

A comprehensive review of *Conocarpus*: Preparation strategies, adsorption mechanisms, and applications in wastewater treatment

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ABSTRACT

Plant biomass has become one of the most important sustainable sources of low-cost and high-efficiency adsorption materials for wastewater treatment, and *Conocarpus* is one of the most promising plants in this field due to its availability as a product of urban pruning processes and its outstanding physical and chemical properties. This study comprehensively and critically reviews the latest research findings related to the use of *Conocarpus* derivatives in wastewater treatment, with a focus on the structural and chemical properties of the raw material, and strategies Preparation and modification, adsorption mechanisms, factors affecting performance, and the most important environmental applications. The review shows that carbonization and physical and chemical activation processes, together with advanced surface modifications, lead to improved porosity, increased surface area and enrichment of functional groups, enhancing the efficiency of the removal of heavy metals, dyes, nutrients and emerging organic pollutants. It also describes the various mechanisms involved in adsorption, such as electrostatic attraction, ion exchange, surface complexity, intrapore adsorption, hydrogen bonding and π - π reactions, which have a strong impact on the operating conditions: pH, zero charge point, contact time, and contaminant concentration. Despite the promising results of *Conocarpus* derivatives, practical applications are still limited due to the lack of reuse, continuous operation, real-water evaluation, and economic and environmental assessment. The review also notes that studies on radionuclide removal are still limited, with evidence that these materials can be used to remove ²²⁶Ra, which warrants further research into their selectivity, stability and practical applications. The review emphasizes that linking the properties of the material to operating conditions and adsorption mechanisms provides a basis for the development of more efficient and sustainable water treatment materials.

Keywords: adsorption mechanisms, *Conocarpus*, radionuclide removal, surface functionalization, wastewater remediation.

INTRODUCTION

The world is witnessing a rapid deterioration in the quality of water resources as a result of industrial expansion and human activities, which has led to the accumulation of complex pollutants including heavy metals, industrial dyes, and biodegradable pharmaceutical compounds, as well as radioactive contaminants from medical waste, mining activities, and the nuclear industry, which represent an increasing threat to public health and

the environment This has led to a growing need for effective and sustainable treatment techniques to remove chemical and radioactive contaminants from water (Gatea et al., 2024; Steinhauser, 2018; Xiang et al., 2020).

Despite the significant advancement in traditional treatment techniques, such as chemical deposition (Crini and Lichtfouse, 2019), membrane filtration (Al-Sammarraie et al., 2025), ion exchange (Alsafran et al., 2023), and advanced oxidation processes (Gomber et al., 2013). But its application

still faces challenges related to high construction and operating costs, high energy consumption, toxic sludge production, and low efficiency in the treatment of complex multipollutant water (Crini and Lichtfouse, 2019; Li and Tang, 2021; Xiang et al., 2020; Xin et al., 2021). Therefore, research efforts have been geared towards the development of low-cost, renewable, and environmentally friendly adsorption materials as more sustainable alternatives (de Lima et al., 2025).

Biochar and activated carbon derived from plant biomass are among the most promising materials, due to their large surface area, advanced porous structure, and the possibility of modifying their surface properties to suit different types of pollutants (de Lima et al., 2025).

Among the promising sources of biomass, *Conocarpus* trees (*Conocarpus erectus*) stood out for their wide distribution in hot and semi-arid regions, their high tolerance to salinity and harsh environmental conditions (Rehman et al., 2023). Their pruning processes produce large quantities of plant residues that are a rich resource of cellulose, lignin and active functional groups, such as hydroxyl and carboxyl, making them a suitable feedstock for the production of highly efficient adsorption materials (Al-Wabel et al., 2013; Siddiq et al., 2024). Studies have demonstrated the efficiency of *Conocarpus*-derived leaves, stems and biochar in removing heavy metals, such as lead, cadmium, and zinc, as well as organic dyes, through mechanisms including electrostatic attraction, ion exchange, surface complexity and intrapore adsorption (Sajid et al., 2024; Usman et al., 2016b). The chemical and physical modification of these materials has also improved the surface area and porosity and enriched the surface with functional groups, promoting the removal of dyes and phenolic compounds, while maintaining structural and chemical stability in real water (Alazba et al., 2025b; Alhawas et al., 2023a; Usman et al., 2016b).

Although increasing studies on the use of *Conocarpus* and its derivatives in water treatment, the literature still needs an integrated analysis that clarifies the relationship between biomass properties, preparation and modification methods, operating conditions, and decontaminant removal mechanisms and performance. Evidence on the use of *Conocarpus* derivatives for radionuclide removal is still limited. Therefore, this review aims to provide a critical analysis of these aspects, comparing the performance of materials

under different conditions, identifying the factors and mechanisms governing the removal process, as well as highlighting the future challenges and trends needed to support the practical application of these materials.

PHYSICOCHEMICAL CHARACTERIZATION OF CONOCARPUS

The mechanism of binding and retention of pollutants by *Conocarpus* is related to its physicochemical and structural composition, which is crucial for the success of the adsorption process, since the lignocellulose structure, surface functional groups, and porosity of *Conocarpus* are responsible for this mechanism. The overall physicochemical and structural properties of *Conocarpus* biomass and its derivatives is summarized in Table 1.

Chemical composition, morphology, and porosity

The structural matrix of the *Conocarpus* plant consists of a lignocellulose mixture that includes cellulose, hemicellulose, and lignin. The results of the experimental analysis showed that there is a spatial variation in the distribution of these components within the plant parts, as the percentage of crystallized cellulose accumulates in the stem fibers compared to leaves and branches rich in volatile compounds (Jawaid et al., 2021). This high cellulose content provides the basic structure needed for carbonization. The plant also has lignin levels of 20–30%, which is superior to many other agricultural residues (Aref et al., 2013), ensuring high carbon productivity during pyrolysis and making it an economical option for the production of activated carbon. These differences in composition between plant parts should be taken into account when interpreting the adsorption properties and behavior of *Conocarpus*-derived resulting substances. Nasser et al. (Nasser et al., 2016) determined the proportions of cellulose and hemicellulose at 42% and 23%, respectively. Lignin acts as an essential aromatic precursor that activates the donor-receptor reactions (π - π), increasing the efficiency of the retention of organic dyes and phenolic compounds. This biomass can be purified via the removal of lignin and hemicellulose to produce high-purity crystalline

Table 1. The structural characteristics and physicochemical of the biomass of Conocarpus and its derivatives

