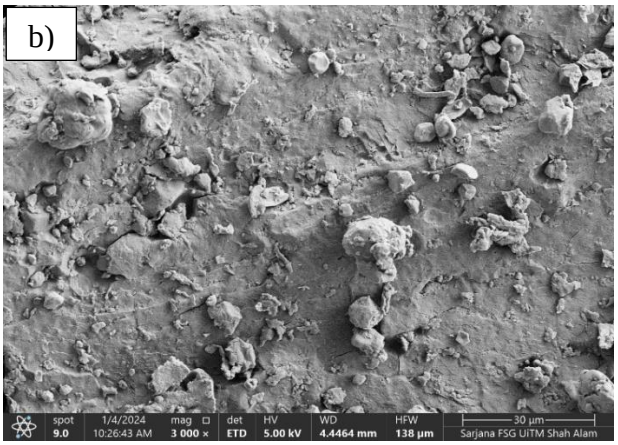
(28.80%) and phosphorus (1.57%) suggest the presence of inorganic hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), a mineral essential for bone strength and regeneration. Nitrogen (11.49%) reflects proteinaceous materials, further confirming the organic content. This combination of morphological and chemical properties makes chicken bone a promising biomaterial for applications in bone tissue engineering and regenerative medicine.

a)



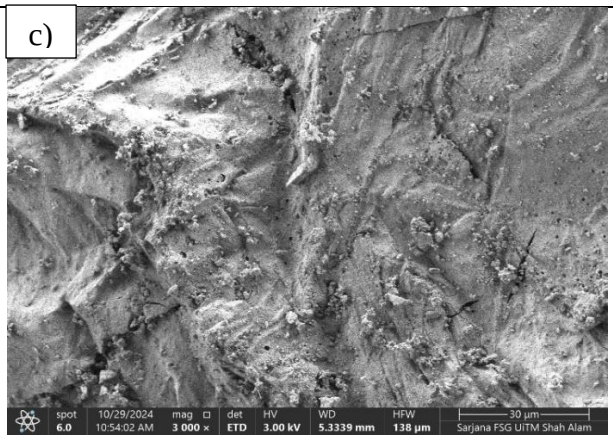
Element	Mass Norm. [%]	Atom [%]
Carbon	58.15	64.45
Oxygen	28.80	23.96
Nitrogen	11.49	10.92
Phosphorus	1.57	0.67

b)



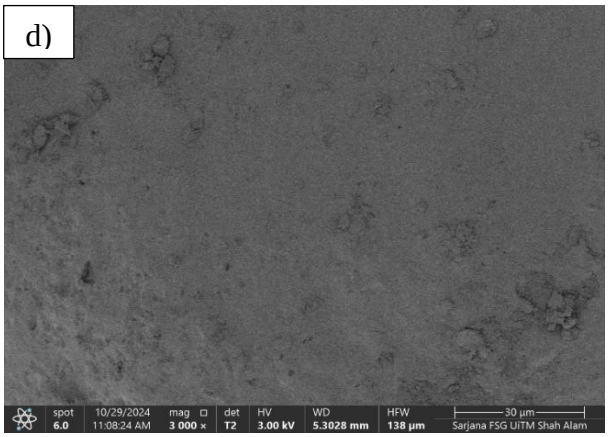
Element	Mass Norm. [%]	Atom [%]
Carbon	45.22	52.28
Oxygen	50.58	43.91
Nitrogen	3.55	3.52
Phosphorus	0.65	0.29

c)



Element	Mass Norm. [%]	Atom [%]
Carbon	72.67	82.98
Oxygen	2.89	6.30
Nitrogen	7.88	7.55
Phosphorus	14.47	6.30
Calcium	2.00	2.44
Magnesium	0.09	0.05

d)



Element	Mass Norm. [%]	Atom [%]
Carbon	75.30	78.43
Oxygen	4.42	3.46
Nitrogen	20.28	18.11

Figure 4.9 FESEM Images at Magnification Power 3000x of (a) RWCB (b) P-RWCBAC and (c) P-RWCBAC After MV Adsorption Followed by EDX Elemental Analysis

Moreover, Figure 4.9 (c) demonstrates the heterogeneous and rough surface of P-RWCBAC, characterized by a significant presence of pore structures. Well-developed pores may enhance the penetration of P-RWCBAC by organic substances such as MV dye. The surface of P-RWCBAC exhibited reduced porosity and the disappearance of surface cracks upon the adsorption of MV dye (Figure 4.9 (d)), indicating successful loading of the MV dye onto the P-RWCBAC adsorbent surface. EDX analysis confirmed the presence of C, O, and N components in P-RWCBAC and P-RWCBAC-MV.

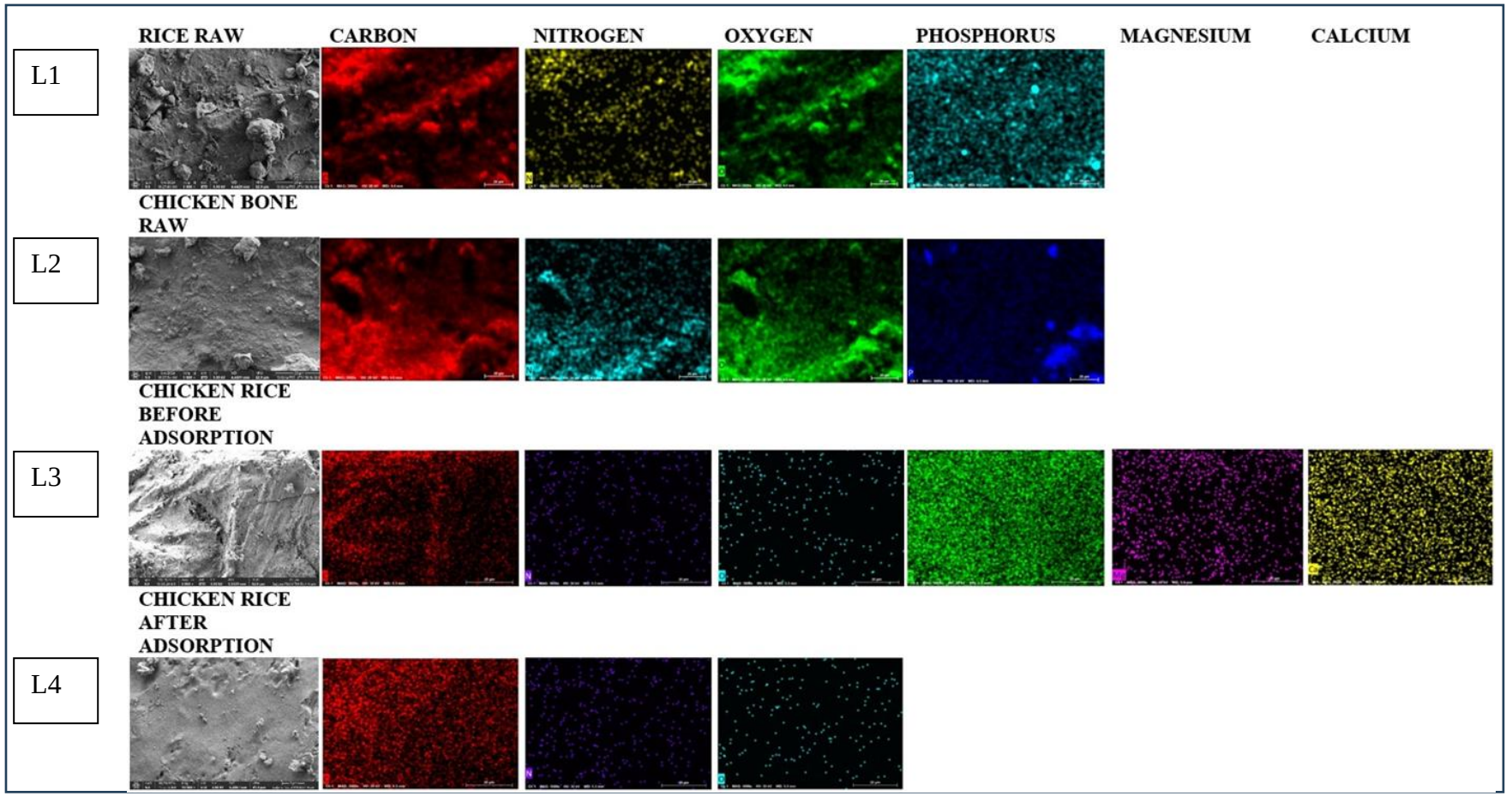
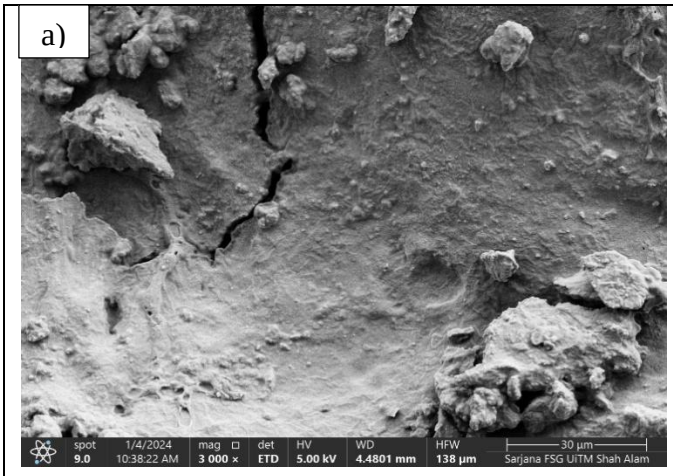


Figure 4.10 EDX Mapping of (L1) CB, (L2) RW, (L3) P-RWCBAC, and (L4) P-RWCBAC-MV

4.2.10 Field Emission Scanning Electron Microscopy (FESEM) M-RWCBAC

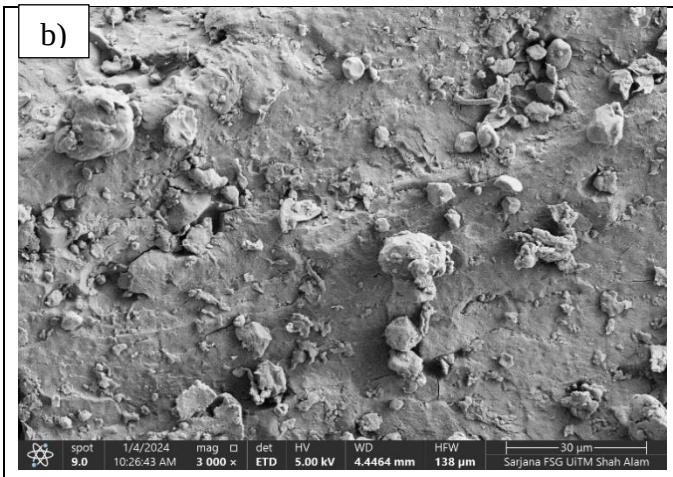
The morphology and chemical composition of CB, RW, M-RWCBAC, and M-RWCBAC-MV were investigated using SEM-EDX analysis. SEM micrographs of these materials are shown in Figure 4.11 (a-d), representing CB, RW, and M-RWCBAC before and after MV dye adsorption. As observed in Figures 4.11 (a-b), CB and RW exhibited rough and fragmented surface textures. In contrast, Figure 4.11 (c) shows that M-RWCBAC contained distinct cracks and visible pores. EDX mapping further indicated that CB and RW primarily consisted of carbon (C), oxygen (O), phosphorus (P), and nitrogen (N) (Figure 4.12 L1-L4). Meanwhile, M-RWCBAC was composed of C, O, P, N, along with magnesium (Mg) and calcium (Ca). After MV adsorption, notable morphological modifications were detected in M-RWCBAC (Figure 4.11 d)), where the surface have less porosity and looks less shrinkage compared to (Figure 4.11 c)), suggesting dye accumulation on the adsorbent surface. EDX analysis confirmed the presence of C, N, and O in the M-RWCBAC composite following MV uptake (Figure 4.12 L4).

a)



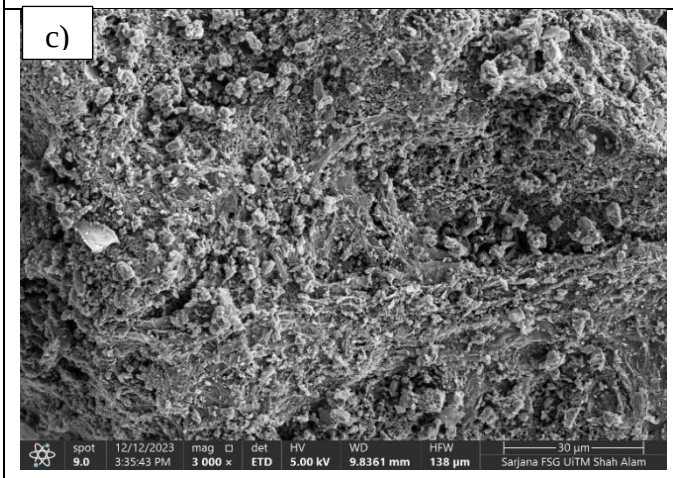
Element	Mass Norm. [%]	Atom [%]
Carbon	58.15	64.45
Oxygen	28.80	23.96
Nitrogen	11.49	10.92
Phosphorus	1.57	0.67

b)



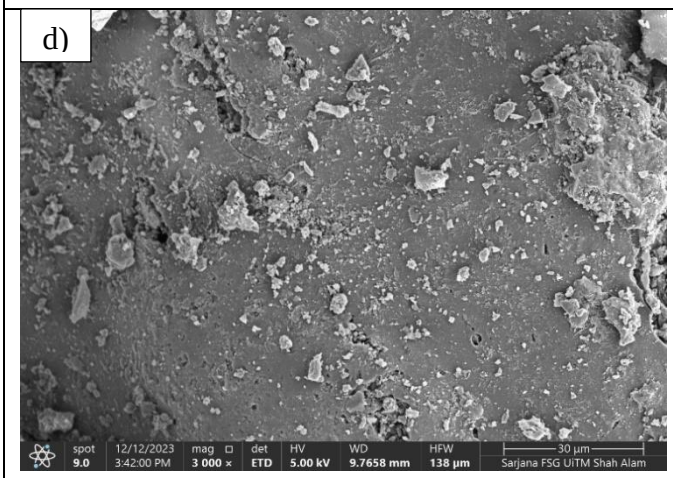
Element	Mass Norm. [%]	Atom [%]
Carbon	45.22	52.28
Oxygen	50.58	43.91
Nitrogen	3.55	3.52
Phosphorus	0.65	0.29

c)



Element	Mass Norm. [%]	Atom [%]
Carbon	58.14	71.98
Oxygen	0.16	0.14
Nitrogen	21.71	19.37
Phosphorus	16.27	7.22
Calcium	3.65	1.25
Magnesium	0.07	0.04

d)



Element	Mass Norm. [%]	Atom [%]
Carbon	82.42	84.65
Oxygen	1.21	0.94
Nitrogen	16.37	14.42

Figure 4.11 FESEM Images at Magnification Power 3000x of (a) CB, (b) RW, (c) M-RWCBAC, and (d) M-RWCBAC After MV Adsorption, Followed by EDX Mapping

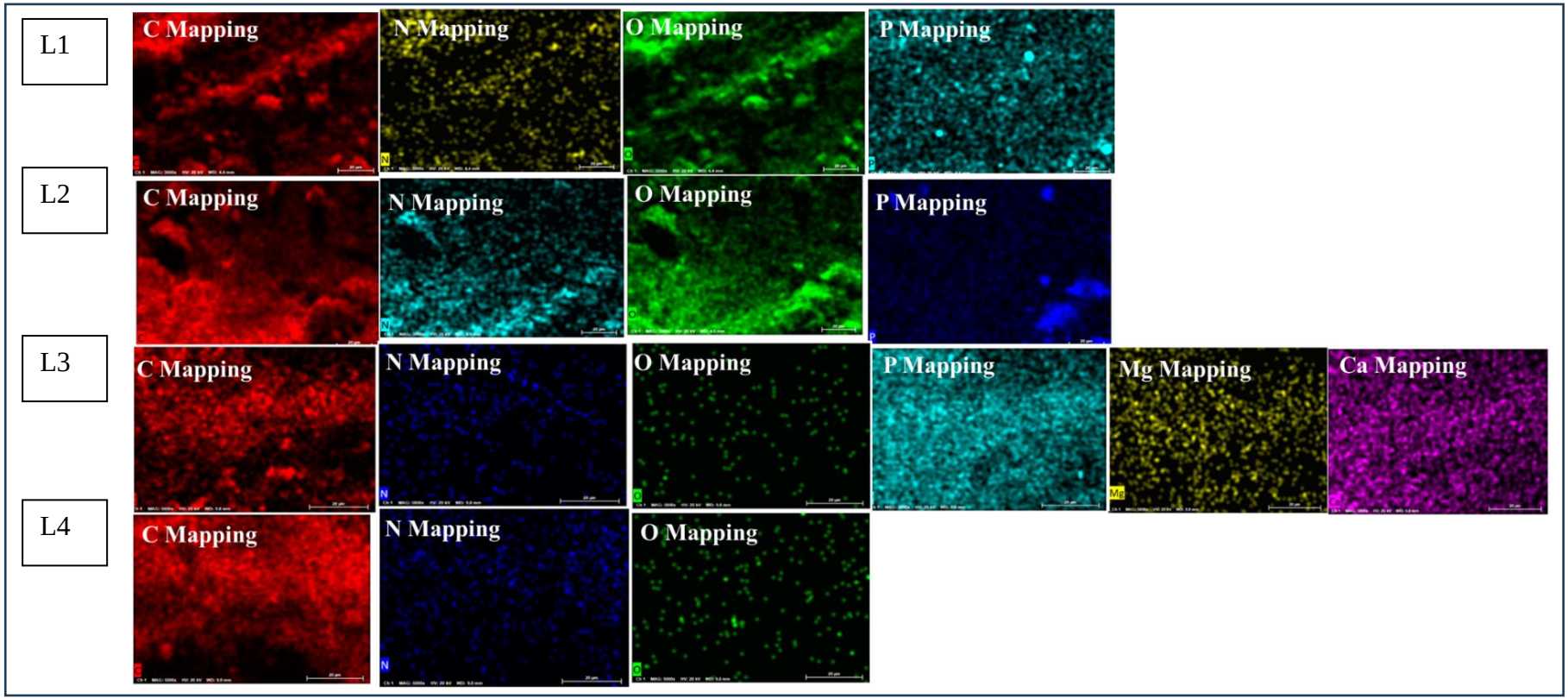


Figure 4.12 EDX Mapping of (L1) CB, (L2) RW, (L3) M-RWCBAC, and (L4) M-RWCBAC-MV

4.3 Box- Behnken Design (BBD) Model Analysis

4.3.1 Box-Behnken Design (BBD) Model Analysis P-RWCBAC

The BBD Model was utilized to design 17 experiments in Table 4.3 to study three independent characteristics that potentially affect the dye removal efficiency. The BBD model in Response Surface Methodology (BBD-RSM) approach was employed to investigate the individual and interactive effects of dose (A), solution pH (B), and time (C) on the MV dye removal as a response, which were tabulated in Table 4.3.

