

Heavy Metals and Dyes Contamination in Water Imposes Hazards on Human Health and Aquatic Ecosystem: its Sustainable Remediation through Activated Carbon generated by Bio-waste

Prerna Rathaur¹, Divya Pandey², Arti Gupta³, Vinod Kumar⁴ and Pramod Kumar Singh⁵

Department of Environment Science, School of Basic Sciences, Babu Banarasi Das University, Lucknow(Uttar Pradesh), India^{1,2,3,4,&5}

ORCID id: 0000-0003-0061-6609

Abstract: Industrialization and rapid urban expansion have significantly increased the discharge of wastewater containing toxic heavy metals and synthetic dyes into aquatic ecosystems. Industries such as textile manufacturing, electroplating, leather tanning, mining, battery production, pharmaceuticals, petrochemicals, and metallurgy contribute substantially to environmental contamination through the release of persistent pollutants that are toxic, non-biodegradable, and capable of bioaccumulation and biomagnification. Heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), and arsenic (As), together with synthetic dyes such as methylene blue, Congo red, crystal violet, and reactive dyes, pose serious threats to aquatic organisms and human health. Chronic exposure to these contaminants has been associated with oxidative stress, endocrine disruption, neurological disorders, reproductive toxicity, and carcinogenic effects. The aims of this review to critically evaluates the sources, environmental impacts, and treatment strategies for dye and heavy metal pollution, with particular emphasis on adsorption technology and biomass-derived activated carbon. The potential of *Hyptis suaveolens* as a sustainable precursor for activated carbon production and its future prospects for wastewater remediation are comprehensively discussed. Conventional wastewater treatment technologies such as chemical precipitation, coagulation–flocculation, membrane filtration, ion exchange, and biological treatment have been widely applied, their effectiveness is often limited by high operational costs, sludge generation, membrane fouling, secondary pollution, and reduced efficiency toward persistent pollutants. Adsorption has emerged as one of the most efficient and environmentally sustainable technologies for wastewater remediation. Activated carbon remains the most widely utilized adsorbent because of its extensive surface area, developed pore structure, and abundance of surface functional groups. Recent research has focused on the development of low-cost activated carbon from renewable biomass resources including agricultural residues, forestry wastes, fruit peels, medicinal plants, and invasive weeds. Among these, *Hyptis suaveolens* (Vilayati Tulsi) has gained considerable attention owing to its rapid growth, abundant biomass production, high lignocellulosic content, and invasive nature. Conversion of *Hyptis suaveolens* biomass into activated carbon represents a sustainable waste-to-wealth approach that simultaneously addresses invasive weed management and wastewater treatment challenges.

Keywords: Heavy metals, Dyes, *Hyptis suaveolens*, Wastewater treatment, Sustainable remediation, Activated Carbon.

1. Introduction

Water is an indispensable natural resource that supports ecological stability, agricultural productivity, industrial development, and human well-being. However, rapid industrialization, urban expansion, and increasing anthropogenic activities have significantly deteriorated water quality worldwide, resulting in the widespread contamination of aquatic ecosystems by various organic and inorganic pollutants [2,12,13]. Among these contaminants, heavy metals and synthetic dyes are considered particularly hazardous because of their persistence, toxicity, bioaccumulation potential, and resistance to natural degradation processes [1,4]. The continuous discharge of untreated industrial effluents into rivers, lakes, and groundwater systems has transformed water pollution into a major environmental and public health concern, especially in developing countries where wastewater treatment infrastructure remains inadequate [3,12].

Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), nickel (Ni), and copper (Cu) are frequently detected in industrial wastewater generated from mining, electroplating, battery manufacturing, metal finishing, leather tanning, fertilizer production, and

petroleum refining industries [1,3]. Unlike many organic contaminants, heavy metals are non-biodegradable and can persist in environmental compartments for extended periods, thereby increasing the risk of bioaccumulation and biomagnification within food chains [4]. Numerous studies have reported that chronic exposure to heavy metals can cause severe physiological disorders including neurological impairment, kidney dysfunction, liver damage, reproductive abnormalities, endocrine disruption, and carcinogenic effects in humans and animals [4,10,11]. Furthermore, heavy metals adversely affect aquatic organisms by inducing oxidative stress, inhibiting enzyme activities, and disrupting cellular metabolism, thereby threatening biodiversity and ecosystem stability [6,9].

In addition to heavy metals, synthetic dyes constitute another major class of environmental pollutants released into aquatic ecosystems. Dye-containing wastewater is primarily generated from textile dyeing and printing industries, although substantial contributions also originate from paper manufacturing, leather processing, cosmetics, food processing, pharmaceutical production, and plastic industries [14–16]. The global production of synthetic dyes exceeds hundreds of thousands of tonnes annually, with a significant fraction entering wastewater streams during industrial processing [15]. Many dyes possess complex aromatic structures that confer exceptional chemical stability and resistance to biological degradation. Consequently, their persistence in aquatic environments reduces light penetration, suppresses photosynthetic activity, decreases dissolved oxygen concentrations, and negatively impacts aquatic life [14,15]. Certain dye classes, particularly azo dyes, may undergo reductive degradation to produce aromatic amines that exhibit mutagenic and carcinogenic properties, thereby posing additional environmental and health risks [16,17].

The increasing occurrence of heavy metals and dyes in wastewater has stimulated extensive research into efficient treatment technologies. Conventional approaches such as chemical precipitation, coagulation–flocculation, membrane filtration, ion exchange, electrochemical treatment, and biological degradation have been widely employed for contaminant removal [17,20]. Although these technologies can achieve varying degrees of treatment efficiency, their practical application is often limited by high operational costs, excessive sludge generation, membrane fouling, incomplete pollutant removal, and secondary pollution problems [14,20]. Consequently, the development of economical, efficient, and environmentally sustainable treatment methods remains a major challenge in wastewater management.

