Preparation of Magnetically Separable and Beetroot Activated *Parthenium* Biochar for Efficient Removal of Brilliant Green Dye from Water

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AUTHOR'S DECLARATION

I, Muhammad Maaz, hereby declare that the work presented in the following thesis is my own effort and the material contained in this thesis is original. I have not previously presented any part of this work elsewhere for any other degree.

Muhammad Maaz

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It is to certify that the research work presented in this thesis, entitled "Preparation of Magnetically Separable and Beetroot Activated *Parthenium* Biochar for Efficient Removal of Brilliant Green Dye from Water" was conducted by **Mr. Muhammad Maaz (Reg. No. 02312113012)** under the supervision of **Dr. Jamshaid Rashid.** No part of this thesis has been submitted else for any other degree. This thesis is submitted to the **Department of Environmental Sciences,** in the partial fulfillment of the requirements for the degree of **Master of Philosophy in the field of Environmental Sciences,** Department of Environmental Sciences, Quaid-i-Azam University Islamabad, Pakistan.

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DEDICATION

I would like to dedicate my thesis work to my Parents, the unwavering pillars of strength and inspiration behind every page of my life's journey.

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Abstract

Water pollution caused by dye contamination has arisen as a major environmental issue, which has motivated extensive research into determination of effective and sustainable strategies. This dissertation investigates the viability of using biochar-based adsorbents to reduce dye contamination in water. The study's major goal is to compare the adsorption efficiency of pristine parthenium biochar and its modified analogues, specifically beetroot activated carbon and iron oxide-infused beetroot activated carbon, in removing Brilliant Green dye from aqueous solutions. These adsorbents were created using a simple procedure, and their efficiency was rigorously tested using a comparative study. A variety of advanced techniques, including Brunauer-Emmett-Teller analysis, Energy-Dispersive X-ray Spectroscopy, X-ray Diffraction, and Fourier Transform Infrared Spectroscopy, were used to investigate the physical, chemical, and structural properties of these adsorbents. The study's findings show the differential adsorption behaviours of several biochar types towards Brilliant Green dye, providing vital insights into the probable mechanisms at work. Furthermore, optimization studies were conducted to improve the adsorption process. The effect of pH and temperature on the performance of the adsorbents in adsorbing the dye was thoroughly investigated. It is worth mentioning that the study found that adsorption is pH-dependent, with larger removal rates observed at higher pH values. The temperature effects were also investigated, indicating the exothermic character of the adsorption process. This study's findings highlight the enormous potential of parthenium biochar-based adsorbents in addressing water purification concerns. These findings not only add to our understanding of biochar's efficiency in combating dye contamination issues in water, but also highlight the importance of developing sustainable strategies to other prevailing environmental concerns.

1. Introduction and Literature Review

1.1. Background

The water on Earth is dispersed among numerous sources, each of which is essential for life. These reservoirs are made up of oceans, glaciers, groundwater, lakes, rivers, and atmospheric water vapours. Oceans cover approximately 97.5% of the Earth's surface and regulate temperature, global heat balance, and marine ecosystems. Glaciers and ice caps, which can be found in polar regions and high-altitude mountains, retain around 68.7% of freshwater, slowly releasing it into rivers as they melt, ensuring supplies during times of drought, governing river flows, and recharging groundwater (Gökçeku, 2023; Gold, 2021; Meran et al., 2020). In addition to the distribution of Earth's water sources, groundwater is stored beneath the surface in porous rock formations known as aquifers. These aquifers contain around 30.1% of the world's freshwater. Groundwater is critical to agriculture, serving as a drinking water source for people, and sustaining ecosystems. Wells and springs allow for easy access to this vital resource. Over-pumping and contamination, on the other hand, pose difficulties to the sustainability of groundwater (Odeh et al., 2019). Similarly, lakes supply a lower fraction of freshwater, accounting for approximately 0.26% of total volume. Small ponds and large lakes like North America's Great Lakes and Russia's Lake Baikal are examples of standing bodies of water. Lakes are ecologically significant because they provide habitat for a variety of animals and provide water for human use, irrigation, and industry (Aguiar et al., 2022; Ho & Goethals, 2019). Rivers are essential, although they account for only 0.0002% of the Earth's water. They continuously transfer water from upstream to downstream areas, supporting agriculture, providing transportation, and supplying residential and industrial water. Rivers are also important for aquatic organisms and nutrient movement in ecosystems. Moreover, atmospheric water vapor amounts to about 0.001% of the water on Earth. This vapor, which exists as moisture in the atmosphere, eventually condenses, forming clouds and precipitating as snow or rainfall, recharging surface water sources such as rivers, lakes, and groundwater (Anderson et al., 2019; Campos-Arias et al., 2019; Lučić et al., 2022).

Water pollution has a deleterious impact on aquatic habitats, disrupting biodiversity and ecological equilibrium. This contamination has a substantial impact on aquatic animals, resulting in a population decrease and possible extinction. Furthermore, polluting freshwater sources can endanger human health by acting as reservoirs for waterborne infections. Access to clean water is critical for protecting public health, reducing the effect of waterborne infections, and promoting overall well-being (Kılıç, 2021).

1.2. Industrialization and Water Pollution

While industrialization has resulted in technological progress and economic growth, it has also had a tremendous impact on natural water sources. Industries release a wide range of pollutants into aquatic bodies via wastewater, including heavy metals, organic chemicals, and synthetic colours. These toxins are regularly dumped into the environment without being properly treated, damaging rivers, lakes, and groundwater (Liu et al., 2022). The textile, pharmaceutical, and chemical industries are notable contributors to water contamination. Textile manufacture, for example, utilizes a lot of water and a lot of chemicals and dyes, which end up in the water without being treated. Similarly, the pharmaceutical and chemical industries discharge effluents that contain dangerous compounds that persist in the environment and offer long-term dangers (Sun et al., 2019). The cumulative impact of industrial pollution on natural water sources is worrisome. It destabilizes aquatic habitats, lowers oxygen levels, reduces biodiversity, and upsets ecological equilibrium. Furthermore, toxic material pollution of water poses major threats to human health, resulting in maladies such as gastrointestinal problems, damaged organs, and even cancer (De Oliveira et al., 2021).

In addition to its environmental consequences, industrialization has greatly contributed to the global crisis of clean drinking water scarcity (De Oliveira et al., 2021). The rapid expansion of industrial operations has resulted in increased pollution flows into water sources, deteriorating water quality, and exacerbating scarcity issues. Industries contribute significantly to worldwide water pollution, generating an estimated 300 million metric tons of contaminants each year (UNEP, 2017). Among these, the textile industry stands out, discharging more than 20% of global wastewater, which is frequently packed with toxic chemicals and dyes (World Bank Group, 2022). In underdeveloped countries, over 70% of industrial waste is dumped untreated into bodies of water (UNEP, 2017). The implications of industrial pollution include a global scarcity of safe drinking water. 2.2 billion people around the world lack access to safe drinking water as a result of contamination caused by industrial sources (UNICEF & WHO, 2023). Due to population growth and increasing industrial activity, projections show that by 2050, more than half of the world's population will live in water-stressed areas (UNESCO, 2023). This scarcity has serious socioeconomic consequences, hurting health, agriculture, and economic output. According to estimates, water scarcity and inadequate sanitation might result in a 6% loss in global GDP by 2050 (World Bank Group, 2016).

1.3. Water Profile of Pakistan and Water Pollution

Pakistan, located in South Asia, has mostly dry to semi-arid climates and a diversified topography, as well as a variety of water resources. The country's water composition includes both surface water and groundwater reserves, both of which are important (Pappas, 2011). Notable rivers in Pakistan include the Indus, Jhelum, Chenab, Ravi, and Sutlej, which form the Indus River System. The Indus River stands out among them, running around 2,900 km (Irfan et al., 2023). Pakistan's annual average river flow is around 208 billion cubic meters (bcm), with the Indus River supplying 173 bcm (Pappas, 2011). Furthermore, the significance of groundwater in meeting the demands of agriculture, industry, and home consumption is critical. According to statistics, yearly groundwater recharge is approximately 60 to 80 bcm, with total usable groundwater reserves estimated to be 50 to 60 million acre-feet (maf) (Qureshi, 2020).

Pakistan's fast development has greatly contributed to the polluting of natural water sources. Textile, chemical, and pharmaceutical industries are significant offenders in this regard. Textile industry, in particular, generates large amounts of wastewater laced with dyes and chemicals (Pandey et al., 2020). Industrial operations in the country generate an estimated 3.8 million cubic meters (mcm) of wastewater per day, with a significant percentage being discharged straight into bodies of water without sufficient treatment (Islam et al., 2022). As a result, both surface water and groundwater have become contaminated, impacting water quality for multiple uses and exacerbating water scarcity concerns.

Pakistan is facing increasing water scarcity difficulties as a result population expansion, climate change, and poor water resource management. Water availability per capita has decreased significantly from 5,260 cubic meters in 1951 to around 908 cubic meters in 2021 (Nation, 2023). The United Nations classifies a country as water-scarce when its yearly availability falls below 1,000 cubic meters per person; Pakistan's status corresponds to this, qualifying it as water-scarce country (Parry et al., 2016). The increase in water demand, combined with inadequate irrigation methods and loss of groundwater reserves, has exacerbated Pakistan's water scarcity situation (Ahmad et al., 2022).

1.4. Contamination of Water Reservoirs by Dyes

Dyes are substances with dye qualities that belong to a group of organic contaminants. They are widely used in industries such as textiles, printing presses, paper, and cosmetics (Hanafi & Sapawe, 2020). These complex chemical compounds, whether synthetic or natural, survive in the environment for extended periods of time, accumulating in bodies of water and endangering ecosystems and the well-being of humans (Tkaczyk et al., 2020). Dyes are classified as emerging pollutants due to their extensive use and possible harm to aquatic environments (Rigoletto et al., 2022). This term refers to compounds that have been identified as possible dangers to the environment and human health but are not widely controlled (Khan et al., 2020). Dyes in water bodies, whether from industrial discharges or home sources, pose environmental challenges due to their permanence, toxicity, and ability to accumulate in organisms. Some dyes are poisonous or carcinogenic, while others disrupt ecological equilibrium and injure numerous life forms (Ahmad et al., 2023). Dyes' water solubility and resistance to degradation allows them to persist in water bodies, harming both surface and groundwater resources (Intisar et al., 2023).

1.4.1. Major Sources of Dyes in Water

Dyes are a substantial source of water contamination, primarily from the following sources (Khan et al., 2021):

a) **Industrial discharges:** During their processes, industries such as textiles, leather, and paper emit dye-laden effluents. Dyes are introduced into water bodies due to inadequate treatment or poor disposal of these effluents.
b) **Domestic wastewater:** Household activities such as laundry or the use of personal care products contribute dye-containing effluents to water sources.
c) **Agricultural runoff:** Dyes from agricultural fertilizers or pesticides can enter surrounding water bodies via runoff, particularly after rainfall or irrigation events.

1.5. Textile Industry as a Major Source of Economy and Water Pollution in Pakistan

The textile industry is important to Pakistan's economy, contributing significantly to exports and jobs. Spinning, weaving, dyeing, printing, and finishing are all examples of activity in the sector. With a GDP contribution of roughly 8.5%, the textile sector is an important economic contributor, employing a sizable workforce (Riaz, 2023). Pakistan is also a major manufacturer and exporter of textiles and apparel, with textiles accounting for a significant portion of total exports (Mehar, 2021). Despite its economic importance, the textile industry's activities requiring dyes, chemicals, and extensive water consumption cause significant water pollution (Hayat et al., 2020). The release of untreated or improperly treated textile effluent into bodies of water poses environmental and health risks. These effluents contain contaminants like dyes, HMs (heavy metals), salts, and chemicals which are used in the dyeing and printing processes. Textile effluent, particularly hazardous dyes and their degradation byproducts, has been shown to have negative effects on water quality, aquatic ecosystems, and public well-being (Al-Tohamy et al., 2022).

Textile wastewater contamination load and toxicity have recently been assessed in Pakistani studies. The findings show significant levels of contaminants such as dyes, heavy metals, and chemical oxygen demand (COD). These findings highlight the importance of strict environmental rules and adequate wastewater treatment procedures in the textile sector (Abbas et al., 2023). Another case study conducted in the Faisalabad district, a textile manufacturing hub, examined pollutant levels in textile wastewater, identifying elevated concentrations of dyes, heavy metals, and other contaminants, emphasizing the importance of sustainable wastewater management practices in the textile sector (Rodrigues et al., 2023).

1.6. Classification of Dyes

Dyes are generally classified based on their chemical structure, application, and origin. The following are examples of common types (Benkhaya et al., 2020):

a) **Synthetic organic dyes:** These dyes, such as azo, anthraquinone, phthalocyanine, and triarylmethane dyes, are produced chemically and are widely used in textiles.
b) **Natural dyes:** Derived from sources such as plants, animals, or minerals, these are considered more environmentally friendly but are used less frequently in industry.
c) **Dyes that react:** They are known for chemically bonding with fabric fibres and are preferred in textiles for their brilliant dyes and robust fixation.
d) **Disperse dyes:** These insoluble dyes, used for synthetic textiles such as polyester, can leach into wastewater during washing or dyeing.

1.7. Effects of Dyes in Water for Aquatic and Terrestrial Organisms

The presence of dyes in water is detrimental to both aquatic and terrestrial organisms. Here are a few examples:

1.7.1. Aquatic Organism

Dyes can have a negative impact on aquatic organisms such as fish, invertebrates, and algae. It is possible that reproductive processes will be disrupted, growth will be hampered, and perhaps death will ensue. In fish, some dyes have been found to cause DNA damage and oxidative stress (Katić et al., 2021). Indian researchers investigated the harmful effects of textile dyes on fish, discovering behavioural alterations, altered biochemistry, and oxidative stress because of exposure, threatening health, and life (Poopal et al., 2022). Another Brazilian study on fish embryos discovered developmental defects and decreased hatching because of textile dye exposure, influencing reproduction and population dynamics (Hernández-Zamora & Martínez-Jerónimo, 2019). Chinese researchers evaluated the effects of dye on aquatic invertebrates, reporting acute toxicity impacting Daphnia magna survival, reproduction, and growth (Li et al., 2023). Turkish researchers discovered growth suppression, changed photosynthesis, and increased pigment content in freshwater algae exposed to textile dyes, emphasizing the ecological dangers in aquatic habitats (Moorthy et al., 2021).

1.7.2. Terrestrial Organisms

Dyes influence terrestrial species such as plants, soil dwellers, and insects. They can influence plant development, soil microbial communities, insect behaviour, and survival. According to research, dye-tainted irrigation water has a negative impact on crop productivity and soil health (Chowdhary et al., 2019). Textile dye-contaminated wastewater had a negative impact on soil microbial biomass, activity, and diversity, affecting critical soil processes and nutrient cycling (Krishnamoorthy et al., 2021). In India, researchers investigated the influence of dye-contaminated water on vegetable crops, discovering detrimental impacts on growth, nutrient uptake, and antioxidant enzymes, underlining agricultural hazards (Lord et al., 2022). Brazilian researchers investigated the effects of dyes on pollinators, discovering that dyes have an impact on bee behaviour, navigation, and reproductive success, posing potential hazards to pollination services and ecosystems (Youngsteadt & Keighron, 2023).

1.8. Brilliant Green Dye

Brilliant Green (BG) is a triarylmethane dye with a triphenylmethane backbone and aromatic ring substituents. It is known chemically as ethanaminium, N-[4-[bis(4-diethylamino) phenyl] phenylmethyl]-N-ethyl-, chloride (CAS number: 633-03-4). Surprisingly, the structural qualities of this dye underpin its unusual properties. Brilliant Green dye is a noteworthy substance that is widely utilized in a variety of applications. It has specific properties that are relevant in a variety of fields.

1.8.1. Application of Brilliant Green Dye

The remarkable qualities of Brilliant Green dye have led to its widespread use in a variety of sectors. Among the notable applications are (Aqeel et al., 2020):

a) **Microbiological Applications:** Brilliant Green dye is used as a selective and differential stain in microbiology. It inhibits Gram-positive bacterial growth while allowing Gram-negative bacteria to flourish in culture media such as Brilliant Green Agar (Zabłocka-Godlewska & Przystaś, 2020). This aids in the identification and differentiation of bacteria associated with enteric disorders, which aids in the diagnosis of microbial infections (Li et al., 2020).

b) **Veterinary Applications:** Brilliant Green dye is used in veterinary medicine as a topical antiseptic and wound dressing for the prevention or treatment of animal infections (Ma et al., 2022). It is also used to stain tissues for microscopic investigation in veterinary histology and pathology (Dibal et al., 2022).

c) **Other Applications:** Brilliant Green dye was originally used as a fabric dyeant in the textile sector, but its use has declined due to environmental concerns and regulations. It's also used in the pharmaceutical industry for medicinal and therapeutic applications (Mansour et al., 2020).

1.9. Conventional Wastewater Treatments for Dyes

Contaminated water containing dyes poses significant issues for both the environment and human health. To address this issue, standard methods for treating dye-polluted water have been used. To alleviate the deleterious effects of dyes, these approaches either eliminate or break them down. These methods, however, have limitations and downsides. This section introduces traditional methods for treating dye-contaminated water while noting their drawbacks, which are supported by current references.

a) Coagulation/Flocculation

Coagulation and flocculation are the processes by which chemical coagulants such as alum or ferric chloride are used to destabilize and agglomerate dye particles (Kurniawan et al., 2022). Sedimentation or filtering can then be used to remove them. While this approach is effective for suspended dye particles, it may struggle with remaining dye molecules in solution, resulting in partial removal and potential re-release (Ahmad et al., 2022).

b) Biological Treatment:

Microorganisms are used in biological treatment to break down dyes via enzymatic reactions or metabolic processes. Although they are environmentally beneficial and have the ability to mineralize dyes, their efficacy can be impacted by factors such as dye concentration, toxicity, and co-pollutants (Al-Tohamy et al., 2022).

c) Chemical Oxidation:

Chemical oxidation technologies, such as ozonation and advanced oxidation processes (AOPs), use strong oxidants to convert dyes into non-toxic byproducts (Saravanan et al., 2022). These procedures can effectively degrade dyes, but they may require a lot of energy, generate a lot of chemical sludge, and produce potentially toxic byproducts (Ma et al., 2021).

1.9.1. Limitations and Drawbacks of Conventional Methods

Conventional treatment methods frequently necessitate large infrastructure, energy, and chemical inputs, resulting in increased operational costs. Because of their resilience to degradation, several of these approaches may encounter issues when working with complicated dye structures, such as azo dyes. Specific processes generate sludge or byproducts that require additional treatment and disposal, providing waste management and secondary pollution concerns. These traditional methods have varied performance in response to pH and temperature changes, requiring appropriate operational settings for successful dye elimination (Crini & Lichtfouse, 2018).

1.10. Adsorption

Adsorption techniques use different kinds of adsorbents, such as activated carbon, zeolites, and clay minerals, who physically or chemically interact with pollutants helping in their removal or elimination. It is a well-known and effective wastewater treatment technology, especially for removing dyes from polluted water (Tara et al., 2020). In this method, contaminating particles are bound to solid surfaces of a substance known as adsorbent. This section describes the adsorption strategy in wastewater treatment in detail, stressing its principles, benefits, and case examples demonstrating its efficiency.

1.10.1. Background of Adsorption Technique

The interaction between adsorbent and contaminant in the wastewater influences adsorption. Adsorbents are typically solids with a large surface area and specific features that attract and hold pollutants via physical or chemical interactions (Ambaye et al., 2020).