Table 4.3
The 3-Variables BBD Matrix and Experimental Data for MV Removal (%)

Run	A: P-RWCBAC dose(g)	B: pH	C: Time (Min)	MV Removal (%)
1	0.02	4	12.5	20.1
2	0.1	4	12.5	69.8
3	0.02	10	12.5	37.9
4	0.1	10	12.5	77.9
5	0.02	7	5	29.1
6	0.1	7	5	58.6
7	0.02	7	20	31.7
8	0.1	7	20	90.4
9	0.06	4	5	54.9
10	0.06	10	5	65.8
11	0.06	4	20	67.3
12	0.06	10	20	82.6
13	0.06	7	12.5	46.6
14	0.06	7	12.5	51.4
15	0.06	7	12.5	48.8
16	0.06	7	12.5	49.8
17	0.06	7	12.5	47.3

The optimal operating parameters were an adsorbent dose of (0.1 g), a solution pH of 7, and a contact period of 20 minutes, which resulted in the maximum MV removal (90.4%). The experimental results of MV dye removal were statistically analyzed using analysis of variance (ANOVA), as shown in Table 4.4.

Table 4.4
Analysis of Variance (ANOVA) for MV Removal

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	5951.69	9	661.30	249.94	< 0.0001
A-P-RWCBAC dose	3956.05	1	3956.05	1495.23	< 0.0001
B-pH	339.30	1	339.30	128.24	< 0.0001
C-Time	505.62	1	505.62	191.10	< 0.0001
AB	23.52	1	23.52	8.89	0.0205
AC	213.16	1	213.16	80.57	< 0.0001
BC	4.84	1	4.84	1.83	0.2183
A^2	165.92	1	165.92	62.71	< 0.0001
B^2	335.20	1	335.20	126.69	< 0.0001
C^2	416.64	1	416.64	157.47	< 0.0001
Residual	18.52	7	2.65		
Lack of Fit	3.67	3	1.22	0.3298	0.8055
Pure Error	14.85	4	3.71		
Cor Total	5970.21	16			

The F-value of the model and the accompanying p-value are 249.94 and <0.0001, respectively. The model is significant because the F-value is greater and the p-value is less than 0.05. based on the Table 4.4 (ANOVA analysis), the result show that the actual and the anticipated value have a high correlation as indicated by the coefficient of determination (R^2) because the value being quite close to unity (Pinheiro et al., 2020). On the MV dye removal under the selected conditions and terms, the model with a p-value less than 0.05 (Prob > F< 0.0500) are often significant (Baig et al., 2020). Based on Table 4.3, the BBD model identified the terms A, B, C, AB, AC, A^2, B^2, and C^2 as significant factors influencing MV dye removal under the specified conditions. Model terms with p-values above 0.05 were excluded to ensure a proper fit of the second-order polynomial model. Consequently, the relationship between the tested variables and MV dye removal was expressed through the second-order polynomial equation presented in Equation (4.1):

$$MV\ Removal\ (\%) = +48.78 + 22.24A + 6.51B + 7.95C - 2.43AB + 7.30ACI + 1.10BC - 6.28A^2 + 8.92B^2 + 9.95C^2 \quad (4.1)$$

The validity of the model can also be assessed using graphical methods by examining the distribution of residuals and the correlation between predicted and actual MV dye removal values. As shown in Figure 4.13, the normal probability plot of residuals indicates that the data points align closely with a straight line, suggesting that the residuals follow an approximately normal distribution. This finding supports the validity of the hypotheses and the independence of the residuals (Natarajan & Ponnaiah, 2017).

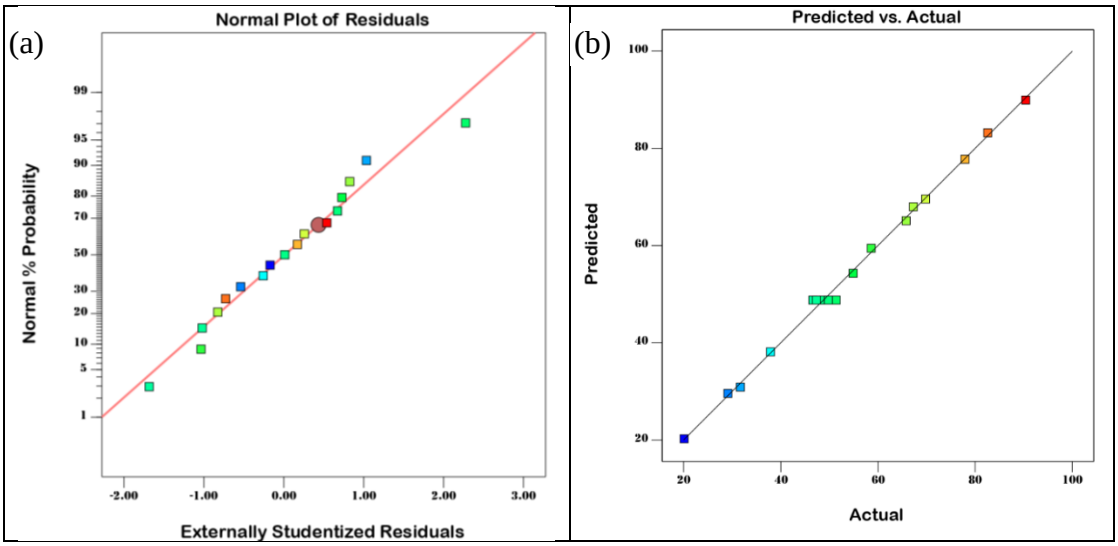


Figure 4.13 (a) Normal Probability Plot of Residuals for MV Removal (%) by P-RWCBAC and (b) The Plot of the Relationship Between the Predicted and Actual Values for MV Removal (%) by P-RWCBAC

A secondary evaluation of the developed models was performed through a normality test (Figure 4.13 (a)) to confirm that the residuals were evenly distributed. The random distribution of points along the 45° reference line in Figures 4.13 (a) and (b) indicates that both the model structure and the ANOVA outcomes are reliable. Furthermore, Figure 4.13 (b) demonstrates that the experimental MV removal values closely align with the predicted values along a straight line, validating the suitability of the models.

4.3.2 Box-Behnken Design (BBD) Model Analysis M-RWCBAC

The analysis of variance (ANOVA) is an important model for checking the correctness of models used in MV dye removal, as well as the importance and suitability of the data used. Table 4.5 shows the results of the analysis of variance (ANOVA) for the removal of MV dye. The results in Table 4.5 show that the p-value for the suggested model was less than 0.0001, with an F-value of 72.11.

Table 4.5
The 3-Variables BBD Matrix and Experimental Data for MV Removal (%)

Run	A: M-RWCBAC dose(g)	B: pH	C: Time (Min)	MV Removal (%)
1	0.02	4	105	14.9
2	0.1	4	105	64.3
3	0.02	10	105	51.2
4	0.1	10	105	96.1
5	0.02	7	10	21.9
6	0.1	7	10	45.6
7	0.02	7	200	34.1
8	0.1	7	200	82.7
9	0.06	4	10	28.4
10	0.06	10	10	50.1
11	0.06	4	200	40.8
12	0.06	10	200	85.1
13	0.06	7	105	58.8
14	0.06	7	105	57.1
15	0.06	7	105	53.3
16	0.06	7	105	55.4
17	0.06	7	105	54.4

The findings indicate that the suggested model accurately captures the relationship between the researched factors and the response variable (Abdulhameed et al., 2024; Kutluay & Temel, 2021). For MV dye removal, the coefficient of determination (R^2) was found to be 0.99, reflecting a strong agreement between experimental and predicted values. The Lack of Fit test confirmed the suitability of the model, while the p-value (4.30) indicated no statistical significance (Ashrafi et al., 2021; Foroutan, Peighambardoust, et al., 2022). Typically, variables with p-values greater than 0.05 are considered insignificant in influencing MV dye removal efficiency. In this

study, the variables A, B, C, AC, BC, and C^2 were statistically significant, whereas the remaining factors were not. Accordingly, second-order quadratic polynomial equations were developed to describe the relationship between the tested variables and MV dye removal, as presented in Equation (4.2).

$$MV\ Removal\ (\%) = +55.8 + 20.8A + 16.7B + 12.1C - 6.23AC + 5.65BC - 7.62C^2 \quad (4.2)$$

4.4 3D Graph of Binary Impact of Parameters P-RWCBAC

The 3D response surface visuals make it much easier to interpret the relationship between the independent variables (P-RWCBAC dosage, pH, and time) and the dependent variable (MV removal). Figure 4.14 shows the association between predicted and actual MV dye removal (%) data. This relationship shows that the expected and actual values are almost identical, supporting the statistical validity of the model. The interaction impact between any two independent factors was evaluated on the MV dye removal. Figure 4.14 (a) and (b) below show that the interaction between dose and pH is significant because the p-value was less than 0.05 while holding time 12.5 min constant. The p-value of this model was 0.0205. As we increased the pH, the MV dye removal would also increase because the surface charge would carry more negative charges as the P-RWCBAC active sites have been occupied within a short time. The interaction impact between any two independent factors was evaluated on the MV dye removal. Figure 4.14 below shows that the interaction between time and dose is significant because the p-value was less than 0.05 while holding the pH constant at pH 7. The p-value of this model was (p-value < 0.0001). Figure 4.14 shows that increasing the adsorbent dose steadily enhanced the MV dye removal (%), which can be attributed to the increased accessible surface area of P-RWCBAC in MV dye solution. This can be due to the rise in P-RWCBAC surface area in the MV dye solution, and a larger P-RWCBAC dose also suggests more active adsorption sites available. The pH_{pzc} analysis, depicted in Figure 4.3, illustrates the point of zero charge for P-RWCBAC. At pH levels above the pH_{pzc}, the surface of the adsorbent becomes negatively charged, facilitating the adsorption of the positively charged MV dye molecules through electrostatic attraction. Conversely, at pH levels below the pH_{pzc}, the

adsorbent surface is positively charged, leading to repulsion of the cationic dye and reduced adsorption efficiency. This behavior underscores the importance of operating at pH values above the pH_{pzc} to optimize the dye adsorption process.

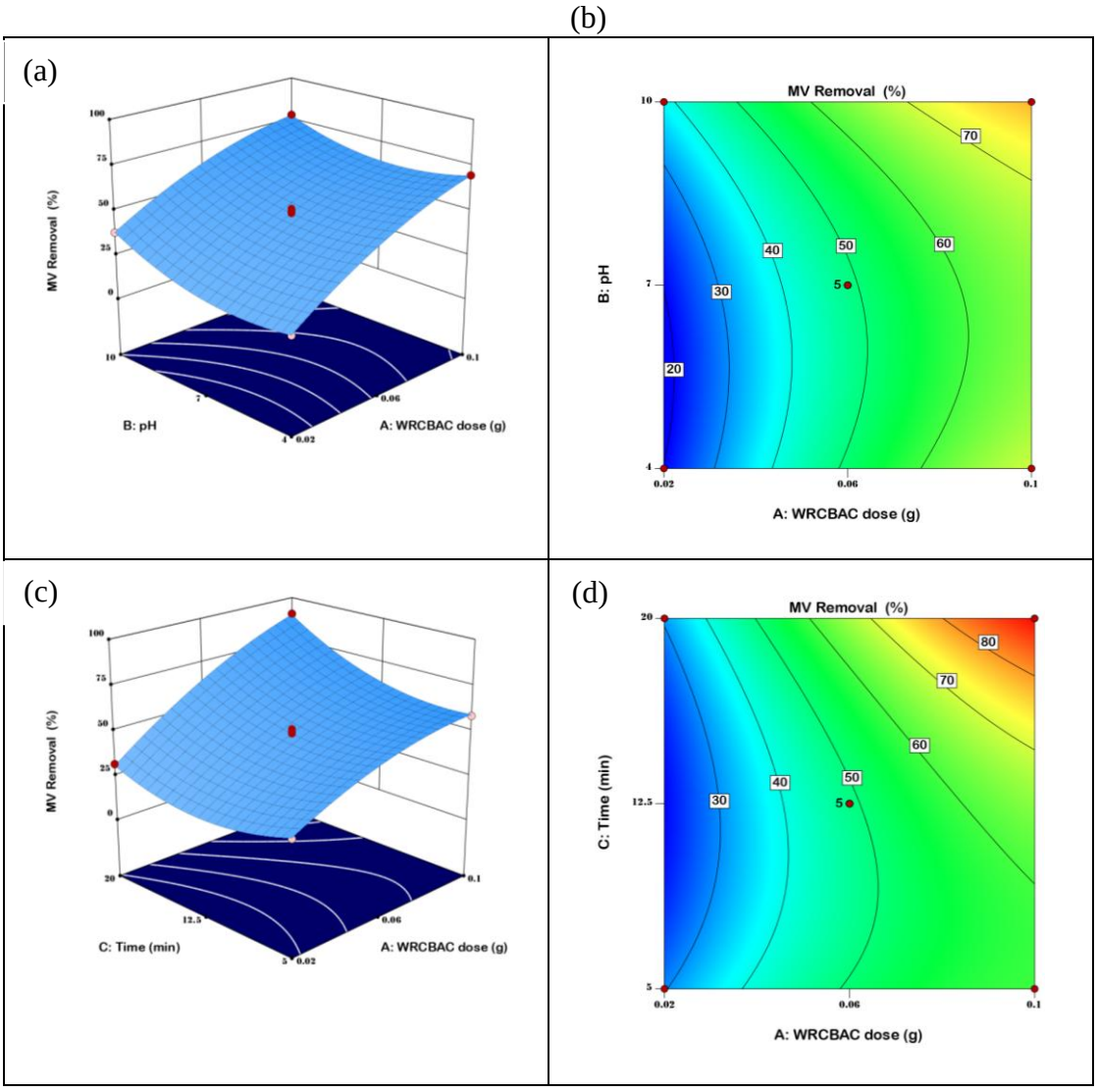


Figure 4.14 (a) 3D Response Surface Plot, (b) Contour Plot of MV Dye Removal Showing The Interaction Between PCRW Time and Dose

Since the P-RWCBAC has a pH_{pzc} value of 3 (see Figure 4.3 pH_{pzc} of P-RWCBAC), its surface is positively charged at pH values below pH_{pzc}. This demonstrates that when pH is higher than 3, the P-RWCBAC surface is dominated by negative charges and tends to grab MV molecules. According to Figure 4.6, the MV removal (%) decreased as the MV concentration increased. This discovery can be explained by the fact that the molecule of MV dye had access to more active sites on the P-RWCBAC surface when the concentration was lower. As a result, the P-

RWCBAC was able to adsorb the majority of the MV molecule in the solution, leading to a significant removal.