Factor/Component	Plant Part/Material	Key findings/Values	Ref.
Cellulose content	Trunk fibers	~42.0% (high crystallization)	(Fouad et al., 2020)
Hemicellulose content	Agricultural waste	~23.0%	(Abdel-Aal and Rabalski, 2013)
Lignin content	Leg/Wood	~20–30% (higher than many agricultural waste)	(Aref et al., 2013)
Metal composition	Trunk fibers	Mg, Ca, K, P, Si, S (rich mineral profile)	(Jawaid et al., 2021)
Thermal stability	Raw fiber	Decomposition Start: 273.9–316.2 °C	(Jawaid et al., 2021)
Zero charge point pH _{pzc}	Biochar	~6.0–7.2 (variable based on modification)	(Saleh et al., 2025; Pourmohammad et al., 2018)
Specific surface area	Activated carbon	Highly developed microporosity (>500 m ² /gm)	(El-naggar et al., 2016)
Functional groups	Biochar/ NCC	-OH, C=O, C=C (aromatic), Metal-O	(Alazba et al., 2025a; Fouad et al., 2020)
Morphological features	Raw fiber	Striped, compact, and bundled fibers	(Jawaid et al., 2021)

nanocellulose (Khan et al., 2021). Figure 1 shows the quantitative distribution of these biopolymers across the different parts of the plant. This variation in chemical composition highlights the importance of the choice of plant part when interpreting the different properties of Conocarpus-derived materials after treatment.

Morphologically, raw trunk fibers under scanning electron microscope (SEM) appear to have a compact appearance and a fibrous bundle-shaped outline (Jawaid et al., 2021). This compact structure is converted into a highly efficient porous material via chemical treatments that result in the removal of lignin and amorphous (amorphous) matrix of hemicellulose, isolating cellulose nanofibers (Fouad et al., 2020). Thermal and chemical activation processes contribute to the development of a vast network of micropores exceeding (>500 m²/g) (El-Naggar et al., 2015), enhancing

the kinetics of material transport and the pore-filling mechanism, thereby reducing the time required to reach adsorption equilibrium. Thus, the final porous structure is closely related to the processing pathway used to convert the raw biomass into the adsorbent derived from it.

Surface chemistry, functional groups and electrochemical properties

The surfaces of Conocarpus are distinguished by the diversity of their functional groups that have been scanned and their molecular vibrations have been identified by infrared spectroscopy (FTIR) technology. Alazba et al., (Alazba et al., 2025b) demonstrated that the surface of Conocarpus-derived biochar can be grafted with transition metals such as iron (Fe) and manganese (Mn), as FTIR data showed unique vibrations

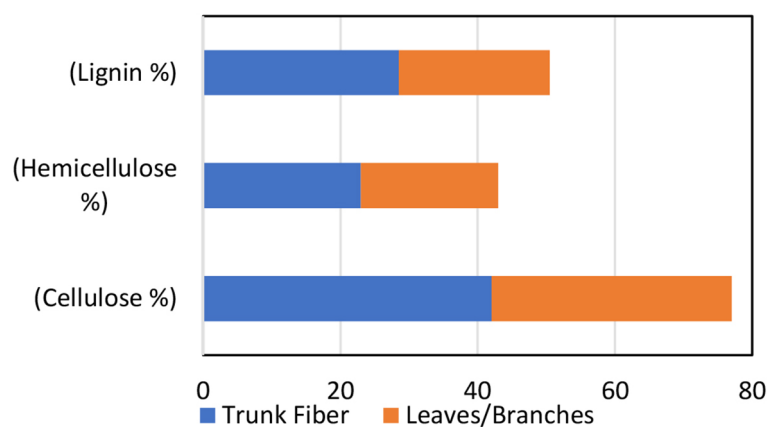


Figure 1. Comparison of cellulose, hemicellulose, and lignin content in different parts of Conocarpus biomass. (Figure was prepared by authors based on data reported by (Abdel-Aal and Rabalski, 2013; Jawaid et al., 2021))

of the (Metal-O) bonds, producing hybrid surfaces capable of removing multiple contaminants via chemical complexation mechanisms. The presence of sophisticated crystalline cellulose bands contributes to enhancing the mechanical and chemical stability of the material in harsh aquatic environments (Fouad et al., 2020). The crude functional groups transform during activation to produce stable aromatic bonds (C=C) and oxygen-containing groups such as hydroxyl and carboxyl (El-Naggar et al., 2015). These groups act as the primary driving force for ion exchange, directly linking structural chemistry with heavy metal capture. The zero-charge point (pH_{pzc}) controls the electrostatic behavior of the material and determines the protonation or deprotonation of surface sites (Papari et al., 2017). Pourmohammad et al., (P. Pourmohammad et al., 2018) explained that the adsorption of cadmium (Cd^{2+}) on the nanostructures of Conocarpus is strongly influenced by this factor, with adsorption behavior being evaluated at pH 6. Therefore, the pH_{pzc} value should be interpreted in conjunction with the pH value of the solution and the specific modification type of the adsorbent when interpreting the electrostatic reactions. Biochar also achieved maximum pesticide adsorption capacities under near-equilibrium conditions (M Saleh et al., 2025). Studies of polyionic systems demonstrate that chemically modifying the surface allows for the simultaneous adsorption of cations and anions such as nitrate, ammonium, and phosphate by changing the inter-charge density (Sayadi et al., 2020). In addition, modifying biochar with humic acid or phosphate rocks alters the surface charge to achieve higher efficiency in separating heavy metals (Alhawas et al., 2023b). Figure 2 illustrates the electrochemical behavior of the conocarpus surfaces and the reported zero-charge point at pH 6.2. The pH_{pzc} value provides a reference for explaining the change in surface charge with pH, thus understanding the difference in electrostatic interactions between the surface of the material and ionic contaminants.

Thermal stability, mineral content and inorganic synergy

Thermal gravimetric analysis (TGA) of conocarpus fibers reveals high thermal stability, with the decomposition temperature starting between 273.9 °C and 316.2 °C (Jawaid et al., 2021). This stability is due to the high content of crystalline

cellulose and lignin, which allows the material to maintain its structural integrity under moderate temperatures and makes it suitable for use as bio-fillers in polymeric composites. The natural structure of Conocarpus has a compact mineral profile rich in elements and includes: (Mg, Si, P, S, Cl, K, Ca) (Jawaid et al., 2021). This mineral content has a direct impact on the ash resulting from thermochemical decomposition. Ion exchange and chemical deposition of heavy metals (Odetoye et al., 2020) is an additional active site of ash that can be utilized in adsorption processes, while high ash content may have negative effect in certain bioenergy applications. These mineral components are natural catalysts in the process of thermal activation, which helps to create activated carbon with larger surface and higher amount of functional sites (El-Naggar et al., 2015). Finally, this inorganic system is improved by combining the natural minerals of Conocarpus with phosphate rocks, which results in a better product in which the organic and inorganic phases work together to achieve an even better heavy metal removal efficiency (Alhawas et al., 2023b).