1.10.1.1. Types of Adsorption Processes

Adsorption processes are of two types: physical adsorption (physisorption) and chemical adsorption (chemisorption) (**Figure 1**). Physical adsorption is caused by weak forces such as dispersion and dipole-dipole interactions between the adsorbent surface and adsorbate molecules. It has no chemical bonding and is reversible. Adsorption via chemical bonds, on the other hand, is a more powerful and distinct interaction that often results in irreversible adsorption (Jiang et al., 2023).

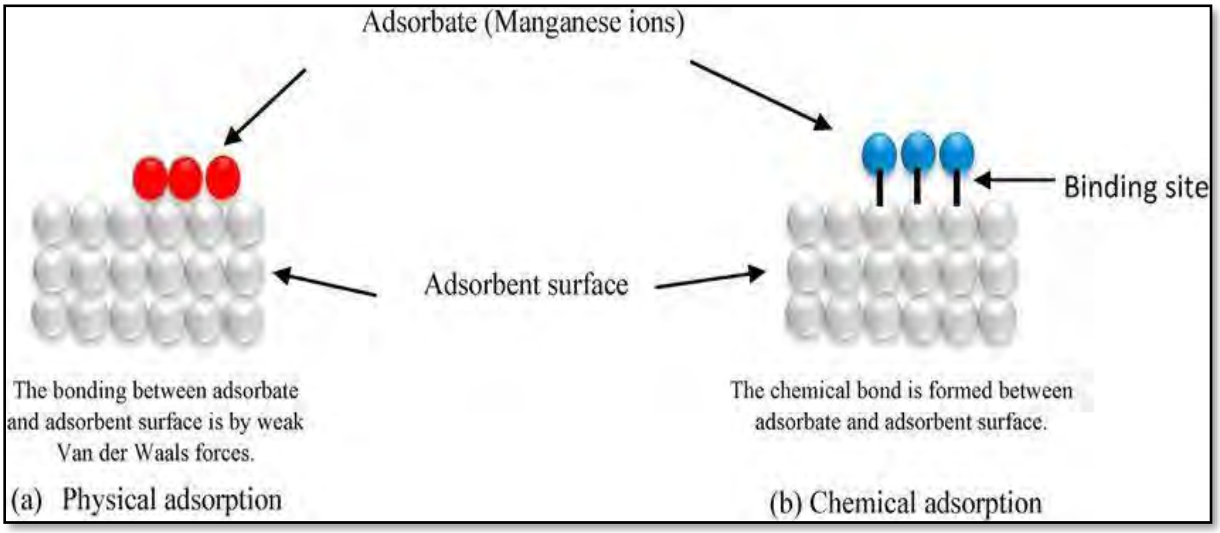

Figure 1: Mechanism of physical and chemical adsorption (Rudi et al., 2020).

Both physical and chemical techniques help to remove dye from wastewater. Intermolecular interactions such as Van der Waals forces and electrostatic attraction between adsorbent and dye regions draw dye molecules to the adsorbent surface during physical adsorption. Chemical adsorption, on the other hand, stimulates the chemical bonds formation between theadsorbent and the dye via processes that result in covalent or ionic interactions that secure dyemolecules to the adsorbent surface. The adsorption of dyes from wastewater has received a great deal of attention, with multiple research publications confirming its effectiveness and underlying concepts. In a study examining dye removal techniques in textile wastewater, for example, adsorption outperformed coagulation and biodegradation (Zhang, 2022). Another review article emphasized the benefits of adsorption over chemical oxidation for the treatment of dye contaminated wastewater (Shabir et al., 2022).

1.10.2. Scope of Adsorption for Wastewater Treatment

Adsorption techniques in wastewater treatment are a significant and promising subject, particularly for dye-contaminated wastewater. Adsorption is a versatile and effective strategy for dealing with the environmental and health risks connected with dye pollution (Rathi et al., 2021). Recent investigations and research have highlighted the extensive scope of adsorption in wastewater treatment. A study assessed the efficacy of a magnetic adsorbent for textile dyes removal from wastewater, demonstrating remarkable adsorption capacity as well as simple separation using a magnetic field (Sanad et al., 2021). In a separate study, the performance of agricultural waste-derived biochar as an adsorbent for wastewater dye removal was explored, with significant adsorption capacity and a sustainable solution revealed (Kumar et al., 2023). In Bangladesh, a case study investigated the adsorption of textile effluent dyes using locally available, low-cost adsorbents (Rahman et al., 2022). Another work revealed efficient dye removal using agricultural waste-derived activated carbon and clay minerals, emphasising the utility of low-cost adsorbents in the treatment of industrial wastewater (Hamad & Idrus, 2022).

1.10.3. Physicochemical Factors Affecting Adsorption

Adsorbate characteristics, surface reactivity, pH, and temperature are all elements that influence dye adsorption (Rápó & Tonk, 2021). The chemical characteristics of the adsorbate, notably its functional groups, determine the possibility for chemical interactions with the adsorbent surface. Active spots on the adsorbent surface aid chemical adsorption. Furthermore, variations in pH and temperature may influence the surface charge and reactivity of the adsorbent, influencing adsorption effectiveness (Jiang et al., 2020). These parameters have been investigated in numerous studies, expanding our understanding, and optimizing the dye removal adsorption process. The tuning of adsorption conditions is critical to optimizing dye removal efficacy. Researchers are focusing on understanding and fine-tuning variables such as temperature, pH contact time, adsorbent quantity, and starting dye concentration. This optimization aims to improve the process's adsorption capacity, kinetics, and overall efficacy (Nabbou et al., 2019).

a) pH

The solution pH is very important in adsorption mechanisms. It influences both the surface charge of the adsorbent and the degree of ionization of the adsorbate, hence influencing the adsorption capacity. A study on chitosan-based adsorbents for methylene blue dye removal found that increasing the pH level increased adsorption capacity due to electrostatic attraction between positively charged adsorbents and negatively charged dye molecules (Wan et al., 2022). Similarly, studies on acid orange 7 dye adsorption using graphene oxide nanosheets revealed pH-dependent surface charge variations that affected adsorption capacity and efficiency (Zhang et al., 2021).

b) Temperature

Temperature also has an impact on the adsorption process since it affects the kinetics and thermodynamics of the adsorption system. Temperature-induced effects can be explained by using parameters such as equilibrium constants and activation energies (Mahdavi-Shakib, 2023). An experiment into crystal violet dye adsorption with activated carbon revealed that adsorption capacity increased with increasing temperature, indicating an endothermic adsorption mechanism (Ji & Li, 2021). A separate investigation on the adsorption of methylene blue dye using magnetic nanocomposites found that higher temperatures accelerated both the rate and capacity of adsorption (Sharma et al., 2022).

c) Dose of Adsorbent

The amount or dose of adsorbent used in the process has a significant impact on adsorption efficiency. The optimum dose is determined by variables such as adsorbate concentration and specific surface area of the adsorbent (Kasirajan et al., 2022). A study focusing on discarded tea leaves for Congo red dye removal, for example, found that increasing adsorbent dosage associated with increased dye removal until an optimal dose was reached, after which effectiveness remained constant (Abbas et al., 2023). In a similar investigation on modified clay adsorbents and their role in malachite green dye adsorption, increasing the adsorbent dose increased adsorption capacity until saturation was reached (Largo et al., 2023).

d) Nature of Adsorbate

The adsorbate's qualities and properties, including its molecular structure, size, and charge, have a significant impact on the adsorption procedure (Tan et al., 2021). Various adsorbates have varying preferences for different adsorbents. In a study that investigated clay-based adsorbents for cationic dye adsorption, such as methylene blue and crystal violet, the results showed that dyes with bigger molecular dimensions and higher charge densities had a higher adsorption capacity (Gautam & Hooda, 2020). Another study focused on anionic dye adsorption using activated carbon-based adsorbents. The results uncovered that the presence of functional groups on the adsorbent surface determine the effectiveness and selectivity of anionic dye adsorption (Thakur et al., 2023).

e) Surface Reactivity/Active Sites

The adsorbent surface's active sites contribute to its reactivity and adsorption capability, with their availability and accessibility influencing the adsorption process (Hong et al., 2022). Adsorption of phenolic compounds from used water using graphene oxide-based adsorbents highlighted the role of surface functional groups, such as hydroxyl and carboxyl groups, in improving adsorption capacity via unique interactions (Velusamy et al., 2021). Another study looked at heavy metal ion adsorption using biochar-based adsorbents, with surface functional groups and porosity playing important roles in affecting adsorption capacity and selectivity towards metal ions (Cuong et al., 2022).

1.10.4. Novel Adsorbent Materials

The creation of new adsorbent materials is an active scientific endeavour aimed at enhancing the efficacy of dye removal via adsorption. Researchers are interested in carbon-based chemicals, metal-organic frameworks (MOFs), nanocomposites, and bio-derived adsorbents (Huynh et al., 2023). These materials offer a variety of properties. These include enhanced surface areas and specific functions, that increase the potential of adsorption techniques. An example study used a metal-organic framework (MIL-101) as an adsorbent for wastewater dye removal. The findings of the study emphasised MIL-101's improved adsorption capacity and specificity for several dye compounds (Huynh et al., 2023). Another study investigated the usage of cellulose-based adsorbents for dye removal. The low cost and renewable nature of cellulose-based adsorbents, as well as their efficiency in dye removal, were highlighted in this work (Kausar et al., 2023).

1.10.5. Sustainable and Cost-Effective Solutions

Adsorption is being applied for wastewater treatment to produce sustainable and cost-effective solutions. Researchers are actively conducting novel research on the use of low-cost adsorbent materials derived from waste or agricultural leftovers to provide environmentally friendly and economically viable alternatives (Chowdhury et al., 2022). This strategy helps to reduce the need of expensive commercial adsorbents while also contributing to waste utilisation. One study, for example, investigated the use of used coffee grounds as a cheap adsorbent for dye extraction from wastewater. The study discovered that spent coffee grounds have the potential to be a cost-effective and sustainable adsorbent with substantial methylene blue dye removal capacity (Cuccarese et al., 2023). Another study investigated the use of agricultural waste as an adsorbent remediating dye contaminated wastewater. Orange peel's encouraging adsorptionpotential was highlighted in this study, presenting an eco-friendly and cost-effective alternativefor dye wastewater treatment (Eddy et al., 2022).

1.11. Advantages of Adsorption as a Wastewater Treatment Method

Adsorption stands out as a wastewater treatment technology because of the several advantages it has over traditional methods:

a) High Efficiency

Adsorption has a high removal effectiveness for a wide range of pollutants, including dyes, heavy metals, organics, and emerging contaminants (Rashid et al., 2021). Several investigations have confirmed its outstanding performance. Azanaw et al. (2022) discussed in a review study that adsorption outperformed coagulation/flocculation and biological treatments in textile dye removal with activated carbon. Guillossou et al. (2020) found that adsorption had higher removal rates and overall efficacy when compared to chemical oxidation (ozonation) for dye removal.

b) Versatility

Adsorption is suitable for a wide range of wastewater types, efficiently eliminating many contaminants at the same time, and is relevant in both industrial and home settings (Rashid et al., 2021). This versatility emphasizes its usefulness. Textile wastewater treatment using adsorption demonstrated its capacity to remove numerous dyes at the same time, addressing the complexity of dye mixes in effluents (Velusamy et al., 2021). Adsorption was evaluated for concurrent removal of dyes and heavy metals in complicated industrial effluents (Ajiboye et al., 2021).

c) Diverse Adsorbents

A variety of materials, including activated carbon, zeolites, biochar, and modified clays, that are suited for specific contaminants improve removal capabilities (Bilal et al., 2022). In dye-contaminated wastewater treatment, modified biochar adsorbents outperformed conventional counterparts (Sharmila et al., 2023). Agricultural waste-based adsorbents such as rice husk and coconut shell have demonstrated effectiveness in dye removal, providing cost-effective and environmentally friendly alternatives (Le et al., 2021).

d) Regeneratability

Some adsorbents may be regenerated and reused, which improves long-term sustainability and cost-effectiveness (Li et al., 2019). For example, reusable activated carbon maintains adsorption capability across cycles (Lins et al., 2020). The possibility of regenerating spent dye removal adsorbents also contributes to the sustainability aspect.

1.12. Biochar as a Promising Adsorbent

The use of plants or weeds derived biochar for adsorbing dye-contaminated wastewater has gained popularity as an efficient and environmentally friendly method of water treatment. Biochar, a carbon-rich substance generated from plant biomass or agricultural waste via pyrolysis, has unique physical and chemical properties that make it appropriate for adsorption (Saletnik et al., 2019). Plant-based biochar has a porous structure with a high surface area and porosity, providing plenty of sites for dye molecules' attachment. These characteristics can change depending on the feedstock and pyrolysis circumstances. Furthermore, plant-based biochar contains a wide range of surface functional groups, including hydroxyl, carboxyl, and phenolic groups, which enable interactions with dyes via hydrogen bonding and electrostatic effects (Murtaza et al., 2022). Example of biochar obtained from plant-based material is shown in **Figure 2**. Plant-based biochar is primarily composed of carbon, which ensures its stability and longevity as an adsorbent. It also provides pH buffering capacity, which helps to maintain optimal pH values during adsorption. Furthermore, the high cation exchange capacity (CEC) seen in plant-based biochar improves the removal of positively charged dyes or those that interact with cations (Khan et al., 2023). Furthermore, biochar derived from plants has specific advantages in wastewater treatment. It improves agricultural waste valorization and cost-effectiveness because it is derived from abundant and renewable plant biomass. Its strong adsorption capacity, which is influenced by physical and chemical properties, effectively removes dyes and improves water quality (Gopinath et al., 2021). Furthermore, it targets other contaminants such as heavy metals and organic compounds, increasing the efficacy of wastewater treatment (Zeghioud et al., 2022). Carbon sequestration, reduced greenhouse gas emissions during production, and alignment with sustainable waste management and circular economy concepts are all environmental benefits (Gupta et al., 2020).

Recent research articles support the efficacy and use of plant-based biochar in dye removal and wastewater treatment. Madikizela (2021) investigated the ability of water hyacinth-derived biochar to remove dye from aqueous solutions, finding its high adsorption capacity and efficacy in dye removal. Similarly, Ali et al. (2022) used agricultural waste-derived biochar to remove malachite green dye from wastewater, proving its efficacy and sustainability. These studies, among others, provide critical insights into the physical and chemical properties of plant-based biochar, demonstrating its effectiveness as an adsorbent for dealing with dye-contaminated wastewater.

***Figure 2**: Examples of weed-based biochar (a) reference image (Gardengu_Admin, n.d.) (b) PPAC prepared in lab.*

1.12.1. Chemical Composition of Plants

Plants produce high-quality biochar with exceptional adsorption properties due to their chemical makeup. The chemical makeup of these plants, which contains both organic and inorganic materials, has a significant impact on the adsorption efficacy of the resulting biochar.

1.12.1.1. Organic Components

Plants have an extensive range of organic compounds that are required for the synthesis of biochar and its adsorptive characteristics. These molecules include cellulose, hemicellulose, lignin, proteins, and other organic compounds (Barhoum et al., 2020). During pyrolysis, these constituents undergo thermal breakdown and modification, resulting in stable carbon structures inside the biochar (Yang et al., 2022).

a. **Cellulose:** It is a complex carbohydrate that serves as the principal structural component of plant cell walls. It generates long chains by connecting glucose units. The inclusion of cellulose improves the structural integrity and porosity of biochar, altering its adsorptive potential.
b. **Hemicellulose:** A polysaccharide that surrounds cellulose fibres and has a more complicated and diversified structure than cellulose. Its presence in plants aids in the formation of a porous structures within the resulting biochar.
c. **Lignin:** The aromatic polymer lignin provides plant cell walls with endurance and toughness. Lignin, which contains a variety of phenolic chemicals, improves the aromatic character and durability of biochar. The addition of lignin from plants increases the adsorption potential and stability of the resulting biochar.
d. **Proteins and Organic Matter:** plants may contain proteins and other organic components, which can generate functional groups on the biochar surface, including amino, carboxyl, and hydroxyl groups that participate in adsorption mechanisms.

1.12.1.2. Inorganic Components

Large amounts of inorganic materials, such as minerals and trace elements, can be found in plants. These components influence the chemical and physical properties of biochar, e.g surface area, porosity, and adsorption capacity. During pyrolysis, these inorganic elements can be converted into biochar (Islam et al., 2021). Diverse minerals and trace elements from the soil can accumulate in plants, including calcium, magnesium, potassium, phosphorus, iron, and manganese. Once present in biochar, these elements influence its surface properties, pH regulation capabilities, and interactions with adsorbate particles (Islam et al., 2021). The chemical composition of plants is determined by elements such as species, growth conditions, and environmental influences. Variations in organic and inorganic elements are seen among different weed species, resulting in biochar with unique properties and adsorption effectiveness (Yaashikaa et al., 2020). When selecting acceptable weed species for biochar formation, the desired adsorption properties and target pollutants in wastewater treatment should be considered.

1.13. Production of Activated Carbon/Biochar

Activated carbon, which is frequently used for wastewater pollutant adsorption, goes through ‘activation’, a critical manufacturing process. This type of carbon has a high porosity and internal surface area, providing plenty of adsorption sites for pollutants (Alharbi et al., 2022). Activation, whether physical or chemical, produces diverse activated carbon types with varying properties and adsorption capabilities.

a) Physical Activation

The carbonization of raw materials occurs prior to activation, which is accomplished through physical means such as high temperatures and gases (Su et al., 2023). Among the most common physical activation methods are:

- **Steam Activation:** Elevated temperatures (800-1000°C) and steam exposure promote interactions with carbonized materials, promoting pore formation and increasing activated carbon surface area. This process is extensively used in the manufacturing of commercial activated carbon (Im et al., 2019).
- **Gas Activation:** Gas activation is distinguished by the use of carbon dioxide (CO_2) or air, and it is carried out at lower temperatures than steam activation (Wang et al., 2020).

The physical activation of activated carbon is the subject of research. Poovaragan et al. (2021), for example, investigated steam-activated fruit shell-based biochar for the removal of heavy metals from discarded water. They emphasized the function of steam activation in increasing activated carbon porosity and adsorption capacity. Ayedi et al. (2023) investigated gas-activated wood-derived activated carbon with the goal of removing organic contaminants. They demonstrated the effect of gas activation on activated carbon pore structure and adsorption efficiency.

b) Chemical Activation

Chemical activation is the process of impregnating carbonized material with chemicals and then heating it to high temperatures to produce activated carbon. Phosphoric acid, potassium hydroxide, and zinc chloride are examples of common compounds (Gao et al., 2020).

- Phosphoric acid activation is common because it dehydrates material and generates holes while requiring lower temperatures than physical activation (Han et al., 2020).

Chemical activation is demonstrated in the synthesis of activated carbon via research. Alharbi et al. (2022) investigated phosphoric acid activation of date palm leaf-based activated carbon with the goal of removing pharmaceutical contaminants. They underlined the importance of chemical activation in increasing adsorption capacity and surface area. Wang et al. (2023) studied the influence of zinc chloride activation on the porosity structure and adsorption properties of biomass-derived activated carbon for wastewater dye removal.

1.14. Scope of Weed Derived Biochar for Wastewater Treatment in Pakistan

The examples highlighted show various activation methods for producing activated carbon that can be used in wastewater treatment. Due to limited resources and infrastructure, economic problems impede efficient wastewater treatment systems in Pakistan. Traditional approaches are expensive and less practicable given budgetary constraints. Biochar made from plants appears to be a potential alternative. Biochar can be produced from locally available biomass, such as invasive plants or agricultural waste. Its manufacturing is inexpensive, scalable, and feasible using simple pyrolysis processes, addressing economic constraints in nations such as Pakistan (Kaur et al., 2023). Furthermore, the advantageous adsorption features of plant-based biochar, which include surface area, porosity, and functional groups, enhance its ability to remove dyes from wastewater. This feature distinguishes it as a less expensive alternative to more expensive standard dye removal processes. Pakistan can take advantage of its abundant plant biomass resources by using plant-based biochar for wastewater treatment. This method effectively combats water pollution while considering both economic and environmental factors. Using invasive weed species as charcoal feedstock not only mitigates environmental damage but also converts them into important adsorbents. Plant-based biochar is compatible with Pakistan's economic circumstances, providing a cost-effective and long-term option for wastewater treatment.