4.5 Three Dimensions (3D) and Two Dimensions (2D) of Dual Impact Parameters M-RWCBAC

Three dimensions (3D) and two dimensions (2D) response surface plots were utilized to examine the influence of factors under study and to identify significant interactions affecting MV dye removal. Figure 4.15 (a-b) illustrates the combined effects of M-RWCBAC dosage and contact time, with pH fixed at 10. As shown, increasing the dosage of M-RWCBAC from 0.06 g to 0.1 g enhanced the dye removal efficiency, which can be attributed to the larger surface area and greater number of active adsorption sites available at higher dosages. Similarly, extending the contact time from 105 to 200 minutes improved MV removal, as sufficient time is required for dye molecules to diffuse into the pores of M-RWCBAC.

Figure 4.15 (c-d) presents the effect of M-RWCBAC dosage and pH on dye removal, with contact time maintained at 200 minutes. The results indicate that adsorption efficiency increased significantly under alkaline conditions, particularly at pH 10, and at higher adsorbent dosages. This behaviour was further clarified by the point of zero charge (pH_{pzc}) analysis, shown in Figure 4.4, where M-RWCBAC exhibited a pHpzc of 4. At solution pH values above this point, especially under alkaline conditions, the surface of M-RWCBAC becomes negatively charged, while MV dye molecules carry a positive charge. The resulting electrostatic attraction enhances adsorption, explaining the higher removal efficiency observed at elevated pH levels (as expressed in Equation (4.3).

$$M - RWCBAC^{-} + MV^{+} \leftrightarrow M - RWCBAC^{-} \ldots MV^{+} \quad (4.3)$$

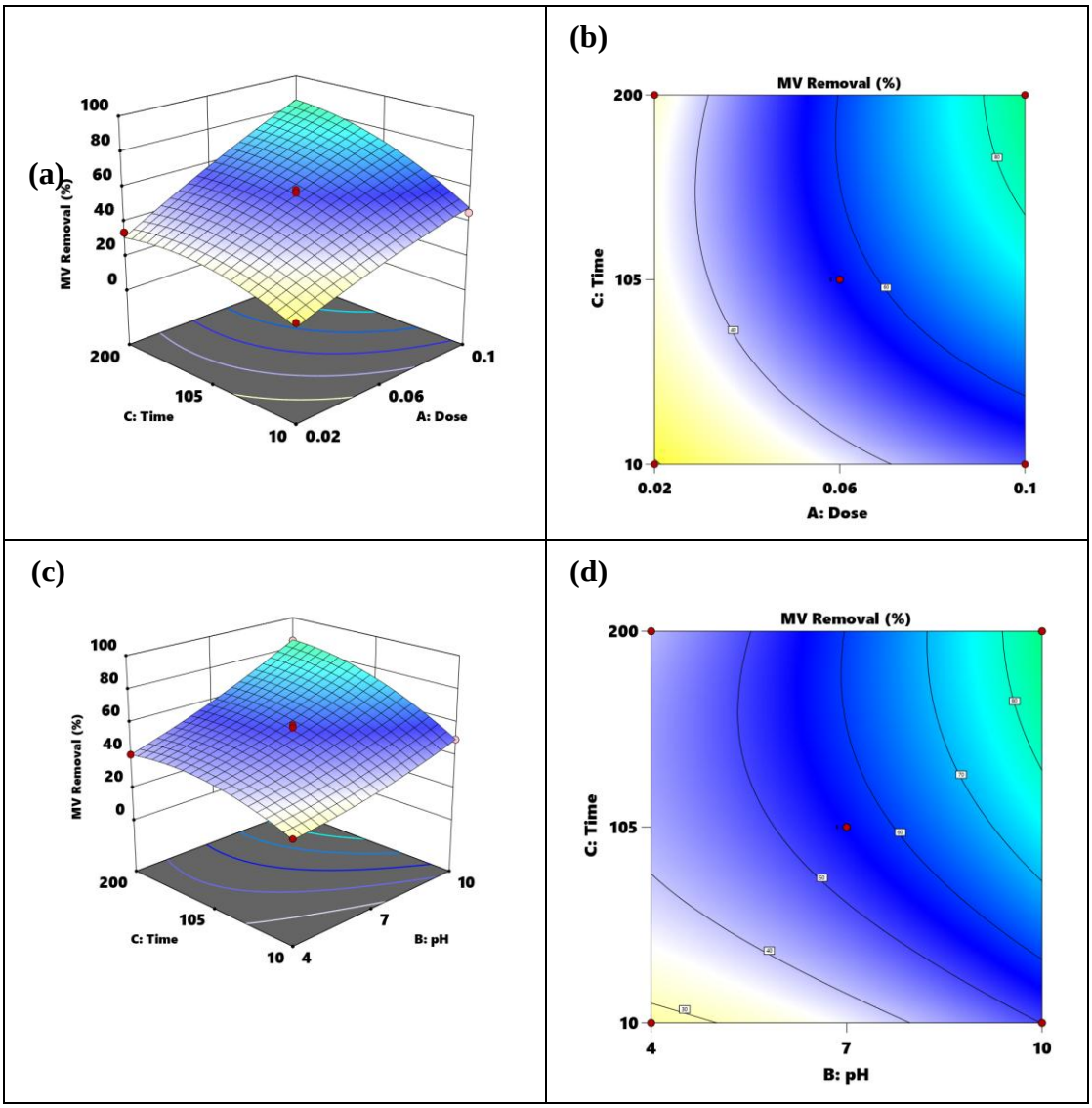


Figure 4.15 2D and 3D Response Surface Plots Showing Significant Interactions on MV Dye Removal Efficiency by M-RWCBAC (a-b) AC Interaction; (c-d) BC Interaction

4.6 Adsorption Study

4.6.1 Adsorption Study of P-RWCBAC

The adsorption capacity of P-RWCBAC was investigated as a function to contact time and MV's initial concentration. The effects of changing the initial MV solution concentration (20, 50, 100, 150, 200 and 250 mg/L) on the effectiveness of P-RWCBAC's adsorption are shown in Figure 4.16, respectively. The adsorbent dose (0.099 g), pH of the solution (9.8), and contact time (15 min) were fixed for the P-RWCBAC' adsorption study test. While the adsorption capacity of P-RWCBAC was substantially increased from 17.69 to 89.109 mg/g with the increment in initial MV concentration from 20 to 250 mg/L, the adsorption ability of P-RWCBAC was considerably improved from 40.6 to 285.9 mg/g with the same increase. The fairly large concentration gradient, which increases the movement of RO16 within the pores of the adsorbent and leads to the transfer of RO16 to the reactive surface of the adsorbent, is something that causes to this behaviour (Jawad et al., 2022).

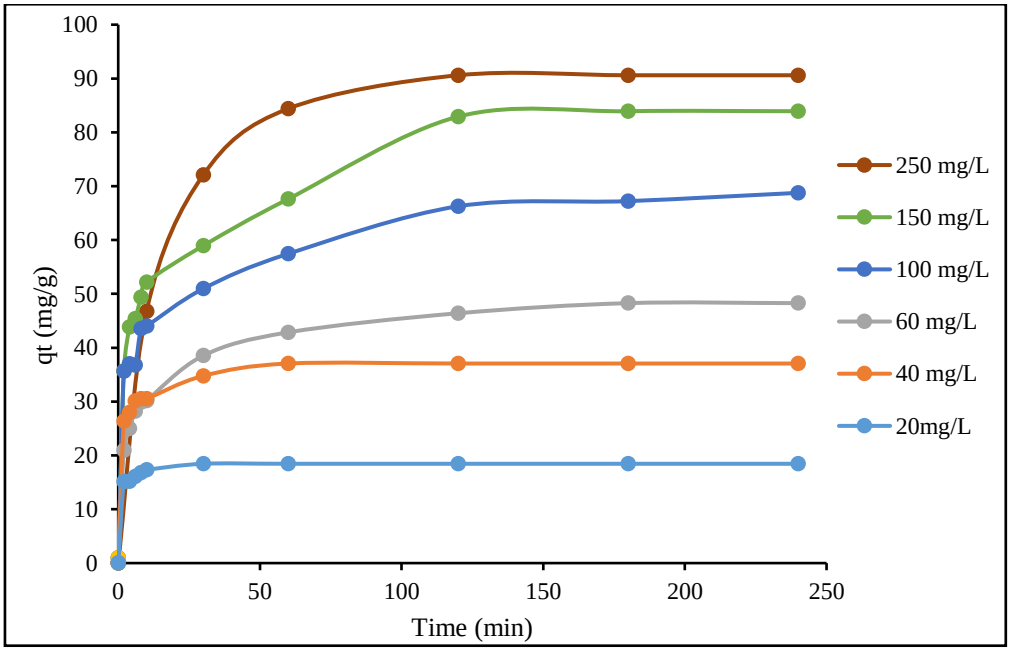


Figure 4.16 Effect of Time and Concentration Variation to The P-RWCBAC Adsorption Capacity

4.6.2 Adsorption Study of M-RWCBAC

The adsorption efficiency of M-RWCBAC is contingent upon the initial concentration of MV, as illustrated in Figure 4.17. The dye adsorption efficiency of M-RWCBAC rose from 13.97 to 98.64 mg/g with an increase in the initial MV dye concentration from 20 to 250 mg/L. This trend is attributable to an increase in the driving force for mass transfer, which occurs with elevated initial dye concentrations. The enhanced mass transfer leads to a higher concentration of dye capable of infiltrating the internal pores of M-RWCBAC in its liquid form (Wei & Kamali, 2021).

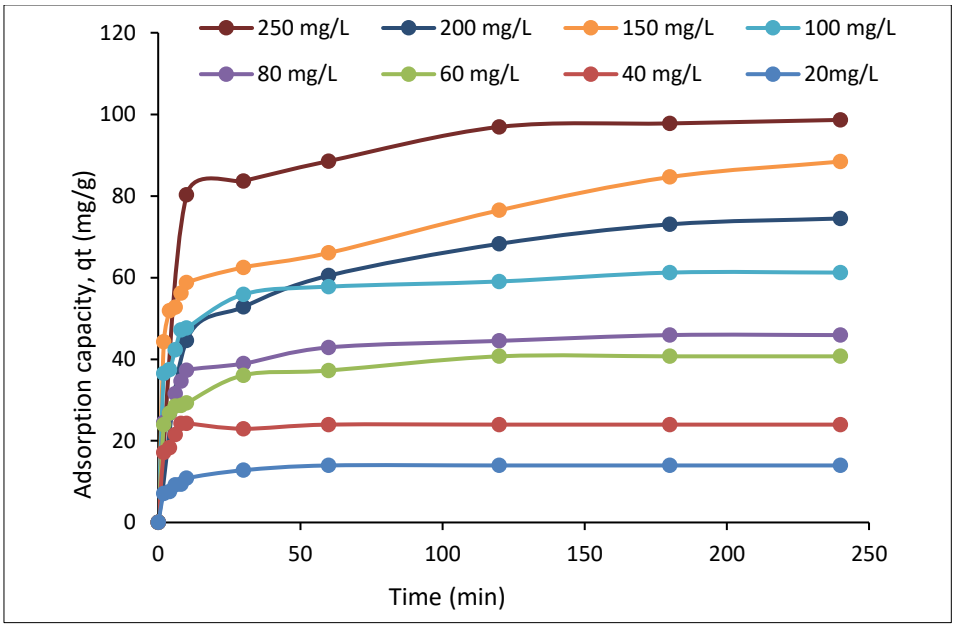


Figure 4.17 Impact of Concentration and Time Interval on The Adsorption Capacity of M-RWCBAC

4.7 Adsorption Kinetics

4.7.1 Adsorption Kinetics of P-RWCBAC

Kinetic models were applied to elucidate the adsorption mechanism and efficiency of MV onto P-RWCBAC. Two commonly used models, the pseudo-first-order (PFO) model (Lagergren, 1898) and the pseudo-second order (PSO) model (Ho & McKay, 1998), were employed to describe the adsorption dynamics of the system. The nonlinear forms of these models are presented in Equations (3.3) and (3.4), along

with definitions of the respective parameters. The estimated kinetic parameters derived from these models are summarized in Table 4.6.

Table 4.6
PFO and PSO Kinetic Parameters for MV Adsorption on P-RWCBAC

Concentration (mg/L)	$q_{e\ exp.}$ **(mg/g)**	**PFO**			**PSO**		
		$q_{e\ cal}$ **(mg/g)**	k_1 **(1/min)**	R^2	$q_{e\ cal}$ **(mg/g)**	$k_2 \times 10^{-2}$ **(g/mg min)**	R^2
20	18.44	17.69	0.8154	0.96	18.38	9.2638	0.99
40	37.06	34.56	0.5365	0.92	36.46	2.5630	0.98
60	48.28	44.30	0.1694	0.91	46.89	0.5500	0.97
100	68.76	60.88	0.1938	0.84	64.25	0.4817	0.92
150	83.92	74.60	0.1683	0.85	79.63	0.3059	0.93
250	90.60	89.109	0.0649	0.99	96.54	0.1012	0.99

Table 4.6 presents the high R^2 values obtained for the PSO model, confirming that the adsorption behaviour of MV onto P-RWCBAC follows this kinetic model. A strong correlation was also observed between the experimental and calculated PSO qe values. These results suggest that MV molecules undergo chemisorption and exhibit strong affinity toward the P-RWCBAC surface. During chemisorption, chemical interactions occur between the dye molecules (MV) and the adsorbent surface (P-RWCBAC) (Jawad et al., 2023). This is further supported by the material's high adsorption capacity and the uniform distribution of MV species across its surface. Hence, chemisorption can be regarded as the dominant mechanism governing MV adsorption on P-RWCBAC, highlighting its potential for application in advanced water treatment technologies.

4.7.2 Adsorption Kinetics of M-RWCBAC

The kinetic analysis offers essential insights into the expansion and development of the MV adsorption process utilizing M-RWCBAC. The adsorption mechanism and kinetics of methylene violet (MV) adsorption were examined utilizing two kinetic models: the pseudo-first order model (Lagergren, 1898) and the pseudo-second order model(Ho & McKay, 1998). Equations (3.3) and (3.4) define the non-linear equations for these models, and Table 4.7 summarizes the estimated kinetic parameter values.

Table 4.7 shows that the PSO model outperformed the PFO model in terms of R^2 values. The predicted q_e values for the PSO model closely correspond to the actual (experimental) q_e values. The results show that a PSO framework accurately predicts MV adsorption by M-RWCBAC. The findings indicate that the MV dye adsorption is attributed to a chemisorption process (Xue et al., 2022). The rate constants (k_2) exhibit a decline as the initial dye concentrations increase from 20 to 250 mg/L. The decrease in k_2 values can be attributed to the prolonged time needed to achieve equilibrium, suggesting a diminished adsorption rate as initial dye concentrations increase (Normi et al., 2023).

Table 4.7
PFO and PSO Kinetic Parameters for MV Adsorption on M-RWCBAC at pH 9.8 and 25 °C

Concentration (mg/L)	$q_{e\ exp.}$ **(mg/g)**	**PFO**			**PSO**		
		$q_{e\ cal}$ **(mg/g)**	k_1 **(1/min)**	R^2	$q_{e\ cal}$ **(mg/g)**	$k_2 \times 10^{-2}$ **(g/mg min)**	R^2
20	13.9	13.5	0.19	0.93	14.2	23.3	0.98
40	23.9	23.7	0.51	0.97	24.4	4.85	0.97
60	40.7	37.5	0.28	0.90	39.3	1.27	0.96
80	45.9	42.7	0.26	0.94	44.9	0.99	0.98
100	61.2	57.3	0.28	0.92	59.9	0.85	0.97
150	88.4	65.7	0.13	0.90	70.6	0.26	0.95
200	74.5	73.1	0.27	0.83	77.4	0.56	0.91
250	98.6	92.5	0.21	0.96	97.3	0.34	0.98

4.8 Adsorption Isotherm

4.8.1 Adsorption Isotherm of P-RWCBAC

Adsorption isotherm models were applied to determine the amount of MV retained on the surface of P-RWCBAC and to examine the nature of their interactions. Three commonly used models were considered in this study: (Langmuir, 1918), (Chattoraj & Freundlich, 1906), and (Temkin, 1940), which describe the equilibrium relationship between MV and P-RWCBAC. The nonlinear equations for these isotherms are presented in Equations (3.5)-(3.7) along with their descriptions. The

corresponding model parameters and isotherm plots are summarized in Table 4.8 and Figure 4.18, respectively.