PREPARATION AND MODIFICATION STRATEGIES

To build high-performance materials from Conocarpus biomass from raw waste, the raw materials need to be modified in an accurate way to compensate for their intrinsic low porosity and surface area. Physical, chemical and hybrid modifications restructure the carbon framework, adding adsorption mechanisms of critical importance such as ion exchange, electrostatic attraction and surface complexation. At the nanoscale, physical

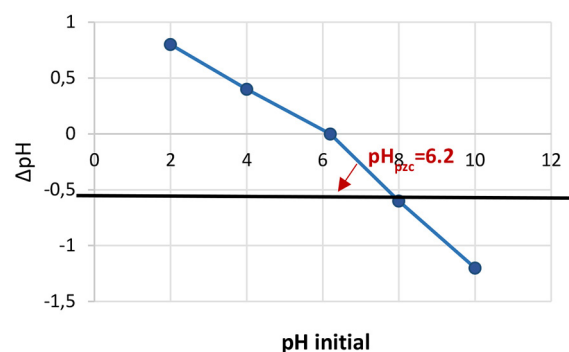


Figure 2. Point of zero charge (pH_{pzc}) plot for Conocarpus-derived adsorbents. (Data synthesized from Saleh et al., 2025; Pourmohammad et al., 2018)

methods like optimized pyrolysis and high energy mechanical milling can improve aromaticity, pore distribution and surface-to-volume ratios. Chemical activation in KOH, H_3PO_4 or ZnCl_2 can achieve deep etching of the structure and the introduction of functional groups; alkaline treatment can increase the porosity of the material, and acid treatment can adjust the surface charge of the material to meet the demands for selective adsorption of ions.

Recent developments involve using engineered nanocomposites containing the incorporation of metallic nanoparticles or layered double hydroxides in the carbon matrix that provide synergistic catalytic effects. The techniques from simple carbonization to very sophisticated functionalization are systematically summarized in Table 2, thus creating a technical basis for high-efficient environmental remediation.

Physical activation

Physical activation and modification of the components of *Conocarpus* trees are a fundamental step that has to be taken as a strategy to improve the performance of *Conocarpus* as a biosorbent. The components is an essential part of improving its performance as a biosorbent. It has been shown in various studies that the structural integrity and surface properties of this biomass can be greatly improved by carefully controlling thermal and mechanical processes. El-Naggar et al. (El-Naggar et al., 2015) studied the process of converting the pruning waste of the tree *Conocarpus* to non-activated and activated carbon and their use in the remediation of aqueous solutions contaminated with heavy metals. They applied the carbonization process at 400 °C and then activated with

potassium hydroxide (KOH) and zinc chloride (ZnCl_2). The results showed that the adsorption efficiency of KOH-Activated carbon (CK) showed higher removal than others, with more than 50% cadmium (Cd^{2+}) and copper (Cu^{2+}) removed, and a 100% removal rate for lead (Pb^{2+}) at an initial concentration of 40 mg/L. This result suggests that the effect of treatment is not limited to the conversion of biomass to activated carbon, but is related to the resulting changes in surface properties and porous structure, which can be reflected in the adsorption behavior and performance towards the target contaminant. The researchers found that under certain conditions, activated carbon made from *Conocarpus* is more effective than commercially manufactured activated carbon. Likewise, Pejman et al. (Pourmohammad et al., 2018) investigated the efficiency of the nanostructures of *Conocarpus* in the removal of Cadmium. The method they used was to reduce the biomass to a nanometer scale through a high-energy ball milling process. Based on the parameters they studied including pH, they found that the pH of 6 was the best for adsorption with a maximum removal efficiency of 80.9%. The experimental results were found to be in good agreement with Langmuir and Ho models, making the nano-*Conocarpus* a reliable high-performance adsorbent, their conclusion said. In addition, Alhawas et al. (Alhawas et al., 2023b) investigated a modification method of mechanical milling, using humic acid and rock phosphate modified *Conocarpus* biochar. The biochar made at 600 °C demonstrated that dual modification greatly enhanced the adsorption capacity of heavy metals, and that it was possible to provide a sustainable method for water treatment. To complement these results, Sayadi et al. (Sayadi et al., 2020) investigated the removal of nitrates, ammonium and phosphates

Table 2. The physical and chemical modification strategies for biomass of *Conocarpus* and their structural impacts

Author (Year)	Feedstock part	Modification agent	Pyrolysis temp. (°C)	Key structural/Surface changes
(El-naggar et al., 2016)	Pruning waste	KOH / ZnCl_2	400	Development of high porosity; enhanced surface functional groups.
(Usman et al., 2016b)	Whole biomass	Mg/Fe Oxides + NaOH	-	Significant increase in surface area (up to 391.8 m ² /g).
(Akanji et al., 2022)	Biochar	H_2SO_4	-	Systematic reduction in pH by 6.84 units; optimizing surface net-positive charge for anionic sequestration
(Abudi et al., 2025)	Biochar	H_3PO_4 / KOH / LDH	-	High surface acidity (H_3PO_4) vs. sponge-like topography (KOH).
(P. Pourmohammad et al., 2018)	Nano-conocarpus	Ball milling (Mechanical)	-	Reduction to nano-scale; increased surface-to-volume ratio.
(Mehdi et al., 2024)	Pruning residues	KOH (High Conc.)	Two-stage	Superior pore development compared to other bio-sources.

from contaminated groundwater using a ferrous chloride (FeCl_3) and KOH treated *Conocarpus* biochar. Their findings showed that the pH conditions play an important role in their maximum removal efficiency, and that the use of modified biochar shows versatile adsorption properties according to the chemical environment of the water. These studies show that the choice of modification path is related to the nature of the target contaminant and the chemical environment of the solution, as mechanical minimization, double modification and chemical modification have led to different adsorption behavior depending on the type of contaminant and the operational conditions studied.