1.15. Parthenium hysterophorus

Parthenium hysterophorus, often known as parthenium weed or carrot grass, has become a common invasive plant in many parts of the world, including Pakistan (**Figure 3**). Despite its reputation as one of the most destructive and toxic plants, it offers a unique avenue for application in wastewater treatment due to its negative effects on ecosystems (Khan et al., 2020). The focus of this study is to maximize the potential of *Parthenium hysterophorus* as a biochar precursor material, with a particular emphasis on its efficacy in dye removal from wastewater. *Parthenium hysterophorus* is not native to Pakistan, yet it has spread widely throughout the country (Khan et al., 2020). Its introduction was most likely unintended, maybe via tainted seeds or inadvertent transmission via imported commodities. The plant's resilience to an elastic range of environmental conditions, plus its prolific reproductive abilities, have propelled its fast spread in Pakistan. Because of its competitive nature with native plant species, it has caused significant biodiversity disturbances and ecological imbalances. The invasion of *Parthenium hysterophorus* has posed significant challenges to agriculture, human well-being, and general environmental balance in Pakistan (Bajwa et al., 2019).

***Figure 3**: Parthenium hysterophorus species.*

Because of its negative impacts on human and animal health, *Parthenium hysterophorus* is classified as the seventh most poisonous plant in the world (Kaur et al., 2021). It contains hazardous chemicals such as allergenic proteins and sesquiterpene lactones, which cause allergic reactions, respiratory problems, and skin irritations in people. Animals fed *Parthenium hysterophorus* may develop health problems such as liver damage and decreased milk output (Bashar et al., 2021). Despite these detrimental health effects, the plant's wastewater treatment potential is being examined. This research focuses on the use of Parthenium hysterophorus to produce biochar, which has the potential to successfully remove dyes from wastewater. By exploiting this invasive plant to manufacture biochar, a long-lasting and low-cost adsorbent can be developed to prevent water pollution while also addressing the issue of invasive weeds. This technology not only provides a strategy for managing Parthenium hysterophorus, but it also provides an environmentally friendly choice for dye-contaminated wastewater treatment.

Ain et al. (2022) performed a study that underlined the necessity of generating biochar from Parthenium hysterophorus biomass. This plant was effectively used to produce biochar, which was then tested for its efficacy in adsorbing dyes from wastewater (Fito et al., 2020). The study discovered a relationship between the invasiveness of Parthenium hysterophorus, its application in biochar production, and its potential for wastewater treatment. The research presents data to demonstrate the economic and environmental viability of converting this invasive plant into a lucrative resource to tackle water pollution concerns.

1.16. Modification of Biochar

Flexible adsorbents such as activated carbon and biochar are often utilised to remove pollutants from water and wastewater. Researchers have investigated a variety of modification approaches in an attempt to improve the efficiency of adsorption and adjust features for certain applications. Surface functionalization, physical and chemical treatments, and composite manufacturing are examples of these alterations (Mariana et al., 2021). Recent studies have investigated the effect of these activated carbon and biochar changes on adsorption capacity and selectivity.

The process of adding functional groups to the surface of activated carbon or biochar to improve adsorption capabilities is known as surface functionalization. Hydroxyl, carboxyl, amine, and sulfonic acid groups are all common functional groups (Qiu et al., 2022). Functionalization is accomplished using chemical processes such as oxidation, impregnation, or grafting of appropriate chemicals (Jha et al., 2021). For example, Li et al. (2023) investigated biochar modification via hydrothermal treatment with citric acid. Surface functionalization increased the presence of carboxyl groups on the biochar surface, which improved the effectiveness of medicinal removal from water.

Physical treatments alter the surface morphology and pore structure of activated carbon or biochar, affecting their adsorption properties. These treatments include steam activation, microwave irradiation, and thermal or chemical pretreatments. A study looked into the effect of microwave irradiation on the surface modification of activated carbon for heavy metal ion removal (Sultana et al., 2022). Microwave treatment enhanced pore volume surface area, resulting in enhanced adsorption capacity.

Chemical treatments use specific chemicals to alter the properties of activated carbon or biochar. Common compounds include acids, bases, and oxidising agents. A group of researchers studied how nitric acid may be used to alter activated carbon for dye removal (Demiral et al., 2021). The use of chemicals increased the amount of oxygen on the surface and introduced acidic functional groups, which improved dye adsorption ability.

By mixing activated carbon or biochar with other materials, hybrid adsorbents with improved properties are created (Zinicovscaia et al., 2020). Polymer composites, metal oxides, and nanomaterials are examples of common composites. According to research, an organic pollutant removal composite was developed by incorporating magnetic nanoparticles into activated carbon. Magnetic properties simplified adsorbent separation, resulting in an efficient and reusable adsorption device (Sriram et al., 2019).

Using this information, the researchers want to alter the surface characteristics of parthenium biochar by activation methods such as magnetization with iron oxide and beetroot activation with beetroot extract. These modifications have the potential to improve the adsorption performance and selectivity of parthenium biochar, making it more efficient in dye removal from wastewater.

Magnetically activated biochar separates easily from treated water using magnetic forces, enabling for cost-effective adsorbent reusability (Yao et al., 2020). Beetroot-activated biochar, on the other hand, provides additional surface functional groups through natural compounds contained in beetroot extract, which may improve adsorption performance (Rashid et al., 2019). The utilisation of these modified forms of parthenium biochar in wastewater treatment has numerous advantages. For starters, it makes use of an invasive weed species, providing an ecologically sound method for controlling and regulating this difficult plant. Second, converting parthenium into biochar provides an efficient and sustainable wastewater treatment solution, which is especially significant in resource-constrained countries like Pakistan. Finally, parthenium biochar modifications may boost its adsorption capacity, resulting in more effective dye removal from polluted water sources.

1.17. Problem Statement

Dye contaminants are frequently reported in both drinking water and wastewater effluents, underlining the inadequacies of present treatment procedures. While advanced treatment technologies are successful, their enormous energy requirements make them prohibitively expensive. Furthermore, the high bioaccumulation of these organic contaminants raises the possibility of health concerns. This highlights the critical need for cost-effective and efficient dye removal techniques in water and wastewaters.

1.18. Aim and Objectives

This study is aimed to look into the efficacy of pure biochar derived from *Parthenium hysterophorus* and its magnetically activated variety using iron oxide, as well as the organically activated variety using beetroot extract, for the treatment of wastewater contaminated with brilliant green dye. The study objectives are:

1. To create high-quality biochar from *Parthenium hysterophorus* via pyrolysis, ensuring the appropriate properties.
2. To activate/modify Parthenium-derived biochar is produced by combining a) iron oxide to produce magnetically activated biochar and b) beetroot extract to produce organically activated biochar, thereby improving adsorption characteristics.
3. To compare the adsorption performance of the three biochar types to determine the most effective adsorbent for brilliant green dye extraction from wastewater.
4. To investigate and improve operational settings (adsorbent dosage, pH, contact time, and temperature) for peak adsorption effectiveness in brilliant green dye removal.
5. To characterize the physical and chemical properties of three biochar types (pure, magnetically activated, and organically activated) using surface area BET analysis, SEM, FTIR, and elemental analysis via EDS.

1.19. Significance of the Study

This research is significant in terms of both science and practical applications in the wastewater treatment industry. The study's emphasis on the use of *Parthenium hysterophorus*, an invasive weed species, as a charcoal feedstock is an important step toward sustainable wastewater treatment. The study provides an eco-friendly and sustainable strategy for addressing water pollution challenges by changing this difficult plant into a beneficial asset for wastewater management. In places like Pakistan, where limited resources make conventional wastewater treatment methods difficult, this discovery provides a viable avenue. The study suggests an economically viable alternative by investigating biochar generated from *Parthenium hysterophorus*, a readily available and cost-effective raw material. This method is in line with the requirement for affordable and cost-effective wastewater treatment options. Because of the extensive usage of brilliant green dye in numerous industries, the specialized focus on removing this dye is especially important. The possible environmental and health problems linked to its presence in bodies of water highlight the critical importance of effective removal measures. The study's implications span the environmental and economic spectrums. The study addresses the ecological consequences of *Parthenium hysterophorus* by changing it into a valuable resource. The research helps to control and manage this invasive weed by harnessing it for biochar production. Furthermore, the use of biochar in wastewater treatment projects holds the possibility of reducing water pollution and protecting ecosystems. The study's cost-effective strategy makes it a practical solution for places dealing with financial constraints.

Finally, the significance of this study rests in its ability to give a sustainable, economically practical, and environmentally responsible solution to wastewater tainted with vivid green dye. The findings of this study have the potential to improve the development of effective and relevant wastewater treatment and overall management solutions

2. Materials and Method

2.1. Identification and Collection of *Parthenium hysterophorus*

The methods used in this study to gather *Parthenium hysterophorus*, often known as Parthenium weed, were inspired by existing procedures with a few optimizations to obtain the best carbonization results (Kumar et al., 2013; Mondal et al., 2016). Fresh Parthenium weed specimens were carefully collected from the Quaid-i-Azam University campus in Islamabad.

2.2. Pre-treatment of *Parthenium hysterophorus*

The harvested plant materials were washed thoroughly with tap water and then exposed to an air-drying procedure for a week, allowing it to achieve ideal dryness. Following that, the dried Parthenium weed was sliced into smaller fragments ranging in size from 30 to 50 mm, providing uniformity in preparation. To assure the study's precision and reproducibility, a carefully calculated amount of air-dried Parthenium weed material was carefully deposited in the oven and dried at 100 °C for 2 hours. The remaining oven-dried plant material was further subjected to air drying for 2 days to ensure complete loss of any remaining moisture content (**Figure 4**).

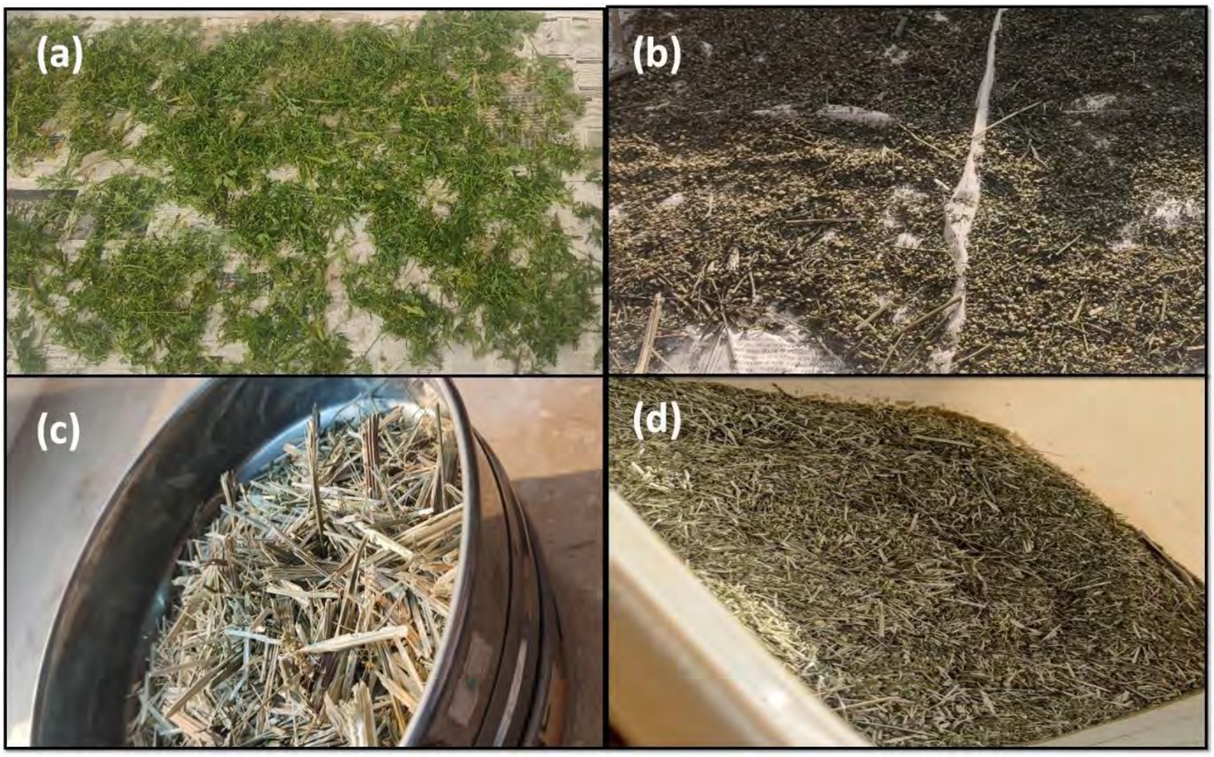

Figure 4*: Pre-treatment of Parthenium hysterophorus to make biochar, which involves, (a) air-drying after washing (b) slicing (c) oven-drying (d) air-drying.*

2.3. Synthesis of Biochar

After the drying process was completed, plant material was transferred to the ceramic crucibles and then subjected to 400°C for 2 hours within the controlled atmosphere of an electric muffle furnace, with a ramping temperature of 3 °C/min. Following the carbonization procedure, the resulting carbon material was ground using a pestle and mortar. The biochar obtained was then completely rinsed with distilled water until the discharge was colourless. Following that, the washed biochar samples were oven-dried for 2 h at a heat of 80 °C and subsequently air-dried for 2 h (**Figure 5**).

Figure 5*: Synthesis of activated carbon from pristine Parthenium. (a) carbonization at 400 °C (b) manual grinding (c) washing with distilled water (d) sieving through 2 mm sieve.*

The obtained carbonized material was then sieved using a 2 mm sieve to achieve a fine, homogenous mix of biochar. The obtained biochar was then weighed precisely to 982 g and stored in zip lock bags. With the produced biochar in hand, the adsorption efficacy of various contaminants was evaluated. Based on the results of these adsorption tests, the carbon-based substance with the highest adsorption efficiency was chosen for further activation treatment. It is vital to highlight that the experimental design was carefully duplicated three times to ensure the results' robustness and repeatability.

2.4. Beetroot Activation of Biochar

For the experiment, the methodology proposed by Rashid et al. (2019) was followed. Beetroot was acquired from a local fruit shop. 500 g of beetroot was thoroughly rinsed with distilled water to assure cleanliness. After washing the beetroot, it was blended for 10 minutes with 1 L of distilled water as the blending medium. This step was designed to effectively extract the beet juice. Following the blending operation, the remaining beet juice was filtered to remove any solid particles or contaminants (**Figure 6**). 10 g of pristine parthenium biochar was blended with 40 mL of filtered beetroot juice to begin the next step of the experiment. A vigorous stirring operation began, lasting one hour and maintaining a temperature of 80 °C. This temperature and time combination was chosen to promote the necessary interactions between the biochar and the components of the beetroot juice. Following the completion of the stirring period, the mixture was dried in an oven for 2 h at 80 °C. This drying procedure removed superfluous moisture and enhanced interaction between the biochar and beetroot juice components, resulting in the desired results. Notably, the remaining beetroot juice filtrate that was not used in the experiment was safely stored in a refrigerator. This precaution was taken to protect the integrity of the unused beetroot juice for future use or analysis.

2.5. Iron Oxide Activation of Beetroot Activated Biochar

The combined activation of biochar with beetroot extract and iron oxide was achieved following previous studies. A solution was prepared by dissolving 4 g of $Fe(NO_3)_3.9H_2O$ in 5 ml of acetone. 5 g of beetroot activated carbon was mixed in this solution and stirred manually for 10 minutes. Then the mixture was oven dried for 18 hrs at 115 °C. The resultant activated carbon was named IOB-AC i.e., iron oxide and beetroot activated carbon.

Figure 6: Filtration of beetroot extract for activation of pristine biochar.

2.6. Characterization Studies

Characterization of the biochar was done using various analytical techniques. The BET analysis was one of these procedures, and it was used to determine the surface area of a solid substance. The physical adsorption of N_2 gas molecules onto the surface of the biochar sample is the basis for this technology, named after its developers Brunauer, Emmett, and Teller. The biochar's surface area was calculated by quantifying its gas adsorption, which shed insight on its porosity and reactivity. Energy-Dispersive X-ray Spectroscopy (EDS) can also be used to look into the elemental makeup of biochar. This method, when combined with scanning electron microscopy (SEM), enables for a microscopic examination of the elemental composition of biochar. Fourier-Transform Infrared Spectroscopy (FTIR) was utilised to assess the presence of functional groups in biochar to delve deeper into its properties. FTIR was used to investigate the wavelengths of infrared light absorbed by biochar, which offers chemical bonds and functional groups information inside the material. Additionally, the elemental presence of biochar particles was determined by Energy Dispersive X-ray (EDX) analysis. This method provides a quantitative assessment of the elements, which aids in understanding the biochar's overall composition and prospective applications. Combining these methods allowed for a comprehensive characterization of the biochar samples, yielding valuable insights into their physicochemical properties and potential applications.

2.7. Adsorption Experiments

2.7.1. Preparation of Stock Solution

In a graduated flask, a solution containing 100 mg L-1 Brilliant Green dye was created. This involves dissolving the Brilliant Green dye in 1000 mL of de-ionized water using magnetic stirring. From the initial stock solution, a series of working solutions were created to offer solutions of varying concentrations for experimental application. The following equation (1) guided the diluting process:

$$C_1V_1 = C_2V_2 \quad (1)$$

C_1 and C_2 represent the stock solution and working solution concentrations in mg L^{-1}, respectively, while V_1 and V_2 represent the corresponding volumes in L.

Appropriate procedures were followed to ensure that the residual stock solution could be used in future experiments. To achieve a regulated temperature environment, the dye solution was carefully stored below 4 °C. It is worth noting that this storage method was followed for a period of no more than 15 days, maintaining the purity and integrity of the dye solution.

2.7.2. Adsorption Studies

Several studies of adsorption were carried out to assess the effectiveness of the newly synthesized adsorbent. The major goal was to evaluate its capacity to interact with Brilliant Green, a representative textile dye that served as a model pollutant. The experimental protocol included 180 min of continuous stirring. Within this interval, an adsorbent dose of 0.5 g L^{-1} was added to a 100 mL Brilliant Green working solution, with stirring maintained at 200 revolutions per minute (rpm). External influences were minimized to achieve ideal experimental conditions. Aluminium foil was wrapped around the Erlenmeyer flask containing the Brilliant Green solution, effectively hiding the reaction from any stray light. A careful sample plan was used during the 3-hour trial period. For the first six samples, the sampling interval was set at 5-min intervals. Following that, a time interval of 30 min was set for the remaining samples. Each sample event required the collection of 5 mL aliquots. A rigorous filtration procedure was carried out to ensure the integrity of the collected samples and subsequent analyses. The samples were passed through 0.22 µm filter firmly connected to a syringe before to storage in amber glass vials to remove any particle matter and ensure the purity of the samples for proper analysis. A stock solution of four different concentrations was prepared, concentrations of 100, 50, 25, and 10 mg L^{-1}. These concentrations were carefully adjusted, from which a succession of dilution steps were carried out in a methodical manner to match the capabilities of the equipment and the established Brilliant Green calibration curve. Following the dilution process, the remaining BG concentrations in the samples were quantified with UV Spectrophotometer at a maximum absorption (max) wavelength of 629 nm. The concentration of treated samples was set on calibration curve basis, developed by the UV spectrophotometer, which ultimately provided the final concentration in mg L^{-1}.

$$y = mx \pm c \qquad (2)$$

In equation (2), y represents UV-Absorbance value, x is the concentration of sample used to analyze, m represents the slope, and c is the intercept value.