Among the available remediation technologies, adsorption has emerged as one of the most promising approaches because of its simplicity, flexibility, high efficiency, and ability to remove contaminants even at low concentrations [20,25]. The adsorption process involves the accumulation of dissolved pollutants on the surface of a solid adsorbent through physical or chemical interactions. Activated carbon is widely recognized as the most effective adsorbent because of its extensive surface area, highly porous structure, and abundance of surface functional groups capable of interacting with diverse contaminants [15,22,23]. However, the relatively high production and regeneration costs associated with commercial activated carbon have encouraged the search for alternative low-cost precursor materials derived from renewable biomass resources [17,24].

Biomass-derived activated carbons have attracted considerable scientific interest owing to their low cost, renewability, and environmental sustainability. Agricultural residues, forestry wastes, food-processing by-products, aquatic plants, and invasive weeds have been successfully utilized as carbon precursors for activated carbon production [17,24]. In recent years, invasive plant species have emerged as particularly attractive feedstocks because of their abundant biomass production and minimal economic value. The conversion of invasive weeds into activated carbon not only provides an effective adsorbent material but also contributes to invasive species management, biomass utilization, and circular bioeconomy development.

Among invasive weeds, *Hyptis suaveolens* (L.) Poit., commonly known as Vilayati Tulsi, is widely distributed throughout tropical and subtropical regions and is recognized for its rapid growth, ecological adaptability, and prolific biomass production [30]. The plant frequently colonizes roadsides, wastelands, degraded lands, forest margins, and abandoned agricultural fields, often forming dense populations that compete with native vegetation [30]. Despite being considered an invasive species, *H. suaveolens* possesses a favorable lignocellulosic composition rich in cellulose, hemicellulose, and lignin, making it a potentially valuable precursor for activated carbon production. Furthermore, its widespread availability and rapid biomass accumulation provide an opportunity for developing low-cost adsorbents from an otherwise underutilized biological resource.

Although substantial research has been conducted on biomass-derived activated carbons, studies focusing specifically on activated carbon prepared from *Hyptis suaveolens* remain limited. In particular, comprehensive investigations concerning carbonization behavior, activation processes, physico-chemical characterization, pore development, surface chemistry, and adsorption performance toward dyes and heavy metals are still scarce. Therefore, the preparation and characterization of activated carbon derived from *Hyptis suaveolens* biomass and its application for wastewater treatment represent an important area of research with significant environmental and practical relevance.

The present study is therefore aimed at evaluating the suitability of *Hyptis suaveolens* as a precursor material for activated carbon production and assessing its potential as a low-cost adsorbent for the removal of dyes and heavy metals from contaminated water. The study further seeks to contribute to sustainable wastewater treatment, invasive weed management, and biomass valorization through the development of an environmentally friendly adsorption system.

2. Heavy Metal and Dye Pollution

2.1 Sources and Classification of Heavy Metal Pollution

Heavy metal contamination has become a global environmental concern due to rapid industrialization, urbanization, mining activities, and agricultural intensification. Heavy metals are generally defined as metallic elements possessing relatively high atomic weight and density that exhibit toxicity even at low concentrations. Unlike organic pollutants, heavy metals are non-biodegradable and can persist in environmental compartments for prolonged periods, resulting in bioaccumulation and biomagnification throughout food chains [1,4].

Table 1. Major heavy metals, sources of contamination and associated health effects

Heavy Metal	Major Sources	Environmental Effects	Human Health Effects
Lead (Pb)	Batteries, paints, electroplating, plumbing systems	Bioaccumulation in aquatic organisms	Neurological disorders, anemia, developmental defects
Cadmium (Cd)	Electroplating, phosphate fertilizers, batteries	Soil and water contamination	Kidney dysfunction, skeletal damage, carcinogenicity
Chromium (Cr)	Tanneries, electroplating, dye industries	Aquatic toxicity	Skin irritation, liver damage, cancer
Mercury (Hg)	Mining, chlor-alkali industries, fossil fuel combustion	Biomagnification in food chains	Neurological impairment and cognitive dysfunction
Arsenic (As)	Mining, pesticides, geological weathering	Groundwater contamination	Skin lesions, cardiovascular diseases, cancer
Nickel (Ni)	Electroplating, metal-finishing industries	Aquatic toxicity	Allergic reactions, respiratory disorders
Copper (Cu)	Metallurgical industries, wastewater discharge	Toxicity to aquatic organisms	Gastrointestinal and liver disorders
Zinc (Zn)	Galvanization, industrial wastewater	Ecotoxicity at elevated concentrations	Nausea, vomiting and metabolic disturbances

Major anthropogenic sources of heavy metal contamination include mining and smelting operations, electroplating industries, battery manufacturing units, leather tanning facilities, fertilizer production plants, petroleum refineries, thermal power stations, and municipal wastewater discharge [1,3]. Among the various heavy metals detected in contaminated water bodies, lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), nickel (Ni), copper (Cu), and zinc (Zn) are considered the most environmentally significant because of their toxicity, persistence, and widespread occurrence [4,21]. Chromium contamination is predominantly associated with electroplating, leather tanning, and pigment

manufacturing industries, whereas lead contamination commonly originates from battery industries, paints, pigments, and plumbing systems. Cadmium is frequently released from electroplating operations, phosphate fertilizers, and metallurgical industries, while mercury contamination is linked to mining activities and fossil fuel combustion [1,4]. The continuous discharge of these contaminants into aquatic environments has resulted in extensive deterioration of water quality worldwide.

2.2 Sources and Classification of Dye Pollution

Synthetic dyes constitute another major category of industrial pollutants discharged into aquatic ecosystems. Dyes are colored organic compounds designed to impart permanent coloration to substrates such as textiles, paper, leather, plastics, pharmaceuticals, cosmetics, and food products. The textile industry is recognized as the largest consumer of synthetic dyes and consequently represents the principal source of dye-containing wastewater [15,16]. During dyeing operations, a considerable proportion of applied dyes remains unbound to fibers and is subsequently released into industrial effluents.

