Review:

Activated Carbon Adsorbents Derived from Agricultural Waste for Phenolic Pollutant Removal: A Review

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Received: December 20, 2024
Accepted: March 10, 2025

DOI: 10.22146/ijc.102884

Abstract: *The widespread discharge of phenol into the environment has posed a threat to the environment. Phenol waste in the aquatic environment is mainly due to its involvement in various industries such as the petrochemical, pharmaceutical, and wood product sectors. Recent studies have shown that industrial waste contains phenol in the concentration range of 2.8 to 6800 mg/L. The presence of phenol in water can cause bioaccumulation in aquatic organisms, thus posing a risk to the food chain and human health through the consumption of phenol-contaminated seafood. Long-term exposure of humans to phenol-contaminated water causes health problems such as anorexia, progressive weight loss, and liver disorders. This emphasizes the importance of addressing and reducing phenol contamination to safeguard human health. Various treatment methods have been applied, including filtration, reverse osmosis, and adsorption. Among these, adsorption is widely used due to its simplicity and cost-effectiveness, with activated carbon as the most commonly used adsorbent. This study comprehensively reviews previous studies on agricultural waste-based activated carbon (palm shell, candlenut, and rubber) for phenolic compound removal. It examines characterization data (BET, XRD, SEM-EDX, and FTIR) and adsorption performance, aiming to provide recommendations of the most promising biomass for developing efficient activated carbon.*

Keywords: *phenol; adsorbent; coconut palm; candlenut shell; rubber shell*

INTRODUCTION

The world is currently experiencing rapid development in various sectors, including agriculture, transportation, and industry, which is directly proportional to the significant increase in the release of inorganic and organic pollutants into the environment [1]. Extensive discharge of pollutants into the environment poses a serious threat, especially to domains such as water, land, and air, causing significant adverse impacts on ecosystems and humans [2]. Despite rapid global progress, there has been a marked shift in public awareness of environmental issues, with particular emphasis on water security as an essential issue in environmental discourse [3]. Increasing awareness of the importance of maintaining water quality reflects a growing collective awareness of the interdependence between activities and overall human well-being. As we navigate the complexities of modern progress, a growing understanding of environmental sustainability becomes vital to mitigate the adverse impacts of industrial and technological development measures. Advances in science and technology must also be balanced with environmental sustainability, so reducing the negative impacts of industrial development steps is important. This pressing problem has attracted much attention, driven by factors such as increasing water demand, population growth, industrialization, urbanization, and other processes that generate waste in the aquatic environment [4-5]. A recent study by Ahmaruzzaman [6] in 2021, revealed that approximately 80% of wastewater, originating from both industries and households, is discharged into bodies of water without proper processing techniques. The continuous disposal of pollutants into water bodies raises awareness about the steep deterioration of water quality at the source, underscoring the urgency of implementing effective waste management and processing methods to protect water quality and environmental health [7].

Phenol is a hazardous organic pollutant that poses a dangerous threat in the environment. Phenol production reaches approximately 6 million tons per year, and the amount continues to grow significantly [8]. In natural environments, a wide range of phenolic compounds are produced by multiple industries, such as petrochemical, pharmaceutical, oil refining, paper manufacturing, plastics, and various wood processing sectors [9]. Several studies have indicated that the concentration phenol in industrial waste can range from 2.8 to 6800 mg/L [10]. Phenol and phenolic compounds represent a hazardous category due to their significant toxicity, low biodegradation, and high bioaccumulation potential [11], even at low concentration levels ranging from 9 to 25 mg/L [12]. The presence of phenolic pollutants in water bodies can lead to the contamination of various agricultural products and has the potential to cause human health problems, such as anorexia, progressive weight loss, diarrhea, vertigo, salivation, dark coloration of urine, and blood and liver abnormalities [13].

Various methods have been employed to reduce and eliminate phenol and phenolic compounds, encompassing physical, chemical, and biological methods [14]. Distillation, a physical method used to remove phenol, was known to suffer from several drawbacks, such as high operational costs and excessive energy consumption [15]. Another method, such as reverse osmosis, is limited by their ability to handle numerous pollutants and incur high operational costs [16]. Although considered a viable option, the phytoremediation use in phenol removal has been associated with challenges when operating at higher concentrations [4], while enzymatic methods lack due primality to the involvement of expensive purification stage [17]. The use of ozonation for phenol reduction is marked by its low efficiency [18]. In contrast, adsorption is favored for its economic feasibility, especially when utilizing waste materials as a source, and its flexibility in adapting to different concentrations based on the adsorbent used [19-20]. Literature research has indicated that the adsorption method is the most widely applied technique in mitigating water pollution due to its simplicity.

