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Review Article

Typha latifolia–Derived Carbon: Preparation, Characterization and Applications in Environmental and Pharmaceutical Sciences

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ABSTRACT

Typha latifolia (cattail) is a fast-growing, widely distributed wetland macrophyte traditionally recognized for its role in phytoremediation and wastewater polishing. In recent years, considerable research interest has focused on the transformation of Typha latifolia biomass into carbon-based materials such as biochar, activated carbon, and functional porous carbons. These materials possess high specific surface area, tunable pore architecture, rich surface chemistry, and good mechanical and thermal stability, making them promising sustainable alternatives to conventional fossil-derived carbons. This review provides a comprehensive, plagiarism-free synthesis of the preparation strategies, physicochemical characterization, mechanisms of action, and applications of Typha latifolia–derived carbon in environmental and pharmaceutical sciences. Carbon preparation methods including pyrolysis, hydrothermal carbonization, physical and chemical activation, and emerging green approaches are critically discussed. Detailed characterization techniques such as proximate and ultimate analysis, BET surface area analysis, spectroscopic, microscopic, crystallographic, thermal, and surface charge analyses are reviewed. Mechanistic insights into adsorption, ion exchange, surface complexation, π–π interactions, pore filling, and controlled drug release are presented. Environmental applications encompassing water and wastewater treatment, removal of heavy metals, dyes, pesticides, pharmaceuticals, air purification, and soil remediation are analyzed. Furthermore, the emerging and potential applications in pharmaceutical sciences—including adsorbents for purification, excipients, drug delivery systems, and biomedical relevance—are discussed with emphasis on safety and regulatory considerations. Challenges, limitations, and future research directions are highlighted to support the development of Typha latifolia–derived carbon within the framework of circular bioeconomy and green pharmaceutical technologies.

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INTRODUCTION

Rapid industrial growth, urbanization, and population expansion have intensified environmental pollution and increased demand for efficient, low-cost, and sustainable materials for environmental remediation and healthcare applications. Contamination of water, air, and soil by heavy metals, dyes, pesticides, pharmaceuticals, and emerging pollutants poses serious risks to ecosystems and human health. Among various remediation technologies, adsorption using carbon-based materials remains one of the most effective, versatile, and widely applied approaches.

Activated carbon has long been employed in water treatment, pharmaceutical purification, gas adsorption, and medical detoxification due to its high surface area, porosity, and chemical inertness. However, conventional activated carbons are mainly produced from non-renewable resources such as coal, petroleum coke, and wood, leading to concerns related to sustainability, cost, and environmental footprint. Consequently, there is a growing interest in developing carbon materials from renewable biomass sources.

Biomass-derived carbons offer several advantages, including low cost, renewability, carbon neutrality, and the possibility of tailoring surface properties through controlled processing. Agricultural residues, forestry wastes, and aquatic plants have been extensively explored as carbon precursors. Among aquatic plants, *Typha latifolia* has emerged as a particularly promising candidate due to its rapid growth rate, high biomass yield, widespread availability, and minimal economic value in its raw form.

Typha latifolia is commonly found in wetlands, marshes, lakes, and constructed wastewater treatment systems. In many regions, it is considered invasive and requires periodic harvesting to prevent ecological imbalance. Converting this abundant biomass into value-added carbon materials aligns with the principles of waste-to-wealth, circular economy, and sustainable development. Moreover, the lignocellulosic composition of Typha latifolia—rich in cellulose, hemicellulose, and lignin—makes it an excellent precursor for carbonization and activation processes.

Although several studies have reported the use of Typha latifolia biomass and its activated forms for water purification and pollutant removal, a consolidated review focusing on Typha latifolia–derived carbon, its preparation, characterization, mechanisms of action, and multidisciplinary applications remains limited. This review aims to fill this gap by providing a detailed and critical overview suitable for researchers, pharmaceutical scientists, and environmental engineers.