Chemical activation

The chemical treatment of *Conocarpus* biochar with acidic, alkaline and saline agents is a qualitative change in the surface properties of biochar, as shown in a rigorous scientific study. In the study of Usman et al. (Usman et al., 2016a) introduced a method to synthesize modified biochar by loading them with metal oxides using the wet impregnation method. Magnesium (Mg) and iron (Fe) salt precursors were placed inside the *Conocarpus* biomass, and the pH of the biomass was adjusted to 10 with sodium hydroxide (NaOH) to ensure the metal oxides precipitation prior to pyrolysis. The changes of the specific surface area ($391.8 \text{ m}^2/\text{g}$) and nitrate (NO_3^-) adsorption capacity (45.36 mmol/kg) after this modification were drastic. Alkaline impregnation is a powerful method in the study for increasing the affinity of ions in the waste material and making it useful for creating materials with high ionic affinity. This result suggests that alkaline modification can alter the surface properties of a substance in a way that enhances its familiarity with ions, demonstrating that the choice of activation agent should be related to the nature of the target contaminant and the required surface characteristic. As opposed to alkaline methods, (Akanji et al., 2022) examined the acidification of *Conocarpus* biochar with sulfuric acid (H_2SO_4) to produce Acidified Biochar. The main goal was to reduce the naturally high pH value of *Conocarpus* so that it can be used in calcareous soils. The results indicated that the pH decreased by 6.84 units, thereby successfully changing the functional groups on the surface, and enhancing the release of micronutrients and phosphorus. Thus, it appears that acid and alkaline treatment do not necessarily result in the

same change in the properties of the material, but that different treatment agent can produce different surface properties depending on the purpose of the modification. Additionally, examined the activation process with phosphoric acid (H_3PO_4) and KOH, and also with the introduction of a layered double hydroxide. The results showed that the acid modification resulted in high acidity, while the KOH activation resulted in different surface topography and alkalinity which directly enhanced the adsorption capacity of the biochar for the complex pharmaceutical pollutants. In the same study, Ataa et al. compared the morphological effect of chemical activators; it was found that KOH treatment results in a sponge-like open structure, while H_3PO_4 results in a highly microporous and acidic surface, which would enable the choice of a modification path depending on the application needs (Ataa et al., 2026). The recent study Mehdi et al. (Mehdi et al., 2024) focused on the two-stage process, primary carbonization and high-concentration KOH activation, to convert the carbon residues of *Conocarpus* into activated carbon for use in wastewater recycling. It was found that the porosity developed was very high as compared to other bio-sources, demonstrating its potential for applications of water purification. Comparison of activation agents indicates that the selection of the curing agent can change the nature of the porous structure and surface properties of the material, and therefore the effect of the modification depends on the type of agent used and the purpose of the adsorption process.

Advanced modifications

Studies on *Conocarpus* have now moved to more sophisticated directions, such as the synthesis of nanocomposites and the more sophisticated surface functionalization for environmental and economic sustainability. The researchers Vázquez-Núñez et al. (Vázquez-Núñez et al., 2025) talked about the development of engineered biochar based nanocomposites (EBNCs) for improving Agricultural Productivity. They discovered that the use of nano-scale additives not only benefits water management, nutrient availability and soil structure, but also has a key role in heavy metal stabilization, following circular economy principles. As a similar study, the researchers (Lalmalsawmdawngliani et al., 2024) focused on the synthesis of biochar-metallic nanoparticle (BC-MNP) composites which

involved integration of biochar with metallic nanoparticles, providing enhanced physical and chemical properties, including thermal stability. As regards functionalization of surfaces, Geça et al. (Geça et al., 2023) summarized the various treatment methods including the use of silanes and coupling agents such as diazonium salts asserting that surface engineering enables precise functionalization for targeted applications in energy and agriculture. Elbasiouny et al. (Elbasiouny et al., 2023) confirmed this trend by investigating the nano-biochar (NBC) functionalized with metallic nanoparticles, which demonstrated higher adsorption capacity than the simple biochar at reported conditions. These results demonstrate that advanced modifications are not just means of increasing the surface area, but can alter the physical and chemical properties of the material in order to affect its interaction with the target pollutant. Furthermore, Joshi et al. (Joshi et al., 2023) concentrated on the effect of pyrolysis temperature and biomass nature, emphasizing the need to use eco-friendly modification techniques. In a technical comparison, Rajprakash et al. (Rajprakash et al., 2025) compared traditional thermal synthesis with mechanochemical synthesis, emphasizing the energy-efficient nature of mechanochemical synthesis as a sustainable alternative. Lastly, Ahmad et al. (Ahmad et al., 2026) investigated the

application of plant-based nanocomposites, such as Conocarpus, in desulfurization process. It was found that green synthesis methods yielded materials with huge surface areas that are able to efficiently remove sulfur from fossil fuels.

A comparative study of the maximum capacities and optimal adsorption conditions for different pollutants on modified Conocarpus adsorbents is presented in Table 3, to give a quantitative idea of these advances. This information clearly illustrates the importance of the selected modification strategy on the performance of sequestration. The comparison shows that the advantage of Conocarpus derivatives is not only related to removal efficiency, but is more evident when the abundance of raw material is combined, its surface properties can be modified, and the performance is achieved under different operating conditions.

FACTORS AFFECTING ADSORPTION PERFORMANCE

Adsorption efficiency depends on a set of operational factors that control the nature of the reaction between the adsorbent and the contaminant, directly affecting the adsorbent amplitude, removal efficiency, adsorption mechanism, and the speed of reaching equilibrium. The most

Table 3. Adsorption performance and experimental conditions of Conocarpus adsorbents for various aqueous pollutants