Current research has shown that activated carbon is the most frequently used adsorbent [21]. Various carbon sources have already been explored, including activated carbon derived from base bamboo, demonstrating an adsorption performance exceeding 70% [22]. Additionally, activated carbon from coconut shells and corn stems exhibit adsorption capacities within the range of 1.99 to 2.25 [23-24] and 8.15 to 12.67 mg/g [25], respectively. Activated carbon obtained from coconut shell palm has been found to exhibit adsorption efficiency exceeding 95% [26]. Other potentially activated carbon sources have also been explored for effectively reducing phenol pollutant concentration, including candlenut shells [27]. Another activated carbon derived from waste materials was evaluated for efficient adsorption-based removal of strontium, barium, and combined pollutants [28]. The activated carbon derived from natural sources have been well characterized for its physical and chemical properties using several analytical instruments such as scanning electron microscopy (SEM) and energy dispersive X-ray (EDX), X-ray diffractometer (XRD), and Fourier transform infrared spectroscopy (FTIR) [29] to provide detail insights into their initial structure and chemical changes during the adsorption process.

Several research findings suggest that coconut palm, candlenut shells, and rubber shells have been extensively investigated as distinctive sources of activated carbon. Studies have also suggested the characterization of the activated carbons after their use in the adsorption process to determine not only the adsorption mechanism but also to seek the long-term viability and environmental impact of the activated carbons. For example, SEM-EDX with Phenom ProX was utilized to investigate activated carbons' morphology and elemental composition. XRD diffractometer and FTIR were employed to analyze activated carbons' crystal structure and surface functional groups [30-31]. This comprehensive analysis contributes valuable information to understanding how these materials evolve during the removal of pollutants, thereby aiding in the development of sustainable and effective solutions for environmental remediation.

This review aims to summarize the removal of phenolic compounds using activated carbons, focusing on those fabricated using coconut palm, candlenut shells, and rubber shells. The review emphasizes the physical and chemical properties of the prepared activated carbons and highlights their adsorption capacities, drawing insights from a comprehensive literature survey. This review will also focus on the thorough discussion on the characterization of the fabricated adsorbent using several instruments such as Brunauer-Emmett-Teller (BET), XRD, SEM-EDX, and FTIR. Finally, the unique characteristics of the activated carbon produced from this raw material were compared, and their efficiencies in removing phenolic compounds from water were assessed.

■ PHENOL

Phenol is an organic compound with the chemical formula of C_6H_5OH (Fig. 1), constituting an aromatic ring and a hydroxyl group [4]. This compound can be naturally produced by various organisms and synthetically produced for human-made applications across various industrial sectors. Given its extensive applications in industry, phenol can be potentially released into the environment, especially when improperly treated waste is discharged [32]. Consequently, phenol can pose a serious threat to the organisms and human health. Phenol has been recognized from the outset as a pollutant resistant to degradation through physical, chemical, and biological processes [33-34]. Previous studies have estimated that various industries dispose of over 10 million tons of phenolic compounds into the environment [35].

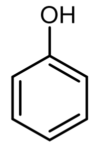

Fig 1. The chemical structure of phenol

Source of Phenol

Phenol and phenolic compounds are known for their resistance to degradation, and their presence in the environment can be originated from various sources, including household activities, industries, and agricultural processes [36-37]. Chlorophenol is widely used in the production of pesticides, preservatives, and disinfectants [38-39]. Nitrophenol can originate from the production of pesticides, plasticizers, drugs [40], and the reaction of nitrite under UV [41]. The persistent nature of these compounds can result in their accumulation in the environment, posing a carcinogenic risk to humans [42-43]. Fig. 2 illustrates a detail depiction of the sources of phenolic compounds in water, along with a comprehensive breakdown of the various chemical compounds that contain phenol [4].