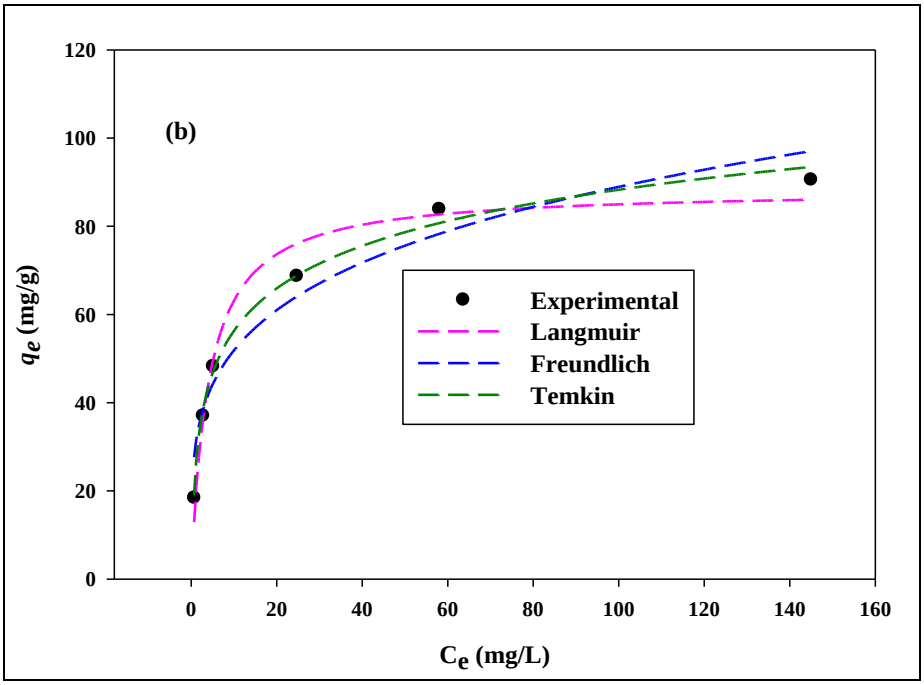


Figure 4.18 Isotherm Analyses (Langmuir, Freundlich, and Temkin) of MV Dye Removal by P-RWCBAC

Table 4.8
The Parameters of Isotherm Models for MV Adsorption on P-RWCBAC

Adsorption isotherm	**Parameter**	**Value**
Langmuir	q_{max} (mg/g)	88.4
	K_a (L/mg)	0.25
	R^2	0.97
Freundlich	K_f (mg/g) $(L/mg)^{1/n}$	30.2
	n	4.26
	R^2	0.95
Temkin	K_T (L/mg)	1.74
	b_T (J/mol)	178.1
	R^2	0.99

The equilibrium adsorption of MV onto P-RWCBAC, as described by the Langmuir model, is reflected by the R^2 value shown in Table 4.8. The results demonstrate that MV molecules were adsorbed uniformly as a monolayer on the active

sites of P-RWCBAC (Razali et al., 2022). This indicates a strong affinity of the material toward MV dye, enabling efficient adsorption from aqueous solutions. The maximum theoretical adsorption capacity (q_{max}) was determined to be 88.37 mg/g, which was compared with the capacities of other reported adsorbents (Table 4.9). The comparison highlights that P-RWCBAC exhibits notably high adsorption capacity, reinforcing its potential as an effective material for water treatment. These findings provide valuable insight into developing sustainable methods for removing cationic dyes such as MV from polluted water sources.

Table 4.9
A Comparison of MV Adsorption Capacities by Various Adsorbents

Adsorption Isotherm	**q_{maz} mg/g**	**Value**
P-RWCBAC	88.4	Present study
Palm kernel activated carbon	83.91	(Mehr et al., 2020)
Hagenia abyssinica leaf powder (HALP)	68.96	(Geremew & Zewde, 2022)
Activated carbon oak wood/ZnO/Fe_3O_4	48.59	(Foroutan, Mohammadi, et al., 2022)
HNT–Fe_3O_4 composite	20.04	(Bonetto et al., 2015)

4.8.2 Adsorption Isotherm of M-RWCBAC

The modeling of adsorption isotherms is essential for comprehending the interaction between the dye solution and the adsorbent, offering significant insights into the efficiency of the adsorption process of MV dye by M-RWCBAC material. The study utilized three established isotherms: the Langmuir (1918), Chattoraj and Freundlich (1906), and Temkin (1940) isotherms to analyze the adsorption profiles at equilibrium. The equations for these isotherm models are presented in Equations (3.3) and (3.4), while Figure 4.19 illustrates the graphs that represent the adsorption isotherm profiles.

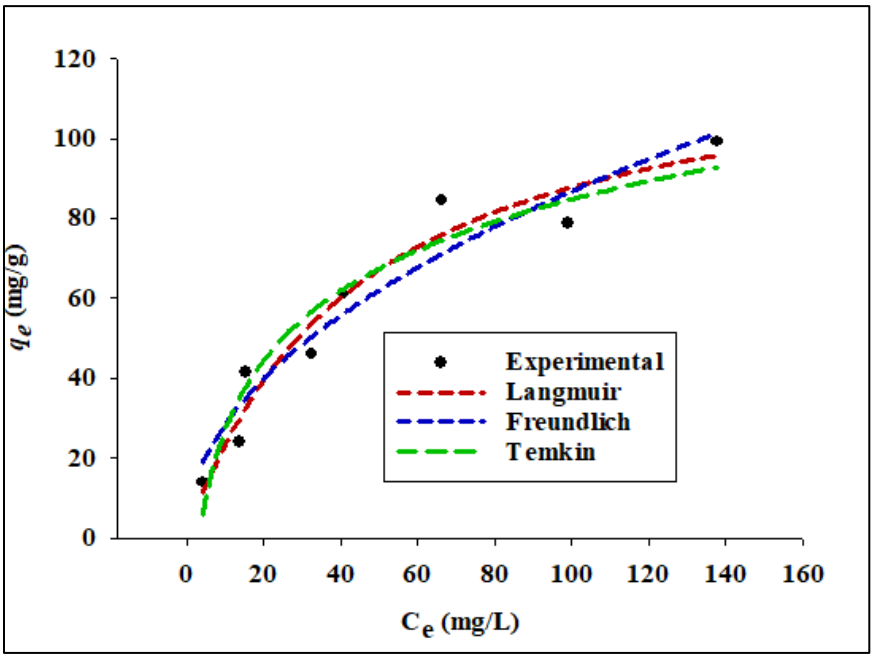


Figure 4.19 Isotherm Profile (Langmuir, Freundlich, and Temkin) of MV Dye Adsorption by M-RWCBAC

Table 4.10 summarizes the isotherm parameters obtained from the study. Both the Langmuir and Freundlich models showed a strong fit to the experimental data, with R^2 values of 0.94 and 0.93, respectively, whereas the Temkin model exhibited weaker agreement. The good correlation with the Langmuir and Freundlich models suggests that M-RWCBAC adsorbs MV dye primarily through a monolayer mechanism, while also involving heterogeneous adsorption sites (Vinayagam et al., 2022). According to the Langmuir model, the maximum monolayer adsorption capacity (q_{max}) of M-RWCBAC for methylene violet was calculated to be 126.8 mg/g. This q_{max} value differs from those reported for other adsorbents, as presented in Table 4.10, underscoring the distinctive adsorption performance of M-RWCBAC compared with previously studied materials.

Table 4.10
The Parameters of Isotherm Models for MV Dye Adsorption by M-RWCBAC

Adsorption isotherm	**Parameter**	**Value**
Langmuir	q_{max} (mg/g)	126.8
	K_a (L/mg)	0.02
	R^2	0.94
Freundlich	K_f (mg/g) $(L/mg)^{1/n}$	9.33
	n	2.06

	R^2	0.93
Temkin	K_T (L/mg)	2.71
	b_T (J/mol)	90.6
	R^2	0.92

Table 4.11 includes an analysis of the q_{max} values, which allows for an evaluation of the effectiveness of various adsorbents in removing MV. The M-RWCBAC material, generated from food waste, has a high adsorption capacity, indicating its potential as an efficient adsorbent for MV dye removal from aqueous solutions.

Table 4.11
A Comparison of MV Adsorption Capacities of M-RWCBAC by Various Adsorbents

Adsorption Isotherm	**Parameter**	**Value**
M-RWCBAC	126.8	This study
Artocarpus heterophyllus (Jackfruit) Seed	126.7	Dahri et al. (2016)
Carboxymethyl cellulose graphitic-carbon nitride/zinc oxide (CMC/g-C_3N_4/ZnO)	96.43	Sharma et al. (2020)
Hydrogen titanate nanotubes	106	Santos et al. (2022)
Artocarpus odoratissimus	263.7	Kooh et al. (2016)

4.9 Adsorption Mechanism

4.9.1 Adsorption Mechanism of P-RWCBAC

Porous carbon materials adsorb organic dyes such as MV through multiple interactions, including electrostatic attraction, pore diffusion, π-π stacking, and hydrogen bonding. The possible interaction mechanisms involved in MV adsorption are illustrated in Figure 4.20. Given that MV molecules have a size of 1.42 nm and P-RWCBAC possesses an average pore diameter of 4.76 nm, the dye molecules can diffuse into and occupy the pores of the adsorbent. For P-RWCBAC, the adsorption process is mainly governed by electrostatic attraction and π–π interactions. FTIR results

confirm the presence of functional groups such as O-H and C=O, which contribute to surface interactions. Under basic conditions, the surface functional groups of P-RWCBAC become negatively charged (e.g., $-O^-$, $-COO^-$), which enhances attraction toward the cationic MV dye. Pore filling also contributes to adsorption but plays a secondary role.

In addition, π-π interactions occur between the aromatic structure of the carbon material and the benzene rings of MV, enhancing adsorption performance. Hydrogen bonding may also occur as a secondary interaction between oxygen-containing functional groups on the adsorbent surface and the dye molecules. Although pseudo-second-order kinetics suggests chemisorption, it does not exclude the contribution of physical interactions; therefore, the adsorption process involves a combination of chemisorption and physisorption mechanisms.

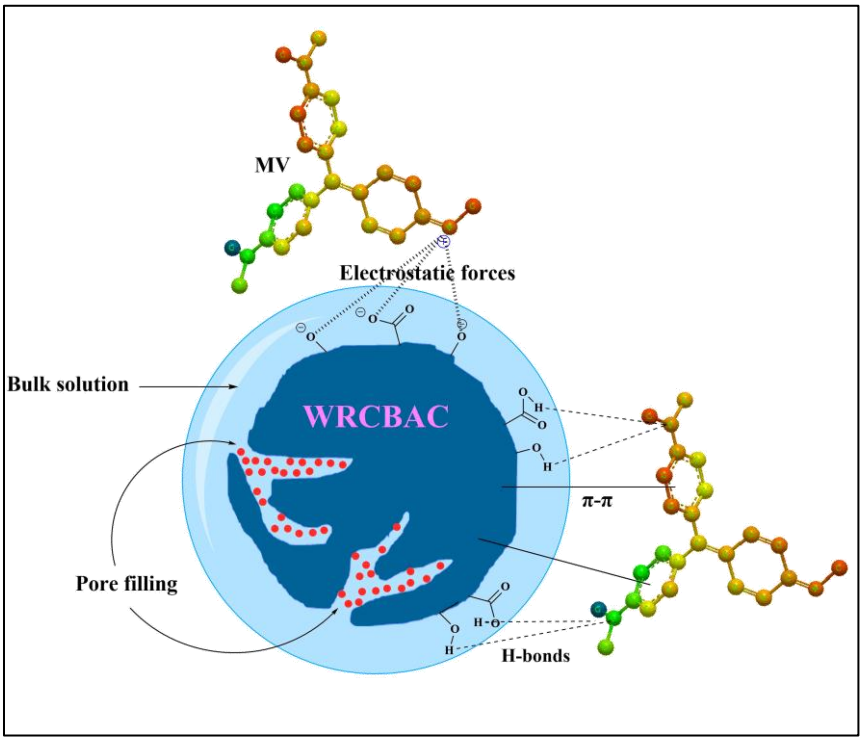


Figure 4.20 The Possible Interaction of MV Dye onto P-RWCBAC (Pore Filling, Electrostatic Attraction, Hydrogen Bonding and π-π Interaction)

4.9.2 Adsorption Mechanism of M-RWCBAC

A For M-RWCBAC, the adsorption mechanism is mainly controlled by electrostatic attraction and π-π interactions and may be slightly enhanced due to surface

modification that increases the number of active sites. A thorough understanding of MV adsorption on M-RWCBAC can be explained through pH_{pzc} and FTIR analysis. The adsorption of MV, a cationic dye, is more favourable under alkaline conditions (pH > pH_{pzc}), where the surface of M-RWCBAC becomes negatively charged, allowing strong electrostatic attraction with positively charged MV molecules. FTIR analysis confirms the presence of functional groups such as -OH, C=O, C-H, and C=C on the surface of M-RWCBAC, which contribute to surface interactions with the dye. These functional groups support hydrogen bonding and other surface interactions, where hydrogen atoms associated with oxygen-containing groups may act as hydrogen donors to the nitrogen atoms in MV. In addition, π-π interactions occur between the aromatic structure of M-RWCBAC and the benzene rings of MV, enhancing adsorption performance.

FESEM results after adsorption show surface coverage, indicating that pore filling also occurs due to the pore structure (6.57 nm from BET analysis), allowing dye molecules to diffuse into the adsorbent pores. However, like P-RWCBAC, pore filling is considered a secondary mechanism rather than the dominant one. Lastly, isotherm analysis shows that both Langmuir and Freundlich models fit well with the experimental data, suggesting that adsorption occurs on heterogeneous surfaces with possible multilayer contribution at higher concentrations. Overall, the adsorption of MV onto M-RWCBAC is governed by a combination of electrostatic attraction, π-π interactions, hydrogen bonding, and pore filling, with electrostatic attraction and π-π interaction being the dominant mechanisms. There is no contradiction. PSO indicates that adsorption is mainly controlled by surface interactions, but π-π stacking and pore filling are also involved. So, the mechanism is mixed: electrostatic and π-π are dominant, while pore filling and hydrogen bonding are secondary.

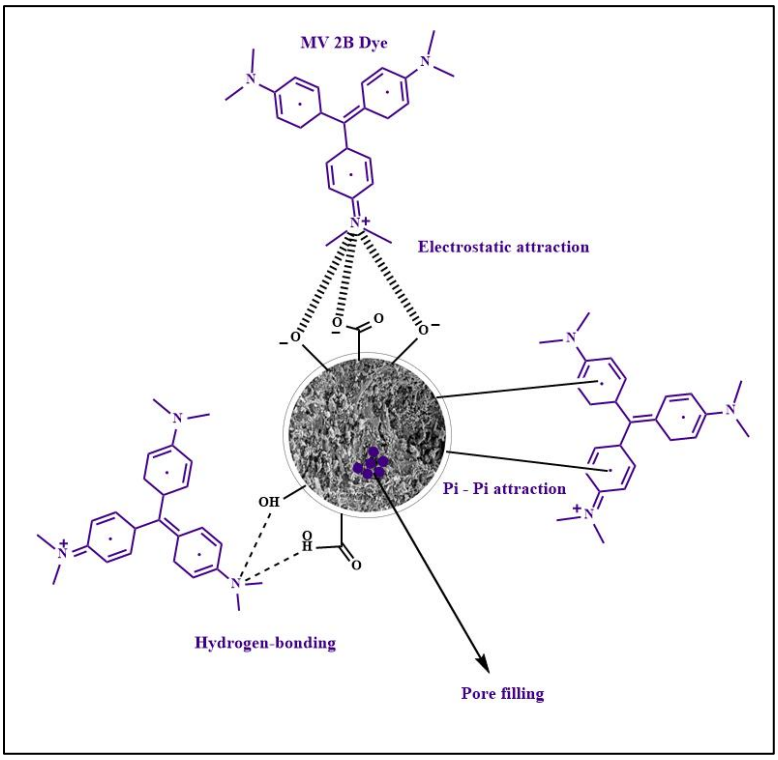


Figure 4.21 Illustration of the Potential Interactions Between the M-RWCBAC Surface and the MV Dye, Including Electrostatic Attraction, H-Bonding and π-π Interactions

4.10 Summary

The adsorption of methyl violet (MV) onto both P-RWCBAC and M-RWCBAC was successfully studied using equilibrium, kinetic, and mechanism analysis. The results show that both adsorbents are effective for dye removal, with adsorption behaviour influenced by surface properties and interaction mechanisms between the dye and adsorbent.

4.10.1 Summary of P-RWCBAC

This study demonstrates that food waste materials, specifically waste rice (RW) and chicken bones (CB), can be utilized as sustainable precursors for producing activated carbon (P-RWCBAC) through H3PO4-assisted pyrolysis. Based on the statistical desirability function, the optimal conditions for MV removal were identified as pH 9.8, an adsorbent dosage of 0.099 g/L, and a contact time of 17.3 minutes, achieving a decolorization efficiency of 91.49%. Equilibrium and kinetic analyses confirmed that MV adsorption followed a monolayer adsorption mechanism on

heterogeneous surface sites, while also suggesting that multilayer adsorption may occur at higher dye concentrations, which is common in real adsorption systems and does not fully contradict the Langmuir model under practical conditions (Alharbi et al., 2022; Duran et al., 2011).

The adsorption process was primarily driven by electrostatic attraction and π–π interactions, supported by the presence of functional groups observed in FTIR analysis. Hydrogen bonding also contributes as a secondary mechanism, while pore filling plays a supporting role in dye uptake. Because of its superior water adsorption, porosity, and large surface area, P-RWCBAC shows strong potential for diverse applications, particularly in the removal of cationic dyes and other organic pollutants from aqueous systems (Shi et al., 2023).