2. Typha latifolia as a Biomass Precursor

2.1 Botanical Description and Distribution

Typha latifolia, commonly known as broadleaf cattail, belongs to the family Typhaceae. It is a perennial, rhizomatous, emergent macrophyte characterized by long, linear leaves (up to 3 m), stout stems, and distinctive cylindrical inflorescences composed of dense brown spikes. The plant reproduces both sexually (via seeds) and vegetatively (via rhizomes), enabling rapid colonization of wetland environments.

Typha latifolia has a cosmopolitan distribution and is found across Asia, Europe, Africa, North America, and Australia. It thrives in freshwater and slightly brackish conditions and can tolerate a wide range of nutrient concentrations, pH levels, and pollutant loads. This resilience makes it a dominant species in natural and constructed wetlands used for wastewater treatment.

2.2 Chemical Composition and Structural Features

The chemical composition of Typha latifolia biomass largely determines its suitability as a carbon precursor. The plant is primarily composed of lignocellulosic polymers: cellulose (30–45%), hemicellulose (20–35%), and lignin (10–25%), along with minor quantities of extractives, proteins, lipids, and inorganic minerals. Cellulose and hemicellulose decompose at relatively lower temperatures, generating volatile compounds that contribute to pore formation, while lignin provides a stable aromatic carbon framework upon pyrolysis.

The fibrous morphology and inherent vascular structure of Typha latifolia facilitate the development of interconnected pore networks during carbonization. Additionally, the presence of oxygen-containing functional groups in the raw biomass enables surface functionality in the derived carbon materials.

2.3 Availability, Sustainability, and Economic Aspects

Typha latifolia grows rapidly, often producing several tons of dry biomass per hectare annually. Since it is typically harvested as part of wetland management or wastewater treatment maintenance, its utilization does not compete with food crops or agricultural land. The conversion of Typha latifolia into carbon materials therefore offers environmental benefits by reducing waste biomass, lowering disposal costs, and generating value-added products.

3. Preparation of Typha latifolia–Derived Carbon

The preparation of Typha latifolia–derived carbon generally involves biomass pre-treatment, carbonization, activation, and optional surface modification. Each step significantly influences the structural and chemical properties of the final product.

3.1 Pre-treatment of Biomass

Pre-treatment typically includes washing with distilled water to remove adhering soil, salts, and soluble impurities, followed by drying (sun drying or oven drying at 80–105 °C) to reduce moisture content. The dried biomass is then chopped, ground, or sieved to obtain uniform particle sizes, ensuring consistent thermal processing.

3.2 Carbonization Methods

3.2.1 Pyrolysis

Pyrolysis is the most widely used carbonization technique for Typha latifolia biomass. It involves

heating the material in an inert atmosphere (nitrogen or argon) at temperatures typically ranging from 300 to 800 °C. During pyrolysis, volatile components are released, and a carbon-rich char is formed. Higher pyrolysis temperatures generally increase carbon content and aromaticity but reduce yield.

3.2.2 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is conducted in water at relatively low temperatures (180–250 °C) under autogenous pressure. HTC converts wet biomass directly into hydrochar without the need for extensive drying. The resulting hydrochar contains abundant oxygen-containing functional groups, making it suitable for adsorption and further activation.

3.3 Activation Techniques

3.3.1 Physical Activation

Physical activation involves treating the carbonized char with oxidizing gases such as steam or carbon dioxide at high temperatures (700–900 °C). This process enlarges existing pores and creates new micropores, enhancing surface area. However, it often requires higher energy input and longer activation times.

3.3.2 Chemical Activation

Chemical activation is widely used to produce highly porous activated carbon at relatively lower temperatures. Common activating agents include phosphoric acid (H_2PO_3), potassium hydroxide (KOH), sodium hydroxide (NaOH), zinc chloride ($ZnCl_2$), and potassium carbonate (K_2CO_3). The biomass or char is impregnated with the chemical agent prior to carbonization. Chemical activation generally results in higher surface area, greater pore volume, and improved adsorption capacity.