Notably, the remaining sample concentrations were calculated using the equation derived from equation **Error! Reference source not found.**, as illustrated by the following equation:

$$x = \frac{y - c}{m} \qquad (3)$$

The adsorption capacity is calculated using the following equation.

$$q_e = \frac{(C_o - C_t) \times V}{m} \qquad (4)$$

In above equation, C_o represents the starting concentration of BG dye, C_t represents the dye concentration at time interval t, V is the volume of the solution in L, and m is the mass of the adsorbent in grams.

The Adsorption efficiency or percentage removal efficiency of the adsorbent is calculated using the following equation:

$$\% \, Removal = \frac{(C_o - C_t)}{C_o} \times 100 \qquad (5)$$

In this equation (5), C_o is the dye initial concentration whereas C_t is the dye concentration at any time (t).

2.8. Optimization Studies

A series of optimization studies were carried out to completely examine the influence of numerous parameters and determine ideal conditions for adsorption tests. These investigations included varying the concentrations of Brilliant Green, adsorbent dosages, and pH levels in the working solutions.

2.8.1. Experiments of Adsorbate Concentrations

The initial concentration of the adsorbate, BG in this example, has a considerable impact on the adsorbent's adsorption capability (Rashid et al., 2021). To learn more about how the initial concentration of BG affects the adsorption process, 100 mL working solutions with varied concentrations of BG, from 10 to 100 mg L^{-1}, were taken. Each solution was poured in a beaker and supplemented with 1 g of adsorbent. In accordance with the aforementioned technique, this experimental design aided in understanding how varying BG concentrations influenced adsorbent binding capacity and performance. Notably, the leftover concentrations from each experiment were analyzed using a UV-Vis spectrophotometer.

2.8.2. Experiments on Dose of Adsorbent

An inquiry was also conducted to investigate the effect of adsorbent dose on the adsorption process and the ideal dose for maximal adsorption. A series of 100 mL solutions containing 50 mg L^{-1} of BG dye were created. The adsorbent was then added to these solutions in varied amounts, ranging from 0.25 to 1.5 g L^{-1}. Assessing the link between adsorbent dose and adsorption efficiency is critical for determining the optimal dose that maximizes adsorption while preventing overloading or inefficiencies.

2.8.3. Experiments with Different pH

Solution pH plays a vital role and is much important factor in the adsorption process. pH of the solution has a direct influence over the charge properties of both the adsorbent and adsorbate molecules. This has far-reaching consequences for their interaction, adsorption capacity, and overall adsorption behaviour. Therefore, pH fluctuations provide useful insights into their impact on adsorbed quantity and adsorbent molecule dissociation behaviour. A series of six separate working solutions, each with a 100 mg L^{-1} concentration, were methodically createdin this context. Using 0.1M hydrochloric acid (HCl) and sodium hydroxide (NaOH), the pH of these solutions was adjusted to levels: 3, 5, 7, 8,9, and 11 (**Figure 7**). The method followed the aforementioned approach, with an adsorbent dosage of 0.5 g L^{-1} remaining constant. The solutions were then continuously stirred for 3 hours, with 5 mL aliquots sampled at varied time intervals.

Figure 7: *Adjusting pH of the BG dye solution for adsorption.*

2.8.4. Experiments for Determination of Point of Zero Charge

The idea of the isoelectric point (IEP) or point of zero charge (pH_{ZPC}) is critical to understanding adsorption dynamics. The adsorbent surface is normally positively charged below the IEP, but it gains a negative charge above its pH_{ZPC}. The examination of pH_{ZPC} aids in understanding the surface charge behaviour of the adsorbent, which influences the electrostatic attraction and repulsion forces driving the adsorption process in conjunction with solution pH. The addition of salt method was applied in the study to determine the pH_{ZPC}. To begin, a 20 mL KCl solution with a molarity of 0.1 was produced. The solution pH was systematically varied by altering the pH throughout a range of 3 to 11, using the identical hydrochloric acid (HCl) and sodium hydroxide (NaOH) solutions as in the preceding section. Following that, 20 mg of previously prepared activated carbon was added. The adsorbent dose was kept constant at 1 g L^{-1}, and the mixture was left undisturbed for 24 hours in a dark environment. The pH of each solution was tested after 24 hours, and the results were plotted against the original pH values (Li et al., 2020).

2.8.5. Thermodynamic Studies

Four BG dye solutions with 50 mg L-1 and a volume of 100 mL were created. PPAC, BAC and IOB-AC adsorbents were used in the experiment. In the flask holding the dye solution, 50 mg of each adsorbent was added. The purpose of the study was to look into the temperature effect on the adsorption process. Temperature adjustments of 60°C, 50°C, 40°C, and 30°C were applied to all four flasks (**Figure 8**). The flasks were shaken for three hours. Following the shaking period, samples from each flask were taken and analysed with a UV- visible spectrophotometer. The goal of this work was to see how different temperatures affectthe BG dye adsorption by the two adsorbents, PPAC and BAC.

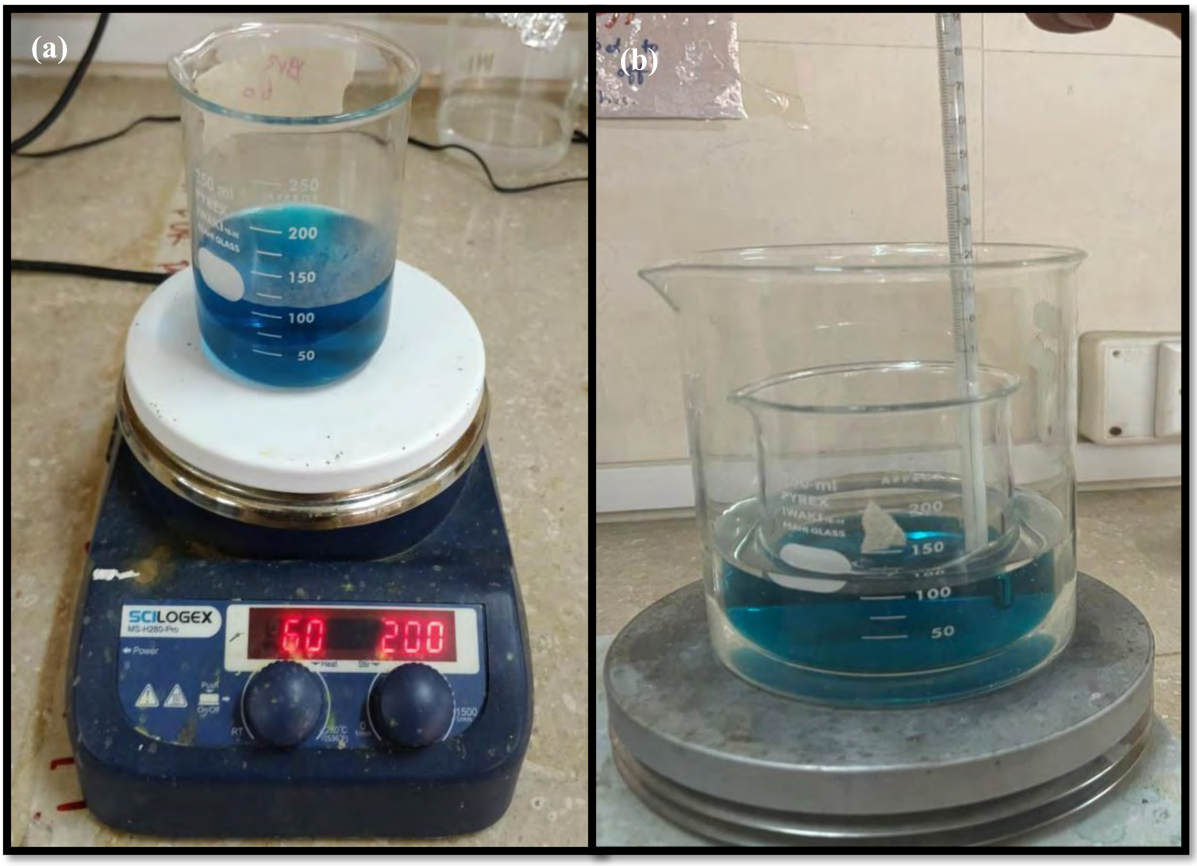

***Figure 8**: Thermodynamic studies (a) adjusting temperature on hot plate (b) solution temperature measurement.*

2.1.1. Reusability Studies

There are numerous methods for reviving spent adsorbents, but the solvent desorption technique is the most popular due to its cost-effectiveness and efficiency in the regeneration process (Baskar et al., 2022). Using this unique regeneration method, the reusability of pristine biochar (PPAC), beetroot-derived activated carbon (BAC) and iron oxide plus beetroot acticated biochar (IOB-AC) was evaluated. During the operation, the adsorbent saturated with contaminants was agitated at an ambient speed of 80 rpm for 2 h. Following this vigorous desorption phase, the mixture was filtered using conventional filter paper and dried in an oven. This regenerated material was then used in up to five sequential adsorption-desorption cycles to assess its potential for reuse (Santhosh et al., 2020).

3. Results and Discussion

3.1. Results of Characterization Studies

3.1.1. FTIR Analysis

The surface functional groups of biochar produced from *Parthenium hysterophorus* (PPAC) and its modified forms, comprising iron oxide and beetroot activated carbon (IOB-AC) and beetroot activated carbon (BAC), were determined using FTIR spectra. **Figure 9** (a) and (c) for PPAC and BAC each showed seven distinct peaks, while **Figure 9** (b) for IOB-AC showed six, the values of which are provided in Table 1. These varying peaks reflect the adsorbents' complex composition. Signals ranging between 3200 and 3600 cm^{-1} highlights hydroxyl groups presence, either free or intermolecularly attached. These hydroxyl groups could be linked to organic acids, alcohols, or phenolic compounds, as well as vibrations from O-H bonds with hydrogen bonds. Alkane C-H stretches are visible at 2929 cm^{-1} for PPAC and 2921 cm^{-1} for BAC, resulting in a faint band, whereas an alkene double bond stretch appears at 3152 cm^{-1} for BAC (Bedada et al., 2020). Peaks for PPAC, IOB-AC, and BAC at 1600, 1611, and 1613 cm^{-1}, respectively, correlate to C=C presence, which is normally in the 1500 to 1600 cm^{-1} range. The minimal O-H bond bending range is around 1395-1440 cm^{-1}. The presence of C-X, C-Cl, and C-H groups is suggested by bands at 872 and 781 cm^{-1} for PPAC and 873 and 781 cm^{-1} for BAC. Peaks at 582, 586, and 579 cm^{-1} for PPAC, IOB-AC, and BAC indicate the presence of a C-X bond, either C-Cl or C-Br, across all adsorbents. Notably, IOB-AC frequencies 586 and 433 cm^{-1} emphasize the Fe_3O_4 stretch, confirming the presence of magnetite on the biochar surface (Liang et al., 2020; Fito et al., 2023). These peaks represent the multiple functional groups on the adsorbent's surface that can interact with different solute molecules in a solution. (Libretexts, 2020)

Table 1*: Functional groups' peaks observed in FTIR.*

Adsorbents	Functional Group Region			Fingerprint Region			
PPAC	3417.04	2920.72	1600.57	1412.26	872.91	781.76	582.40

IOA-BC	3412.59	3153.07	1611.63	1403.17	586.97	433.83	-
BAC	3423.65	2921.87	1613.88	1413.91	873.37	781.51	579.73

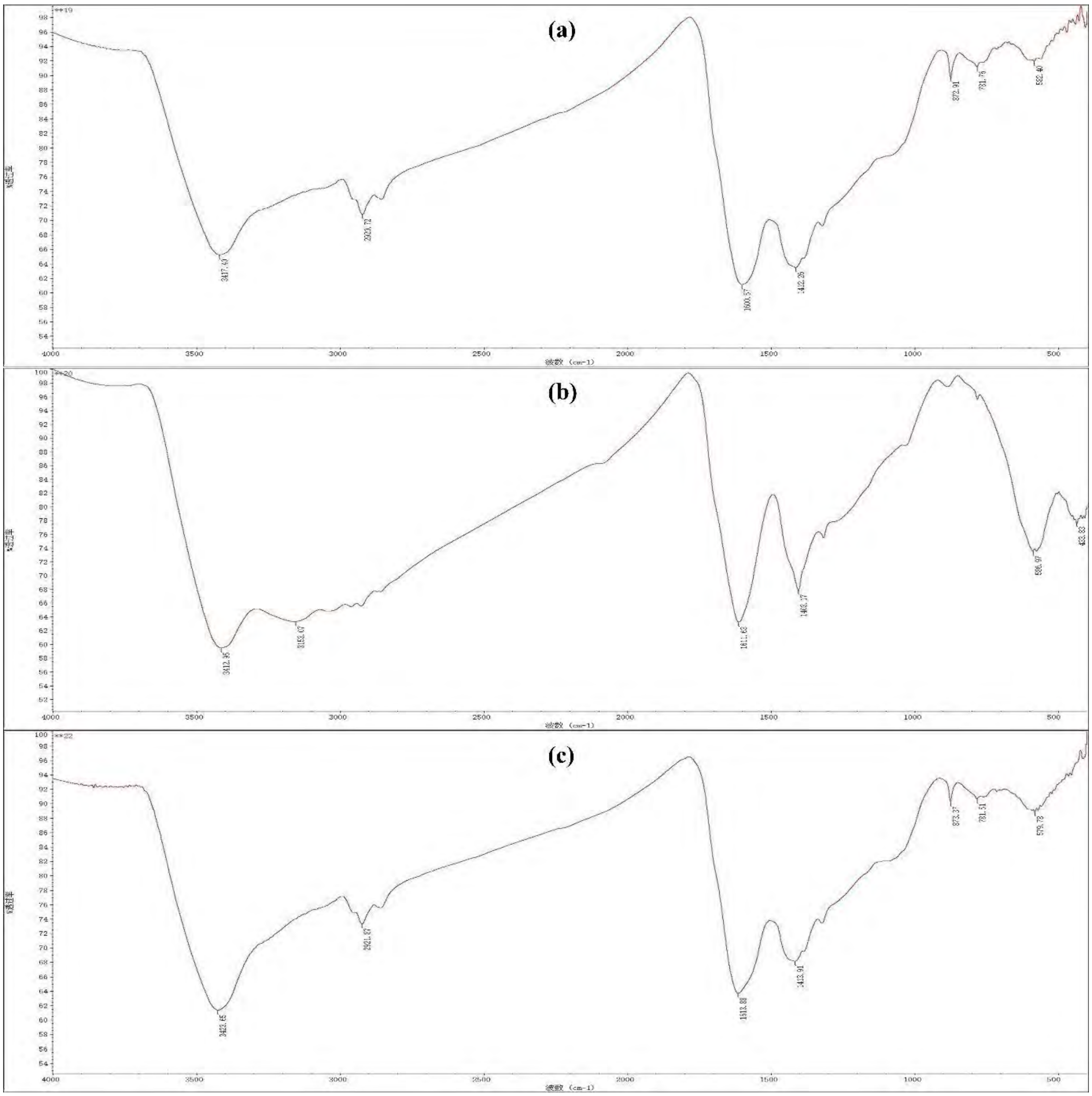

***Figure 9**: FTIR patterns for (a) pristine biochar, (b) iron oxide and beetroot activated carbon, and (c) beetroot activated carbon.*

3.1.2. SEM Analysis

SEM was used to examine the surface structures of biochar from *Parthenium hysterophorus* (PPAC), a mixture of iron oxide and beetroot activated carbon, and simply beetroot activated carbon before they were used in adsorption. **Figure 10** shows the SEM visualizations. The pictures from the SEM investigation of PPAC at a 10-micrometer scale revealed a variety of pore sizes and configurations. **Figure 10** (a) depicts a remarkable uneven surface on the composite adsorbent, filled with several features mimicking a honeycomb structure, such as cavities, ruptures, voids, and more. **Figure 10** (b), on the other hand, shows a pattern of channels and fissures, indicating a crystalline character. These surface characteristics help to improve adsorption (Bedada et al., 2020). This suggests that high temperatures employed in carbonization and calcination cause the release of volatile components from the interior structure of the particle, resulting in pore development on the adsorbent.

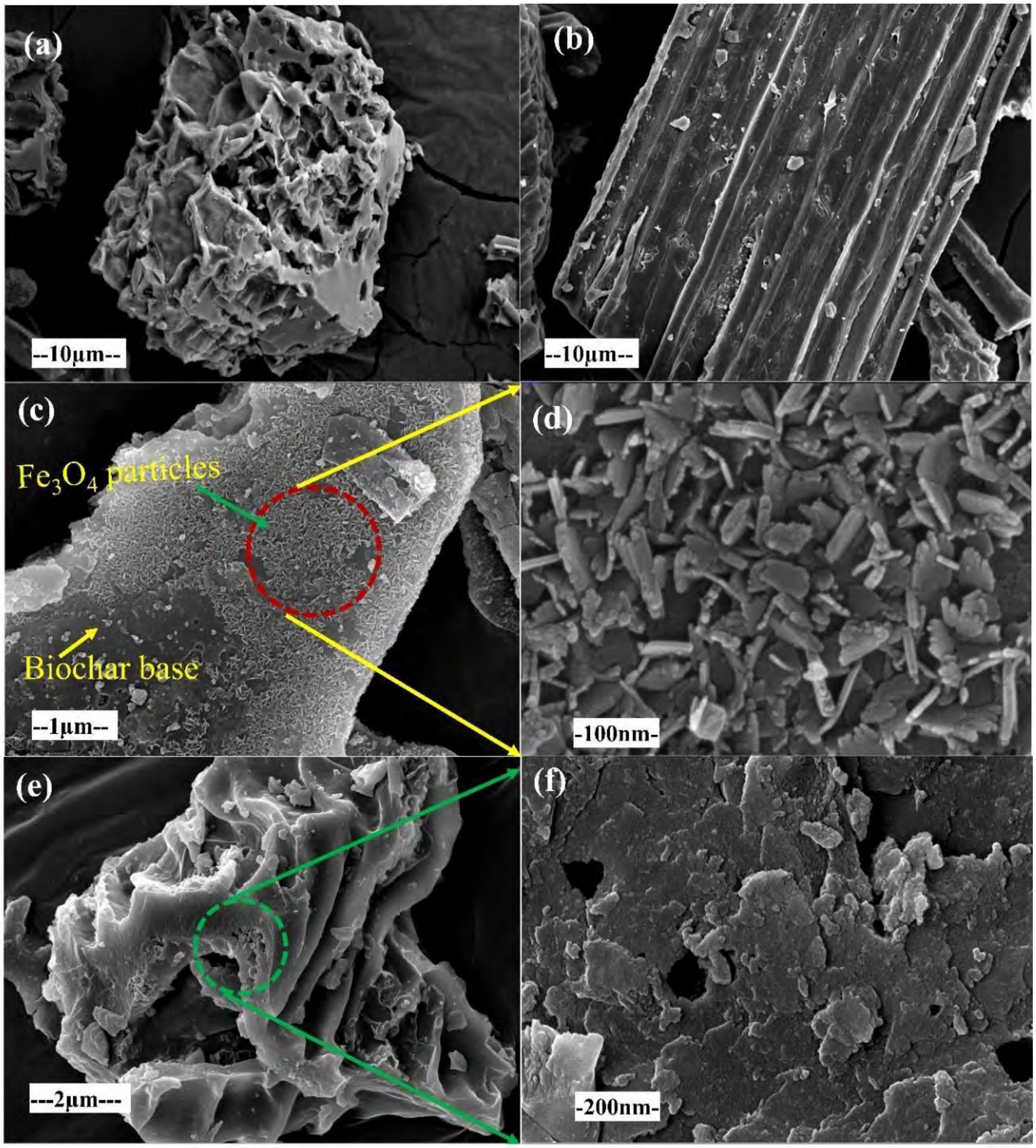

***Figure 10**: SEM determining surface morphology of (a) PPAC-surface image (b) PPAC-longitudinal image (c) IOB-AC- surface image (d) Fe_2O_3 attached to the PPAC surface (e) BAC-surface image (d) BAC- surface image at 200 nm.*

The attachment of iron oxide particles to the biochar base is highlighted in SEM images for IOB-AC, resulting in an increased porous and coarse surface (Fito et al., 2023). An uneven surface of the adsorbent typically improves effective pollutant removal from aqueous solutions (Ighalo & Adeniyi, 2020). The SEM images of BAC show a varied pore architecture with a rough surface texture. The obvious clumping and presence of numerous channels demonstrate to the varied character of BAC, likely assisting in the adsorption of dye molecules (Rashid et al., 2019).