4.10.2 Summary of M-RWCBAC

Activated carbon derived from food waste (RWCBAC) proved highly effective for removing MV dye from aqueous solutions. According to the BBD model, the optimum conditions for achieving 94.4% dye removal were an M-RWCBAC dosage of 0.08 g/100 mL, solution pH of 9.8, and a contact time of 105 minutes. The model yielded an F-value of 72.11, confirming its strong statistical validity, and an R^2 value of 0.99, indicating excellent predictive accuracy.

Kinetic and equilibrium studies revealed that MV adsorption occurred predominantly as a monolayer on heterogeneous surface sites, with possible multilayer adsorption at higher dye concentrations, which reflects real adsorption behaviour in non-ideal systems (Alharbi et al., 2022; Hameed, 2008). The maximum adsorption capacity (q_{max}) was calculated as 126.8 mg/g at 25 °C. The adsorption process followed a chemisorption mechanism, supported by the PSO kinetic model and strong interaction between the adsorbent and dye molecules. The dominant adsorption mechanism for M-RWCBAC is electrostatic attraction and π-π stacking, while hydrogen bonding and pore filling act as secondary mechanisms that assist dye uptake. Overall, M-RWCBAC demonstrated excellent efficiency as an eco-friendly adsorbent, combining sustainable raw materials, simple synthesis, and high adsorption performance for the removal of organic dyes from contaminated water.

CHAPTER 5
CONCLUSION

5.1 Conclusion

The increasing discharge of dye-containing wastewater from industrial activities has become a significant environmental concern due to its detrimental effects on aquatic ecosystems and water quality. Among the available treatment technologies, adsorption using activated carbon remains one of the most effective and environmentally sustainable methods for dye removal. However, the high production cost of commercial activated carbon has encouraged the exploration of alternative low-cost precursors derived from agricultural and food wastes. Therefore, this study investigated the conversion of chicken bone and rice waste into activated carbon through pyrolysis and microwave-assisted phosphoric acid (H_3PO_4) activation for the removal of Methyl Violet 2B (MV) dye from aqueous solutions.

The first objective of this study was successfully achieved through the synthesis of activated carbon from chicken bone and rice waste using pyrolysis and microwave-assisted H_3PO_4 activation. The combination of thermal carbonization and chemical activation effectively transformed the biomass waste into functional adsorbents with enhanced adsorption properties. The pyrolysis and microwave process facilitated the decomposition of organic constituents and the formation of a carbon-rich structure. This method also success in promoted pore development and surface modification. The successful production of P-RWBAC and M-RWBAC demonstrates the feasibility of converting food waste materials into value-added products for environmental remediation applications, thereby supporting sustainable waste management and circular economy initiatives.

The second objective involved the characterization of the physicochemical properties of the synthesized activated carbons using FESEM, FTIR, BET, XRD, CHNS, and pH_{pzc} analyses. The characterization results confirmed the successful preparation of activated carbons with distinct structural and surface properties. FESEM analysis revealed the development of porous surface morphologies, while BET analysis showed that P-RWBAC possessed a significantly higher specific surface area (369.3 m^2/g) than M-RWBAC (83.3 m^2/g). FTIR analysis identified the presence of oxygen-

containing and phosphorus-containing functional groups that serve as active adsorption sites. XRD analysis demonstrated the coexistence of amorphous carbon structures and mineral phases originating from the chicken bone precursor, whereas CHNS analysis confirmed successful carbonization and activation. The pHpzc values of 3.0 for P-RWBAC and 4.0 for M-RWBAC indicated that both adsorbents acquired a negatively charged surface under alkaline conditions, favouring the adsorption of cationic dye molecules which is positively charge. These findings collectively verified that both activation methods produced activated carbons with physicochemical characteristics suitable for adsorption applications.

The third objective was successfully accomplished through the optimization of MV dye removal using Response Surface Methodology (RSM) based on the Box-Behnken Design (BBD). The effects of adsorbent dosage, solution pH, and contact time on dye removal efficiency were systematically evaluated using a second-order polynomial regression model. The developed models demonstrated excellent agreement with the experimental data, with a coefficient of determination (R^2) of 0.98 and significant F-values of 249.94 and 72.11 for P-RWBAC and M-RWBAC, respectively, confirming the adequacy and reliability of the models. The numerical optimization results revealed that the highest removal efficiency for P-RWBAC was 90.4% at an adsorbent dosage of 0.10 g, pH 7, and a contact time of 20 minutes. In contrast, M-RWBAC achieved a superior removal efficiency of 96.1% at the same adsorbent dosage and pH, but with a contact time of 105 minutes. These results demonstrate the effectiveness of RSM as a statistical optimization tool and highlight the significant influence of operating parameters on adsorption performance.

The fourth objective was to investigate the adsorption behaviour, adsorption mechanism, and adsorption capacity of the prepared activated carbons through kinetic, isotherm, and thermodynamic studies. The adsorption kinetic data for both adsorbents were best described by the pseudo-second-order model, indicating that the adsorption process was primarily governed by chemisorption involving interactions between the dye molecules and active sites on the adsorbent surface. Isotherm studies showed that the adsorption equilibrium was best represented by the Langmuir and Temkin models, suggesting monolayer adsorption with adsorbate–adsorbent interactions. The maximum adsorption capacities determined from the Langmuir model were 88.4 mg/g for P-RWBAC and 126.8 mg/g for M-RWBAC, demonstrating the superior adsorption capability of the microwave-activated adsorbent. The removal of MV dye was caused

by a combination of electrostatic attraction, hydrogen bonding, π-π interactions, and n-π interactions between the dye molecules and the functional groups on the activated carbon surface, according to the adsorption mechanism revealed by FTIR, XRD, and pH_{pzc} analyses.

A comparative evaluation of both adsorbents revealed that although P-RWBAC possessed a substantially larger surface area and more structured porosity, M-RWBAC exhibited superior adsorption performance toward Methyl Violet dye. This enhanced performance can be attributed to the greater abundance of surface functional groups, increased structural disorder, and more accessible mesoporous structure generated through microwave-assisted activation. These characteristics promoted stronger adsorbent–adsorbate interactions and facilitated more efficient diffusion of dye molecules into the adsorbent matrix. The findings indicate that adsorption performance is not solely dependent on surface area but is also strongly influenced by surface chemistry, pore accessibility, and the nature of adsorption interactions.

The findings of this study revealed that chicken bones and rice waste have the potential to serve as environmentally friendly precursor materials for the synthesis of activated carbon. Pyrolysis and microwave-assisted phosphoric acid activation were used to create efficient adsorbents with excellent adsorption capacities and Methyl Violet dye removal efficiencies. This work allows for the development of economical and environmentally sustainable wastewater treatment technologies in addition to offering a viable treatment alternative for dye-contaminated wastewater. It also helps to value food waste resources. The results serve as the groundwork for further study and industrial use in wastewater remediation and offer insightful information on the design and use of biomass-derived activated carbons.

5.2 Recommendations

Based on the results obtained in this study, several recommendations are suggested for future work to further explore the potential of activated carbon derived from chicken bone and rice waste. Since P-RWBAC and M-RWBAC showed promising performance in removing Methyl Violet dye, future studies could investigate their effectiveness in adsorbing other types of dyes commonly found in industrial wastewater, such as azo, anthraquinone, and reactive dyes. This would provide a better understanding of the adsorption behaviour of the prepared activated carbons and

determine whether they can be applied to a broader range of dye-contaminated wastewater. In addition, further research on different activation methods and activating agents is recommended, as these factors may influence the surface characteristics and adsorption performance of the activated carbon. Exploring alternative activation approaches may lead to the development of adsorbents with improved properties and higher treatment efficiency.

Besides dye removal, the potential application of P-RWBAC and M-RWBAC for the removal of other contaminants, including heavy metals, pharmaceutical compounds, pesticides, and emerging pollutants, should also be investigated. Such studies would help evaluate the versatility of these adsorbents and expand their potential use in water and wastewater treatment. Future research should also focus on the regeneration and reusability of the activated carbons, as the ability to maintain adsorption performance after several adsorption-desorption cycles is important for practical and economic applications. Furthermore, since this study was conducted using synthetic dye solutions under controlled laboratory conditions, it would be beneficial to evaluate the performance of the prepared activated carbons using actual industrial wastewater. Testing under real wastewater conditions would provide a more realistic assessment of their effectiveness and help determine their suitability for large-scale implementation in wastewater treatment systems.

REFERENCES

Abd Rahman, M. R., Salehin, M. I. S. M., Murad, M. C., & Abbas, M. K. (2024). Hydroxyapatite Powders from Chicken Bone Waste: Effect of Low and High-Temperature Calcination. *International Journal of Integrated Engineering*, *16*(8), 236–245.

Abdelilleh, M., Ben Ticha, M., Kordoghli, B., Khiari, R., Meksi, N., & Dhaouadi, H. (2023). Dyeing of modified acrylic fibers with indigo carmine: Modeling and optimization of the dyeing process using a combination of rsm and ann methodologies. *Fibers and Polymers*, *24*(7), 2377–2389.

Abdulhameed, A. S., Wu, R., Reghioua, A., Mbuvi, H. M., Yaseen, Z. M., & Garba, Z. N. (2024). Activated carbon derived from rice husk biomass using pyrolysis-assisted tartaric acid activation for removal of reactive orange 16 dye: adsorption modeling using response surface methodology. *AUIQ Complementary Biological System*, *1*(1), 89–95.

Adegoke, K. A., Okon-Akan, O. A., Adebusuyi, T. A., Adewuyi, O. I., Adu, P. O., Bamisaye, A., Adegoke, O. R., Babarinde, C. O., & Bello, O. S. (2025). Adsorptive removal of gaseous contaminants using biomass-based adsorbents. *RSC advances*, *15*(18), 13960–13999.

Adeoye, J. B., Tan, Y. H., Lau, S. Y., Tan, Y. Y., Chiong, T., Mubarak, N. M., & Khalid, M. (2024). Advanced oxidation and biological integrated processes for pharmaceutical wastewater treatment: a review. *Journal of Environmental Management*, *353*, 120170.

Aggour, Y. A., Kenawy, E.-R., Magdy, M., & Elbayoumy, E. (2025). Multifunctional copolymers for brilliant green dye removal: adsorption kinetics, isotherm and process optimization. *Environmental Science: Advances*, *4*(5), 787–808.

Agha, H. M., Jawad, A. H., ALOthman, Z. A., & Wilson, L. D. (2025). Loading walnut shell powder into polymeric matrix of chitosan for enhanced cationic methyl violet 2B dye removal: Process optimization and adsorption mechanism. *International Journal of Biological Macromolecules*, *319*, 145208.

Ahmad, K. (2023). Feasibility of the adsorption as a process for its large scale adoption across industries for the treatment of wastewater: Research gaps and economic assessment. *Journal of Cleaner Production*, *388*, 136014.

Ahmad, N., Rahman, N. Z. A., & Vaiappuri, S. K. (2025). Advancing Sustainable Waste Management in Malaysia: Lessons from Southeast Asia.

Al-Ghurabi, E. H., Boumaza, M. M., Al-Masry, W., & Asif, M. (2025). Optimizing the synthesis of nanoporous activated carbon from date-palm waste for enhanced CO2 capture. *Scientific Reports*, *15*(1), 17132.

Al-Onazi, W. A., Ali, M. H., & Al-Garni, T. (2021). Using pomegranate peel and date pit activated carbon for the removal of cadmium and lead ions from aqueous solution. *Journal of Chemistry*, *2021*(1), 5514118.

Alardhi, S. M., Ali, N. S., Saady, N. M. C., Zendehboudi, S., Salih, I. K., Alrubaye, J. M., & Albayati, T. M. (2023). Separation techniques in different configurations of hybrid systems via synergetic adsorption and membrane processes for water treatment: a review. *Journal of Industrial and Engineering Chemistry*.

Alegbe, E. O., & Uthman, T. O. (2024). A review of history, properties, classification, applications and challenges of natural and synthetic dyes. *Heliyon*, *10*(13).

Alfred, R., Leikson, C., Boniface, B., Tanakinjal, G. H., Kamu, A., Kogid, M., Sondoh, S. L., Mohd Nawi, N., Arumugam, N., & Andrias, R. M. (2022). Modelling and

Forecasting Fresh Agro-food Commodity Consumption Per Capita in Malaysia using Machine Learning. *Mobile Information Systems*, *2022*(1), 6106557.

Alharbi, H. A., Hameed, B. H., Alotaibi, K. D., Al-Oud, S. S., & Al-Modaihsh, A. S. (2022). Recent methods in the production of activated carbon from date palm residues for the adsorption of textile dyes: A review. *Frontiers in Environmental Science*, *10*, 996953.

Ali, Nisreen S, Jabbar, N. M., Alardhi, S. M., Majdi, H. S., & Albayati, T. M. (2022). Adsorption of methyl violet dye onto a prepared bio-adsorbent from date seeds: isotherm, kinetics, and thermodynamic studies. *Heliyon*, *8*(8).

Ali, A., Chiang, Y. W., & Santos, R. M. (2022). X-ray diffraction techniques for mineral characterization: A review for engineers of the fundamentals, applications, and research directions. *Minerals*, *12*(2), 205.

Ali, R. M., Hamad, H. A., Hussein, M. M., & Malash, G. F. (2016). Potential of using green adsorbent of heavy metal removal from aqueous solutions: adsorption kinetics, isotherm, thermodynamic, mechanism and economic analysis. *Ecological Engineering*, *91*, 317–332.

Allgayer, R., Yousefi, N., & Tufenkji, N. (2020). Graphene oxide sponge as adsorbent for organic contaminants: comparison with granular activated carbon and influence of water chemistry. *Environmental Science: Nano*, *7*(9), 2669–2680.

Alsuhybani, M., Aleid, M., Alzidan, R., Bander, K. B., & Alrehaili, A. (2024). High removal of methylene blue and methyl violet dyes from aqueous solutions using efficient biomaterial byproduct. *Heliyon*, *10*(17).

Alvarez, J., Lopez, G., Amutio, M., Bilbao, J., & Olazar, M. (2015). Physical activation of rice husk pyrolysis char for the production of high surface area activated carbons. *Industrial & Engineering Chemistry Research*, *54*(29), 7241–7250.

Alzain, H., Kalimugogo, V., Hussein, K., & Karkadan, M. (2023). A review of environmental impact of azo dyes. *Int J Res Rev*, *10*(6), 673–689.

Amini, A., Latifi, M., & Chaouki, J. (2021). Electrification of materials processing via microwave irradiation: A review of mechanism and applications. *Applied Thermal Engineering*, *193*, 117003.

An, J.-H., & Dultz, S. (2007). Adsorption of tannic acid on chitosan-montmorillonite as a function of pH and surface charge properties. *Applied Clay Science*, *36*(4), 256–264.

Andas, J., & Jusoh, N. F. E. (2022). Converting waste chicken bones into heterogeneous catalyst for biodiesel synthesis from waste cooking oil. *Malaysian Journal of Analytical Sciences*, *26*(5), 1102–1111.

Angeles-Agdeppa, I., Toledo, M. B., & Zamora, J. A. T. (2023). Does plate waste matter?: A two-stage cluster survey to assess the household plate waste in the Philippines. *BMC Public Health*, *23*(1), 17.

Aragaw, T. A., & Bogale, F. M. (2023). Role of coagulation/flocculation as a pretreatment option to reduce colloidal/bio-colloidal fouling in tertiary filtration of textile wastewater: A review and future outlooks. *Frontiers in Environmental Science*, *11*, 1142227.

Ashrafi, S. D., Safari, G. H., Sharafi, K., Kamani, H., & Jaafari, J. (2021). Adsorption of 4-Nitrophenol on calcium alginate-multiwall carbon nanotube beads: Modeling, kinetics, equilibriums and reusability studies. *International Journal of Biological Macromolecules*, *185*, 66–76.

Ateia, M., Helbling, D. E., & Dichtel, W. R. (2020). Best practices for evaluating new materials as adsorbents for water treatment. *ACS Materials Letters*, *2*(11), 1532–1544.

Awang, H. F., Abdulhameed, A. S., Jawad, A. H., ALOthman, Z. A., & Wilson, L. D. (2023). A thermochemical treatment of food waste: Preparing activated carbon for optimized removal of methyl violet dye via the Box-Behnken design method. *Biomass Conversion and Biorefinery*, 1–12.

Awang, H. F., Jawad, A. H., Annuar, N., ALOthman, Z. A., & Wilson, L. D. (2024). Converting blended chicken bone and rice food wastes into activated carbon via microwave process: Box-benken optimization for methyl violet dye removal. *Water, Air, & Soil Pollution*, *235*(12), 764.

Bahrodin, M. B., Zaidi, N. S., Hussein, N., Sillanpää, M., Prasetyo, D. D., & Syafiuddin, A. (2021). Recent advances on coagulation-based treatment of wastewater: Transition from chemical to natural coagulant. *Current Pollution Reports*, *7*(3), 379–391.

Baig, U., Uddin, M. K., & Gondal, M. (2020). Removal of hazardous azo dye from water using synthetic nano adsorbent: Facile synthesis, characterization, adsorption, regeneration and design of experiments. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *584*, 124031.