Based on chemical structure and application characteristics, synthetic dyes are generally classified into azo dyes, anthraquinone dyes, triphenylmethane dyes, sulfur dyes, reactive dyes, vat dyes, basic dyes, acidic dyes, and disperse dyes [16,17]. Among these groups, azo dyes account for approximately 60–70% of total dye production due to their ease of synthesis, wide color range, and excellent stability. However, many azo dyes can undergo reductive degradation to produce aromatic amines that exhibit mutagenic and carcinogenic properties [14,16]. Common dyes frequently detected in industrial wastewater include methylene blue, Congo red, methyl orange, crystal violet, malachite green, rhodamine B, and reactive black dyes [15].

Table 2. Common synthetic dyes used in industries and their environmental impacts

Dye Type	Industrial Application	Environmental Concern
Methylene Blue	Textile and paper industries	Toxicity to aquatic organisms
Congo Red	Textile dyeing	Carcinogenic degradation products
Crystal Violet	Textile and biological staining	Mutagenic and cytotoxic effects
Malachite Green	Textile and aquaculture industries	Carcinogenic and teratogenic effects
Methyl Orange	Textile and chemical industries	Persistent water contamination
Rhodamine B	Textile and printing industries	Toxicity and bioaccumulation
Reactive Black	Textile dyeing	Reduced light penetration in water bodies
Reactive Red	Textile processing	Inhibition of photosynthesis
Brilliant Green	Textile and laboratory applications	Aquatic toxicity

2.3 Environmental and Human Health Impacts of Heavy Metals and Dyes

The presence of heavy metals and synthetic dyes in aquatic ecosystems poses severe environmental and public health risks. Heavy metals disrupt enzymatic activities, induce oxidative stress, alter membrane permeability, and impair cellular metabolism in aquatic organisms [4,6]. Their accumulation in sediments and biological tissues facilitates biomagnification through food chains, ultimately exposing human populations to toxic concentrations through contaminated water and food resources [9,10]. Chronic exposure to heavy metals has been associated with neurological disorders, kidney dysfunction, liver damage, endocrine disruption, developmental abnormalities, and various forms of cancer [4,11].

Similarly, dye-contaminated wastewater adversely affects aquatic ecosystems by reducing light penetration, inhibiting photosynthesis, decreasing dissolved oxygen concentrations, and disrupting ecological balance [14,15]. Numerous synthetic dyes and their degradation products exhibit toxic, mutagenic, teratogenic, and carcinogenic properties, thereby posing substantial risks to both aquatic

organisms and human health [14,16]. The simultaneous occurrence of dyes and heavy metals in industrial wastewater further complicates treatment processes and necessitates the development of highly efficient and sustainable remediation technologies.

The growing environmental burden associated with heavy metal and dye contamination has therefore intensified research efforts toward the development of advanced wastewater treatment technologies. Among the available approaches, adsorption has emerged as one of the most promising methods owing to its simplicity, high efficiency, and economic feasibility. Consequently, adsorption technology and biomass-derived activated carbon have received increasing attention as sustainable solutions for wastewater remediation.

3. Conventional Wastewater Treatment Technologies

The increasing contamination of aquatic ecosystems by heavy metals and synthetic dyes has necessitated the development of effective wastewater treatment technologies capable of reducing pollutant concentrations to environmentally acceptable levels. Over the past several decades, various physical, chemical, and biological treatment methods have been employed for the remediation of contaminated wastewater. These technologies include chemical precipitation, coagulation–flocculation, membrane filtration, ion exchange, electrochemical treatment, advanced oxidation processes, and biological degradation systems. Although many of these approaches have demonstrated considerable effectiveness under specific operating conditions, their practical implementation is frequently constrained by economic, operational, and environmental limitations. Consequently, the search for sustainable and cost-effective alternatives continues to be a major focus of environmental research [1,14,17].

3.1 Chemical Precipitation

Chemical precipitation is one of the most widely applied methods for the removal of dissolved heavy metals from industrial wastewater. The process involves the addition of chemical reagents such as hydroxides, carbonates, sulfides, or phosphates to convert soluble metal ions into insoluble precipitates that can subsequently be separated through sedimentation or filtration [20,25]. Heavy metals including lead, cadmium, chromium, copper, and zinc are commonly removed through hydroxide precipitation because of its simplicity and relatively low capital cost.

Despite its widespread application, chemical precipitation possesses several limitations. The process often generates large quantities of toxic sludge requiring further treatment and disposal. Furthermore, its efficiency decreases significantly at low metal concentrations, and precise pH control is essential for optimum removal efficiency. These limitations increase operational costs and create secondary environmental concerns associated with sludge management [1,20].

3.2 Coagulation–Flocculation

Coagulation–flocculation is another extensively utilized wastewater treatment technology, particularly for the removal of suspended solids, colloidal particles, and colored substances. In this process, coagulants such as aluminum sulfate, ferric chloride, ferric sulfate, and polyaluminum chloride destabilize suspended particles, promoting their aggregation into larger flocs that can be removed by sedimentation or filtration [17].

The method is effective for reducing turbidity and partially removing dye molecules from wastewater. However, the process requires substantial chemical inputs and generates considerable amounts of sludge. In addition, the disposal of chemical sludge presents environmental and economic challenges, thereby limiting the long-term sustainability of coagulation–flocculation processes [14,16].

3.3 Membrane Filtration

Membrane-based technologies, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, have gained considerable attention because of their high separation efficiency and ability to remove dissolved contaminants from wastewater. These technologies operate by selectively allowing water molecules to pass through semi-permeable membranes while retaining pollutants such as heavy metals, dyes, salts, and microorganisms [17].

Among membrane processes, reverse osmosis and nanofiltration have demonstrated particularly high removal efficiencies for heavy metals and dye molecules. However, membrane systems suffer from several operational limitations including membrane fouling, concentration polarization, high energy consumption, frequent maintenance requirements, and elevated capital costs. These factors often restrict their large-scale application, particularly in developing regions [3,17].

3.4 Ion Exchange

Ion exchange technology involves the reversible exchange of ions between a solid ion-exchange material and ions present in solution. Synthetic resins containing functional groups capable of selectively binding metal ions are commonly employed for the removal of heavy metals from wastewater [20].