3.1.3. XRD Analysis

The XRD traces for PPAC, IOB-AC and BAC are shown in **Figure 11**. Across all examined samples, the diagram displays more wide peaks and less sharp peaks indicative of graphitic carbon. The lack of identifiable diffraction peaks in PPAC and BAC indicates that the carbon compounds generated are non-crystalline, as also shown by SEM images (Rashid et al., 2019), contradictory to the sharp peaks with crystalline carbonaceous structure reported in a prior study (Mondal et al., 2016). The crystalline characteristics of the iron oxide particles were validated by X-ray diffraction of the iron oxide and beetroot activated sample. Specific diffraction peaks and related Miller indices were observed at 2 theta alues of 30.2° (220), 35.5° (311), 43.21° (400), 54° (422), and 66° (511). In addition, a slight, widened peak within the 2 theta range of 20° to 25° developed, indicating the presence of magnetic nanoparticles on activated carbon surfaces. The overall pattern for IOB-AC has somewhat blurred peaks, indicating a semi-crystalline shape (Jain et al., 2018; Fito et al., 2023).

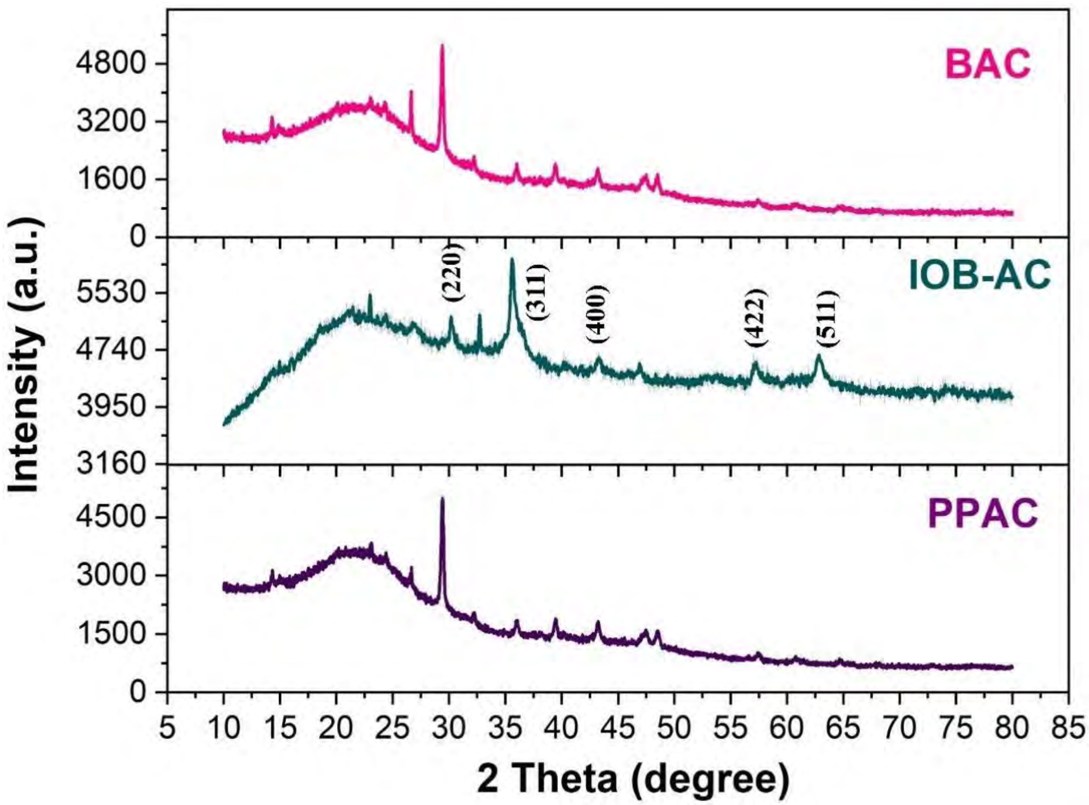

***Figure 11**: XRD analysis of PPAC, IOB-AC, and BAC.*

3.1.4. EDS Analysis

Figure 12 (a), (b), and (c) show how EDS analysis was used in conjunction with SEM to identify the elemental composition and distribution of PPAC, IOB-AC, and BAC. PPAC's EDS data showed peaks for C and O, which corresponded to its botanical sources. The elemental distribution of IOB-AC demonstrated the presence of Fe, confirming the incorporation of iron oxide into the biochar. A minor N signal in BAC's EDS data suggested the presence of organic substances, along with other discovered elements such as K, P, S, Ca, and O. This shows that the carbonization temperature was chosen to convert the plant into biochar while preserving its elemental content and adsorptive capacity.

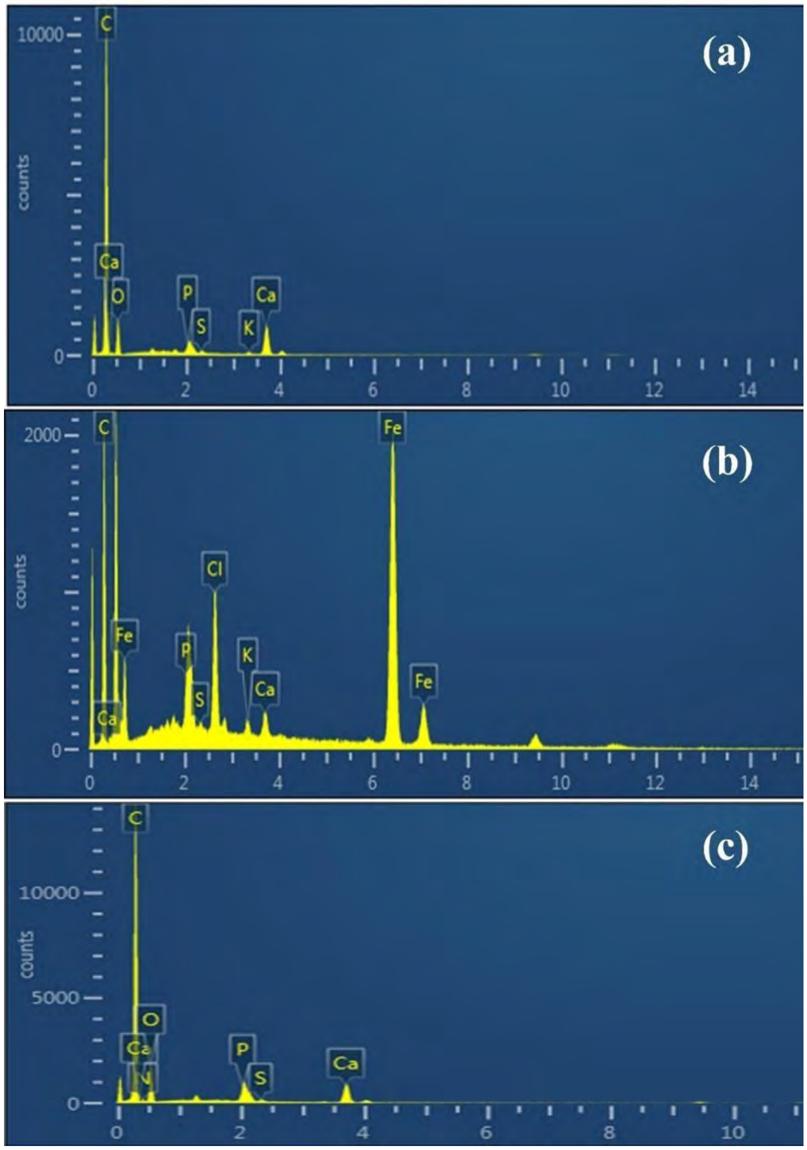

Figure 12*: Elemental mapping of (a) PPAC (b) IOB-AC and (c) BAC.*

3.2. Curve of Brilliant Green (BG) Dye

The calibration curve for the brilliant green dye using a UV-VIS spectrophotometer demonstrated a linear connection, as shown by the equation y = 1.548x - 0.0067, where 'y' represents absorbance and 'x' indicates concentration (**Figure 13**). The line's slope (m) was calculated to be 1.548, and the y-intercept (c) was calculated to be -0.0067. The coefficient of determination (R^2) for this calibration curve was calculated to be 0.9937, showing a significant association between absorbance readings and brilliant green dye concentrations. The UV-VIS spectrophotometer allowed for spectral scanning of the samples in a range of 200 to 800 nm wavelength. Notably, the greatest measurable concentration of brilliant green dye was 25 mg L^{-1} using this system.

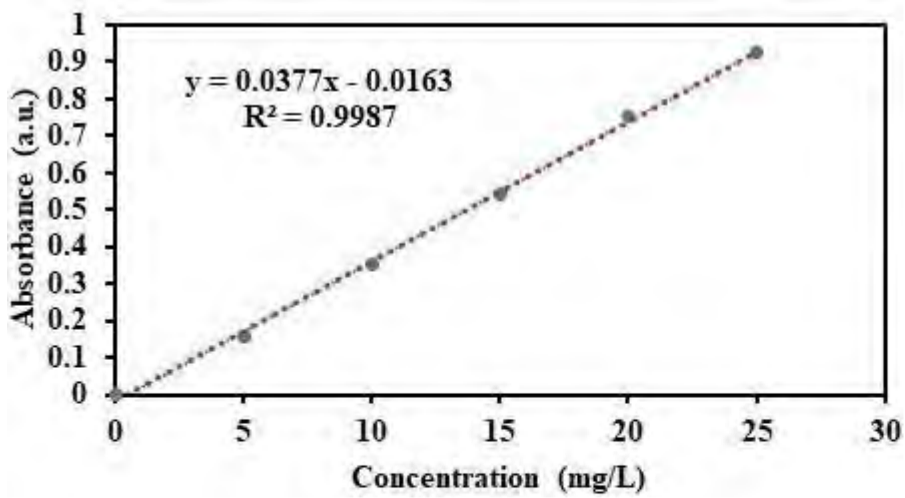

***Figure 13**: Calibration curve of BG dye.*

3.3. Effect of Initial Concentration of Brilliant Green on Adsorption

The adsorption behaviour of Brilliant Green dye onto three different adsorbents, namely PPAC, BAC, and IOB-AC, was investigated in this study where four different initial dye concentrations were used: 10, 25, 50, and 100 mg L^{-1}. The initial dye concentrations have a substantial influence on BG dye adsorption. This is consistent with previous research, which emphasizes the importance of initial dye concentration in dye removal effectiveness and adsorbent capacity (Pandey et al., 2020). The availability of active adsorption sites on the adsorbent's surface was shown to be related to the initial dye concentration. The **Figure 14** (a, b) in the study shows the influence of BG dye concentrations on the efficiency and capacity of the adsorption (qe) of pristine Parthenium activated carbon (PPAC) adsorbent. For example, while studying the adsorption of BG dye onto PPAC, discovered that the adsorption effectiveness was inversely proportional to the starting concentration of the dye. At a constant adsorbent dosage of 1 g L^{-1}, the percentage removal of BG dye decreased as its starting concentration in the solution increased between 10 and 100 mg L^{-1}. The percentage removal declined from 78.7% at an starting concentration of 10 mg L^{-1} to 34.71% at an

initial concentration of 100 mg L^{-1}. Furthermore, the adsorption capacity (qe) of PPAC changed as the original dye concentration changed. When the starting dye concentration was 100 mg L^{-1},adsorption capacity (qe) of 34.29 mg g^{-1} was observed. At an initial dye concentration of 10 mg L^{-1}, the qe value of 7.87 mg g^{-1} was observed.

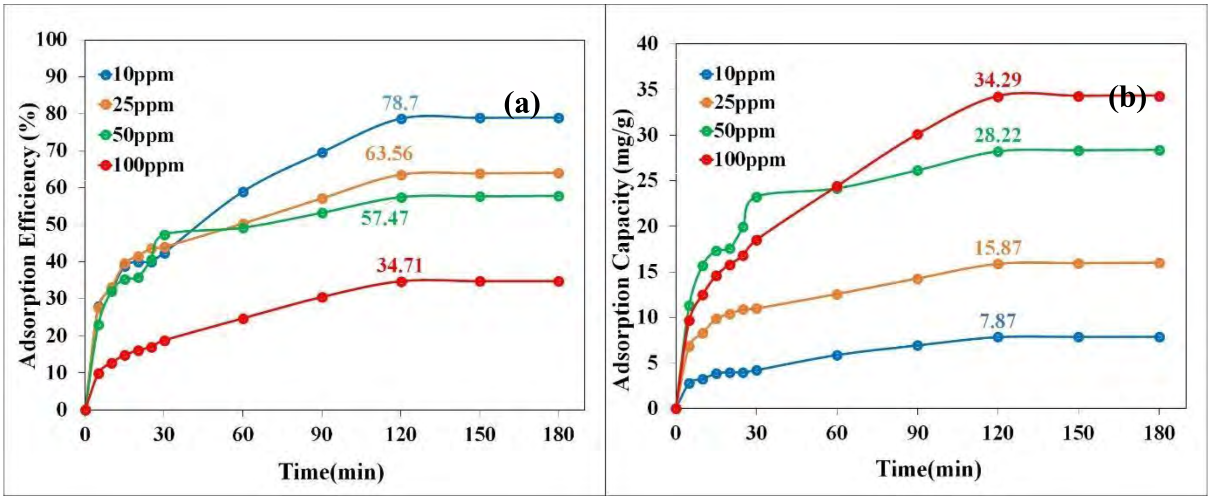

***Figure 14**: Adsorption of BG dye at different concentrations using PPAC (a) adsorption efficiency of PPAC, and (b) adsorption capacity PPAC.*

The research was expanded to look at the adsorption properties of Brilliant Green (BG) dye utilizing Beetroot Activated Carbon (BAC) as an adsorbent. The primary goal was to determine the % removal and adsorption capacity under various initial dye concentrations. Upon closer inspection, a distinct pattern emerged, that is, the percentage removal of BG dye decreased with increasing pollutant concentrations. At a constant adsorbent dosage of 1 g L^{-1}, this result was regularly seen. **Figure 15** (a, b) show that the percentage removal by BAC decreased from an initial concentration of 10 mg L^{-1} to 100 mg L^{-1}. The percentage removal decreased from 79.3% to 41%, demonstrating that the initial BG content influenced dye removal efficiency. The evaluation of BG dye adsorption capacity (qe) using BAC revealed a similar reliance on starting dye concentrations. Notably, when the starting dye concentration was 100 mg L^{-1}, the highest adsorption capacity (qe) of 40 mg g^{-1} was reached. When the initial dye concentration was set to 10 mg L^{-1}, the minimum qe value of 8 mg g^{-1} was obtained. These findings are consistent with previous research, which suggests a negative relationship between dye removal and initial dye concentration. This is due to the existence of binding sites on the surface of the adsorbent. These binding sites stay empty when the initial dye concentrations are modest. As a result, as the concentration of the dye molecules increases, these active binding sites become insufficient, resulting in a decrease in the percentage of dye removal (Piri et al., 2019).

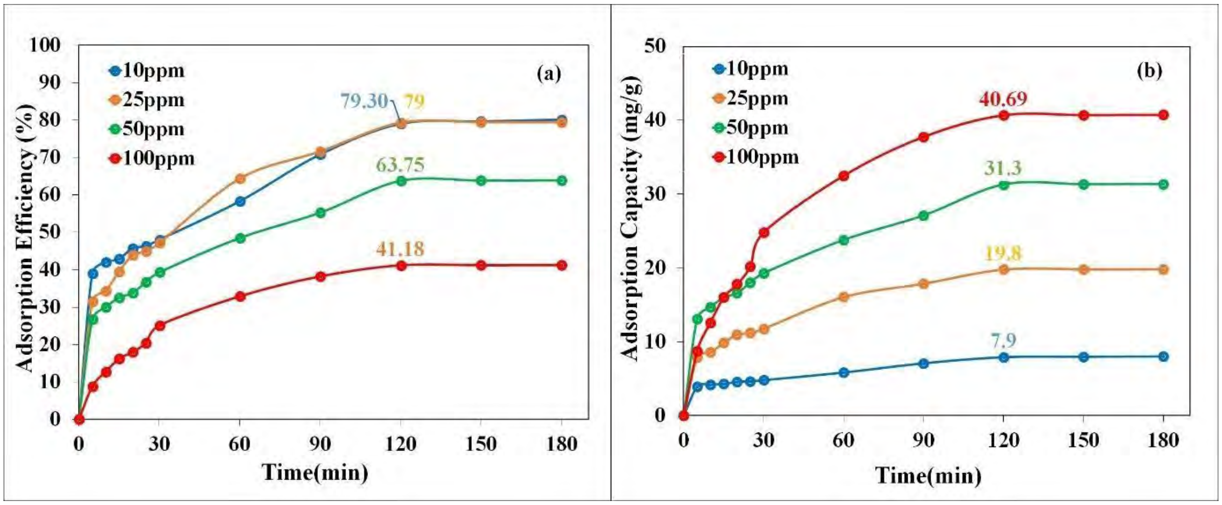

Figure 15: *Adsorption of BG dye at different concentrations using BAC (a) adsorption efficiency of BAC, and (b) adsorption capacity of BAC.*

The adsorption behaviour of Brilliant Green (BG) dye was also investigated in a similar context using iron oxide plus beetroot activated carbon (IOB-AC) as the adsorbent. The major goal was to determine the % removal and adsorption capacity while considering differences in the starting dye concentrations and comparing the efficiency of removal compared to PPAC and BAC. Trends observed for percentage removal and adsorption efficiency were similar to previous results. Error! Reference source not found. (a, b) s how that the percentage removal decreased from an initial concentration of 10 mg L^{-1} to 100 mg L^{-1}. This percentage shift was seen to be from 78.48% to 35.86%. This indicated that the influence of the starting concentration of BG dye on the efficacy of removal by IOB-AC was better than PPAC but not as efficient as BAC. This could be related to its characterization results. EDS revealed the incorporation of Fe element IOB-AC; however, no functional group of Fe was observed according to FTIR analysis. This shows that though Fe became a part of IOB-AC, it was unsuccessful at forming enough bonds and functional groups to facilitate and enhance adsorption capacity compared to BAC.

Notably, the adsorption efficiencies of PPAC, BAC, and IOB-AC peak at initial dye concentration of 50 mg L^{-1}, with 57.47%, 63.75%, and 65.41%, respectively. This attention is thought to be more practical and applicable in real-world situations. At 50 mg L^{-1} starting dye concentration, the adsorption capacities of these adsorbents are also high, measuring 28.2 mg g^{-1}, 31.3 mg g^{-1}, and 32.34 mg g^{-1} respectively. Considering the removal efficiencies, these results outperform those obtained with an initial dye concentration of 100 mg L^{-1}. Overall, the selection of 50 mg L^{-1} as the ideal beginning dye concentration is supported by improved adsorption efficiency and capacity values for all three adsorbents, indicating a more realistic and relevant scenario (Fito et al., 2023). This practical approach is congruent with the limitations of wastewater treatment environments and emphasizes the critical relationship between theoretical research and practical utility.