Phenol Toxicity

Proper handling of phenolic compounds in the environment is crucial due to their known negative impacts on human health and biotic systems [44]. Phenols are considered toxic, carcinogenic, and mutagenic, particularly in their effects on humans [45]. Research has identified that phenol pollutant is associated with various diseases and disorders, including genotoxicity, liver and kidney dysfunction, metabolism disorders, diarrhea, irregular breathing, and disruption to the central nervous system [46-48]. The toxicity level of phenolic compounds has been identified within the range of 10 to 24 mg/L, with the concentration in the blood reaching approximately 1.5 mg/mL [49-50]. In

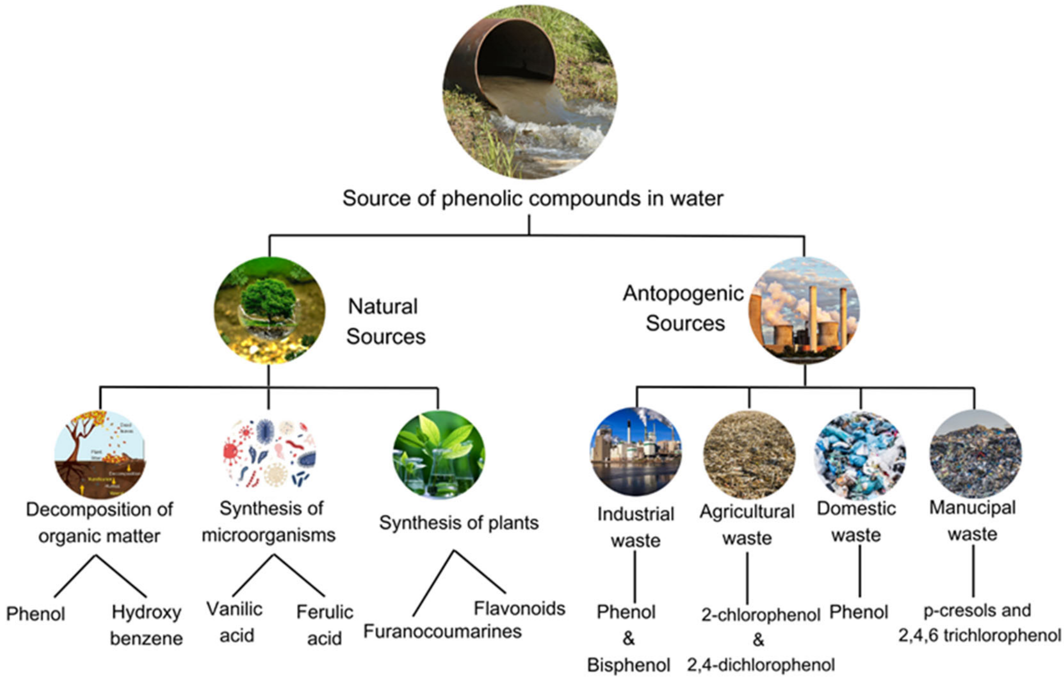

Fig 2. The source and pathways of phenol pollutants

addition, phenols can also cause alterations in plant community structures and accumulate in biological systems such as birds and fish, causing pollution in the food chain, aquatic ecosystems and human health also [51-53]. Thus, effective management of phenols is crucial to protecting human health and the environment.

■ REDUCTION METHOD

The presence of phenol in the environmental waters significantly impact on organisms and humans underscoring the need for effective and efficient processing [4]. Various technologies have been employed to reduce phenol pollution, including distillation, filtration, reverse osmosis, oxidation, ozonation, phytoremediation, biodegradation, and adsorption [54-55]. A detailed explanation of each method's advantages and disadvantages can be found in Table 1.

Adsorption

The adsorption method refers to the enrichment process of a substance in the surface between two adjacent phases, such as solid-gas, solid-liquid, and liquid-gas. This phenomenon is driven by the diffusion of molecules. There are two essential terms associated with the adsorption process: adsorbates and adsorbents. Adsorbates denote the materials or substances undergoing adsorption, while the materials that have the ability to adsorb other materials are known as adsorbents.