Ion exchange processes can achieve high removal efficiencies and allow recovery of valuable metals from industrial effluents. Nevertheless, the technology is often associated with high operational costs, resin fouling, sensitivity to competing ions, and the requirement for chemical regeneration. The regeneration process itself generates secondary waste streams that require additional treatment [25].

3.5 Biological Treatment

Biological treatment technologies utilize microorganisms, algae, fungi, and aquatic plants to degrade, transform, or immobilize pollutants present in wastewater. Activated sludge systems, trickling filters, constructed wetlands, and bioreactors represent some of the most commonly employed biological treatment approaches [5].

Biological methods are generally environmentally friendly and cost-effective for the treatment of biodegradable organic pollutants. However, many synthetic dyes and heavy metals exhibit resistance to microbial degradation or may even inhibit microbial growth at elevated concentrations. Consequently, biological treatment alone is often insufficient for complete removal of persistent contaminants from industrial wastewater [5,14].

3.6 Limitations of Conventional Wastewater Treatment Methods

Although conventional wastewater treatment technologies have contributed significantly to pollution control, each method possesses inherent limitations that restrict its effectiveness for treating complex industrial effluents containing mixtures of heavy metals and synthetic dyes. Chemical methods frequently generate secondary pollutants in the form of sludge, membrane systems require substantial energy inputs and maintenance, biological processes exhibit limited effectiveness toward recalcitrant contaminants, and ion exchange systems involve high operational costs [1,17,20].

Furthermore, increasing environmental regulations and growing concerns regarding sustainability have highlighted the need for treatment technologies that are not only effective but also economically feasible and environmentally benign. These challenges have stimulated extensive research into adsorption-based treatment systems, particularly those utilizing low-cost biomass-derived activated carbons. Adsorption technology has emerged as one of the most promising alternatives because of its simplicity, high efficiency, minimal sludge production, and potential for utilizing renewable biomass resources as adsorbents [14,20]. Therefore, increasing attention has been directed toward the development of activated carbon derived from agricultural residues, forestry wastes, aquatic plants, and invasive weeds such as *Hyptis suaveolens* for sustainable wastewater remediation.

4. Adsorption Technology and Biomass-Derived Activated Carbon for Sustainable Wastewater Remediation

The increasing environmental burden associated with heavy metal and dye contamination has intensified the search for efficient, economical, and environmentally sustainable wastewater treatment technologies. Although conventional treatment methods such as chemical precipitation, coagulation–flocculation, membrane filtration, ion exchange, and biological degradation have been widely employed for pollutant removal, their practical implementation is frequently constrained by high operational costs, excessive sludge generation, membrane fouling, secondary pollution, and reduced effectiveness toward persistent contaminants [1,14,17]. Consequently, adsorption has emerged as one of the most promising

technologies for wastewater remediation owing to its simplicity, operational flexibility, high removal efficiency, and ability to remove pollutants even at trace concentrations [20,25].

Adsorption is a surface phenomenon in which dissolved molecules or ions accumulate on the surface of a solid adsorbent through physical and chemical interactions. The process is governed by several mechanisms including electrostatic attraction, ion exchange, hydrogen bonding, van der Waals forces, pore filling, π - π interactions, and surface complexation reactions [19,20]. Compared with many conventional treatment methods, adsorption offers several advantages, including ease of operation, minimal sludge production, low energy requirements, and applicability to a wide range of contaminants. These characteristics have contributed to its widespread adoption for the treatment of industrial effluents containing dyes, heavy metals, pharmaceuticals, pesticides, and other hazardous pollutants [14,17].

Among the numerous adsorbent materials investigated to date, activated carbon remains the most effective and extensively utilized adsorbent owing to its highly developed porous structure, large specific surface area, and abundance of chemically active surface functional groups [15,16]. Activated carbon consists primarily of amorphous carbonaceous material containing interconnected micro-, meso-, and macropores that provide a large number of adsorption sites for pollutant uptake. The adsorption performance of activated carbon is strongly influenced by pore-size distribution, surface chemistry, carbonization conditions, and activation processes. Functional groups such as hydroxyl, carboxyl, carbonyl, phenolic, and lactone groups facilitate interactions with adsorbate molecules and significantly enhance adsorption capacity toward both organic and inorganic contaminants [15,22].

Despite its excellent adsorption characteristics, the widespread application of commercial activated carbon is frequently limited by high production and regeneration costs. Commercial activated carbons are generally manufactured from coal, wood, petroleum coke, and coconut shell through energy-intensive activation processes, which contribute to elevated production costs and environmental impacts [22,23]. These economic limitations have stimulated extensive research into alternative precursor materials capable of producing low-cost activated carbons without compromising adsorption efficiency.

In recent years, biomass-derived activated carbons have attracted considerable scientific attention because of their abundance, renewability, low cost, and environmental sustainability. Agricultural residues, forestry wastes, fruit peels, food-processing by-products, aquatic plants, and invasive weeds have all been successfully utilized as carbon precursors for activated carbon production [17,24]. The lignocellulosic composition of plant biomass, primarily consisting of cellulose, hemicellulose, and lignin, provides an excellent carbon source for the development of highly porous carbonaceous structures during carbonization and activation processes. Numerous studies have demonstrated that activated carbons derived from biomass materials can achieve adsorption capacities comparable to, and in some cases exceeding, those of commercial activated carbons [17,24].

The production of activated carbon from biomass typically involves carbonization followed by physical or chemical activation. Physical activation commonly employs oxidizing gases such as steam or carbon dioxide at elevated temperatures to develop porosity, whereas chemical activation utilizes activating agents including phosphoric acid (H_3PO_4), potassium hydroxide (KOH), zinc chloride (ZnCl_2), and sulfuric acid (H_2SO_4) [22,24]. Chemical activation is generally preferred because it promotes extensive pore development at lower temperatures and enhances the formation of surface functional groups responsible for adsorption. Consequently, the physicochemical properties and adsorption performance of biomass-derived activated carbon are strongly dependent on precursor characteristics and activation conditions.