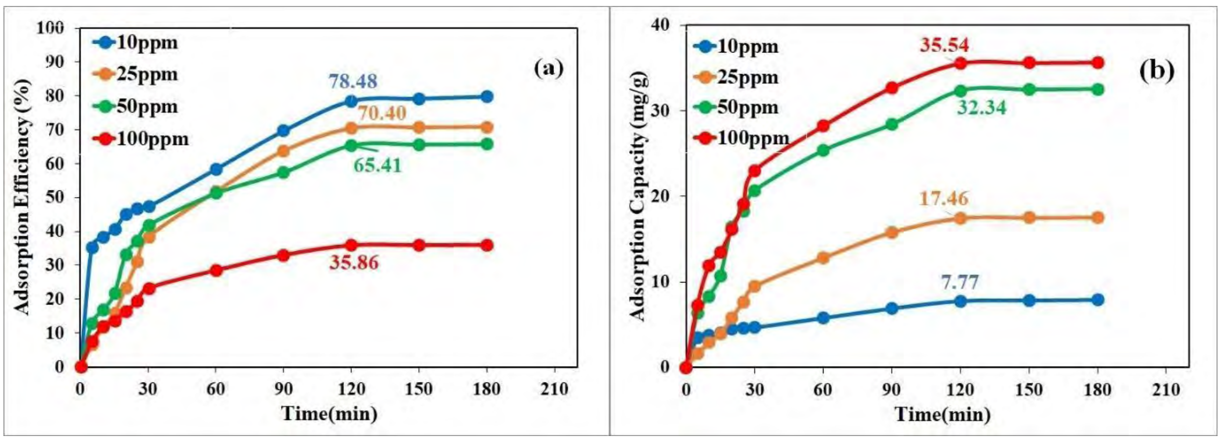

Figure 16: *Adsorption of BG dye at different concentrations using IOB-AC (a) adsorption efficiency of IOB-AC, and (b) adsorption capacity of IOB-AC.*

3.4. Determination of Point of Zero Charge

The salt addition method was used to determine the point of zero charge (pH_{PZC}) for pristine Parthenium activated carbon, and beetroot activated carbon, as shown in **Figure 17** (a, b, and c). This approach identifies the pH values at which the surfaces of these adsorbents have no net charge. The pH_{PZC} was determined to be 7.79 for PPAC, 7.85 for BAC, and 7.88 for IOB-AC. These observations are significant because they reveal the pH values under which adsorbents' surfaces remain un-charged. Furthermore, this understanding reveals that the surfaces of the adsorbents have a positive charge below the pH_{PZC} values, and a negative charge above these pH values (Kosmulski, 2020). This dual nature of charge provides vital insight into the adsorbents' electrochemical capabilities, offering light on their behaviour in a variety of pH situations which is discussed further in next section.

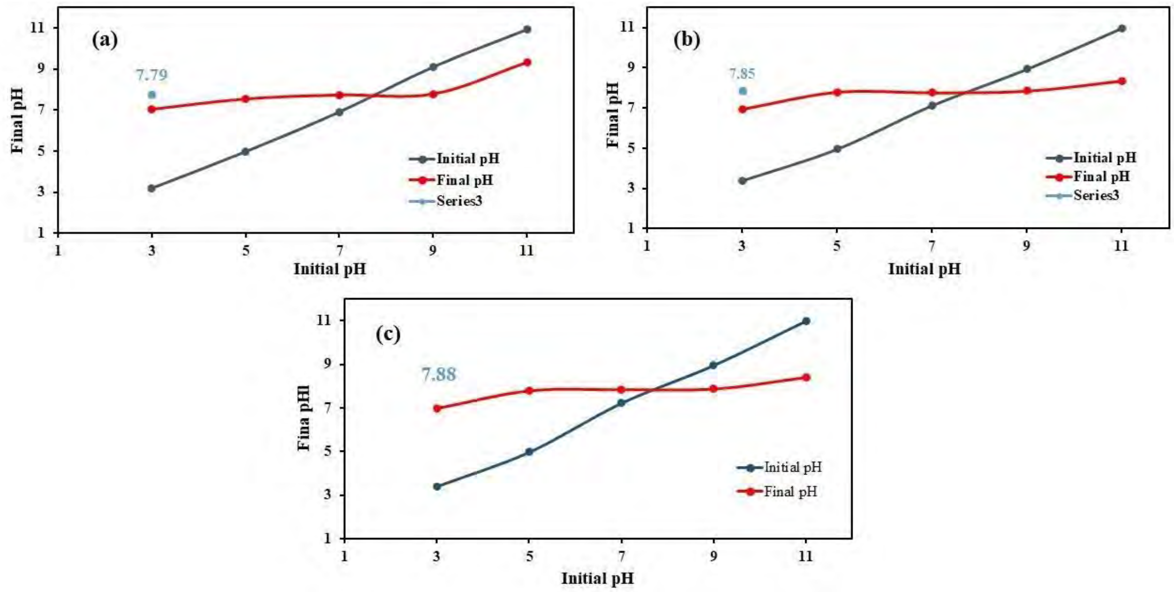

***Figure 17**: Determination of point of zero charge for (a) PPAC, (b) BAC, and (c) IOB-AC.*

3.5. Effect of Solution's pH on Adsorption

The importance of solution pH in dye adsorption in wastewater cannot be overstated, as it is one of the most important variables in the adsorption process. The importance of pH on both percentage removal and adsorption capacity is undeniable, as changes in solution pH cause significant fluctuations in the solubility of dye and the quantity of dye removal. To further analyze this, a range of pH levels ranging from 3 to 11 were examined to determine ideal settings. **Figure 18** (a, b), **Figure 19** (a, b), and **Figure 20** (a, b) show the effect of pH on the removal of BG dye using PPAC, BAC, and IOB-AC adsorbents.

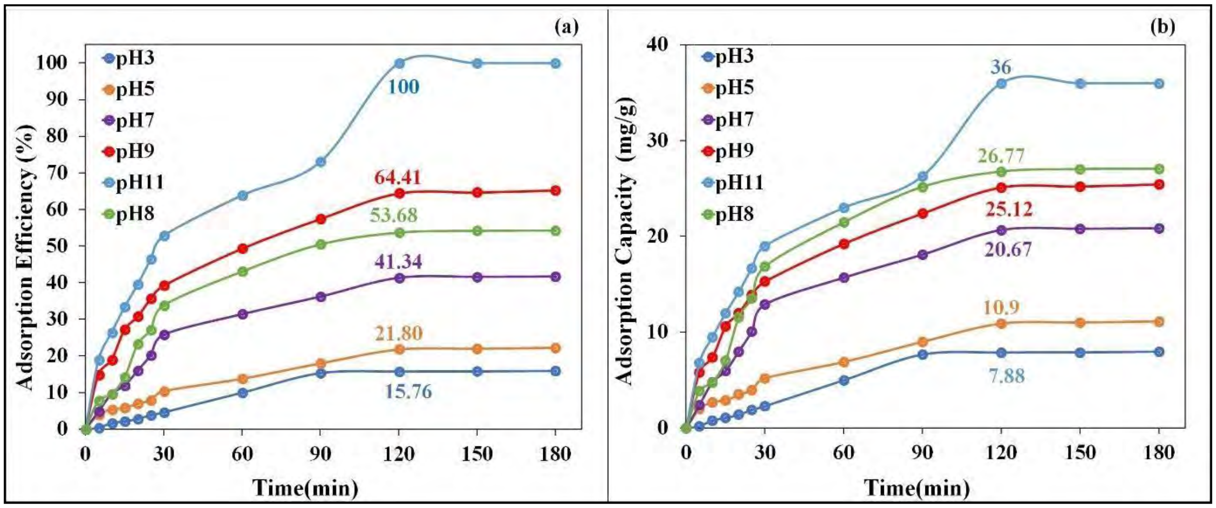

***Figure 18**: Adsorption of BG dye at different pH using PPAC (a) adsorption efficiency, and (b) adsorption capacity.*

Figure 18 (a and b) show the adsorption efficiency and capacity of BG dye using PPAC at pH ranges ranging from 3 to 11. At pH 11, the percentage removal achieved by PPAC was observed to be 100%. Whereas only 15.76% removal of dye was observed at the lowest pH value of 3, indicating an unfavorable adsorption in acidic environment. Similarly, the peak adsorption capacity for PPAC was at basic conditions (pH 11), witha value of 36, while the adsorption capacity with lowest results was at acidic conditions (pH 3), with avalue of 7.88 mg g^{-1}.

Figure 19 and **Figure 20** demonstrate the patterns of BG dye removal by BAC and IOB-AC, with the maximum percentage removal of 100% at pH 11 with both adsorbents. At pH 3, the least dye removal of 21.22% and 18.84% was observed, respectively. Adsorption capacity followed a similar pattern to % removal, peaking at pH 11 and troughing at pH 3 (Samiyammal et al., 2022).

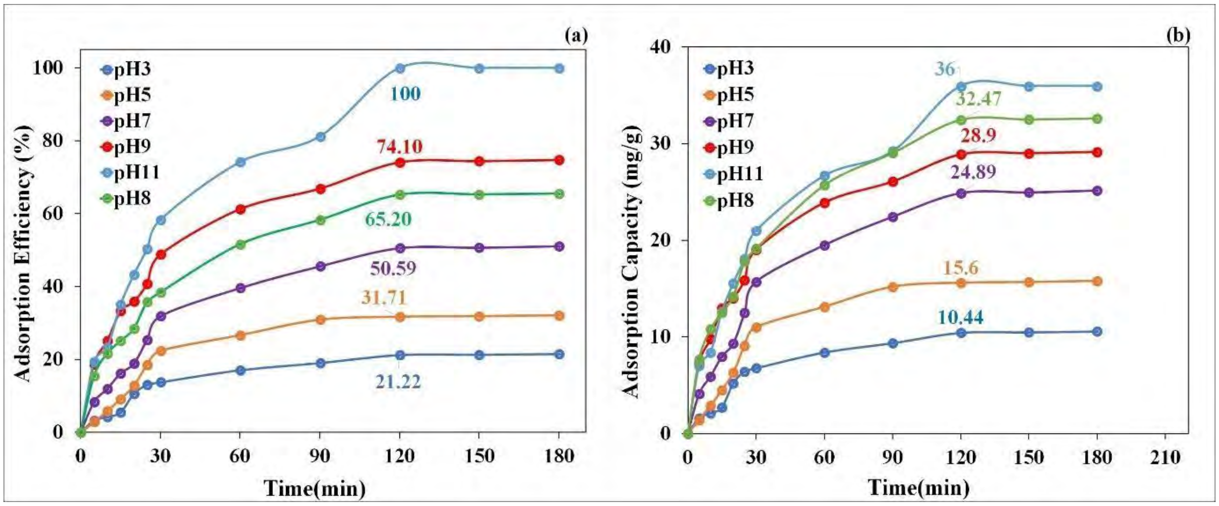

Figure 19: *Adsorption of BG dye at different pH using BAC (a) adsorption efficiency, and (b) adsorption capacity.*

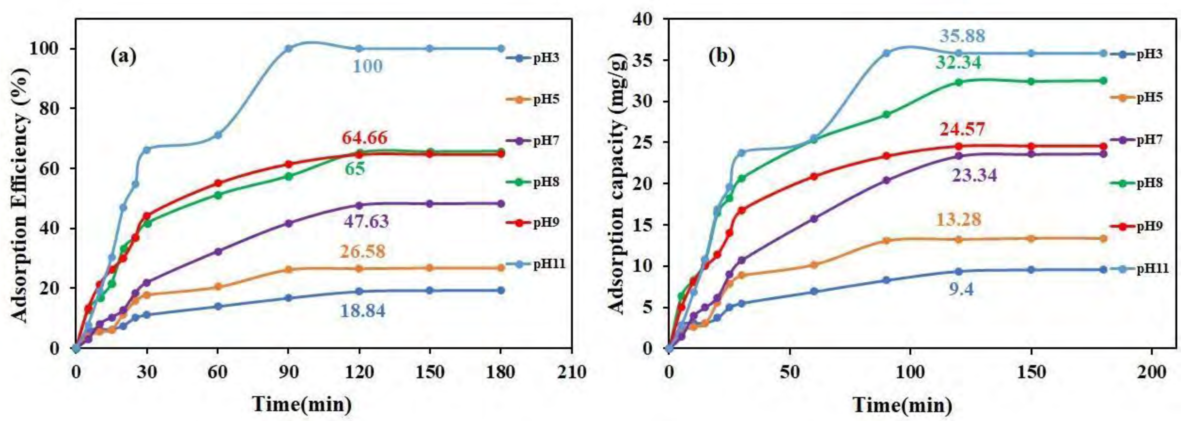

Figure 20: *Adsorption of BG dye at different pH using IOB-AC (a) adsorption efficiency, and (b) adsorption capacity.*

An in-depth review of the data in the table reveals an interesting trend involving dye solubility as influenced by pH levels. As the pH scale progresses beyond 8, there is a substantial drop in dye solubility. This drop in solubility corresponds directly to a decrease in the initial concentration of dye available for research (Baidya & Kumar, 2021). At pH 9, the starting dye concentration drops to 39 mg L^{-1}, and at pH 11, it drops even more to 36 mg L^{-1}. This finding highlights a clear relationship between increasing pH and decreasing dye solubility. This phenomenon is critical to comprehending the reported changes in % dye removal at various pH values. Notably, the percentage removal of the dye is reduced at pH 9 and 11 as compared to pH 8. This is due to the increased starting concentration of Brilliant Green (BG) dye at pH 8. Essentially, when pH rises, dye solubility decreases, reducing the available initial dye concentration and, as a result, the efficiency of dye removal (Baidya & Kumar, 2021). This discovery adds to our understanding of the relationship between pH, dye solubility, and the percentage removal achieved, shedding light on the many nuances of the adsorption process.

3.6. Effect of the Dose of Adsorbent on Adsorption

The adsorption capacity of an adsorbent is determined by its dosage, which is an important component in determining the efficacy of dye removal with minimal adsorbent quantities. To investigate this, the experiment used a variety of adsorbent dosages ranging from 0.25 g L^{-1} to 1.5 g L^{-1}. The effects of altering adsorbent dosage on BG dye removal via PPAC, BAC, and IOB-AC are depicted in **Figure 21, Figure 22,** and **Figure 23**. Adsorption efficiency is observed to be minimum i.e., 20% for PPAC, 27.51% for BAC, and 24.50% for IOB-AC, at the lowest adsorbent dose of 0.25 g L^{-1}. Whereas the adsorption capacities are observed to be maximum at the absorbent's dose of 0.5 g L^{-1} in the order of BAC > IOB-AC > PPAC.

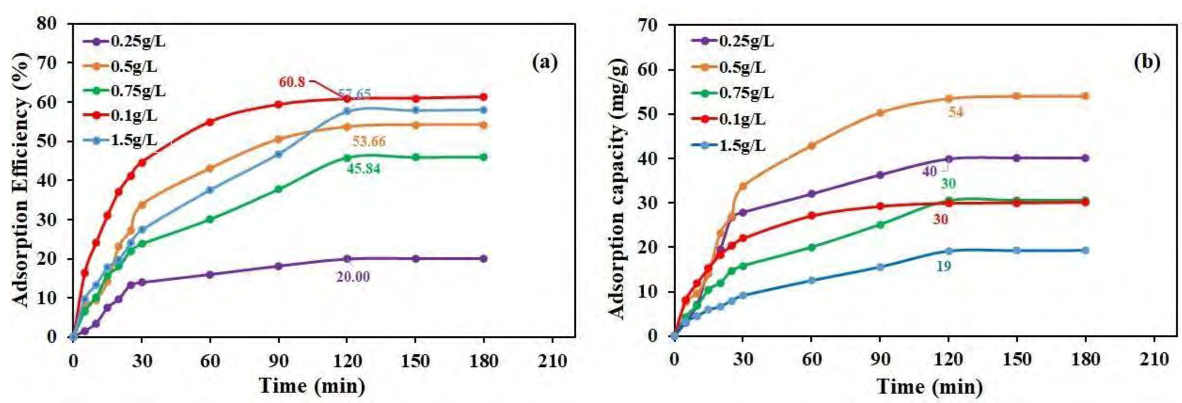

Figure 21*: Adsorption of BG dye at different doses of PPAC (a) adsorption efficiency, and (b) adsorption capacity.*

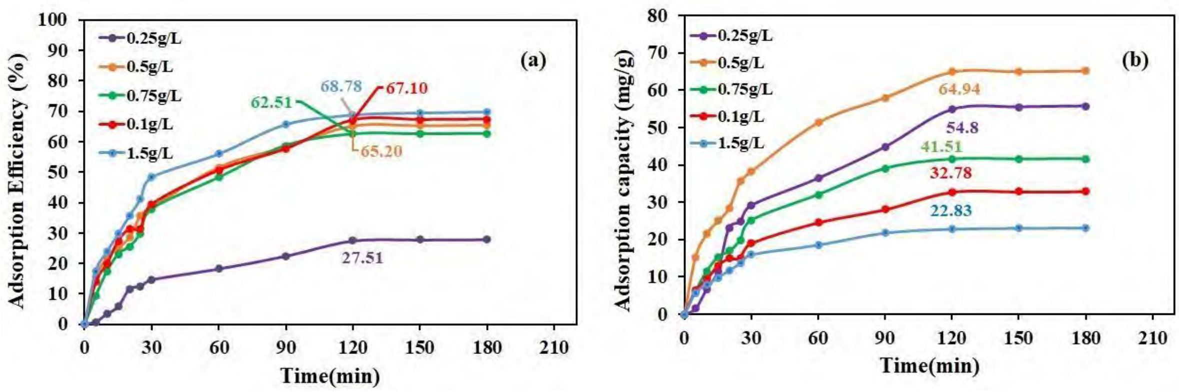

***Figure 22**: Adsorption of BG dye at different doses of BAC (a) adsorption efficiency, and (b) adsorption capacity.*

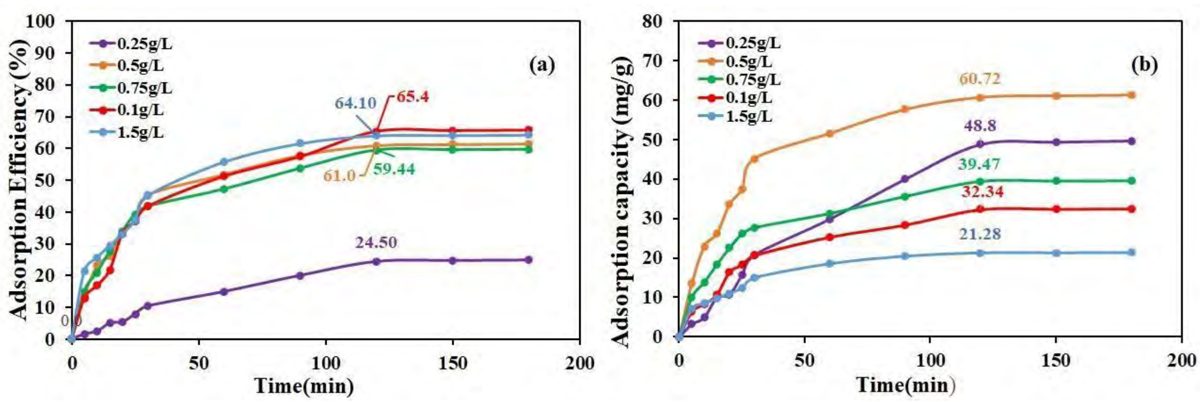

***Figure 23:** Adsorption of BG dye at different doses of IOB-AC (a) adsorption efficiency, and (b) adsorption capacity.*

The increased availability of vacant active sites on the adsorbent's surface can explain the trend toward higher percentage removal with increasing adsorbent dose. However, the decrease in adsorption capacity was noted due to the complex interplay between increased dose and dye molecule accessibility to the adsorbent. The deviation from the normal trend of increasing adsorption efficiency with increasing dose at 0.75 g L^{-1} and 1.5 g L^{-1} can be attributed to saturation of available active sites or increased competition among dye molecules for these active sites (Zaimee et al., 2021). This is consistent with previous findings, which emphasize that increased adsorbent dosage can decrease the rate ofadsorption per unit weight (Gupta et al., 2022; Yadav & Dasgupta, 2022).