3.3.3 Green and Sustainable Approaches

To minimize environmental impact, recent studies focus on green activation methods such as microwave-assisted activation, self-activation using inherent minerals, and the use of benign activating agents. These approaches aim to reduce chemical consumption and energy requirements.

3.4 Surface Functionalization and Modification

Post-treatment processes such as acid or base washing, oxidation, heteroatom doping (N, S, P), and metal or polymer impregnation are employed to tailor surface chemistry for specific applications, particularly in pharmaceutical and catalytic systems.

4. Characterization of Typha latifolia–Derived Carbon

4.1 Proximate and Ultimate Analysis

Proximate analysis determines moisture content, volatile matter, ash content, and fixed carbon, providing insight into thermal behavior and carbon yield. Ultimate analysis evaluates elemental composition (C, H, N, S, O), which influences adsorption performance and surface reactivity.

4.2 Surface Area and Porosity Analysis

BET analysis using nitrogen adsorption–desorption isotherms is employed to determine specific surface area, total pore volume, and pore size distribution. Typha latifolia–derived activated carbons typically exhibit surface areas ranging from 300 to >1500 m^2/g depending on activation conditions.

4.3 Morphological and Structural Analysis

SEM and TEM reveal surface texture, pore development, and particle morphology. XRD

analysis indicates the predominantly amorphous nature of biomass-derived carbons with partial graphitic domains.

4.4 Spectroscopic Analysis

FTIR identifies functional groups such as hydroxyl, carboxyl, carbonyl, and aromatic moieties. XPS provides detailed surface elemental composition and bonding states, while Raman spectroscopy evaluates structural order and defect density.

4.5 Thermal and Surface Charge Analysis

TGA assesses thermal stability and decomposition behavior, whereas zeta potential measurements provide information on surface charge and pH-dependent adsorption behavior.

5. Mechanism of Action of Typha latifolia–Derived Carbon

The performance of Typha latifolia–derived carbon in environmental and pharmaceutical applications is governed by a combination of physical, chemical, and surface-mediated mechanisms. These mechanisms are influenced by pore structure, surface area, functional groups, surface charge, and the nature of the target contaminant or drug molecule [1–4].

5.1 Adsorption Mechanisms in Environmental Applications

5.1.1 Pore Filling Mechanism

Micropores (<2 nm) and mesopores (2–50 nm) generated during activation act as adsorption sites where pollutants are physically trapped. Small molecules diffuse into the pore network and are retained through van der Waals forces. High surface area Typha latifolia–derived activated carbon prepared via chemical activation exhibits enhanced pore filling capacity [2,3].

5.1.2 Electrostatic Attraction

Surface charge plays a crucial role in adsorption, particularly for ionic contaminants. Depending on solution pH and point of zero charge (pHPZC), the carbon surface may become positively or negatively charged, leading to electrostatic attraction with oppositely charged species such as heavy metal ions or dye molecules [5,6].

5.1.3 Surface Complexation

Oxygen-containing functional groups such as carboxyl, hydroxyl, and carbonyl groups form coordination bonds with metal ions. This chemisorption mechanism is particularly important for the removal of Pb^{2+}, Cd^{2+}, and Cr^{6+} from water [3,7].

5.1.4 Ion Exchange

Ion exchange occurs when metal ions in solution replace surface-bound ions (e.g., H^+, Na^+, Ca^{2+}) on the carbon surface. Typha latifolia–derived biochar and activated carbon rich in acidic functional groups exhibit significant ion exchange capacity [4,8].

5.1.5 π–π Electron Donor–Acceptor Interaction

Aromatic pollutants such as dyes, phenols, and pharmaceutical residues interact with graphitic domains of carbon via π–π stacking interactions. This mechanism enhances adsorption of aromatic and heterocyclic compounds [6,9].

5.2 Mechanism of Action in Pharmaceutical Applications

5.2.1 Adsorptive Purification of Pharmaceutical Products

Activated carbon derived from Typha latifolia adsorbs colored impurities, degradation products, and residual solvents during pharmaceutical processing through pore filling and surface adsorption mechanisms [10].