The growing emphasis on sustainable resource utilization has further encouraged the exploration of invasive plant species as precursor materials for activated carbon production. Invasive weeds often generate substantial biomass, exhibit rapid growth rates, and create ecological disturbances through competition with native vegetation. Their utilization as carbon precursors therefore offers a dual environmental benefit by simultaneously addressing invasive biomass management and wastewater remediation challenges. This approach aligns closely with circular bioeconomy principles and sustainable environmental management strategies [24].

Among invasive plant species, *Hyptis suaveolens* (L.) Poit., commonly known as Vilayati Tulsi, has emerged as a promising biomass resource because of its extensive distribution, rapid growth, high biomass productivity, and favorable lignocellulosic composition. The species frequently colonizes roadsides, wastelands, degraded ecosystems, and abandoned agricultural lands, producing large

quantities of biomass with limited economic utilization [30]. These characteristics make *H. suaveolens* an attractive precursor material for activated carbon production. Furthermore, the conversion of invasive biomass into value-added adsorbents represents an environmentally sustainable “waste-to-wealth” strategy capable of contributing to both pollution control and ecosystem restoration.

Although biomass-derived activated carbons have been extensively investigated, relatively limited attention has been devoted to activated carbon prepared from *Hyptis suaveolens*. Comprehensive studies examining activation optimization, physicochemical characterization, pore development, adsorption mechanisms, and pollutant removal efficiency remain scarce. Therefore, further investigation into *H. suaveolens*-based activated carbon is necessary to establish its suitability as a sustainable adsorbent for heavy metal and dye removal from wastewater. This may contribute significantly to the development of low-cost, environmentally friendly adsorption technologies capable of addressing contemporary water pollution challenges.

Table 3. Biomass resources investigated for activated carbon production and wastewater remediation

Biomass Precursor	Target Pollutant	Major Characteristics
Rice Husk	Pb, Cd, Cr	High silica content
Coconut Shell	Methylene Blue	High surface area
Sugarcane Bagasse	Heavy metals	Abundant lignocellulose
Sawdust	Dyes and metal ions	Low-cost adsorbent
Banana Peel	Organic pollutants	Rich functional groups
Water Hyacinth	Heavy metals	Rapid biomass production
Agricultural Residues	Multiple contaminants	Renewable precursor
<i>Hyptis suaveolens</i>	Dyes and Heavy Metals	Invasive biomass, high lignocellulosic content

5. *Hyptis suaveolens* as a Sustainable Biomass Resource for Activated Carbon Production

The growing demand for low-cost and environmentally sustainable adsorbents has stimulated extensive research into the utilization of renewable biomass resources for activated carbon production. Among the various biomass materials investigated, invasive plant species have recently attracted considerable attention because of their rapid growth, abundant biomass generation, ecological adaptability, and limited economic utilization. The conversion of invasive weeds into activated carbon not only provides an alternative precursor for adsorbent production but also contributes to invasive species management, biomass valorization, and environmental sustainability. In this context, *Hyptis suaveolens* (L.) Poit., commonly known as Vilayati Tulsi or Bush Mint, has emerged as a promising biomass resource for the development of activated carbon intended for wastewater remediation applications [24,30].

Hyptis suaveolens belongs to the family Lamiaceae and is native to tropical America, although it is now widely distributed throughout tropical and subtropical regions of Asia, Africa, Australia, and the Pacific Islands [30]. The species exhibits remarkable ecological adaptability and can successfully colonize roadsides, wastelands, abandoned agricultural lands, forest margins, riverbanks, and degraded ecosystems. Its aggressive growth habit, prolific seed production, and high reproductive capacity enable the formation of dense populations that frequently suppress native vegetation and alter ecosystem structure [30]. Consequently, *H. suaveolens* is recognized as one of the most problematic invasive weeds in many tropical regions, creating ecological and management challenges while simultaneously generating large quantities of underutilized biomass.

Despite its invasive nature, *H. suaveolens* possesses several characteristics that make it an attractive precursor material for activated carbon production. The plant exhibits rapid biomass accumulation and can be harvested repeatedly from naturally established populations without competing with food crops

or requiring intensive agricultural inputs. Furthermore, its widespread availability significantly reduces raw material procurement costs, thereby improving the economic feasibility of biomass-derived activated carbon production [24]. The utilization of this invasive weed for environmental applications therefore represents a sustainable “waste-to-wealth” strategy capable of simultaneously addressing invasive species management and wastewater treatment challenges.

The suitability of biomass for activated carbon production is largely determined by its lignocellulosic composition. Plant biomass generally consists of cellulose, hemicellulose, and lignin, which serve as the primary carbon precursors during thermal conversion processes. Previous studies have demonstrated that biomass materials possessing high lignin and cellulose contents are particularly favorable for activated carbon production because these polymers contribute significantly to char formation and pore development during carbonization and activation [17,24]. Like many members of the family Lamiaceae, *H. suaveolens* contains substantial quantities of lignocellulosic components that can be converted into porous carbonaceous structures through appropriate activation procedures. During carbonization, thermal decomposition of cellulose, hemicellulose, and lignin generates a carbon-rich matrix, while subsequent activation develops an extensive pore network and increases surface area, thereby enhancing adsorption capacity [22,24].

In addition to its favorable chemical composition, *H. suaveolens* contains numerous oxygen-containing functional groups that may contribute to the development of chemically active adsorption sites after activation. Surface functionalities such as hydroxyl, carbonyl, carboxyl, and phenolic groups are known to play important roles in the adsorption of dyes and heavy metals through mechanisms including electrostatic attraction, ion exchange, hydrogen bonding, and surface complexation [22,23]. Chemical activation using phosphoric acid, potassium hydroxide, or other activating agents can further enhance pore development and introduce additional surface functionalities, thereby improving adsorption performance toward both organic and inorganic contaminants.