Another important factor in selecting the appropriate adsorbent dose is its practical application in wastewater treatment. The initial doses used in this investigation were calculated to be 0.25, 0.5, 0.75, 1.0, and 1.5 g L^{-1}. The data visualization, as shown in the figures, demonstrates that the percentage removal, relative to the adsorbent dose, does not increase dramatically beyond the 0.5 g L^{-1} dose. Similarly, beyond this dose threshold, the adsorption capacity is significantly reduced. Furthermore, considerations extend to adsorbent's recovery for reusability, which becomes difficult at the 0.25 g L^{-1} dose. Taking these aspects into account, the dose of 0.5 g L^{-1} appears as the more practical option for treating BG dye-tainted wastewater. This discerning judgment considers the ideal mix of efficacy, practical application, and adsorbent reusability, embodying the multifaceted variables required for effective wastewater treatment solutions.

3.7. Effect of Temperature on Adsorption

The most suitable temperature solution for the adsorption of BG dye onto PPAC, BAC, and IOB-AC was investigated to determine if the process is endothermic or exothermic. For this purpose, the experiment was conducted at 4 different temperatures i.e., 30, 40, 50, and 60 ºC, with the initial BG concentration set at 50 mg L^{-1}, the pH kept at 8, and the adsorbent dose set at 0.5 g L^{-1}. **Figure 24**, **Figure 25**, and **Figure 27** show the effect of temperature on BG dye removal by PPAC and BAC adsorbents. **Figure 24** (a) depicts the effect of temperature on BG dye elimination via PPAC. Notably, the lowest temperature, 30°C (room temperature), yielded the best adsorption efficiency of 53.09%, while the highest temperature, 60°C, yielded the lowest percentage adsorption efficiency of 24.28%. **Figure 24** (b) compares the adsorption capability of PPAC for BG dye removal under various temperature conditions. The lowest qe value was 24.22 mg g^{-1} at 60°C, while the maximum qe value was 52.78 mg g^{-1} at 30°C.

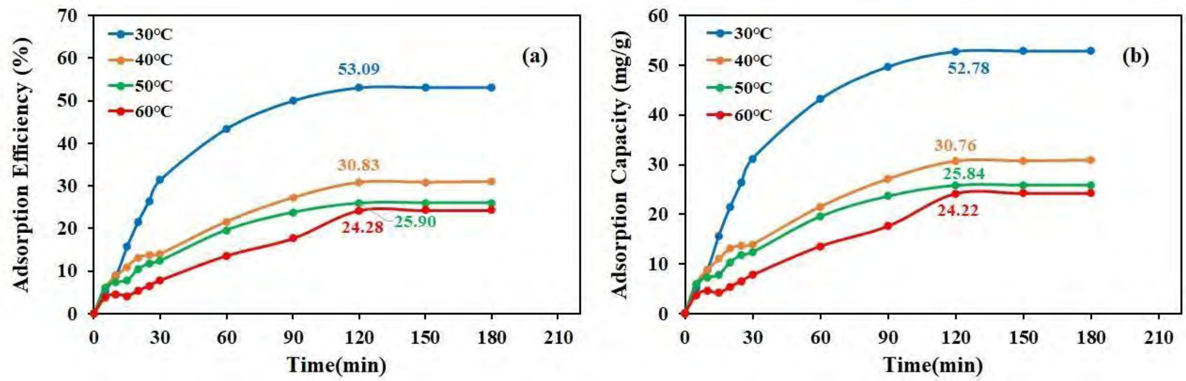

***Figure 24**: Adsorption of BG dye at different temperatures using PPAC (a) adsorption efficiency, and (b) adsorption capacity.*

Similarly, **Figure 25** (a, b) and **Figure 27** (a, b) shows how temperature affects BG dye elimination via BAC and IOB-AC, respectively. The largest percentage reduction of dye was achieved at the lowest temperature of 30°C, as shown in **Figure 25** (a) and **Figure 27** (a). With the temperature increase from 30°C to 60°C, the adsorption efficiency was observed to decrease. **Figure 25** (b) and **Figure 27** (b) examines adsorption capacity of BAC and IOB-AC for BG dye removal at various temperatures, respectively. The highest value of q_e in both cases was obtained at 30°C, while the lowest value of q_e was obtained at 60°C.

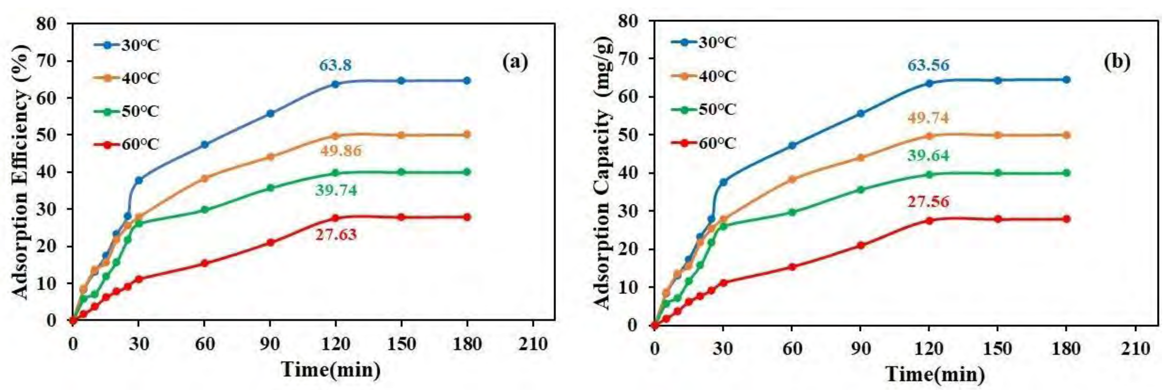

***Figure 25**: Adsorption of BG dye at different temperatures using BAC (a) adsorption efficiency, and (b) adsorption capacity.*

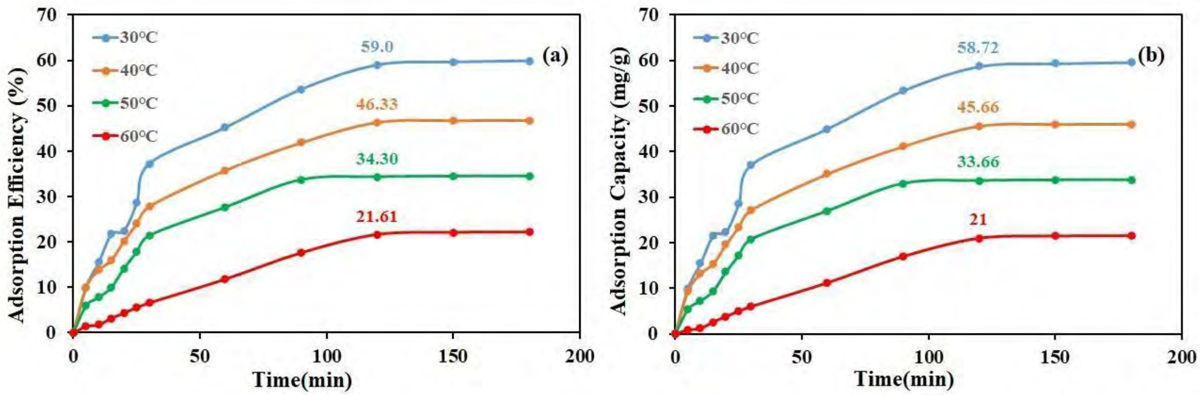

***Figure 26:** Adsorption of BG dye at different temperatures using IOB-AC (a) adsorption efficiency, and (b) adsorption capacity.*

The results show an interesting trend: the temperature increase has a deletrous impact on the procedure. The percent(%) removal of BG dye dropped as temperature increased, indicating an inverse connection between removal efficiency and temperature (Yadav & Dasgupta, 2022). This led to the conclusion that BG adsorption onto all three adsorbents is an exothermic reaction. This behavior is linked to dyes' increased solubility at higher temperatures, which promotes stronger contact forces between dyes and solvents rather than dyes and adsorbents (Foroutan et al., 2021).

3.8. Recovery and Reusability Studies

Over three adsorption-desorption repetitions, the removal effectiveness of PPAC, BAC, and IOB-AC in removing BG dye was tested (**Figure 27**). According to the data, PPAC's initial removal efficiency was 61.24%, but it declined to 52.67% during the third round. BAC, on the other hand, had a greater starting efficiency of 67.3%, which dropped to 59.8% after the third cycle. Both adsorbents experienced a significant decline in efficiency as the cycles progressed. This decrease is most likely due to partial pollutant release during desorption and the retention of certain biochar particles on the filtering medium. Furthermore, a decline in extraction capability over successive cycles indicates the adsorbent's regeneration limits for prospective reuse (Fito et al., 2023). However, IOB-AC showed a steady decline with initial efficiency of 66% and third round efficiency of 60.7%. It was observed that regenerability of IOB-AC was very efficient compared to other two adsorbents. This is due to IOB-AC’s magnetic strength. The results illustrate BAC's better stability and reusability over PPAC, emphasizing its potential utility in actual BG dye extraction applications.

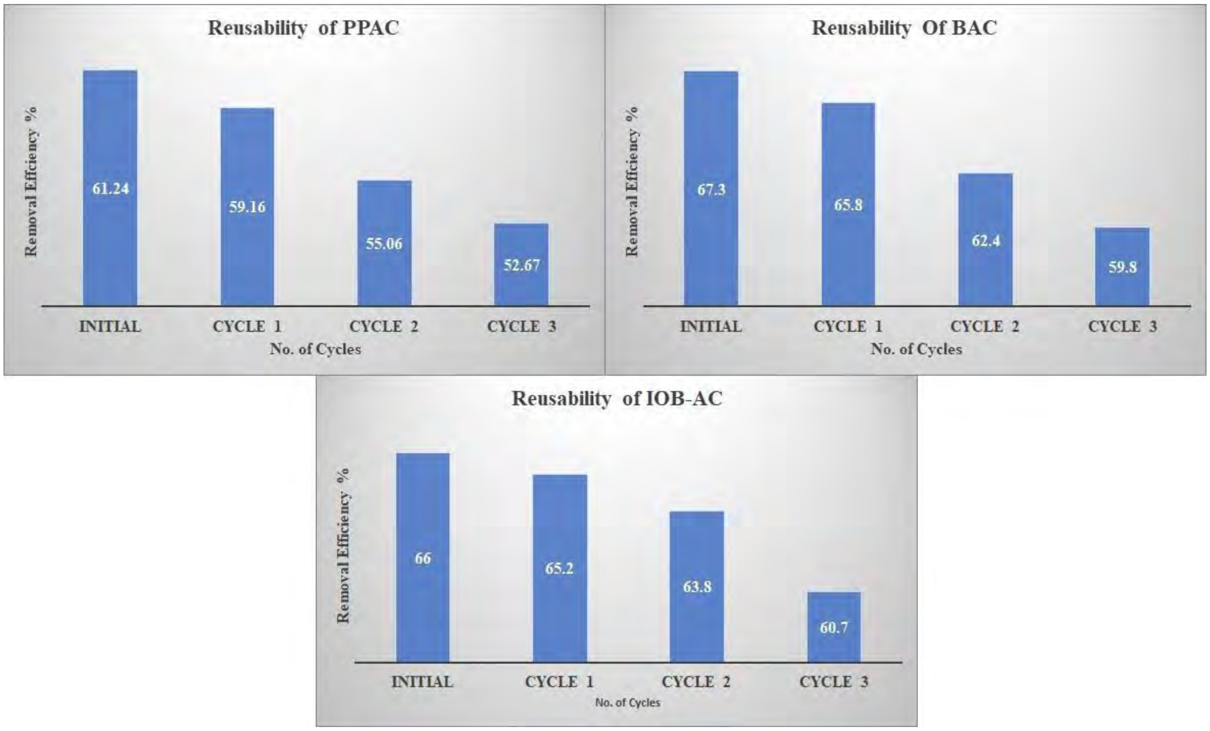

Figure 27*: Adsorbent desorption and its BG removal performance with PPAC, BAC, and IOB-AC.*

3.9. Reaction Kinetics

To interpret the adsorption procedure, pseudo 1st and pseudo 2nd order kinetics models were used on the data. The results of these kinetic models for PPAC, BAC, and IOB-AC for operational parameters are in the tables from **Table 2** to **Table 10**. Pseudo 2nd order kinetics models suggests that nature of adsorption is physical which is also justified by the data. According to previous studies, electrostatic interaction caused BG adsorption onto PPAC, BAC, and IOB-AC (Vyavahare et al., 2021).

***Table 2**: Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye with PPAC at different concentrations.*

		Pseudo 1st order kinetics			**Pseudo 2nd order kinetics**		
BG conc mg/L	**Exp value qe(mg/g)**	**Cal. value qe (mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe(mg/g)**	**K_2 (min^{-1})**	**R^2**
10	7.87	5.491614	-0.00012	0.9687	8.82612	0.00504	0.9654
25	15.87	8.421705	-0.00012	0.9254	16.6113	0.00502	0.9887
50	29.96	25.27551	-0.00027	0.9965	34.7222	0.00158	0.9993
100	34.29	25.78695	-0.00012	0.9954	39.6825	0.00091	0.9654

***Table 3**: Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye with BAC at different concentrations.*

		Pseudo 1st order kinetics			**Pseudo 2nd order kinetics**		
BG conc mg/L	**Exp value qe(mg/g)**	**Cal. value qe (mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe(mg/g)**	**K_2 (min^{-1})**	**R^2**
10	7.9	4.271693	-0.000085	0.9888	8.38926	0.00766	0.9708
25	19.8	13.86117	-0.000153	0.9829	22.0264	0.00240	0.982
50	33.28	28.11901	-0.000153	0.9809	40.1606	0.00079	0.9837
100	40.69	36.31617	-0.00018	0.9515	51.0204	0.00060	0.9896

***Table 4**: Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye with IOB-AC at different concentrations.*

		Pseudo 1st order kinetics			Pseudo 2nd order kinetics		
BG conc mg/L	**Exp value qe(mg/g)**	**Cal. value qe (mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe(mg/g)**	**K_2 (min^{-1})**	**R^2**
10	7.7	4.532105	-0.0001	0.9909	8.31255	0.00729	0.9741
25	17.46	18.01358	-0.00017	0.98	31.0559	0.00036	0.9323
50	32.34	28.3988	-0.00018	0.9584	40.1606	0.00076	0.9831
100	35.54	30.75389	-0.00018	0.9737	43.8596	0.00075	0.9925

***Table 5:** Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye with PPAC at different pH values.*

		Pseudo 1st order kinetics			Pseudo 2nd order kinetics		
pH	**Exp value qe(mg/g)**	**Cal. value qe(mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe(mg/g)**	**K_2 min^{-1})**	**R^2**
3	7.88	8.875647	-0.00013	0.9482	-33.0033	0.0006	0.0884
5	10.9	9.691701	-0.00011	0.9864	14.7929	0.0012	0.9087
7	20.67	19.94344	-0.00018	0.9544	29.41176	0.0006	0.9776
8	29.96	25.27551	-0.00027	0.9965	34.72222	0.0016	0.9993
9	25.12	20.56838	-0.00014	0.9775	30.03003	0.0012	0.9905
11	36	29.62102	-0.00011	0.9456	41.49378	0.0007	0.938

Table 6: *Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye with BAC at different pH values.*

		Pseudo 1st order kinetics			Pseudo 2nd order kinetics		
pH	**Exp value qe(mg/g)**	**Cal. value qe(mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe(mg/g)**	**K_2 min^{-1})**	**R^2**
3	10.44	9.963226	-0.00021	0.9984	13.5318	0.0018	0.9496
5	15.6	16.65329	-0.00024	0.9484	22.6244	0.0008	0.9060
7	24.89	23.91663	-0.00019	0.9655	31.8471	0.0010	0.9866
8	33.28	28.11901	-0.00015	0.9809	39.2157	0.0008	0.9922
9	28.9	24.52449	-0.00020	0.9894	33.2226	0.0013	0.9964
11	36	32.99894	-0.00016	0.9741	26.1780	0.0019	0.9277

Table 7: *Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye with IOB-AC at different pH values.*

		Pseudo 1st order kinetics			Pseudo 2nd order kinetics		
pH	**Exp value qe(mg/g)**	**Cal. value qe(mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe(mg/g)**	**K_2 min^{-1})**	**R^2**
3	9.4	7.610269	-0.00014	0.9529	11.35074	0.0028	0.9584
5	13.28	12.55741	-0.00019	0.8835	20.08032	0.0009	0.8851
7	23.34	24.04916	-0.00014	0.9901	51.28205	0.0001	0.8311
8	32.34	28.3988	-0.00018	0.9532	40.16064	0.0008	0.9831
9	24.57	22.69865	-0.00023	0.9858	30.58104	0.0011	0.9954

11	35.88	32.13661	-0.00016	0.8295	45.45455	0.0004	0.7406

Table 8: *Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye at different dosage of PPAC.*

		Pseudo 1^{st} order kinetics			**Pseudo 2^{nd} order kinetics**		
Adsorbent dose (g/L)	**Exp value qe (mg/g)**	**Cal. value qe (mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe (mg/g)**	**K_2 (min^{-1})**	**R^2**
0.25	39.92	50.281	-0.0007	0.9725	60.976	0.00029	0.8043
0.5	43.54	54.526	-0.00075	0.927	80.645	0.00022	0.9301
0.75	30.49	29.431	-0.00034	0.9905	39.526	0.00056	0.9723
1	29.96	26.909	-0.00059	0.9991	34.722	0.00162	0.9993
1.5	19.17	17.595	-0.00026	0.9922	10.417	0.00466	0.9527

Table 9: *Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye at different dosage of BAC.*

		Pseudo 1^{st} order kinetics			**Pseudo 2^{nd} order kinetics**		
Adsorbent dose (g/L)	**Exp value qe (mg/g)**	**Cal. value qe (mg/g)**	**K_1 (min^{-1})**	**R^2**	**Cal value qe (mg/g)**	**K_2 (min^{-1})**	**R^2**
0.25	54.8	63.811	-0.00045	0.9664	227.27	0.00001	0.0584
0.5	64.94	56.768	-0.00036	0.9789	78.740	0.00043	0.9872

0.75	41.5	40.607	-0.0004	0.9596	55.556	0.00044	0.9929
1	32.78	30.946	-0.00035	0.9629	40	0.00075	0.9839
1.5	22.83	29.437	-0.00051	0.9529	2.0157	3.31245	0.8506

***Table 10:** Pseudo 1st and 2nd order Kinetics parameters of the adsorption of BG dye at different dosage of IOB-AC.*

		Pseudo 1st order kinetics			Pseudo 2nd order kinetics		
Adsorbent dose (g/L)	Exp value qe (mg/g)	Cal. value qe (mg/g)	K_1 (min^{-1})	R^2	Cal value qe (mg/g)	K_2 (min^{-1})	R^2
0.25	48.8	52.036	-0.0001	0.9484	136.99	0.0000	0.6696
0.5	60.72	59.979	-0.0003	0.9627	71.942	0.0006	0.9969
0.75	39.47	36.737	-0.0003	0.9932	44.843	0.0011	0.9939
1	32.34	32.719	-0.0002	0.9705	40.161	0.0008	0.9831
1.5	21.28	17.430	-0.0002	0.9324	24.814	0.0020	0.9910