Practically, adsorption can be categorized into two types: physical and chemical. In the physical adsorption process, chemical bonds are not involved in either formation or deformation. The distinctive characteristics of physical adsorption are fast adsorption rate, weak binding forces, and a small amount of adsorption heat. Thus, it is not selective to certain substances. In contrast, chemical adsorption involves the formation of chemical bonds between the surface of adsorbents and adsorbates. Several characteristics, including slow adsorption rate, substantial adsorption heat, and irreversible adsorption nature indicate this type of adsorption. This type of adsorption is also marked by the difficulties in desorbing the adsorbates from the surface of the adsorbent due to the strong chemical bonds and high energy requirement. Numerous activated carbon derived from various sources have been evaluated for their capacity for the adsorption of phenol, as illustrated in Table 2.

Table 1. The advantages and disadvantages of various technologies for phenol removal

Methods	Advantages	Disadvantages	Ref.
Distillation	High recovery rate, efficient, reusable material	High operational cost, excessive energy consumption, and unsuitable for low-concentration solution	[56]
Filtration	Versatile operation, concentration adaptability, high selectivity, compatible with hybrid system	High initial investment, expensive operational cost, scalability challenges, membrane fouling	[57]
Reverse osmosis	Highly effective in contaminant removal, energy-efficient	Limited capacity for high pollutant loads, high initial investment and operational cost	[58]
Oxidation	Capable of oxidizing high-concentration pollutants, compatible with other technologies for enhanced efficiency	Use hazardous chemical oxidants, potential side product formation at high doses	[59]
Ozonation	Reduce bioactivity and toxicity, potential biological pollutant effects	High operational and investment costs, inefficient pollutant removal	[60]
Phytoremediation	Environmentally friendly, cost-effective, enhance biological diversity	Limited operation at high concentrations due to toxicity requires a large space	[61]
Biodegradation	Environmentally friendly, cost-effective, adaptable to low and high strength wastewater	Sometimes unsuitable for high pollution concentrations, it requires large space	[62]
Adsorption	Cost-effective, especially with waste-based materials, adaptable to varying concentrations with adsorbent capacity adjustments	Less effective at high concentrations, challenging adsorbent-adsorbate separation, requires regeneration before disposal	[63]

■ ACTIVATED CARBON

The adsorption capacity is significantly influenced by the conditions under which the pores are formed. The greater the size of the pores within the activated carbon, the higher the resulting adsorption capacity. Depending on the pore sizes, the activated carbons can be classified into several types, including micropores (size < 40 Å), mesopores (40 < size < 5000 Å), and macropores (size > 5000 Å).

Several studies have used various biomass as activated carbon and are summarized in Table 2. Activated carbon from palm oil shells, rubber shells, and candlenut shells is used as an adsorbent for heavy metal waste, toxic dyes, and phenol. The adsorption capacity for dyes is very high, namely 353.357 and 418.15 mg/g, but is still very low for phenol waste, namely 62.89 mg/g for activated carbon from palm oil shells. This fact has become a focus for innovating adsorbents with more effective adsorption capacity.

Based on the comparison results from Table 2, the best activated carbon is coconut fiber-activated carbon for adsorbing methylene blue. A research on coconut-activated carbon fiber by Foo [70] in 2018 showed an adsorption capacity of 418.15 mg/g, a significant carbon yield, and a sustained adsorption capacity over multiple adsorption-desorption cycles. This method provided substantial improvements over conventional regeneration due to its efficiency, effectiveness, processing speed, as well as economic benefits in handling volatile vapor pollutants. Palm shells are the best biomass for activated carbon due to their superior porous structure, high adsorption efficiency, and high carbon content. Extensive research has been done to assess the removal of phenol compound using natural adsorbents, such as activated carbon. In addition, while phenol used as the main adsorbate, the investigation also encompasses several additional pollutants, such as heavy metals, dyes, and organic pollutants. This distinguishes supporting this paper as a literature review of various aspects of pollutants handled. The various types of activated carbon suitable for phenol removal are detailed in Table 3.

Adsorption is an effective method for removing phenol from water. A variety of adsorbents can be used, as shown in Table 3, with chitosan, activated carbon, zeolite, and agricultural waste being common choices.