Reference	Conocarpus-derived adsorbent	Modification/preparation	Target pollutant	Adsorption capacity ($q_{\max}$)	Removal efficiency	Water matrix / experimental context
(El-naggar et al., 2016)	Activated and non-activated carbon from Conocarpus pruning waste	Carbonization at 400 °C; KOH and ZnCl ₂ activation	Cd ²⁺ , Cu ²⁺ , Pb ²⁺	65.61 $\mu\text{mol g}^{-1}$ (Cd ²⁺); 66.12 $\mu\text{mol g}^{-1}$ (Cu ²⁺); 223.05 $\mu\text{mol g}^{-1}$ (Pb ²⁺) for non-activated carbon	100% Pb ²⁺ removal at 40 mg L ⁻¹ using KOH-activated carbon; >50% Cd ²⁺ and Cu ²⁺	Aqueous solution; single- and multi-solute experiments
(Pourmohammad et al., 2018)	Nano-Conocarpus	High-energy ball milling	Cd ²⁺	NR	80.9%	Batch adsorption; aqueous solution
(Usman et al., 2016b)	Chemically modified Conocarpus biochar	Mg/Fe oxide loading; NaOH-assisted modification	NO ₃ ⁻	45.36 mmol kg ⁻¹	NR	Aqueous solution
(Sayadi et al., 2020)	Modified Conocarpus biochar	FeCl ₃ and KOH treatment	NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ³⁻	NR	High efficiency	Contaminated groundwater
(Alhawas et al., 2023b)	Conocarpus biochar and modified biochar	Ball milling; humic acid and/or rock phosphate modification	Pb, Cd, Cu, Zn	Pb: 18.85 mg g ⁻¹ ; Cu: 24.02 mg g ⁻¹ ; Zn: 187.14 mg g ⁻¹ ; Cd: 30.89 mg g ⁻¹	NR	Aqueous solution
(Almasoud et al., 2020)	Conocarpus biochar	Pyrolysis of chopped Conocarpus wood waste at 400 °C for 4 h	²²⁶ Ra	0.498 Bq g ⁻¹ (Langmuir parameter)	35.50% (1 Bq L ⁻¹); 33.50% (3 Bq L ⁻¹); 29.90% (5 Bq L ⁻¹); 31.71% (7 Bq L ⁻¹)	Aqueous ²²⁶ Ra solutions and contaminated groundwater

important of these factors are pH, contact time, and adsorbent dose, the effects of which vary depending on the characteristics of the adsorbent and the type of contaminant. To facilitate comparison between previous studies, Table 4 summarizes the most important operating conditions and factors affecting the performance of adsorbents, derived from *Conocarpus* and similar biomaterials.

Effect of pH

pH and pH_{PZC} are two of the most important factors controlling adsorption efficiency, as they determine the nature of the surface charge of the adsorbent and hence the strength of the electrostatic attraction or repulsion with the contaminants. When the pH value is less than the pH_{PZC} value, the surface acquires a positive charge as a result of the protonation of the functional groups, while a higher pH above pH_{PZC} results in the removal of protons and gaining a negative charge on the surface, which enhances the adsorption of metal cations and reduces the effect of competition with hydrogen ions.

Studies on *Conocarpus* derivatives indicate clear agreement on the pivotal role of pH in improving adsorption efficiency, but the optimal pH value varies depending on the method of preparation of the adsorbent and the type of contaminant. Pourmohammad et al. (Pejman Pourmohammad et al., 2018) showed that the best removal of cadmium using the nanostructure of *Conocarpus* was achieved at $pH = 6$, a value that corresponds to the zero-charge point of the material, which was related with the reported cadmium adsorption conduct. Similarly, Al-Tameemi and Al-Sultani (Al-tameemi et al., 2012) showed that raising the pH value within the domain (3–9) resulted in increased lead and cadmium removal efficiency as a result of reduced competition of hydrogen ions at active sites. The study of Maryem and Rana et al. (Rana et al., 2026b) also showed that functional groups on dead *Conocarpus* roots are the main factor in the retention of mineral cations, while El-Naggar et al. (El-naggar et al., 2016) showed that chemical activation with KOH not only does it increase the number of active sites, but it also changes the

Table 4. The operational parameters affecting the adsorption performance of *Conocarpus*-derived adsorbents and related comparative biosorbents

A. <i>Conocarpus</i> -derived adsorbents						
Reference	Adsorbent	Pollutant	Optimum pH/PZC	Equilibrium/Contact time	Dosage effect	Key finding
(Pourmohammad et al., 2018)	<i>Conocarpus</i> nanostructure	Cd	$pH = 6$	Specific finite period	Increasing dosage enhances removal	High Cd removal due to favorable surface charge and high nanostructure activity.
(Al-tameemi et al., 2012)	Dried <i>Conocarpus</i> leaves	Pb, Cd	$pH\ 3\text{--}9$	60 min	Removal increased with dosage	Increasing pH and dosage significantly improved Pb and Cd adsorption.
(Rana et al., 2026a)	<i>Conocarpus</i> dead root biomass	Ag, Pb, Cd, Zn	—	6 h	—	Surface functional groups enabled efficient heavy-metal biosorption (up to 98% Cd).
(El-naggar et al., 2016)	Activated carbon from <i>Conocarpus</i> waste	Cd^{2+} , Cu^{2+} , Pb^{2+}	Chemical activation (KOH)	Modification-dependent	Mass optimization required	Chemical activation enhanced adsorption efficiency and Pb removal reached 100%.
(Alhawas et al., 2023b)	<i>Conocarpus</i> biochar	Aqueous contaminants	pH modification	—	Higher dosage enhanced capacity	Chemical modification improved adsorption efficiency.
B. Comparative biosorbents						
(Dada et al., 2024)	Bamboo-supported nZVI	Cu(II)	$pH = 6$	Specific period	Dosage optimization required	Nanoparticles enhanced adsorption kinetics and Cu(II) removal.
(Duwiejuah et al., 2025)	Coconut husk biochar	Cd, Pb (also As, Cr, Ni)	Relative to PZC	Fast equilibrium	Higher dosage increased active sites	Adsorption efficiency increased with pH, dosage
(Echeofun et al., 2025)	Corn stalk-derived carbon	Co(II)	—	60 min	Capacity decreased with increasing dosage	Particle aggregation reduced adsorption capacity at high dosage.
(Iheanacho et al., 2023)	Thermally modified corn cob	Heavy metals / Phenol	$PZC = 5.83$	60 min	Increased dosage favored adsorption	Adsorption improved above PZC and at elevated temperature.

pH_{PZC} value and the charging properties of the surface, which is reflected in the higher efficiency of the removal of heavy metals, especially lead.

Overall, these studies confirm that the pH effect is related to the relationship between pH and pH_{PZC} , the nature of the functional groups and the characteristics of the adsorbent material, which explains the difference in optimal values between studies and highlights the importance of determining the appropriate operating conditions for each adsorption system, as shown in Figure 3. This framework shows that a change in pH can alter the surface charge and the availability of active sites, which is reflected in the nature of the interaction between the adsorbent and the contaminant.