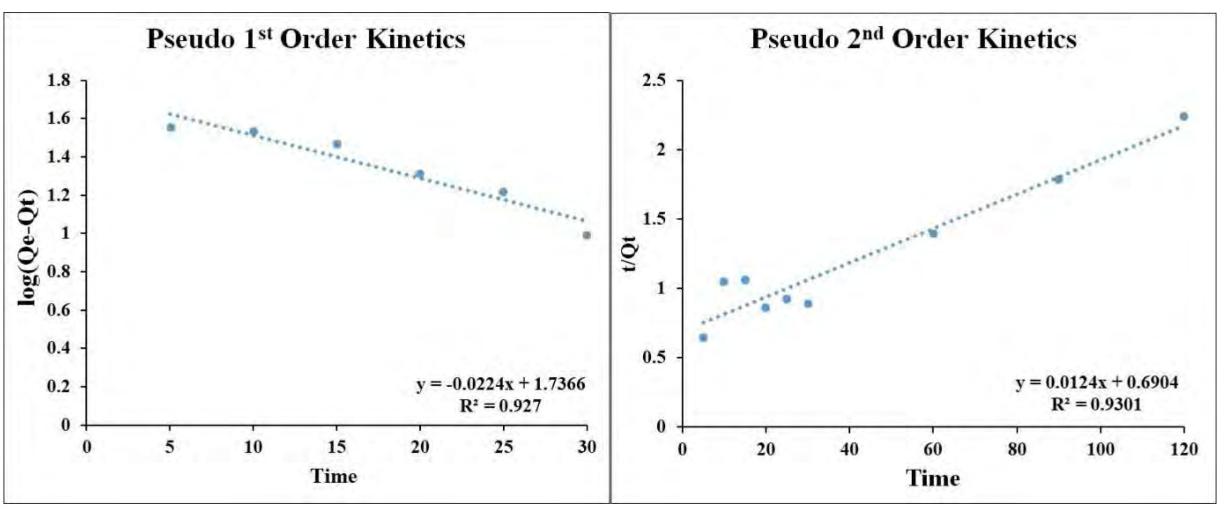

***Figure 28:** Kinetics plot of BG adsorption onto PPAC at optimum conditions.*

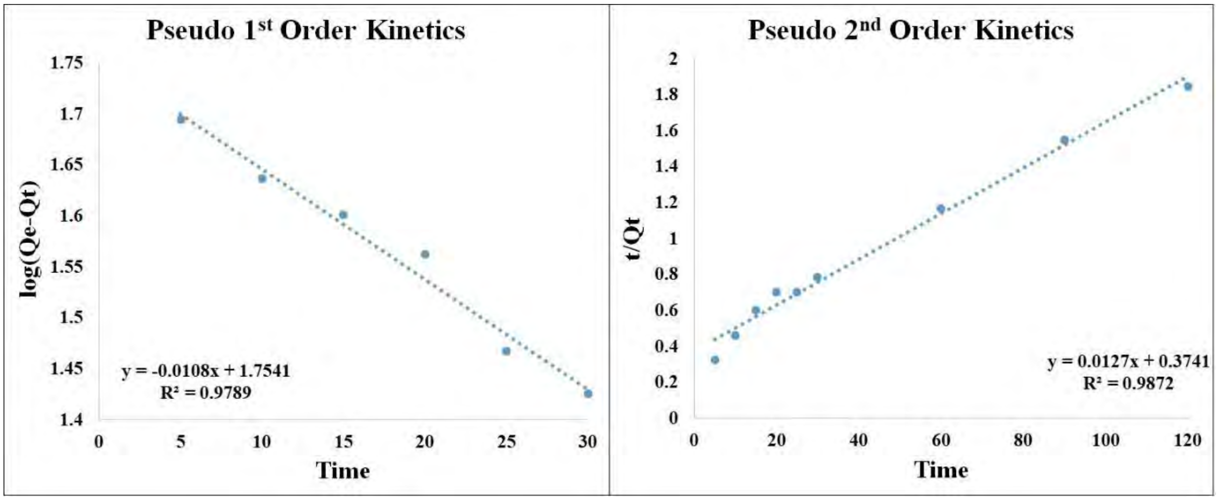

Figure 29: *Kinetics plot of BG adsorption onto BAC at optimum conditions.*

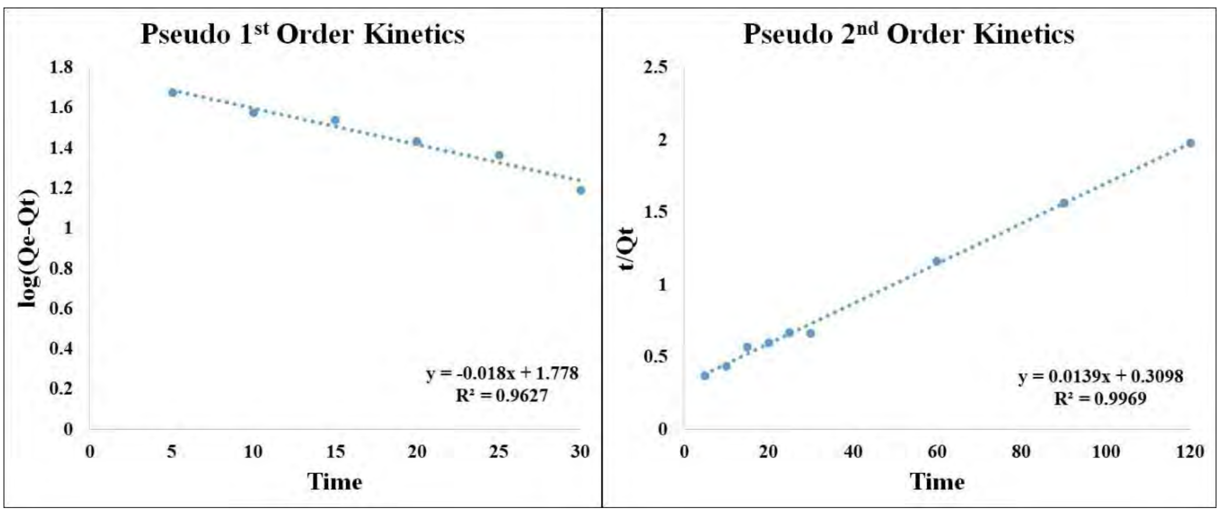

Figure 30: *Kinetics plot of BG adsorption onto IOB-AC at optimum conditions.*

The data in the figure also suggests that pseudo 2st order kinetics was followed at the optimum conditions (conc = 50 mg/L, pH = 8, and dose = 0.5 g/L) the R^2 value of pseudo 2st order kinetic model were higher i.e. 0.9301 for PPAC, 0.9872 for BAC, and 0.9969 for IOB-AC as compared to the pseudo 1st order kinetic model i.e. 0.927 for PPAC,). 09789 for BAC, and 0.9627 for IOB-AC.

3.10. Isotherms

Isotherms are analysed to describe the process of adsorption. BG dye was removed from water using PPAC, BAC, and IOB-AC and the isotherms were analysed by using 0.5 g/L of adsorbent dose and keeping the solution at an optimum pH 0f 8. The initial concentration of dye was varied i.e., 25 mg/L, 50 mg/L, 75 mg/L and 100 mg/L, and studies at four different temperatures (30ºC, 40ºC, 50ºC, and 60ºC). Freundlich and Langmuir isotherm equations were applied to the equilibrium data of adsorption.

Freundlich isotherm------------------ $\ln qe = \ln K_f + (1/n_f)\ln C_e$

Langmuir isotherm-------------------- $Ce/qe = (Ce/q_m) + (1/bq_m)$

The parameters were calculated using MS Excel software. Values explaining the nature of adsorption process are mentioned in the tables below.

The linear equation of Langmuir and Freundlich models were tested on BG dye removal by PPAC, BAC, and IOB-AC in the **Table 11**, **Table 12** and **Table 13**, respectively..

Table 11: *Langmuir and Freundlich adsorption constants for BG dye adsorption on PPAC.*

	Langmuir isotherm			Freundlich isotherm		
Temp ^{0}C	**q_m (mg/g)**	**b (L/mg)**	**R^2**	**K_f (L/g)**	**n_f**	**R^2**
30	49.7	24.86	0.9942	8.763952	2.177226	0.985
40	27.16	36.3	0.9825	4.470952	1.833181	0.9825
50	23.66	38.05	0.9489	2.277194	1.614726	0.9489
60	17.62	41.07	0.9905	1.032761	1.302083	0.9905

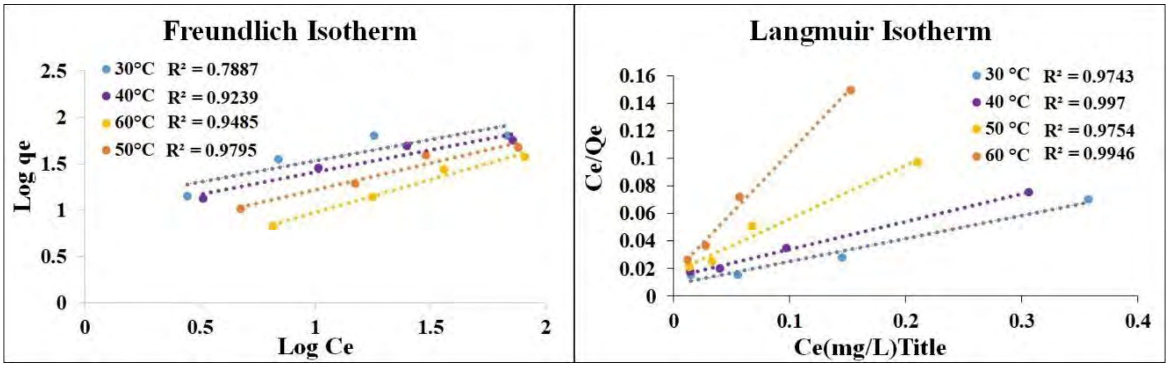

Figure 31: *Freundlich and Langmuir Isotherms for adsorption of BG dye using PPAC at optimum pH (8) and dose (0.5 g/L) at different temperatures.*

Table 12: *Langmuir and Freundlich Isotherms for adsorption of BG due using BAC at optimum pH (8) and dose (0.5 g/L) at different temperatures.*

	Langmuir isotherm			Freundlich isotherm		
Temp ^{0}C	**q_m (mg/g)**	**b (L/mg)**	**R^2**	**K_f (L/g)**	**n_f**	**R^2**
30	5.966587	0.001441	0.9743	11.84132	2.173441	0.7887
40	4.98008	0.002851	0.997	8.529037	2.081599	0.9239
50	2.577984	0.006749	0.9754	4.322152	1.721467	0.9485
60	1.130327	0.014332	0.9946	1.838231	1.412429	0.9795

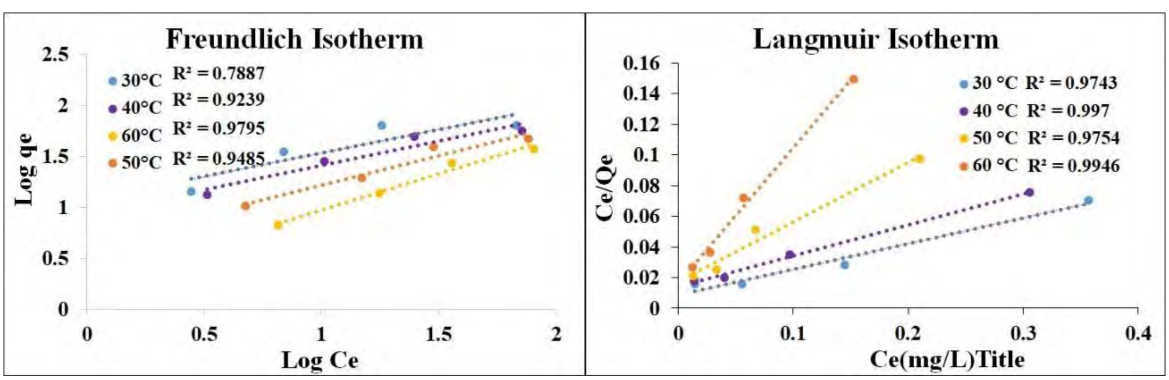

Figure 32: *Freundlich and Langmuir isotherms for the adsorption of BG dye by BAC at optimum pH (8) and dose of adsorbent (0.5 g/L) at different temperatures.*

	Langmuir isotherm			Freundlich isotherm		
Temp ^0C	q_m (mg/g)	b (L/mg)	R^2	K_f (L/g)	n_f	R^2
30	5.274262	0.002029	0.9737	10.89432	2.271695	0.7651
40	4.230118	0.003735	0.9812	7.559621	2.072968	0.8699
50	1.882885	0.009772	0.944	3.241156	1.616554	0.8681
60	0.838715	0.013592	0.9737	1.454119	1.350439	0.9332

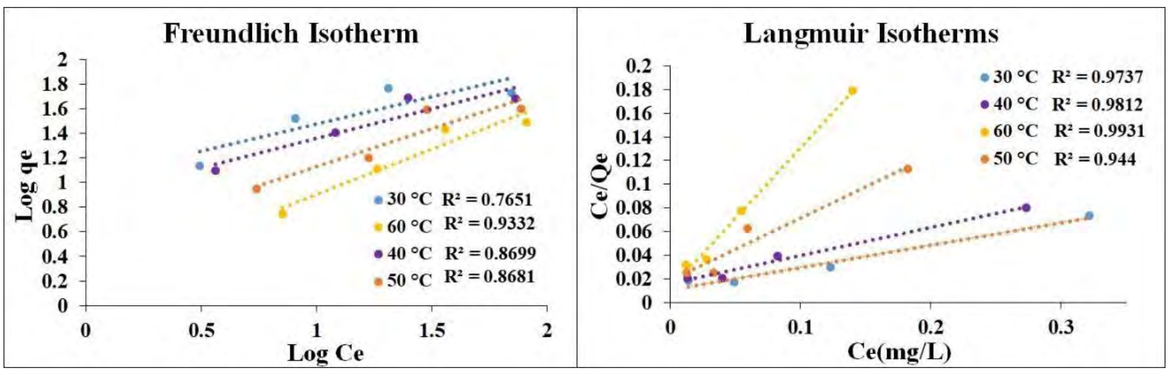

Figure 33: Freundlich and Langmuir isotherms for the adsorption of BG dye onto IOB-AC at optimum pH (8) and dose (0.5 g/L) at different temperatures.

Figure 31, **Figure 32**, and **Figure 33** shows the adsorption was followed by the Langmuir model of isotherms at all 4 temperatures in comparison to freundlich isotherm model. The R^2 values of linear plot for Langmuir model were higher than the Freundlich model. This illustrated that Langmuir isotherm model better explained the BG dye adsorption onto PPAC, BAC and IOB-AC, and the adsorbents' surfaces are homogeneous and there is monolayer interaction between dye molecules and all three adsorbents (Rehman et al., 2015).

3.11. Comparison of Adsorption Capacity

We investigated how effectively PPAC and BAC function as adsorbents for removing BG dye from water in this study. Their adsorption capacity was compared to that of other natural and synthetic adsorbents. When it comes to extracting BG dye from aqueous solutions, the data clearly show that both the adsorbents, especially BAC, outperform many of these other adsorbents. As a result, they may be a cost-effective and efficient option for the BG dye removal process.

Table 13: *Comparison of adsorption capacity of PPAC and BAC with other adsorbents used in BG removal process.*

Adsorbent	**q_e (mg g^{-1}) BG Dye**	**Reference**
EDTA modified Fe_3O_4/sawdust carbon nanocomposites	285	(Kataria & Garg, 2019)
Cashew nutshell activated carbon by KOH activation	243.90	(Samiyammal et al., 2022)
Chemically modified areca nut husk	18.21	(Baidya & Kumar, 2021)
Biochar prepared from lignocellulosic bioethanol plant waste	111.11	(Rehman et al., 2015)
Sodium carbonate treated *Bambusa Tulda*	41.67	(Laskar & Kumar, 2018)
Rice husk ash	12.57	(Mane et al., 2007)
Activated carbon derived from guava tree wood	90	(Mansour et al., 2020)
Chemically treated *Lawsonia inermis* seeds powder (CTLISP)	34.96	(Ahmad & Ansari, 2020)
Nanocomposite with the core TiO_2/hydrogel	140.69	(Aljeboree et al., 2022)

4. Conclusion

We performed a comparative analysis in this work to determine how effective different types of biochar adsorbents are at extracting BG dye from contaminated water. We examined pure parthenium biochar as well as modified variants known as beetroot activated carbon and iron oxide-infused beetroot activated carbon. These adsorbents were created using a simple manner and demonstrated various ability to adsorb BG dye. We discovered that at different concentrations of 10mg L^{-1} and 25 mg L^{-1}, pure biochar eliminated around 79% and 64% of BG dye, respectively. After a three-hour experiment, its adsorption capacity was evaluated at 7.9 mg g^{-1} and 15.99 mg g^{-1} for these values. For the same dye concentrations, the adsorption capabilities of beetrootactivated carbon were 8.01 mg g^{-1} and 19.83 mg g^{-1}, respectively. The combined iron oxide and beetroot activated carbon, on the other hand, did not work to improve the adsorption. The characterization of all three adsorbents provides an explanation for their different adsorption capacities. SEM images reveal the non-crystalline structure of all three adsorbents which was also confirmed by XRD analysis showing very few sharp peaks. SEM images also reveal other morphological features, indicating a honeycomb like formation for PPAC, semi-crystalline structure of IOB-AC with numerous tiny cracks and fissures, and clumpy structure of BAC with formation of channels providing enhanced surface area than other two adsorbents for adsorption. The weak performance of IOB-AC can be attributed to absence of Fe functional as revealed by FTIR analyses. PPAC and BAC, on the other hand, showed 4 peaks indicating prominent presence of hydroxyl, alkane, alkenes, and various other functional groups providing active sites for enhanced adsorption. Elemental mapping of adsorbents and comparison with the literature also revealed activation of BAC due to incorporation of nitrogen. The removal percentages for PPAC and BAC climbed to 57.82% and 63.87%, respectively, as the BG dye concentration was rised to 50 mg L^{-1}, accompanied by significant increases in their adsorption capabilities. The iron oxide and beetroot mixed biochar, on the other hand, did not show substantial improvements. For instance, as the BG concentration climbed from 10 mg L^{-1} to 50mg L^{-1}, its removal efficiency improved only from 39% to 45%, and its adsorption capacity at50 ppm was only 22.77 mg g^{-1}. As a result, we chose to concentrate our optimization efforts on PPAC and BAC. We also discovered that changing the pH of the solution from 3 to 8 resulted in faster BG removal rates. PPAC and BAC both displayed their maximum clearance percentages at pH 8: 54.24% for PPAC and 65.5% for BAC. At pH 8, the comparable adsorption capabilities were 27 mg g^{-1} for PPAC and 33.6 mg g^{-1} for BAC. Furthermore, at pH 8, when the adsorbent dose was increased to 1.5 g L^{-1}, BAC outperformed PPAC, with removal rates of 69.76% and 58.13%, respectively. However, at a dosage of 0.5 g L^{-1}, both adsorbents reached their maximal adsorption capacities, with PPAC reaching 38 mg g^{-1} and BAC reaching 58 mg g^{-1}. Higher temperatures resulted in lower adsorption effectiveness, indicating an exothermic adsorption process, according to our studies into temperature impacts. The study concluded that biocharbased PPAC generated from the invasive species *Parthenium hysterophorus* could be a viable alternative to commercially available activated carbons. Furthermore, beetroot-modified activated carbon shows potential for effective cationic dye removal.

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