Table 2. Various types of miscellaneous adsorbents used in adsorption

Adsorbent	Adsorbate	Capacity (mg/g)	Ref.
Activated carbon shell coconut	Phenol	144.93	[64]
Activated carbon leaf dates	Phenol	17.38	[65]
Activated carbon dregs sugarcane	Phenol	158.96	[66]
Activated carbon skin pomegranate	Phenol	148.38	[67]
Activated carbon shell Cocoa	Diclofenac sodium	50.90	[68]
Skin seed flower sun	Methylene blue	353.36	[69]
Activated carbon fiber coconut	Methylene blue	418.15	[70]
Activated carbon husk paddy	Pb(II)	143.45	[71]
Activated carbon skin tree Carica	Cu(II)	23.08	[72]
Activated carbon straw	Hg(II)	50.00	[73]
Banana stem biochar	Zn(II)	108.10	[74]
Skin biochar peanut land	Cu(II)	48.73	[75]
Activated carbon shell coconut palm	Phenol	62.89	[76]
Activated carbon candlenut shells	Co(II)	150.00	[77]
Activated carbon rubber seed shell charcoal (RSS-CH) and activated carbon (RSS-AC) from rubber seed shell (RSS)	Cr(VI) and methylene blue (MB)	RSS-CH =217.39 RSS-AC = 370.37	[78]
Activated carbon jackfruit leaves	Methyl orange (MO)	833	[79]
Activated carbon granular activated carbon (GAC), powder activated carbon (PAC) and superfine powder activated carbon (SPAC)	Methylene blue	SPAC = 112.57–122.21 PAC = 34.67–0.96 GAC = 4.34–16.66	[80]
Activated carbon dragon fruit peel	Methylene blue	54.12	[81]
Activated charcoal coffee dregs	Cu(II) and Ag(I)	Cu(II) = 31.42 Ag(I) = 27.74	[82]
Activated carbon from rice husk	Zn(II)	71.47	[83]

Table 3. Type of adsorbent for phenol removal

Adsorbent	Capacity	Ref.
Chitosan	2–36 mg/g	[84]
Sugarcane bagasse	2–101 mg/g	[85]
Powdered *Opuntia ficus-indica*	25.58 mg/g	[44]
calcined clays	2.932 mg/g	[86]
Pomegranate peel	148.38 mg/g	[67]
Zeolite	93–100%	[87]
Wood apple rind	19.8–47.1 mg/g	[88]
Bamboo culms	2.213 mg/g	[89]
Orange peels	1.14–1.23 mg/g	[90]
Pineapple waste	288.34 mg/g	[91]
Coffee grounds	100 mg/g	[92]
Rice husk	296.26 mg/g	[93]
Activated carbon shell coconut	144.93 mg/g	[64]
Activated carbon leaves dates	17.38 mg/g	[65]
Activated carbon dregs sugarcane	158.96 mg/g	[66]
Activated carbon skin pomegranate	148.38 mg/g	[67]

Factors such as surface area, pore structure, solution pH, and initial phenol concentration must be considered when selecting the proper adsorbent. The use of environmentally friendly and low-cost adsorbents is a priority in managing phenol waste. Table 3 shows that adsorption with activated carbon has the highest value of adsorption capacity. Activated carbon is the most used adsorbent to adsorb phenol because it has a large surface area and small pores. Activated carbon can be produced from various materials, such as coal, wood and palm oil. Despite their successful application in removing various pollutants, further research is required to enhance the quality and optimize the performance of activated carbon-based adsorbents. According to El-Bery et al. [66], dye adsorption showed that water-based activated carbon could remove more than 95% of the dye. Meanwhile, Afsharnia et al. [67] revealed that pomegranate peel carbon can remove phenols from aqueous solutions, with an efficiency of more than 98%.

Biomass Coconut Palm Shell

In Indonesia, coconut palm represents a significant agricultural commodity. Currently, the byproduct of coconut palm, in the form of coconut palm shells, is commonly burned and discarded, leading to environmental issues like greenhouse gas emissions [94]. Numerous research studies have indicated the potential utilization of discarded coconut palm shells as an adsorbent material in adsorption [95]. The process of utilizing coconut palm shells as the source of activated carbon involves several essential steps, which include the preparation of charcoal from coconut palm shells [96], the activation of palm kernel shells [97], the activation of the charcoal to form activated carbon [98], the characterization of the resulting activated carbon using several analytical instruments, such as SEM, BET, FTIR, and XRD [76], and the examination of the adsorption experiments to assess the efficacy of the resulting activated carbons [98-99].