Effect of contact time

Contact time is one of the most important operational variables that control adsorption kinetics and determine the time required to reach equilibrium, as it directly affects the efficiency of the transfer of contaminants from the solution to the active sites on the surface of the adsorbent material. The adsorption process is usually characterized by two main stages: the first is rapid adsorption due to the abundance of active sites on the outer surface, while the process gradually slows down as the contaminants move to the inner pores until the dynamic equilibrium is reached. Studies of *Conocarpus* derivatives indicate that the equilibrium time depends more on the nature and structural properties of the adsorbent than on the type of contaminant alone. Pourmohammad et al. (Pourmohammad et al., 2018) showed

that the nanostructure of *Conocarpus* achieves rapid equilibrium due to the rise in surface area, while the dried *Conocarpus* leaves in the study of Al-Tameemi and Al-Sultani (Al-tameemi et al., 2012) recorded a breakdown in about 60 minutes. The result of rapid adsorption in the early stages. Conversely, biomass derived from dead *Conocarpus* roots required about 6 hours to reach equilibrium due to the control of diffusion within deep pores, while El-Naggar et al. (El-naggar et al., 2016) showed that chemical activation of activated carbon reduces mass transfer resistance and accelerates the attainment of equilibrium. This comparison suggests that the difference in equilibrium time is related to the porous structure characteristics of the preparation method, which in turn controls the resistance to mass transfer and the contaminant's access to the active sites. These studies show that the difference in equilibrium time is related to the degree of development of the porous structure, surface area, and the method of preparation of the adsorbent material, and not the time factor alone, which makes determining the optimal contact time an essential step to achieve the highest adsorption efficiency while reducing energy consumption and operating time, as illustrated in Figure 4, which summarizes the stages of the transition of contaminants from surface diffusion to diffusion within pores and then reaching dynamic equilibrium.

Effect of adsorbent dosage

Adsorbent dosage is one of the most important operational factors affecting adsorption efficiency, as it controls the number of active sites and

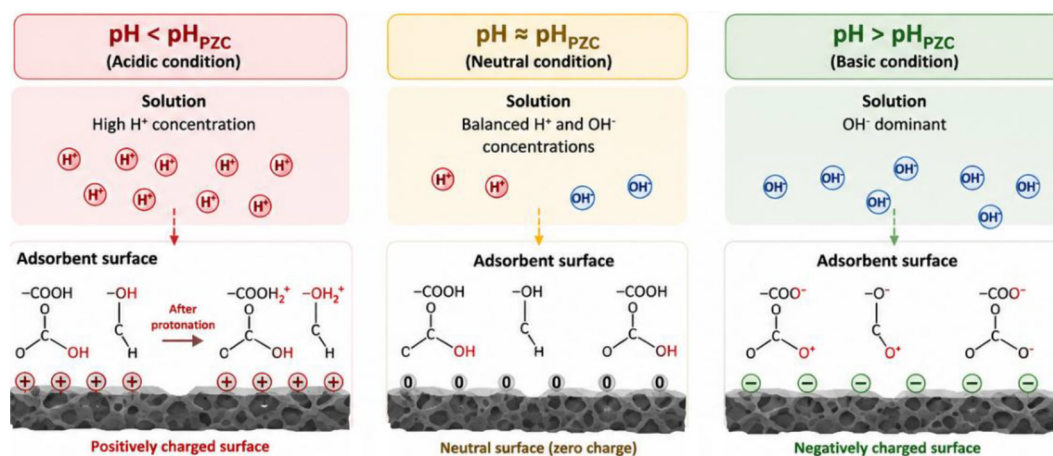


Figure 3. Schematic illustration of the effect of solution pH relative to the point of zero charge (pH_{PZC}) on the adsorption mechanism

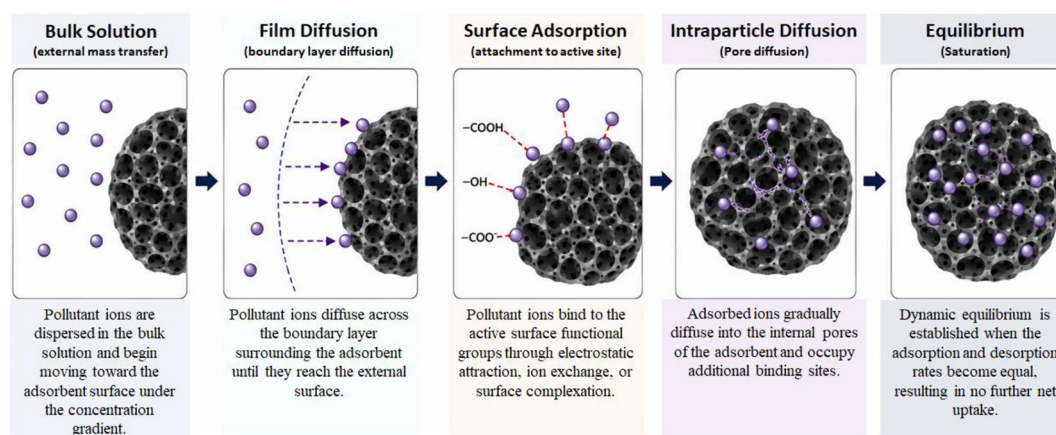


Figure 4. Schematic representation of the adsorption kinetic stages and mass transfer mechanisms

the surface area available for the contaminants to bind. Increasing the dose usually increases the removal efficiency due to the provision of a larger number of adsorption sites, but this increase does not continue linearly as the process reaches an optimal level after which the dose increase has a limited effect due to particle interference, reduced effective surface area, and not all available sites are utilized. Studies of *Conocarpus* derivatives have shown a direct relationship between increasing the dose and improving the decontaminant removal efficiency until the optimal dose is reached. Pourmohammad et al. (Pourmohammad et al., 2018) showed that increasing the amount of nanomaterial improved cadmium removal due to the increased number of active sites, while the study of Al-Tameemi and Al-Sultani (Al-tameemi et al., 2012) recorded a significant increase in lead and cadmium removal with increasing the dose of *Conocarpus* leaves until the best operational efficiency was reached.

The results of these studies confirm that the optimum dose is dependent on the properties of the adsorbent and the nature and initial concentration of the contaminant with identification being a key component of the process to obtain the maximum removal efficiency with minimum use of adsorbent and operating costs. Thus, determining the optimal dose depends not only on increasing the number of active sites, but also requires a balance between site availability, utilization efficiency, material consumption and operating costs.

Differences in results between studies may be due to different characteristics of the prepared materials, operating conditions and type of contaminant, limiting the possibility of direct comparison between reported performance values.