Recent advances in biomass-based adsorbent research have demonstrated that activated carbons prepared from agricultural residues, forestry wastes, aquatic weeds, and medicinal plants can exhibit adsorption capacities comparable to those of commercial activated carbons [17,24]. However, relatively limited attention has been devoted to activated carbon derived specifically from *Hyptis suaveolens*. Most published investigations involving *H. suaveolens* have focused on its phytochemical composition, antimicrobial activity, antioxidant properties, essential oil constituents, and medicinal applications, whereas systematic studies concerning activated carbon production, physicochemical characterization, and wastewater treatment performance remain scarce [30]. Consequently, significant opportunities exist for exploring the potential of this invasive biomass as a precursor for sustainable adsorbent development.

The utilization of *H. suaveolens* for activated carbon production offers several environmental and economic advantages. First, it provides a productive use for an invasive species that otherwise contributes to ecological degradation. Second, it reduces dependence on conventional carbon precursors such as coal and wood, thereby promoting sustainable resource utilization. Third, it supports circular bioeconomy principles through the conversion of low-value biomass into high-value environmental remediation materials. Finally, the development of *H. suaveolens*-based activated carbon may contribute to the establishment of low-cost wastewater treatment technologies suitable for application in developing countries where access to commercial activated carbon is often limited.

Although the available evidence suggests considerable potential for the utilization of *Hyptis suaveolens* biomass in activated carbon production, further investigations are required to optimize activation conditions, evaluate physico-chemical characteristics, understand adsorption mechanisms, and assess large-scale applicability. Characterization of activated carbon derived from *H. suaveolens* is essential for determining its suitability as a sustainable adsorbent for the removal of dyes and heavy metals from contaminated wastewater.

6. Preparation and Characterization of Activated Carbon Derived from *Hyptis suaveolens*

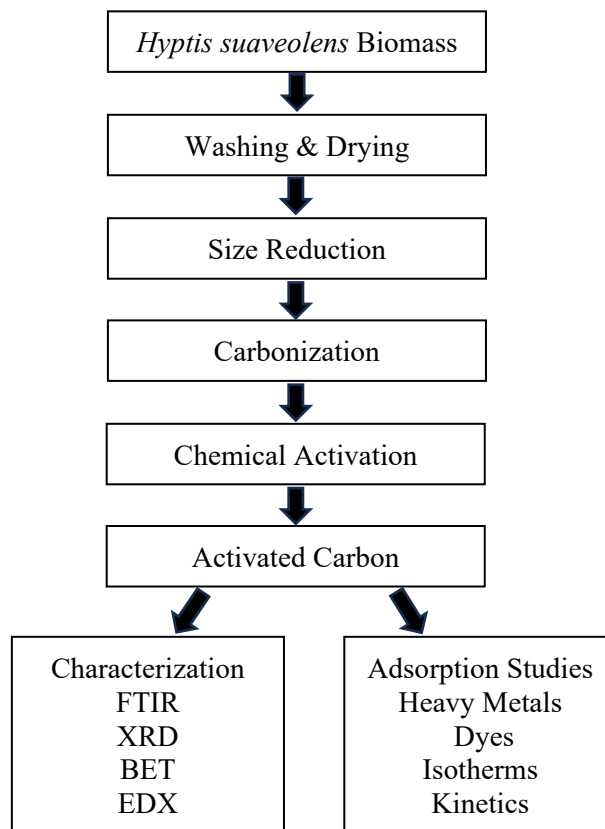


Figure 1. Preparation and Characterization Pathway of Activated Carbon Derived from *Hyptis suaveolens* Biomass

The performance of activated carbon as an adsorbent is primarily governed by its physicochemical properties, including surface area, pore structure, pore-size distribution, surface functional groups, and elemental composition. These characteristics are strongly influenced by the nature of the precursor material and the activation process employed during carbon preparation. Biomass-derived activated carbons have attracted considerable attention because activation treatments can transform lignocellulosic materials into highly porous carbonaceous structures capable of efficiently adsorbing a wide range of organic and inorganic pollutants [22,24]. In the case of *Hyptis suaveolens*, its abundant lignocellulosic content and widespread availability provide a promising basis for the production of low-cost activated carbon suitable for wastewater remediation applications.

The production of activated carbon generally involves two sequential processes, namely carbonization and activation. Carbonization converts raw biomass into carbon-rich char through thermal decomposition under oxygen-limited conditions, whereas activation develops porosity and increases surface area by removing volatile components and restructuring the carbon matrix [22,23]. During carbonization, cellulose, hemicellulose, and lignin undergo thermal degradation, producing aromatic carbon frameworks and creating the initial pore structure. However, carbonization alone is insufficient to generate the extensive porosity required for effective adsorption. Consequently, activation processes are employed to enhance pore development and improve adsorption performance.

Activation may be achieved through either physical or chemical methods. Physical activation typically utilizes steam or carbon dioxide at elevated temperatures to enlarge existing pores and generate additional porosity. In contrast, chemical activation employs activating agents such as phosphoric acid (H_3PO_4), potassium hydroxide (KOH), zinc chloride (ZnCl_2), and sulfuric acid (H_2SO_4), which facilitate dehydration, inhibit tar formation, and promote extensive pore development at comparatively lower temperatures [22,24]. Numerous studies have demonstrated that chemical activation generally produces activated carbons with higher surface areas, larger pore volumes, and superior adsorption capacities than those obtained through physical activation alone [17,24]. Among these activating agents, phosphoric acid is particularly attractive because it enhances both pore formation and surface

functionalization, resulting in activated carbons possessing improved adsorption affinity toward dyes and heavy metals.

The adsorption behavior of activated carbon is closely related to its structural and surface properties, making comprehensive characterization essential for understanding adsorption mechanisms and evaluating adsorbent performance. Scanning Electron Microscopy (SEM) is widely employed to investigate surface morphology and pore development. SEM analysis provides valuable information regarding surface texture, pore distribution, and structural changes induced during activation. Activated carbons exhibiting highly porous and interconnected structures generally demonstrate superior adsorption performance due to the greater accessibility of adsorption sites [22].