SEM characterization is used to determine the morphology of biomass. An example of a particle shape of activated carbon resembling a plate can be seen in Fig. 3. The surface of porous carbon appears uneven and irregular. These structures and pores are formed during the activation process. Meanwhile, XRD diffraction characterization is used to analyze the crystal structure of activated carbon materials [77]. FTIR characterization was used to determine the functional groups present in the activated carbon sample within the wavelength range of 400–4000 cm^{-1} [30]. The BET method is used to determine the adsorption-desorption isotherm.

When conducting adsorption experiments, it is crucial first to identify and understand the adsorbent material's wide surface and morphological properties [100]. In a research study focused on utilizing waste coconut palm shells as an adsorbent, observations were

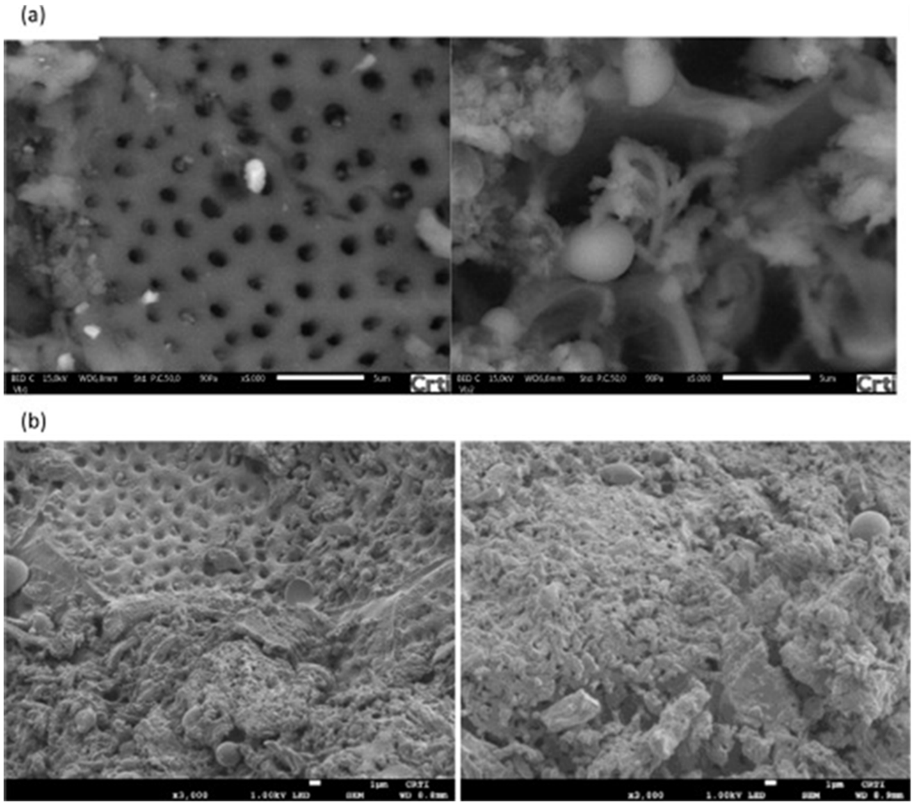

Fig 3. SEM image with (a) 5000× and (b) 3000× magnification [97]. Adapted with permission from Elsevier, Copyright 2023

carried out to analyze the morphology of the adsorbent (coconut palm shell). Based on Fig. 3, it is evident that evenly distributed pores can be observed on the surface of palm kernel shells, serving as a nutrition supply nutrition for the embryo during the germination process [101]. The test results reveal that the specific outside surface area of the adsorbent is approximately 320 m^2/g. Further observation indicates that the morphology of palm kernel shell and palm kernel husk is predominantly characterized by mesopores, along with a notable presence of macropores [102]. The characterization of the activated carbon from palm oil shells to evaluate its surface area was conducted using BET method [103-104]. Baloo et al. [104] reported that the BET surface value obtained for activated carbon derived from palm waste was at 35.63 m^2/g to remove phenol pollutants. Based on Table 4, the highest surface area is 657.4 m^2/g, with a pore volume of 0.34 nm as a phenol adsorbent with an adsorption capacity of 230.7 mg/g. Surface area and pore volume are physical factors for the absorption process. The higher the value, the greater the load on the adsorption capacity. It was concluded that activated carbon from oil palm shell biomass has an effective adsorption value.