APPLICATIONS IN WASTEWATER TREATMENT

Heavy metals removal

The removal of toxic heavy metals, such as lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and chromium (Cr), from aqueous solutions is a major environmental and engineering challenge due to their high toxicity and bioaccumulation in living organisms. The use of biochar and nanostructures derived from *Conocarpus erectus* as well as other agricultural residues have been wide interest as economical and sustainable alternatives to traditional commercial adsorbents. The study of Alhawas et al. (Alhawas et al., 2023a) were used ball milling to modify the biochar of the *Conocarpus* plant and graft it with humic acid and rock phosphate. The results showed that this modified biochar has high adsorption capacities for multiple heavy metals (Pb, Cd, Cu, and Zn), where the highest adsorption capacity of the lead element was recorded at a value of 18.85 mg/g. Also (Pourmohammad et al. (P. Pourmohammad et al., 2018) has focused on the study of the efficiency of nanostructures of the *Conocarpus* tree processed via ball mills in capturing cadmium contaminant. Batch adsorption laboratory experiments proved a removal efficiency reached 80.9% at pH= 6, as found that the Langmuir model is the most accurate in characterizing the chemical dynamics of adsorption and monobonding to the nano surface. The process of holding metal ions on the surface of *Conocarpus*-derived materials is attributed to several adsorption mechanisms, including electrostatic attraction, ion exchange and nanoconfinement, as shown in Figure 5.

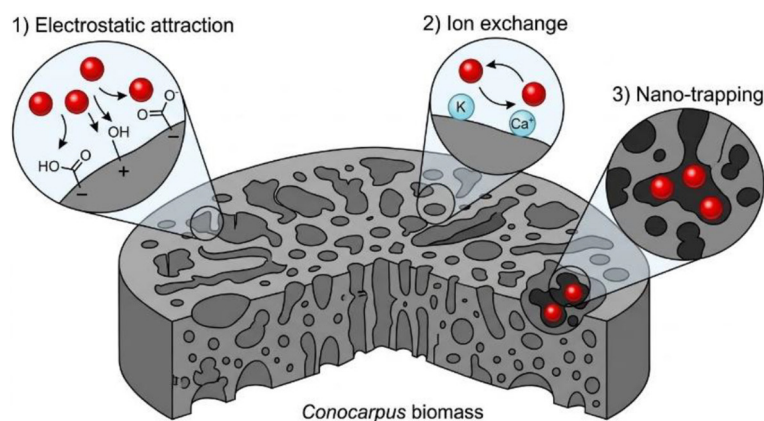


Figure 5. Schematic diagram of the multiple heavy metal adsorption mechanisms on the modified *Conocarpus* biomass surface

These mechanisms reflect the multiplicity of pathways of the interaction of metal ions with the porous surface of the material, supporting the explanation of the adsorption behavior observed in previous studies.

Radionuclide removal

Although studies on the use of *Conocarpus*-derived materials for radionuclide removal are limited, the study of Almasoud et al (Almasoud et al., 2020) showed that biochar derived from *conocarpus* residues can be used to remove radium-226 (^{226}Ra) from contaminated aqueous solutions and groundwater. Biochar from pyrolysis cut *Conocarpus* was prepared at 400 °C for 4h. The results showed a removal efficiency of 35.50% at 1 Bq L⁻¹, 33.50% at 3 Bq L⁻¹, 29.90% at 5 Bq L⁻¹, and 31.71% at 7 Bq L⁻¹, with a value of 0.498 Bq g⁻¹ as the Langmuir parameter.

These results suggest that *Conocarpus* -derived biochar can be used in the treatment of water containing ^{226}Ra , noting that the level of removal varied with the initial concentration of radium. The direct applications of *Conocarpus* in radionuclide removal remain limited compared to available studies on other chemical contaminants, highlighting the importance of further evaluating the performance of these materials in radionuclide-containing water treatment applications.

Organic pollutants (dyes, pharmaceuticals, and phenolic compounds)

Organic pollutants, such as industrial dyes, pharmaceutical residues, and toxic phenolic compounds, pose an imminent environmental risk to

aquatic systems due to their high chemical stability and difficulty in biodegradability. The recent literature has focused on evaluating the efficiency of biochar and low-cost biosorbents, in particular those derived from *Conocarpus erectus* plant residues, as a green and sustainable water purification strategy, the operational parameters and kinetic modeling are summarized in Table 5.

Gzar and Sabri (Gzar and Sabri, 2019) conducted study in which *Conocarpus* leaf powder was used as a natural and low-cost biosorbent to remove methylene blue dye of aqueous solutions. Batch adsorption experiments showed that the efficiency of removal depends intrinsically on operational variables such as pH, and adsorbent dosage, and contact time, where the dried leaves have recorded excellent removal efficiency that is in line with the economic trends of recycling plant waste without the need for complex chemical activation. Furthermore, Kanwal et al. (Kanwal et al., 2023) studied in the development of magnetic biochar derived from *Conocarpus* residues and modified by iron to remove Congo red dye of artificial wastewater. The study demonstrated that insertion of magnetic properties not only accelerated the separation of the adsorbent after treatment, but rather doubled the total adsorption capacity as a result of the expansion of the surface area, the activation of electrostatic attraction mechanisms, and the interference of hydrogen bonds between the functional surface and the anionic dye groups.

In terms of the elimination of emerging pharmaceutical contaminants, Krona studied the use of thermally modified *Conocarpus* biochar to capture and isolate pharmaceuticals from wastewater. Advanced structural analyses have demonstrated that the adsorption process is governed

Table 5. Organic pollutants removal by *Conocarpus* adsorbents

Reference	<i>Conocarpus</i> -derived adsorbent	Target pollutant	Preparation / modification	Reported findings	Main adsorption mechanism / observation
(Gzar and Sabri, 2019)	<i>Conocarpus</i> leaf powder	Methylene blue	Leaves dried, crushed and sieved without chemical activation	Removal was strongly dependent on pH, adsorbent dosage, contact time, and initial concentration	Adsorption performance depended on operational conditions
(Kanwal et al., 2023)	Magnetic <i>Conocarpus</i> biochar	Congo red	Iron oxide nanoparticles incorporated onto pyrolyzed <i>Conocarpus</i> waste	Magnetic modification increased the reported adsorption capacity and facilitated adsorbent separation after treatment	Electrostatic attraction and hydrogen bonding; increased surface-active sites
(Krona, 2017)	Thermally modified <i>Conocarpus</i> biochar	Pharmaceutical contaminants	Thermal modification / carbonization at tailored pyrolytic temperatures	Demonstrated adsorption of pharmaceutical contaminants from wastewater	Surface-charge interactions and intraparticle diffusion
(Mokif and Abdulhusain, 2022)	Dried <i>Conocarpus</i> leaves	Phenolic compounds	Washed, thermally dried and used as a native bio-filter	Demonstrated removal of toxic phenolic compounds from industrial refinery wastewater	π - π interactions involving aromatic structures and surface interactions