Fourier Transform Infrared Spectroscopy (FTIR) is commonly utilized to identify surface functional groups present on activated carbon. Functional groups such as hydroxyl, carboxyl, carbonyl, phenolic, and phosphate moieties significantly influence adsorption behavior through electrostatic attraction, hydrogen bonding, ion exchange, and surface complexation mechanisms [23]. The presence and abundance of these functional groups determine the affinity of activated carbon toward specific pollutants and contribute substantially to adsorption efficiency.

X-ray Diffraction (XRD) analysis is employed to investigate the crystalline and amorphous characteristics of activated carbon materials. Biomass-derived activated carbons typically exhibit predominantly amorphous structures due to the disordered arrangement of carbon atoms produced during thermal conversion processes [22]. The presence of broad diffraction peaks is generally associated with amorphous carbon, whereas sharp peaks may indicate the presence of mineral constituents or crystalline inorganic impurities. The degree of structural order revealed by XRD analysis provides valuable insight into the physicochemical properties of activated carbon and its adsorption potential.

Surface area and porosity represent critical parameters governing adsorption performance and are commonly evaluated using Brunauer–Emmett–Teller (BET) analysis. BET measurements provide quantitative information regarding specific surface area, pore volume, and pore-size distribution. Activated carbons possessing high surface areas and well-developed microporous structures generally exhibit enhanced adsorption capacities because they provide a greater number of active adsorption sites [22,24]. Numerous studies have demonstrated a strong positive relationship between surface area and adsorption efficiency for both dye molecules and heavy metal ions.

Elemental composition is another important factor influencing adsorbent performance and is typically determined using Energy Dispersive X-ray Spectroscopy (EDX). EDX analysis provides information regarding the elemental constituents present on activated carbon surfaces and enables evaluation of carbon enrichment following activation processes. High carbon content is generally associated with improved adsorptive properties, whereas the presence of oxygen-containing functionalities contributes to surface reactivity and adsorption selectivity [22,23].

Collectively, SEM, FTIR, XRD, BET, and EDX analyses provide comprehensive insight into the structural, chemical, and morphological properties of activated carbon derived from *Hyptis suaveolens*. These characterization techniques are essential for establishing relationships between activation conditions, physicochemical properties, and adsorption performance. A detailed understanding of these characteristics is necessary for optimizing activated carbon production and enhancing its effectiveness for the removal of dyes and heavy metals from contaminated wastewater. Consequently, characterization studies constitute a critical component in the development of *Hyptis suaveolens*-based activated carbon as a sustainable adsorbent for environmental remediation applications.

7. Adsorption Mechanisms, Isotherms and Kinetics for Dye and Heavy Metal Removal

The effectiveness of activated carbon in wastewater treatment is governed not only by its physicochemical characteristics but also by the mechanisms through which pollutants interact with the adsorbent surface. Understanding adsorption mechanisms, equilibrium behavior, and adsorption kinetics is essential for evaluating adsorbent performance and optimizing treatment processes. In biomass-derived activated carbons, adsorption occurs through a combination of physical and chemical interactions involving porous carbon structures and surface functional groups. These interactions

determine the adsorption capacity, selectivity, and overall efficiency of pollutant removal from contaminated water [14,19,20].

7.1 Adsorption Mechanisms for Dye and Heavy Metal Removal

The adsorption of dyes and heavy metals onto activated carbon is a complex process involving multiple mechanisms that operate simultaneously. The dominant adsorption pathway depends upon the physicochemical properties of both the adsorbent and adsorbate, including molecular size, charge, polarity, pore structure, and surface chemistry. In activated carbon derived from lignocellulosic biomass, adsorption generally occurs through electrostatic attraction, ion exchange, pore filling, hydrogen bonding, π - π interactions, and surface complexation reactions [22,23].

Electrostatic attraction plays a crucial role in the adsorption of charged pollutants. Positively charged dye molecules and metal ions may interact with negatively charged functional groups present on activated carbon surfaces, whereas negatively charged species may be attracted to positively charged adsorption sites. The magnitude of these interactions is strongly influenced by solution pH and surface charge characteristics of the adsorbent. Surface functional groups such as hydroxyl, carboxyl, phenolic, and carbonyl moieties contribute significantly to electrostatic interactions and metal ion binding [22].

Hydrogen bonding represents another important adsorption mechanism, particularly for organic dyes containing amino, hydroxyl, or sulfonic groups. The formation of hydrogen bonds between dye molecules and oxygen-containing functional groups on activated carbon enhances adsorption affinity and contributes to pollutant retention [19]. In addition, aromatic dye molecules frequently undergo π - π interactions with the graphitic domains present within activated carbon structures. These interactions are especially important for the adsorption of azo dyes, methylene blue, Congo red, and other aromatic compounds commonly encountered in industrial wastewater [14,16].

For heavy metal ions, surface complexation and ion-exchange mechanisms frequently dominate adsorption behavior. Oxygen-containing functional groups act as electron-donating ligands capable of forming stable coordination complexes with metal ions such as Pb^{2+} , Cd^{2+} , Cr^{6+} , Cu^{2+} , and Ni^{2+} . Simultaneously, exchangeable ions present on the adsorbent surface may be replaced by dissolved metal ions, further contributing to metal removal efficiency [20,25]. The combined contribution of these mechanisms enables activated carbon to effectively remove both organic and inorganic contaminants from wastewater.

7.2 Adsorption Equilibrium Studies

Adsorption equilibrium describes the distribution of adsorbate molecules between the solid and liquid phases once equilibrium has been established. Equilibrium studies are essential for understanding adsorption capacity and designing treatment systems. Among the numerous adsorption isotherm models developed, the Langmuir and Freundlich isotherms remain the most widely employed for evaluating adsorption performance [20].

The Langmuir isotherm assumes monolayer adsorption onto a homogeneous surface containing a finite number of identical adsorption sites. It further assumes that each adsorption site can accommodate only one adsorbate molecule and that no interactions occur between adsorbed species.