Biomass Pecan Shell

Activated carbons from numerous biomass sources have been employed to reduce a various water pollutant, including dyes, heavy metals, phenolic compounds, and chlorophenols, which are the most common environmental contaminants in various industrial wastes [111-112]. Various types of biomasses have been utilized, such as residues from sugar cane, corn stalks, sawdust from different wood species, and candlenut shells [113]. Previous research has indicated that palm kernel shells confirmed that the adsorption involves both physisorption and chemisorption, as the Pseudo-First Order and Pseudo-Second Order models demonstrated strong correlation coefficients, indicating their suitability and compatibility with the adsorption mechanism [114]. A study focusing on bioadsorbents indicated that biomass derived from candlenut shells can be utilized to reduce the levels of dyes and heavy metals in water [115]. It is essential to recognize that candlenut shells, considered waste from vegetables, possess cationic compounds that can influence the adsorption of colored substances [116-117]. Another study revealed that candlenut and almond shells, subjected to pyrolysis and activation at 450 °C for 1 h in the presence of air, produced activated carbon with a high surface area (1138–1458 m^2/g) and demonstrated significant adsorption capacity against Cu(II) ions [118].

Several essential steps are required when employing the inner candlenut shell method for reducing phenolic compounds. First, the pecan shells must undergo a carbonization process, typically achieved by heating them at 650 °C [119]. Once the charcoal from candlenut shells is prepared, the subsequent step involves the activation process, which can be carried out through physical or chemical methods [120-121]. Following the

Table 4. Various parameters measured on activated carbon from palm oil shells

BET surface (m^2/g)	Pore volume (nm)	Target pollutant	Result adsorption capacity (mg/g)	Ref.
395.70	0.71	Rhodamine B	182.82	[103]
35.63	0.01	Phenol	30.86	[104]
733.72	779.30	Rhodamine B	903.06	[105]
415.116	0.229	Ni^{2+}	99.11	[106]
1432.94	-	Phenol	1192.29	[5]
302	-	Methyl violet dye	42	[107]
657.40	0.341	Tetracycline	657.44	[108]
666	2.91	Methylene blue (MB)	110	[21]
-	50	Cu^{2+} in waste water	60	[109]
1704	0.984	Yellow 18, a basic textile dye	75.76	[110]

activation, the activated carbon undergoes an examination of its characteristics, including morphology and surface area [122-123]. Subsequently, testing is conducted using adsorption tests to identify the adsorption capacity of the activated carbon [124-125].

An example that aids in understanding the activated carbon derived from candlenut shells can be found in the results of SEM-EDX analysis in Fig. 4. The analysis reveals that the particles exhibit a plate-like form, indicating a distinct particle structure. This alteration in the surface structure of the particles is a consequence of the combination of *Aleurites moluccana* powder with cobalt chloride [77]. Based on Table 5, the surface area of activated carbon from pecan shells can be increased, because the values vary, and the highest reaches 1025 m^2/g for dye adsorbates.

Biomass Rubber Shell

With most of its derivatives, phenol has been considered a highly dangerous environmental pollutant, prevalent in various industrial wastewater sources, such as pharmaceuticals, steel, plastics, oil extraction, and coal processing [126-127]. Numerous methods are available for the separation of phenol, including ion exchange, biological degradation, chemical oxidation, electrochemical oxidation, precipitation, and adsorption [128-129]. Activated carbon derived from rubber seed shells are one potential adsorbent in the adsorption process [78,130]. Rubber production generates a substantial amount of rubber seed shells, which are predominantly treated as waste. These shells are often used as drum fertilizer or discarded and left to decompose [131-132].