Bakari, Z., Fichera, M., El Ghadraoui, A., Renai, L., Giurlani, W., Santianni, D., Fibbi, D., Bruzzoniti, M. C., & Del Bubba, M. (2024). Biochar from co-pyrolysis of biological sludge and woody waste followed by chemical and thermal activation: end-of-waste procedure for sludge management and biochar sorption efficiency for anionic and cationic dyes. *Environmental Science and Pollution Research*, *31*(24), 35249–35265.

Balan, I. M., Gherman, E. D., Brad, I., Gherman, R., Horablaga, A., & Trasca, T. I. (2022). Metabolic food waste as food insecurity factor—Causes and preventions. *Foods*, *11*(15), 2179.

Bandani, M., Najafi, M., Khalili, S., Jahanshahi, M., Peyravi, M., & Salmani, H. (2026). Preparation and characterization of low-cost chemically activated carbons using H3PO4, ZnCl2 and KOH for CO2 adsorption applications. *Scientific Reports*.

Benjelloun, M., Miyah, Y., Evrendilek, G. A., Lalami, A. E. O., Demir, I., Atmaca, B., Ssouni, S., Lairini, S., & Bouslamti, R. (2023). Synergistic effect of coupling ozonation/adsorption system for toxic dye efficient removal: chemometric optimization by Box–Behnken response surface methodology. *Desalination and Water Treatment*, *306*, 220–235.

Benkhaya, S., M'rabet, S., & El Harfi, A. (2025). Corrigendum to "Classifications, properties, recent synthesis and applications of azo dyes"[Heliyon Volume 6, Issue 1, January 2020, Article e03271]. *Heliyon*, *11*(16).

Bergslien, E. (2022). X-ray diffraction (XRD) evaluation of questioned cremains. *Forensic science international*, *332*, 111171.

Bernama. (2022). *National recycling rate rises to 33.2% in 2022*. The Malaysian Insight. Retrieved 30 April 2026 from https://www.themalaysianinsight.com/s/415344

Bian, H., Boguta, P., Huang, J., Deng, C., Kong, D., Zhou, H., & Su, X. (2024). Transforming organic solid waste management: embracing humification for sustainable resource recovery. *ACS Sustainable Resource Management*, *1*(2), 181–198.

Bonetto, L., Ferrarini, F., De Marco, C., Crespo, J., Guégan, R., & Giovanela, M. (2015). Removal of methyl violet 2B dye from aqueous solution using a magnetic composite as an adsorbent. *Journal of Water Process Engineering*, *6*, 11–20.

Brandner, L., & Müller, T. J. (2023). Multicomponent synthesis of chromophores–The

one-pot approach to functional π-systems. *Frontiers in Chemistry*, *11*, 1124209.

Bukva, M., Soares, L. C., Maia, L. C., Costa, C. S. D., & Gurgel, L. V. A. (2023). A review on the design and application of bi-functionalized adsorbents to remove different pollutants from water. *Journal of Water Process Engineering*, *53*, 103636.

Bunaciu, A. A., UdriŞTioiu, E. G., & Aboul-Enein, H. Y. (2015). X-ray diffraction: instrumentation and applications. *Critical reviews in analytical chemistry*, *45*(4), 289–299.

Chattoraj, D., & Freundlich, H. (1906). Over the adsorption in solution. *Journal of Physical Chemistry A*, *57*, 385–470.

Chemica, T. (2023). *What are the Classification of Dyes?* Tiankun Chemical. Retrieved 2 May 2026 from https://www.tiankunchemical.com/What-are-the-Classification-of-Dyes-id65996907.html

Chen, C., Chaudhary, A., & Mathys, A. (2020). Nutritional and environmental losses embedded in global food waste. *Resources, Conservation and Recycling*, *160*, 104912.

Conrad, Z. (2020). Daily cost of consumer food wasted, inedible, and consumed in the United States, 2001–2016. *Nutrition journal*, *19*, 1–9.

Contescu, C. I., Adhikari, S. P., Gallego, N. C., Evans, N. D., & Biss, B. E. (2018). Activated carbons derived from high-temperature pyrolysis of lignocellulosic biomass. *C*, *4*(3), 51.

Côrtes, L. N., Druzian, S. P., Streit, A. F. M., Sant'anna Cadaval Junior, T. R., Collazzo, G. C., & Dotto, G. L. (2019). Preparation of carbonaceous materials from pyrolysis of chicken bones and its application for fuchsine adsorption. *Environmental Science and Pollution Research*, *26*(28), 28574–28583.

Das, B., Dhara, H. N., Dahiya, A., & Patel, B. K. (2022). Recent advances in photocatalytic degradation of dyes using heterogeneous catalysts. *Trends and contemporary technologies for photocatalytic degradation of dyes*, 21–64.

Dehingia, B., Lahkar, R., & Kalita, H. (2024). Efficient removal of both cationic and anionic dyes from water using a single rGO/PSS nanocomposite membrane with superior permeability and high aqueous stability. *Journal of Environmental Chemical Engineering*, *12*(2), 112393.

Diao, K., & Ulanicki, B. (2025). Cutting-edge innovations in drinking water management. In (Vol. 74, pp. iii–iv): IWA Publishing.

Dinani, S. T., Hasić, M., Auer, M., & Kulozik, U. (2020). Assessment of uniformity of microwave-based heating profiles generated by solid-state and magnetron systems using various shapes of test samples. *Food and Bioproducts Processing*, *124*, 121–130.

Dobernig, K., & Schanes, K. (2019). Domestic spaces and beyond: Consumer food waste in the context of shopping and storing routines. *International Journal of Consumer Studies*, *43*(5), 480–489.

Duran, C., Ozdes, D., Gundogdu, A., & Senturk, H. B. (2011). Kinetics and isotherm analysis of basic dyes adsorption onto almond shell (Prunus dulcis) as a low cost adsorbent. *Journal of Chemical & Engineering Data*, *56*(5), 2136–2147.

Dutta, A. (2017). Fourier transform infrared spectroscopy. *Spectroscopic methods for nanomaterials characterization*, 73–93.

El-Ghobashy, M. A., Hashim, H., Darwish, M. A., Khandaker, M. U., Sulieman, A., Tamam, N., Trukhanov, S. V., Trukhanov, A. V., & Salem, M. A. (2022). Eco-friendly NiO/polydopamine nanocomposite for efficient removal of dyes from wastewater. *Nanomaterials*, *12*(7), 1103.

El-Khateeb, M. A., Ahmed, H. M., & Sobhy, N. A. (2022). Recycling of waste chicken bones for greywater pollutants removal. *Desalination and Water Treatment*, *265*, 124–133.

El Meziani, S., Agnaou, H., El Haddaj, H., Boumya, W., Barka, N., & Elhalil, A. (2025). Sustainable adsorption technologies for textile dye removal: advances in biomass-derived and magnetically modified activated carbons. *Cleaner Chemical Engineering*, 100210.

Ensano, B., Borea, L., Naddeo, V., Belgiorno, V., De Luna, M. D., & Ballesteros Jr, F. C. (2016). Combination of electrochemical processes with membrane bioreactors for wastewater treatment and fouling control: a review. *Frontiers in environmental science*, *4*, 210811.

Escalante, J., Chen, W.-H., Tabatabaei, M., Hoang, A. T., Kwon, E. E., Lin, K.-Y. A., & Saravanakumar, A. (2022). Pyrolysis of lignocellulosic, algal, plastic, and other biomass wastes for biofuel production and circular bioeconomy: A review of thermogravimetric analysis (TGA) approach. *Renewable and Sustainable Energy Reviews*, *169*, 112914.

Escobar, N., & Laibach, N. (2021). Sustainability check for bio-based technologies: A review of process-based and life cycle approaches. *Renewable and Sustainable Energy Reviews*, *135*, 110213.

Fiore, T., & Pellerito, C. (2021). Infrared absorption spectroscopy. *Spectroscopy for materials characterization*, 129–167.

Foroutan, R., Mohammadi, R., Ahmadi, A., Bikhabar, G., Babaei, F., & Ramavandi, B. (2022). Impact of ZnO and Fe3O4 magnetic nanoscale on the methyl violet 2B removal efficiency of the activated carbon oak wood. *Chemosphere*, *286*, 131632.

Foroutan, R., Peighambardoust, S. J., Mohammadi, R., Peighambardoust, S. H., & Ramavandi, B. (2022). Development of new magnetic adsorbent of walnut shell ash/starch/Fe3O4 for effective copper ions removal: treatment of groundwater samples. *Chemosphere*, *296*, 133978.

Gao, Y., Yue, Q., Gao, B., & Li, A. (2020). Insight into activated carbon from different kinds of chemical activating agents: A review. *Science of the Total Environment*, *746*, 141094.

GarGeon. (2026, 30 April 2026). Waste Management Malaysia: Complete Enterprise Guide 2026. https://gargeon.com/blog/waste-management-malaysia-enterprise-guid

Gayathiri, M., Pulingam, T., Lee, K., & Sudesh, K. (2022). Activated carbon from biomass waste precursors: Factors affecting production and adsorption mechanism. *Chemosphere*, *294*, 133764.

Geremew, B., & Zewde, D. (2022). Hagenia abyssinica leaf powder as a novel low-cost adsorbent for removal of methyl violet from aqueous solution: Optimization, isotherms, kinetics, and thermodynamic studies. *Environmental Technology & Innovation*, *28*, 102577.

Ghosh, J., & Rupanty, N. S. (2023). Study on a cationic agent-based salt-free reactive dyeing process for cotton knit fabric and comparison with a traditional dyeing process. *Heliyon*, *9*(9).

Godoy Bautista, R., Palomino Infante, R. A., Mendoza Rojas, C., Godoy Bautista, K., Woolcott Hurtado, J. C., Roman-Concha, U., & Gómez Ramírez, H. L. (2025). Enhancing Dye Removal Efficiency Through Sustainable Adsorbent Production from Corncobs (Zea mays L. ssp. amilacea). *Separations*, *12*(11), 322.

Goudjil, S., Guergazi, S., Ghernaout, D., Temim, D., & Masmoudi, T. (2024). Brilliant

green and methyl violet 2B dyes removal using aluminium sulfate (AS) in single and binary systems. *Desalination and Water Treatment*, *319*, 100539.

Guerrero-Pérez, M. O., & Patience, G. S. (2020). Experimental methods in chemical engineering: Fourier transform infrared spectroscopy—FTIR. *The Canadian journal of chemical engineering*, *98*(1), 25–33.

Hameed, B. (2008). Equilibrium and kinetic studies of methyl violet sorption by agricultural waste. *Journal of hazardous materials*, *154*(1-3), 204–212.

Hamzezadeh, A., Rashtbari, Y., Afshin, S., Morovati, M., & Vosoughi, M. (2022). Application of low-cost material for adsorption of dye from aqueous solution. *International Journal of Environmental Analytical Chemistry*, *102*(1), 254–269.

Hasan, H. A., & Muhammad, M. H. (2020). A review of biological drinking water treatment technologies for contaminants removal from polluted water resources. *Journal of Water Process Engineering*, *33*, 101035.

He, X., Chen, X., Wang, X., & Jiang, L. (2023). Optimization of activated carbon production from corn cob using response surface methodology. *Frontiers in Environmental Science*, *11*, 1105408.

Heidarinejad, Z., Dehghani, M. H., Heidari, M., Javedan, G., Ali, I., & Sillanpää, M. (2020). Methods for preparation and activation of activated carbon: a review. *Environmental Chemistry Letters*, *18*, 393–415.

Hermanussen, H., & Loy, J.-P. (2024). Household food waste: A meta-analysis. *Environmental Challenges*, *14*, 100809.

Hessien, M. (2022). Microwave-assisted hydrothermal carbonization of pomegranate peels into hydrochar for environmental applications. *Energies*, *15*(10), 3629.

Ho, Y.-S., & McKay, G. (1998). Sorption of dye from aqueous solution by peat. *Chemical Engineering Journal*, *70*(2), 115–124.

Ho, Y.-S., & McKay, G. (1999). Pseudo-second order model for sorption processes. *Process biochemistry*, *34*(5), 451–465.

Hoque, M., Oyshi, T., Hannan, M. A., Haque, P., Rahman, M. M., Shahid, M. A., & Sheikh, S. (2024). Unraveling the Ecological Footprint of Textile Dyes: A Growing Environmental Concern. Pollut. *Stud*, *5*(2), 3014.

Hossen, M. S., Islam, T., Hoque, S. M., Islam, A., Bashar, M. M., & Bhat, G. (2024). Synthesis, activation, and characterization of carbon fiber precursor derived from jute fiber. *ACS omega*, *9*(33), 35384–35393.

Hu, H., Wageh, S., Al-Ghamdi, A. A., Yang, S., Tian, Z., Cheng, B., & Ho, W. (2020). NiFe-LDH nanosheet/carbon fiber nanocomposite with enhanced anionic dye adsorption performance. *Applied Surface Science*, *511*, 145570.

Huang, X., Hadi, P., Joshi, R., Alhamzani, A. G., & Hsiao, B. S. (2023). A comparative study of mechanism and performance of anionic and cationic dialdehyde nanocelluloses for dye adsorption and separation. *ACS omega*, *8*(9), 8634–8649.

Hutagalung, S. S., Rafryanto, A. F., Sun, W., Juliasih, N., Aditia, S., Jiang, J., Arramel, Dipojono, H. K., Suhardi, S. H., & Rochman, N. T. (2023). Combination of ozone-based advanced oxidation process and nanobubbles generation toward textile wastewater recovery. *Frontiers in Environmental Science*, *11*, 1154739.

Iloamaeke, I. M., Atune, S. I., Onyeije, U. C., & Onuegbu, T. U. (2025). Optimization of coagulation-flocculation process for colour removal in purification of paint industry effluent using novel seed of Spondias mombin Linn. *Desalination and Water Treatment*, *323*, 101284.

Irwansyah, F. S., Amal, A. I., Diyanthi, E. W., Hadisantoso, E. P., Noviyanti, A. R., Eddy, D. R., & Risdiana, R. (2024). How to read and determine the specific surface area of inorganic materials using the Brunauer-Emmett-Teller (BET)

method. *ASEAN Journal of Science and Engineering*, *4*(1), 61–70.
Islam, M. M., Aidid, A. R., Mohshin, J. N., Mondal, H., Ganguli, S., & Chakraborty, A. K. (2025a). A critical review on textile dye-containing wastewater: Ecotoxicity, health risks, and remediation strategies for environmental safety. *Cleaner Chemical Engineering*, 100165.
Islam, M. M., Aidid, A. R., Mohshin, J. N., Mondal, H., Ganguli, S., & Chakraborty, A. K. (2025b). A critical review on textile dye-containing wastewater: Ecotoxicity, health risks, and remediation strategies for environmental safety. *Cleaner Chemical Engineering*, *11*, 100165.
Iwanow, M., Gärtner, T., Sieber, V., & König, B. (2020). Activated carbon as catalyst support: precursors, preparation, modification and characterization. *Beilstein Journal of Organic Chemistry*, *16*(1), 1188–1202.
Januszewicz, K., Kazimierski, P., Klein, M., Kardaś, D., & Łuczak, J. (2020). Activated carbon produced by pyrolysis of waste wood and straw for potential wastewater adsorption. *Materials*, *13*(9), 2047.
Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., Fallatah, O., & Kirchner, J. W. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. *Nature*, *625*(7996), 715–721.
Jawad, A. H., & Abdulhameed, A. S. (2020). Mesoporous Iraqi red kaolin clay as an efficient adsorbent for methylene blue dye: adsorption kinetic, isotherm and mechanism study. *Surfaces and Interfaces*, *18*, 100422.
Jawad, A. H., Abdulhameed, A. S., Wilson, L. D., Syed-Hassan, S. S. A., ALOthman, Z. A., & Khan, M. R. (2021). High surface area and mesoporous activated carbon from KOH-activated dragon fruit peels for methylene blue dye adsorption: optimization and mechanism study. *Chinese Journal of Chemical Engineering*, *32*, 281–290.
Jawad, A. H., Hameed, B., & Abdulhameed, A. S. (2023). Synthesis of biohybrid magnetic chitosan-polyvinyl alcohol/MgO nanocomposite blend for remazol brilliant blue R dye adsorption: solo and collective parametric optimization. *Polymer Bulletin*, *80*(5), 4927–4947.
Jawad, A. H., Rangabhashiyam, S., Abdulhameed, A. S., Syed-Hassan, S. S. A., ALOthman, Z. A., & Wilson, L. D. (2022). Process optimization and adsorptive mechanism for reactive blue 19 dye by magnetic crosslinked chitosan/MgO/Fe3O4 biocomposite. *Journal of Polymers and the Environment*, *30*(7), 2759–2773.
Jayaswal, K., Sahu, V., & Gurjar, B. (2018). Water pollution, human health and remediation. *Water remediation*, 11–27.
Jenkins, R. G. (2020). Thermal gasification of biomass—a primer. Bioenergy,
Jerzak, W., Acha, E., & Li, B. (2024). Comprehensive review of biomass pyrolysis: conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis. *Energies*, *17*(20), 5082.
Jiang, G., Wang, Z., Sun, Q., Zhu, C., Wu, N., Lu, X., Tang, W., & Zhu, J. (2026). Precision engineering of pore connectivity in tobacco stalk-derived carbons via component reconstruction for enhanced molecular accessibility and dye adsorption. *Sustainable Materials and Technologies*, e02133.
Junaid Ibrahim, M. C., and Rahimy Rahim. (2024). Malaysia facing rising solid waste production, says Nga. https://www.thestar.com.my/news/nation/2024/12/05/malaysia-facing-rising-solid-waste-production-says-ng
Kanwal, N., Zhang, M., Zeb, M., Batool, U., & Rui, L. (2024). From plate to palate:

Sustainable solutions for upcycling food waste in restaurants and catering. *Trends in Food Science & Technology*, *152*, 104687.