The Langmuir model is represented as: $q_e = \frac{q_{\text{max}}bC_e}{1+bC_e}$

here q_e represents the equilibrium adsorption capacity (mg g^{-1}), q_{max} denotes the maximum monolayer adsorption capacity, b is the Langmuir constant associated with adsorption affinity, and C_e is the equilibrium concentration of adsorbate in solution [27]. A good fit to the Langmuir model indicates monolayer adsorption and uniform surface energy distribution.

In contrast, the Freundlich isotherm describes adsorption on heterogeneous surfaces possessing sites of varying adsorption energies. Unlike the Langmuir model, it does not assume monolayer coverage and is particularly applicable to biomass-derived activated carbons characterized by heterogeneous pore structures and diverse surface functionalities.

The Freundlich equation is expressed as: $q_e = K_F \frac{1}{n} C_e^{\frac{1}{n}}$

where K_F represents adsorption capacity and $1/n$ describes adsorption intensity and surface

heterogeneity [28]. Freundlich behavior frequently indicates multilayer adsorption and heterogeneous surface characteristics.

7.3 Influence of Surface Charge and pH_{pzc}

The pH of the solution significantly influences adsorption performance because it affects both pollutant speciation and adsorbent surface charge. The point of zero charge (pH_{pzc}) is defined as the pH at which the net surface charge of the adsorbent becomes zero. At pH values below pH_{pzc}, the activated carbon surface becomes positively charged, whereas at pH values above pH_{pzc}, the surface acquires a negative charge [22].

The relationship between solution pH and pH_{pzc} is particularly important for adsorption of ionic pollutants. Positively charged heavy metal ions generally exhibit enhanced adsorption at pH values above pH_{pzc} due to electrostatic attraction toward negatively charged surfaces. Conversely, adsorption of anionic dye molecules may be favored under acidic conditions when the adsorbent surface possesses a positive charge. Consequently, determination of pH_{pzc} provides valuable information regarding adsorption mechanisms and optimal operating conditions.

7.4 Adsorption Kinetics

Adsorption kinetics describe the rate at which pollutants are transferred from solution to adsorption sites and provide important information regarding the controlling mechanisms of adsorption processes. Kinetic studies are essential for understanding mass transfer phenomena and designing large-scale treatment systems [19].

The pseudo-first-order kinetic model assumes that adsorption rate is proportional to the number of unoccupied adsorption sites and is represented by: $\ln(q_e - q_t) = \ln(q_e) - k_1 t$

where q_t and q_e represent adsorption capacities at time t and equilibrium, respectively, and k_1 is the pseudo-first-order rate constant [29].

The pseudo-second-order kinetic model is generally considered more suitable for adsorption involving chemisorption mechanisms and is expressed as:

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

where k_2 represents the pseudo-second-order rate constant [29]. Studies involving biomass-derived activated carbons have reported superior fitting of adsorption data to the pseudo-second-order model, suggesting that chemical interactions between adsorbate molecules and surface functional groups play a dominant role in pollutant removal.

Collectively, adsorption mechanisms, equilibrium isotherms, surface charge characteristics, and kinetic behavior provide the theoretical foundation for understanding the performance of activated carbon derived from *Hyptis suaveolens*. These concepts are essential for evaluating adsorption efficiency, optimizing operating conditions, and developing sustainable wastewater treatment systems capable of effectively removing both dyes and heavy metals from contaminated water.

8. Conclusion

The increasing contamination of water resources by heavy metals and synthetic dyes represents one of the most pressing environmental challenges of the twenty-first century. Rapid industrialization, urbanization, mining activities, textile manufacturing, electroplating operations, and agricultural intensification have substantially increased the release of toxic contaminants into aquatic ecosystems, thereby threatening environmental sustainability, ecosystem integrity, and public health. Heavy metals such as lead, cadmium, chromium, mercury, and arsenic are of particular concern because of their persistence, non-biodegradability, bioaccumulation potential, and long-term toxic effects on living organisms. Similarly, synthetic dyes discharged from textile, leather, paper, and pharmaceutical industries contribute significantly to water quality deterioration owing to their complex molecular structures, resistance to degradation, and potential mutagenic and carcinogenic properties. The simultaneous occurrence of these contaminants in industrial wastewater has further complicated remediation efforts and necessitated the development of efficient and sustainable treatment technologies. Although conventional wastewater treatment methods including chemical precipitation,

coagulation–flocculation, membrane filtration, ion exchange, and biological treatment have demonstrated varying degrees of effectiveness, each technology possesses inherent limitations related to operational cost, sludge generation, membrane fouling, incomplete contaminant removal, and secondary environmental impacts. Consequently, adsorption has emerged as one of the most promising approaches for wastewater remediation because of its operational simplicity, high removal efficiency, economic feasibility, and adaptability to diverse wastewater compositions. Among available adsorbent materials, activated carbon continues to be regarded as the benchmark adsorbent due to its highly porous structure, extensive surface area, and abundance of chemically active functional groups capable of interacting with a broad spectrum of pollutants. Biomass-derived activated carbons offer significant environmental and economic advantages by converting low-value biological materials into high-value adsorbents while simultaneously reducing waste disposal problems and promoting circular bioeconomy principles. Among invasive biomass resources, *Hyptis suaveolens* (L.) Poit. possesses several characteristics that make it particularly suitable for activated carbon production. The species exhibits extensive distribution, rapid biomass accumulation, ecological adaptability, and favorable lignocellulosic composition, all of which contribute to its potential as a sustainable carbon precursor. The conversion of *H. suaveolens* biomass into activated carbon represents a valuable waste-to-wealth strategy capable of transforming an ecologically problematic weed into an environmentally beneficial resource. Furthermore, the lignocellulosic structure of the plant provides an excellent foundation for the development of highly porous carbon materials possessing functional groups favorable for adsorption processes. Thus, *Hyptis suaveolens* possesses considerable potential as a renewable precursor for activated carbon production and wastewater remediation. The conversion of this invasive weed into a high-performance adsorbent provides a sustainable approach for simultaneously addressing environmental pollution, invasive biomass management, and resource recovery. Continued research and technological development in this field may contribute significantly to achieving sustainable water treatment solutions and promoting circular bioeconomy strategies for environmental protection.

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