by surface charge reactions and intra-particle diffusion, where the substance showed exceptional efficiency in reducing reported adsorption performance (Krona, 2017). To support the recycling of local waste, Mokif and Abdulhusain (Mokif and Abdulhusain, 2022) investigated the practical feasibility of exploiting *Conocarpus* leaves in the removal of toxic phenolic compounds from industrial wastewater of oil refineries. The biomass has shown a distinct ability to bind the aromatic rings of phenol through π - π electron donor-acceptor interactions, indicating potential application of the *Conocarpus* tree in the treatment of complex organic pollutants. These results indicate a multiplicity of mechanisms for the binding of organic pollutants to the surface of the *Conocarpus*, including electrostatic interactions, hydrogen bonds, and π - π interactions, as shown in Figure 6.

Real wastewater samples

The transition from synthetic solutions to real wastewater samples is the primary test for evaluating the actual and operational efficiency of *Conocarpus erectus*. Real aquatic environments contain complex arrays of competing salts and overlapping organic matter, requiring highly flexible and efficient biosorbents and coagulants to purify water and improve its physicochemical properties, the most prominent real-world applications and their operational modeling in Table 6. This stage is particularly important because the performance of *Conocarpus*-derived materials in real water may differ from their performance in synthetic solutions due to the complexity and multiplicity of water media. Gudadhe and Katkar investigated the

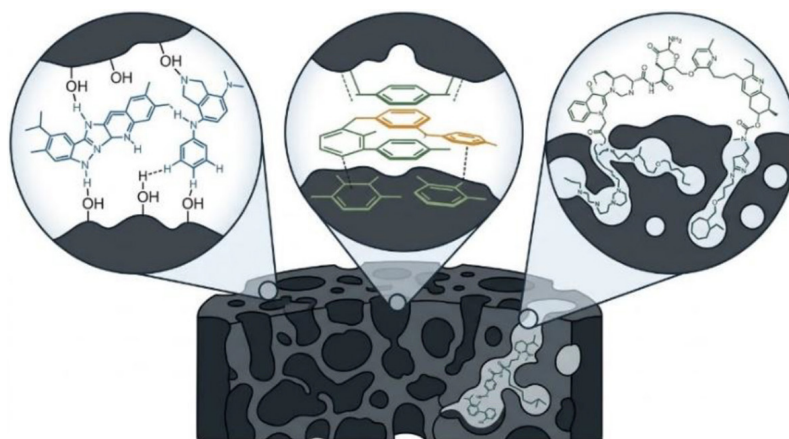
**Figure 6.** Schematic diagram of multiple organic pollutant adsorption mechanisms on the *Conocarpus* biochar surface

Table 6. Applications of real wastewater treatment by *Conocarpus*: adsorption and biofiltration versus plant treatment systems

A. Adsorption and biofiltration applications				
Reference	Conocarpus material/system	Real wastewater/application	Reported observation	Treatment mode
(Gudadhe and Katkar, 2025)	Conocarpus ash	Real wastewater	Reported reduction of heavy metals, organic compounds and nutrients	Biosorption
(Chiban et al., 2011)	Conocarpus biomass	Municipal/industrial wastewater	Reported uptake of nitrate, phosphate and heavy metals, with reduction of COD	Adsorption / biomass treatment
(Yahiaoui et al., 2020)	Conocarpus eco-filters	Domestic wastewater under arid conditions	Reported nitrogen elimination and improvement in dissolved oxygen	Biofiltration
B. Phytoremediation and constructed-wetland applications				
Reference	Conocarpus material/system	Real wastewater/application	Reported observation	Treatment mode
(Gomber et al., 2013)	Conocarpus plants	Textile effluent	Reported improvement in wastewater quality through control of pH, total solids and harmful ions	Phytoremediation
(Geleto et al., 2025)	Conocarpus wetland system	Coffee-mill wastewater	Reported improvement of physicochemical properties of wastewater	Constructed wetland
(Van et al., 2015)	Conocarpus biological matrix	Activated-sludge treatment system	Reported removal of nitrogen and phosphorus	Plant-assisted biological treatment

practical feasibility of using *Conocarpus* ash as a biosorbent for the elimination of contaminants in real wastewater. Field results demonstrated the ability of ash to reduce heavy metals concentrations, complex organic compounds, and excess nutrients, indicating that these materials provide a natural and economical alternative to traditional systems (Gudadhe and Katkar, 2025). The study of Chiban et al. (Chiban et al., 2011) showed that *Conocarpus* biomass can be used in municipal and industrial wastewater treatment, with the removal of nitrates, phosphates and some heavy metals reported and improved treated water quality. Also, Yahiaoui et al. evaluated the performance of *Conocarpus* in removing contaminants from domestic wastewater in arid regions. The system showed effective in nitrogen removal and raised the dissolved oxygen content (Yahiaoui et al., 2020). These applications and their results are summarized in Table 6-A. However, assessing the applicability of these substances in real water requires consideration of the impact of the complexity of the competing water and ion matrix, along with stability and reusability, which need further systematic evaluation across studies.

Some studies have also shown that *Conocarpus* can be used within phytoremediation and wetland techniques to treat various types of wastewaters, including textile wastewater (Gomber et al., 2013), coffee plant water (Geleto et al., 2025) and biological treatment systems (Van et al., 2015),

with improvements in some physical and chemical properties of water and removal of some contaminants. These applications and their results are summarized in Table 6-B.

CONCLUSIONS

This review concludes that *Conocarpus* biomass is an efficient and scalable source for wastewater treatment in a circular economy. The summarized data from the literature show that tuning the thermal profile of the carbonization process, the type of chemical activating agents and the process of surface engineering directly influences the pore architecture, specific surface area and density of functional groups which in turn improves the efficiency of contaminant removal. The review emphasizes the importance of multi-variable synergy between the properties of the adsorbent, chemical properties of the pollutant, and operational parameters (e.g., pH, contact time and dosage) for mass transfer and capture efficiency. Such parameters control competitive processes such as ion exchange, electrostatic attraction, surface complexation and π - π reactions. Finally, the cross-study comparison shows that a wide range of performance differences exist between the different methods, highlighting the need to develop method-specific, pollutant-specific adsorbents, rather than any uniform general method.

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