Karimifard, S., & Moghaddam, M. R. A. (2018). Application of response surface methodology in physicochemical removal of dyes from wastewater: a critical review. *Science of the Total Environment*, *640*, 772–797.

Kazmierczak-Razna, J., Gralak-Podemska, B., Nowicki, P., & Pietrzak, R. (2015). The use of microwave radiation for obtaining activated carbons from sawdust and their potential application in removal of NO2 and H2S. *Chemical Engineering Journal*, *269*, 352–358.

Khalidi-Idrissi, A., Madinzi, A., Anouzla, A., Pala, A., Mouhir, L., Kadmi, Y., & Souabi, S. (2023). Recent advances in the biological treatment of wastewater rich in emerging pollutants produced by pharmaceutical industrial discharges. *International Journal of Environmental Science and Technology*, *20*(10), 11719–11740.

Khan, H., Yerramilli, A. S., D'Oliveira, A., Alford, T. L., Boffito, D. C., & Patience, G. S. (2020). Experimental methods in chemical engineering: X-ray diffraction spectroscopy—XRD. *The Canadian journal of chemical engineering*, *98*(6), 1255–1266.

Khan, I. A., Khan, A. U., Butt, M. S., Janjua, H. A., Uddin, E., Deen, K. M., Sadiq, R., & Ahmad, N. M. (2025). Dye Removal from Contaminated Water Through PES Membranes Enhanced with the Incorporation of Switchable Polyacrylic Acid Grafted on Graphene Oxide. *ACS omega*, *10*(26), 28178–28190.

Kim, Y., Bae, J., Park, H., Suh, J.-K., You, Y.-W., & Choi, H. (2016). Adsorption dynamics of methyl violet onto granulated mesoporous carbon: Facile synthesis and adsorption kinetics. *Water Research*, *101*, 187–194.

Kooh, M. R. R., Lim, L. B., Lim, L.-H., & Malik, O. A. (2018). Phytoextraction potential of water fern (Azolla pinnata) in the removal of a hazardous dye, methyl violet 2B: artificial neural network modelling. *International journal of phytoremediation*, *20*(5), 424–431.

Kumar, A., Ramamoorthy, D., Kumar, N., & Chandra, P. (2023). Food waste conversion into value-added products: different pathways, current challenges, and opportunities. *Bio-based materials and waste for energy generation and resource management*, 387–409.

Kuppusamy, B., Mohamed Ismail, F. R., Balakrishnan, P., Kim, S.-C., Asrafali, S. P., & Periyasamy, T. (2026). From Biomass to Adsorbent: A Comprehensive Review on Bio-Derived Carbons for Dye Removal. *Polymers*, *18*(2), 180.

Kutluay, S., & Temel, F. (2021). Silica gel based new adsorbent having enhanced VOC dynamic adsorption/desorption performance. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *609*, 125848.

Lagergren, S. (1898). Zur theorie der sogenannten adsorption geloster stoffe.

Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical society*, *40*(9), 1361–1403.

Latif, W., Ciniglia, C., Iovinella, M., Shafiq, M., & Papa, S. (2023). Role of white rot fungi in industrial wastewater treatment: a review. *Applied Sciences*, *13*(14), 8318.

Lee, J.-Y., Lee, B.-H., Chung, D.-C., & Kim, B.-J. (2023). CO2 adsorption behaviors of biomass-based activated carbons prepared by a microwave/steam activation technique for molecular sieve. *Materials*, *16*(16), 5625.

Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., Jiang, S., Li, H., & Huang, H. (2021). An overview on engineering the surface area and porosity of biochar.

Science of the Total Environment, *763*, 144204.

Lewczuk, B., & Szyryńska, N. (2021). Field-emission scanning electron microscope as a tool for large-area and large-volume ultrastructural studies. *Animals*, *11*(12), 3390.

Lewoyehu, M. (2021). Comprehensive review on synthesis and application of activated carbon from agricultural residues for the remediation of venomous pollutants in wastewater. *Journal of Analytical and Applied pyrolysis*, *159*, 105279.

Lin, J., Ye, W., Xie, M., Seo, D. H., Luo, J., Wan, Y., & Van der Bruggen, B. (2023). Environmental impacts and remediation of dye-containing wastewater. *Nature Reviews Earth & Environment*, *4*(11), 785–803.

Lin, L., Yang, H., & Xu, X. (2022). Effects of water pollution on human health and disease heterogeneity: a review. *Frontiers in Environmental Science*, *10*, 880246.

López-Pérez, L., Zarubina, V., & Melián-Cabrera, I. (2021). The Brunauer–Emmett–Teller model on alumino-silicate mesoporous materials. How far is it from the true surface area? *Microporous and mesoporous materials*, *319*, 111065.

Ma, D., Yi, H., Lai, C., Liu, X., Huo, X., An, Z., Li, L., Fu, Y., Li, B., & Zhang, M. (2021). Critical review of advanced oxidation processes in organic wastewater treatment. *Chemosphere*, *275*, 130104.

Maalouf, A., & Agamuthu, P. (2023). Waste management evolution in the last five decades in developing countries–A review. *Waste Management & Research*, *41*(9), 1420–1434.

Maezono, T., Tokumura, M., Sekine, M., & Kawase, Y. (2011). Hydroxyl radical concentration profile in photo-Fenton oxidation process: generation and consumption of hydroxyl radicals during the discoloration of azo-dye Orange II. *Chemosphere*, *82*(10), 1422–1430.

Mail, M. (2025, April 30, 2026). From trash to treasure: What is Malaysia doing with its waste? https://www.malaymail.com/news/malaysia/2025/03/03/from-trash-to-treasure-what-is-malaysia-doing-with-its-waste/167831

Mandal, P., Dubey, B. K., & Gupta, A. K. (2017). Review on landfill leachate treatment by electrochemical oxidation: Drawbacks, challenges and future scope. *Waste Management*, *69*, 250–273.

Mansoorian, H. J., Bazrafshan, E., Yari, A., & Alizadeh, M. (2014). Removal of azo dyes from aqueous solution using Fenton and modified Fenton processes. *Health Scope*, *3*(2), e15507.

Mehr, H., Saffari, J., Mohammadi, S., & Shojaei, S. (2020). The removal of methyl violet 2B dye using palm kernel activated carbon: thermodynamic and kinetics model. *International Journal of Environmental Science and Technology*, *17*(3), 1773–1782.

Méndez-Lozano, N., Apátiga-Castro, M., Pérez-Ramírez, E. E., de la Luz-Asunción, M., Soto, K. M., Manzano-Ramírez, A., & de Jesús Ruíz-Baltazar, Á. (2025). Efficient degradation of methylene blue using titanium-substituted hydroxyapatite for water purification. *Results in Chemistry*, *15*, 102197.

Meti, B. S., Kulkarni, S. R., Jigajinni, S. K., & Nainegali, B. (2024). Food Industry By-Products and Waste Management. In *Frontiers in Food Biotechnology* (pp. 229–247). Springer.

MIDA. (2025). *Turning Waste into Wealth: Malaysia's Circular Economy in Action*. Malaysian Investment Development Authority (MIDA). Retrieved 30 April 2026 from https://www.mida.gov.my/turning-waste-into-wealth-malaysias-circular-economy-in-action/

Moges, A., Nkambule, T. T., & Fito, J. (2022). The application of GO-Fe3O4 nanocomposite for chromium adsorption from tannery industry wastewater. *Journal of Environmental Management*, *305*, 114369.

Moghaddam, A. H., & Esfandyari, M. (2025). Optimization of separation and purification processes in diethyl ether production for improved efficiency and sustainability. *Scientific Reports*, *15*(1), 27911.

Mohammad Sabri, N.-S., Mahyudin, N. A., Abdullah Sani, M. S., Han, M. G., Chong, K. H., Padmanabhan, K., Shan, J., & Mahmud Ab Rashid, N. K. (2024). Microbial populations, sensory, and volatile compounds profiling of local cooked rice. *Food Quality and Safety*, *8*, fyad065.

Mohd Radhuwan, S. N., Abdulhameed, A. S., Jawad, A. H., ALOthman, Z. A., Wilson, L. D., & Algburi, S. (2024). Production of activated carbon from food wastes (chicken bones and rice waste) by microwave assisted ZnCl2 activation: An optimized process for crystal violet dye removal. *International journal of phytoremediation*, *26*(5), 699–709.

Moteallemi, A., Dehghani, M. H., Momeniha, F., & Azizi, S. (2024). Nanoplastics as emerging contaminants: A systematic review of analytical processes, removal strategies from water environments, challenges and perspective. *Microchemical Journal*, *207*, 111884.

Nandi, R., Jha, M. K., Guchhait, S. K., Sutradhar, D., & Yadav, S. (2023). Impact of KOH activation on rice husk derived porous activated carbon for carbon capture at flue gas alike temperatures with high CO2/N2 selectivity. *ACS omega*, *8*(5), 4802–4812.

Natarajan, E., & Ponnaiah, G. P. (2017). Optimization of process parameters for the decolorization of Reactive Blue 235 dye by barium alginate immobilized iron nanoparticles synthesized from aluminum industry waste. *Environmental Nanotechnology, Monitoring & Management*, *7*, 73–88.

Nayak, J. (2022). Photo (Catalytic) Oxidation Processes for the Removal of Dye: Focusing on TiO2 Performance. In *Advanced Oxidation Processes in Dye-Containing Wastewater: Volume 1* (pp. 75–90). Springer.

Ndoye, M., Faye, M., Kane, C., Diop, A., & Diop, M. C. G. (2023). Removal of Methyl Violet in Aqueous Solution on Activated Carbon Based on Saba senegalensis Shell Residues. *Journal of Geoscience and Environment Protection*, *11*(5), 197–208.

Ngeno, E. C., Mbuci, K. E., Necibi, M. C., Shikuku, V. O., Olisah, C., Ongulu, R., Matovu, H., Ssebugere, P., Abushaban, A., & Sillanpää, M. (2022). Sustainable re-utilization of waste materials as adsorbents for water and wastewater treatment in Africa: Recent studies, research gaps, and way forward for emerging economies. *Environmental Advances*, *9*, 100282.

Nishat, A., Yusuf, M., Qadir, A., Ezaier, Y., Vambol, V., Ijaz Khan, M., Ben Moussa, S., Kamyab, H., Sehgal, S. S., & Prakash, C. (2023). Wastewater treatment: a short assessment on available techniques. *Alexandria Engineering Journal*, *76*, 505–516.

Noraida Binti, M., Mohamad Hasnan Ahmad, M. H. A., Azli Baharudin@ Shaharudin, A. B. S., Balkish Mahadir Naidu, B. M. N., Ying ChanYing, Y. C., & Hj Tahir Aris, H. T. A. (2018). Food choices among Malaysian adults: findings from Malaysian Adults Nutrition Survey (MANS) 2003 and MANS 2014.

Normi, N. I., Abdulhameed, A. S., Jawad, A. H., Surip, S., Razuan, R., & Ibrahim, M. L. (2023). Hydrothermal-assisted grafting of Schiff base chitosan by salicylaldehyde for adsorptive removal of acidic dye: statistical modeling and

adsorption mechanism. *Journal of Polymers and the Environment*, *31*(5), 1925–1937.

Ojo, D. T., Amuda, O. S., Salam, K. K., Oyediran, O. F., & Yekini, B. B. (2025). Preparation and characterization of steam-activated and green alkali-activated carbon from coconut shells. *Next Nanotechnology*, *8*, 100198.

Olugbenga, O. S., Adeleye, P. G., Oladipupo, S. B., Adeleye, A. T., & John, K. I. (2024). Biomass-derived biochar in wastewater treatment-a circular economy approach. *Waste Management Bulletin*, *1*(4), 1–14.

Oros, A. (2025). Bioaccumulation and trophic transfer of heavy metals in marine fish: Ecological and ecosystem-level impacts. *Journal of Xenobiotics*, *15*(2), 59.

Osterrieth, J. W., Rampersad, J., Madden, D., Rampal, N., Skoric, L., Connolly, B., Allendorf, M. D., Stavila, V., Snider, J. L., & Ameloot, R. (2022). How reproducible are surface areas calculated from the BET equation? *Advanced Materials*, *34*(27), 2201502.

Othmani, A., John, J., Rajendran, H., Mansouri, A., Sillanpää, M., & Chellam, P. V. (2021). Biochar and activated carbon derivatives of lignocellulosic fibers towards adsorptive removal of pollutants from aqueous systems: Critical study and future insight. *Separation and Purification Technology*, *274*, 119062.

Pan, Y., Huang, P., Xue, Z., Wang, X., Zhou, Y., & Huang, Q. (2022). The effect of the secondary reactions on volatile composition during the pyrolysis treatment of scrap tires. *Environmental Technology*, *43*(26), 4054–4065.

Parida, V. K., Singh, N., Priyadarshini, M., Kumari, P., Datta, D., & Tambi, A. (2025). Insights into the synthetic dye contamination in textile wastewater: Impacts on aquatic ecosystems and human health, and eco-friendly remediation strategies for environmental sustainability. *Journal of Industrial and Engineering Chemistry*.

Pellenz, L., de Oliveira, C. R. S., da Silva Júnior, A. H., da Silva, L. J. S., da Silva, L., de Souza, A. A. U., Ulson, S. M. d. A. G., Borba, F. H., & da Silva, A. (2023). A comprehensive guide for characterization of adsorbent materials. *Separation and Purification Technology*, *305*, 122435.

Pundir, A., Thakur, M. S., Prakash, S., Kumari, N., Sharma, N., Parameswari, E., He, Z., Nam, S., Thakur, M., & Puri, S. (2024). Fungi as versatile biocatalytic tool for treatment of textile wastewater effluents. *Environmental Sciences Europe*, *36*(1), 185.

Qiuchen, Z., Ping, Z., & Xiqiang, Z. (2025). Challenges and opportunities of microwave technology in hydrogen production, storage and utilization: A review. *International Journal of Hydrogen Energy*, *134*, 283–298.

Rashid, R., Shafiq, I., Akhter, P., Iqbal, M. J., & Hussain, M. (2021). A state-of-the-art review on wastewater treatment techniques: the effectiveness of adsorption method. *Environmental Science and Pollution Research*, *28*, 9050–9066.

Rathi, B. S., & Kumar, P. S. (2021). Application of adsorption process for effective removal of emerging contaminants from water and wastewater. *Environmental Pollution*, *280*, 116995.

Razali, N. S. A., Ahmed Saud, Jawad, A. H., ALOthman, Z. A., Yousef, T. A., Al-Duaij, O. K., & Alsaiari, N. S. (2022). High-surface-area-activated carbon derived from mango peels and seeds wastes via microwave-induced ZnCl2 activation for adsorption of methylene blue dye molecules: statistical optimization and mechanism. *Molecules*, *27*(20), 6947.