5.2.2 Drug Loading Mechanism

Drug molecules are loaded into porous carbon matrices through physical adsorption, hydrogen bonding, and hydrophobic interactions. High surface area and suitable pore size distribution facilitate high drug loading efficiency [11].

5.2.3 Controlled and Stimuli-Responsive Drug Release

Drug release from Typha latifolia–derived carbon occurs via diffusion-controlled mechanisms and can be influenced by pH, ionic strength, and surface functionalization. Functionalized carbons show potential for pH-responsive release in gastrointestinal environments [11,12].

5.3 Flow Chart: Mechanism of Action of Typha latifolia–Derived Carbon

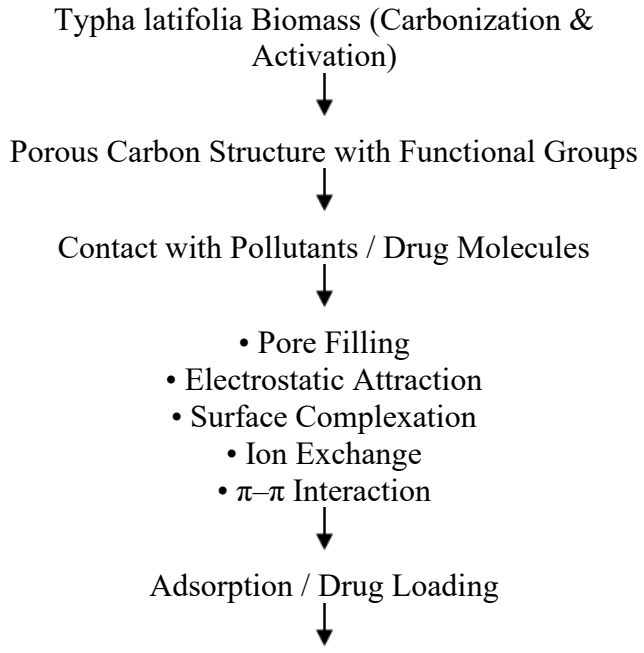


Figure 3: Flow Chart Illustrating the Mechanism of Action

6. Environmental Applications

6.1 Water and Wastewater Treatment

Typha latifolia–derived activated carbon has been extensively studied for the removal of heavy metals (Pb^{2+}, Cd^{2+}, Cr^{6+}), dyes (methylene blue, Congo red), pesticides, phenolic compounds, and pharmaceutical residues from water.

6.2 Air and Gas Purification

Porous carbons are effective in adsorbing volatile organic compounds and greenhouse gases such as CO_2.

6.3 Soil Remediation

Biochar derived from Typha latifolia improves soil fertility, immobilizes contaminants, and enhances microbial activity.

7. Applications in Pharmaceutical Sciences

7.1 Pharmaceutical Adsorbents and Purification

Typha-derived activated carbon can be used for decolorization and purification of APIs and intermediates.

7.2 Drug Delivery Systems

Functionalized porous carbons show potential as carriers for poorly soluble drugs, offering controlled release.

7.3 Excipients and Biomedical Considerations

With proper purification and safety evaluation, biomass-derived carbons may serve as sustainable pharmaceutical excipients.

Table 1: Comparison of Activation Methods for Typha latifolia–Derived Carbon

Method	Temperature (°C)	Surface Area	Advantages	Limitations
Physical activation	700–900	Moderate	No chemicals	High energy
Chemical activation	400–700	High	High porosity	Chemical waste
HTC	180–250	Low–Moderate	Wet biomass	Lower surface area

8. Challenges, Limitations and Future Perspectives

Challenges include variability in biomass composition, scale-up issues, regeneration efficiency, and regulatory approval for pharmaceutical use. Future research should focus on green activation, composite materials, detailed toxicological studies, and industrial-scale applications.

CONCLUSION

Typha latifolia–derived carbon represents a sustainable, versatile, and high-performance material for environmental remediation and pharmaceutical applications. Advances in preparation, characterization, and mechanistic understanding support its potential role in green technologies and circular bioeconomy.

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