Reccessary. (2024). *Malaysian government releases first solid waste circular economy blueprint*. Reccessary. Retrieved 30 April 2026 from

https://www.reccessary.com/en/news/malaysia-waste-circular-economy
Reichenbach, C., Enke, D., Möllmer, J., Klank, D., Klauck, M., & Kalies, G. (2013). Slow gas uptake and low pressure hysteresis on nanoporous glasses: The influence of equilibration time and particle size. *Microporous and mesoporous materials*, *181*, 68–73.
Ren, W., Li, C., Fan, M., Zhou, D., Li, Q., & Hu, X. (2024). One-step microwave pyrolysis-H3PO4 activation of woody biomass: Insight into the product characteristics and life cycle assessment. *Journal of Environmental Chemical Engineering*, *12*(6), 114310.
Riedel, J., Dierker, L., Kwame, A. E., Wagner, K. N., Unterholzner, J. J., Dirks, J. H., & Brüggemann, D. (2026). Advancing research on biomaterials and biological materials with scanning electron microscopy under environmental and low vacuum conditions. *Advanced Engineering Materials*, *28*(7), e202502218.
Saba, B., Bharathidasan, A. K., Ezeji, T. C., & Cornish, K. (2023). Characterization and potential valorization of industrial food processing wastes. *Science of the Total Environment*, *868*, 161550.
Safarzadeh, H., Peighambardoust, S. J., Mousavi, S. H., Mohammadi, R., & Peighambardoust, S. H. (2022). Adsorption of methyl violet dye from wastewater using poly (methacrylic acid-co-acrylamide)/bentonite nanocomposite hydrogels. *Journal of Polymer Research*, *29*(4), 113.
SAHARUDDIN, N. I., NASSIR, M., Shah, A. Z. M., SAHARUDDIN, T. S. T., ABD RAHMAN, N. J., & Yahya, S. (2025). Catalytic transesterification of waste cooking oil using Fe-modified chicken bone catalyst: Characterization and optimization. *Sains Malaysiana*, *54*(2), 493–504.
Sahoo, J. K., Hota, A., Singh, C., Barik, S., Sahu, N., Sahoo, S. K., Sahu, M. K., & Sahoo, H. (2023). Rice husk and rice straw based materials for toxic metals and dyes removal: A comprehensive and critical review. *International Journal of Environmental Analytical Chemistry*, *103*(20), 9131–9153.
Samsami, S., Mohamadizaniani, M., Sarrafzadeh, M.-H., Rene, E. R., & Firoozbahr, M. (2020). Recent advances in the treatment of dye-containing wastewater from textile industries: Overview and perspectives. *Process safety and environmental protection*, *143*, 138–163.
Satyam, S., & Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. *Heliyon*, *10*(9).
Selangor, M. (2022). National recycling rate rises to 33.17 pct. https://mediaselangor.com/en/2022/12/147098
Shah, A., Arjunan, A., Baroutaji, A., & Zakharova, J. (2023). A review of physicochemical and biological contaminants in drinking water and their impacts on human health. *Water Science and Engineering*, *16*(4), 333–344.
Shamsabadi, A. S., Bazarganipour, M., & Tavanai, H. (2021). An investigation on the pore characteristics of dates stone based microwave activated carbon nanostructures. *Diamond and Related Materials*, *120*, 108662.
Shamshad, J., & Rehman, R. U. (2025). Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies. *Environmental Science: Advances*.
Sharma, M. D., Mishra, P., Ali, A., Kumar, P., Kapil, P., Grover, R., Verma, R., Saini, A., & Kulshrestha, S. (2023). Microbial waterborne diseases in India: status, interventions, and future perspectives. *Current microbiology*, *80*(12), 400.
Shen, X., Ma, C., Wang, Y., Liu, X., Wang, B., Fu, Y., Zhang, G., Yang, Y., & Zhang, N. (2025). Research progress on rice starch retrogradation: Insights into

mechanism, influencing factors, detection technology and regulatory approaches. *International Journal of Biological Macromolecules*, *319*, 145452.
Shi, T.-T., Jiang, X.-Y., & Yu, J.-G. (2023). Efficient and selective removal of organic cationic dyes by peel of Brassica juncea Coss. var. gemmifera Lee et Lin-Based Biochar. *Molecules*, *28*(8), 3353.
Sing, K. S. (1985). Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity (Recommendations 1984). *Pure and applied chemistry*, *57*(4), 603–619.
Sing, K. S., & Williams, R. T. (2004). Physisorption hysteresis loops and the characterization of nanoporous materials. *Adsorption Science & Technology*, *22*(10), 773–782.
Singh, B. J., Chakraborty, A., & Sehgal, R. (2023). A systematic review of industrial wastewater management: Evaluating challenges and enablers. *Journal of Environmental Management*, *348*, 119230.
Soleimani, H., Yusuf, J. Y., Soleimani, H., Chuan, L. K., & Sabet, M. (2022). Banana-peel derived activated carbon for microwave absorption at X-band frequency. *Synthesis and Sintering*, *2*(3), 120–124.
Stavropoulos, G., & Zabaniotou, A. (2009). Minimizing activated carbons production cost. *Fuel processing technology*, *90*(7-8), 952–957.
Suriapparao, D. V., & Vinu, R. (2021). Recovery of renewable carbon resources from the household kitchen waste via char induced microwave pyrolysis. *Renewable Energy*, *179*, 370–378.
Tan, Z., Li, Y., Chen, F., Liu, J., Zhong, J., Guo, L., Zhang, R., & Chen, R. (2024). Challenges and perspectives of the conversion of lignin waste to high-value chemicals by pyrolysis. *Processes*, *12*(3), 589.
Tang, K. H. D. (2024). Valorization of organic waste as biosorbents for wastewater treatment. *Water Emerging Contaminants & Nanoplastics*, *3*(4), N/A–N/A.
Taricska, J. R., Taricska, J. M., Hung, Y.-T., & Wang, L. K. (2017). Restaurant waste treatment and management. In *Waste Treatment in the Service and Utility Industries* (pp. 183–206). CRC Press.
Temkin, M. (1940). Kinetics of ammonia synthesis on promoted iron catalysts. *Acta physiochim. URSS*, *12*, 327–356.
Tomul, F., Arslan, Y., Kabak, B., Trak, D., & Tran, H. N. (2021). Adsorption process of naproxen onto peanut shell-derived biosorbent: important role of n–π interaction and van der Waals force. *Journal of Chemical Technology & Biotechnology*, *96*(4), 869–880.
Torres-Herrador, F., Eschenbacher, A., Blondeau, J., Magin, T. E., & Van Geem, K. M. (2022). Study of the degradation of epoxy resins used in spacecraft components by thermogravimetry and fast pyrolysis. *Journal of Analytical and Applied pyrolysis*, *161*, 105397.
Tyagi, U., & Anand, N. (2024). Sustainable and low-cost biomass derived adsorbents for the removal of toxic contaminants from wastewater: Approaches and future perspective. *Waste Management Bulletin*, *2*(2), 308–325.
Ungureanu, N., Vlăduț, N.-V., Biriș, S.-Ș., Gheorghiță, N.-E., & Ionescu, M. (2025). Biomass pyrolysis pathways for renewable energy and sustainable resource recovery: a critical review of processes, parameters, and product valorization. *Sustainability*, *17*(17), 7806.
Vega, M., Díaz-Faes, E., & Barriocanal, C. (2024). Kinetic and mechanistic study of CO2 adsorption on activated hydrochars. *Journal of CO2 Utilization*, *81*, 102716.

Villota, E. M., Lei, H., Qian, M., Yang, Z., Villota, S. M. A., Zhang, Y., & Yadavalli, G. (2018). Optimizing microwave-assisted pyrolysis of phosphoric acid-activated biomass: impact of concentration on heating rate and carbonization time. *ACS sustainable chemistry & engineering*, *6*(1), 1318–1326.

Vinayagam, R., Pai, S., Murugesan, G., Varadavenkatesan, T., Kaviyarasu, K., & Selvaraj, R. (2022). Green synthesized hydroxyapatite nanoadsorbent for the adsorptive removal of AB113 dye for environmental applications. *Environmental research*, *212*, 113274.

Vu, A. N., Nguyen, L. H., Tran, H.-C. V., Yoshimura, K., Tran, T. D., Van Le, H., & Nguyen, N.-U. T. (2024). Cellulose nanocrystals extracted from rice husk using the formic/peroxyformic acid process: isolation and structural characterization. *RSC advances*, *14*(3), 2048–2060.

Wang, B., Lan, J., Bo, C., Gong, B., & Ou, J. (2023). Adsorption of heavy metal onto biomass-derived activated carbon. *RSC advances*, *13*(7), 4275–4302.

Wang, H., Xu, J., Liu, X., & Sheng, L. (2021). Preparation of straw activated carbon and its application in wastewater treatment: A review. *Journal of Cleaner Production*, *283*, 124671.

Wang, M., Bodirsky, B. L., Rijneveld, R., Beier, F., Bak, M. P., Batool, M., Droppers, B., Popp, A., van Vliet, M. T., & Strokal, M. (2024). A triple increase in global river basins with water scarcity due to future pollution. *Nature Communications*, *15*(1), 880.

Wei, S., & Kamali, A. R. (2021). Waste plastic derived Co3Fe7/CoFe2O4@ carbon magnetic nanostructures for efficient dye adsorption. *Journal of Alloys and Compounds*, *886*, 161201.

Workman Jr, J. (2026). Lucidity and Light: The Spectroscopic Legacy of E. Bright Wilson, Jr. *Spectroscopy*, *41*(1).

Wu, X., Zeng, X., Lyu, X., Gao, B., Sun, Y., & Wu, J. (2022). Combined effects of Fe/Al oxyhydroxide coating and pH on polystyrene nanoplastic transport in saturated sand media. *Water, Air, & Soil Pollution*, *233*(1), 2.

Xiao, J., Guo, S., Wang, D., & An, Q. (2024). Fenton-like reaction: recent advances and new trends. *Chemistry–A European Journal*, *30*(24), e202304337.

Xue, H., Wang, X., Xu, Q., Dhaouadi, F., Sellaoui, L., Seliem, M. K., Lamine, A. B., Belmabrouk, H., Bajahzar, A., & Bonilla-Petriciolet, A. (2022). Adsorption of methylene blue from aqueous solution on activated carbons and composite prepared from an agricultural waste biomass: A comparative study by experimental and advanced modeling analysis. *Chemical Engineering Journal*, *430*, 132801.

Xue, Y., Zhou, Y., Liu, J., Xiao, Y., & Wang, T. (2021). Comparative analysis for pyrolysis of sewage sludge in tube reactor heated by electromagnetic induction and electrical resistance furnace. *Waste Management*, *120*, 513–521.

Yang, Ran, Fathy, A. E., Morgan, M. T., & Chen, J. (2022). Development of a complementary-frequency strategy to improve microwave heating of gellan gel in a solid-state system. *Journal of Food Engineering*, *314*, 110763.

Yang, J. L., Zhao, X. X., Ma, M. Y., Liu, Y., Zhang, J. P., & Wu, X. L. (2022). Progress and prospect on the recycling of spent lithium-ion batteries: Ending is beginning. *Carbon Neutralization*, *1*(3), 247–266.

Yang, S. H., Choong, L. W., Mazlan, A. N., & Sorhana, T. S. (2025
). Lessons from developed and developing countries in the EU and Asia: MALAYSIA. *SWITCH-Asia Publication*.

Yatoo, A. M., Hamid, B., Sheikh, T. A., Ali, S., Bhat, S. A., Ramola, S., Ali, M. N.,

Baba, Z. A., & Kumar, S. (2024). Global perspective of municipal solid waste and landfill leachate: generation, composition, eco-toxicity, and sustainable management strategies. *Environmental Science and Pollution Research*, *31*(16), 23363–23392.

Yoğun, K., & Yıldırım, N. (2025). Research and Conceptual Landscape of Food Waste and Business Models in the Context of the Circular Economy: A Literature Review at the Intersection of SDG 2–Zero Hunger and SDG 12–Responsible Consumption And Production. *Journal of Lifestyle and SDGs Review*, *5*(1), e04757–e04757.

Zaman, C. Z., Pal, K., Yehye, W. A., Sagadevan, S., Shah, S. T., Adebisi, G. A., Marliana, E., Rafique, R. F., & Johan, R. B. (2017). Pyrolysis: a sustainable way to generate energy from waste. *Pyrolysis*, *1*, 3–36.

Zhang, C., Huang, H., Guo, W., Ma, T., & Deng, Y. (2021). Encapsulation of methyl violet dyes with polystyrene using double miniemulsion technique. *Materials Express*, *11*(2), 174–180.

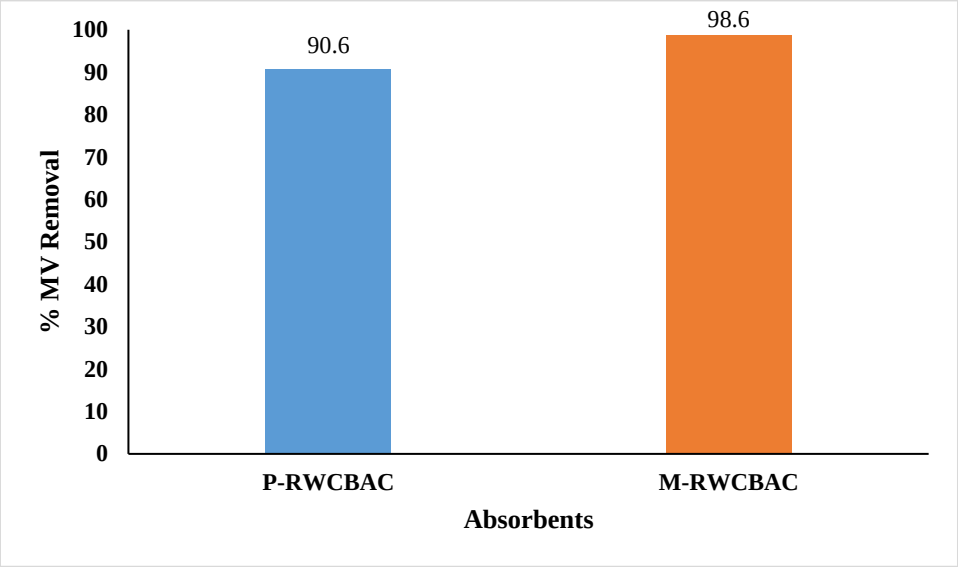
Zheng, M., Sun, Y., Li, C., Lu, Y., Dai, Y., & Wang, Z. (2023). A novel and eco-friendly approach for dyeing polyester fabrics by liquid disperse dyes treated with deep eutectic solvent. *Coloration Technology*, *139*(5), 552–564.

Zhou, D., Li, D., Li, A., Qi, M., Cui, D., Wang, H., & Wei, H. (2021). Activated carbons prepared via reflux-microwave-assisted activation approach with high adsorption capability for methylene blue. *Journal of Environmental Chemical Engineering*, *9*(1), 104671.

APPENDICES

APPENDIX 1

% Methyl Violet Removal



APPENDIX 2

Summary

Analysis	**P-RWCBAC**	**M-RWCBAC**
BET surface area (m^2/g)	369.32	83.3
Langmuir surface area (m^2/g)	691.8	192
Total volume in pores (cm^3/g)	0.31	0.11
Pore Diameter (nm)	4.76	6.57
Kinetic	PSO	PSO
Isotherm	Langmuir	Langmuir
q_{max}	88.4	126.8

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LIST OF PUBLICATION:

1. Awang, H. F., Abdulhameed, A. S., Jawad, A. H., ALOthman, Z. A., & Wilson, L. D. (2024). A thermochemical treatment of food waste: Preparing activated carbon for optimized removal of methyl violet dye via the Box-Behnken design method. Biomass Conversion and Biorefinery, 14(23), 30343–30354.
2. Awang, H. F., Jawad, A. H., Annuar, N., ALOthman, Z. A., & Wilson, L. D. (2024). Converting blended chicken bone and rice food wastes into activated carbon via microwave process: Box-benken optimization for methyl violet dye removal. Water, Air, & Soil Pollution, 235(12), 764.
3. Deris, R. R. R., Jawad, A. H., Mohammad Rudy, A. A., Awang, H. F., ALOthman, Z. A., & Wilson, L. D. (2026). Feasible synthesis of sulphonated hydrochar from guava peel via hydrothermal carbonisation: modelling and statistical optimisation for methylene blue dye removal. International Journal of Environmental Analytical Chemistry, 106(7), 1539–1561.
4. Jawad, A. H., Awang, H. F., Wu, R., & ALOthman, Z. A. (2025). A circular economy approach in converting food (chicken rice) waste into activated carbon

for optimise removal of methyl violet dye by Box-Behnken Design. Indian Chemical Engineer, 1–20.

5. Jawad, A. H., Nafi, M. M., Awang, H. F., Wilson, L. D., & ALOthman, Z. A. (2025). Numerical parametric optimization with desirability functions for methylene blue dye removal by sunflower seed pericarp activated carbon. Biomass Conversion and Biorefinery, 15(7), 11135–11149.
6. Raja Derisa, R. R., Awang, H. F., Hakim Azman, M., Rashid, I. N. H. A., Hapiz, A., Wu, R., Reghioua, A., Yaseen, Z. M., & Wilson, L. D. (2025). Thermal carbonization of biomass wood dust and algae wastes via microwave-assisted H 3 PO 4: Desirability function and statistical optimization. AUIQ Complementary Biological System, 2(1), 60–76.
7. Razuan, R., Jawad, A. H., Adriana, A., Awang, H. F., ALOthman, Z. A., & Wilson, L. D. (2026). Mesoporous Sulfonated Hydrochar from Garcinia Mangostana L Peel for Fast and Effective Methylene Blue Dye Removal: Hydrothermal Activation and Adsorption Statistical Optimization. Water, Air, & Soil Pollution, 237(8), 453.

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CONVERTING BLENDED CHICKEN BONE AND RICE FOOD WASTES INTO ACTIVATED CARBON VIA MICROWAVE PROCESS: BOX-BENKEN OPTIMIZATION FOR METHYL VIOLET DYE REMOVAL

at the

2nd SDG INNOVATION

22 September 2025

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for the paper entitled
A THERMOCHEMICAL TREATMENT OF FOOD WASTE: PREPARING ACTIVATED CARBON FOR OPTIMIZED REMOVAL OF METHYL VIOLET DYE VIA THE BOX-BEHNKEN DESIGN METHOD
ASSOC. PROF. DR. NUR HISHAM IBRAHIM, PMP
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