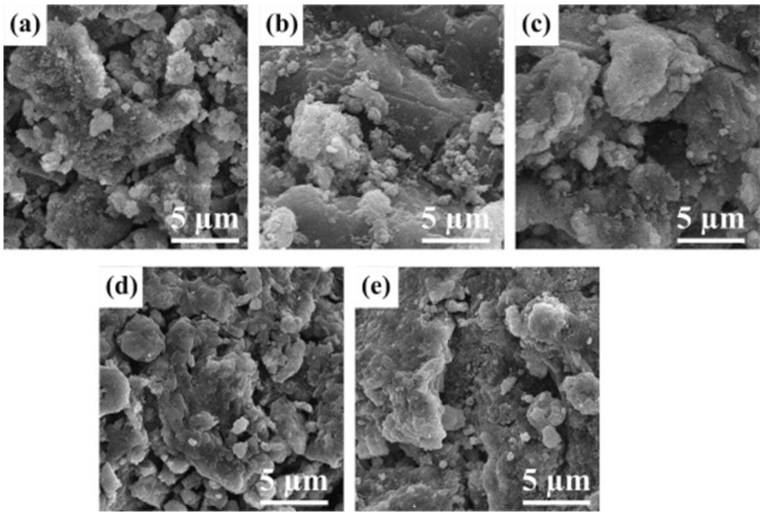

Fig 4. SEM-EDX analysis results of candlenut shells [77]. Adapted with permission from Elsevier, Copyright 2023

Table 5. Various parameters measured on activated carbon from biomass rubber shell

BET surface (m^2/g)	Pore volume (nm^3/g)	Target pollutant	Result (mg/g)	Ref.
889	0.650	Phenol	271.95	[131]
972.16	2.51	Methylene blue	75.76	[78]
302	0.154	Benzene	13.70	[128]
7.07	0.114	Phenol	125.77	[127]
200.14	0.240	Phenol	15.97	[129]
46	0.031	Phenol	178.00	[133]
132.40	0.073	Remazol brilliant violet	125.88	[135]
620	0.284	Phenol	639.73	[137]
1448	901	Synthetic dyes	190.20	[138]
2441	-	Oily wastewater	93.9	[136]

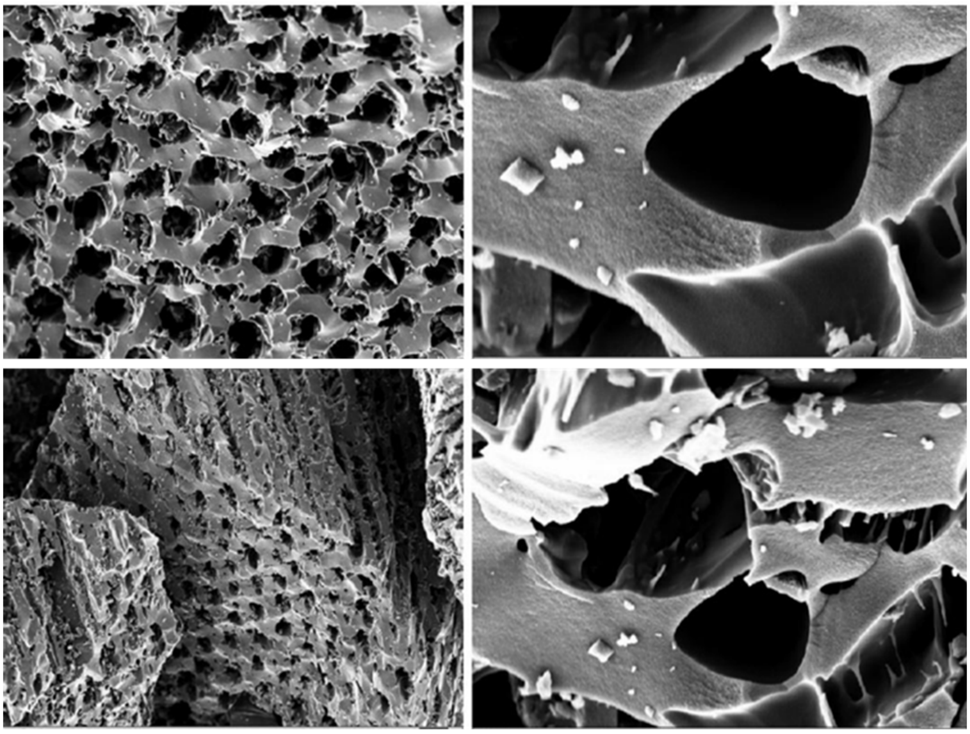

Fig 5. Morphology of FESEM activated carbon shell rubber [139]. Adapted with permission from Elsevier, Copyright, 2018

In the application of rubber seed shells as the source of activated carbon, several essential stages need to be undertaken, including the production of charcoal or the preparation of activated carbon [133-134]. Subsequently, the activation process of the activated carbon is conducted, employing either chemical or physical methods [135-136]. Following activation, a characteristic test is performed to identify aspects such as morphology and surface area [137-138]. Furthermore, adsorption tests on the produced activated carbon are conducted to analyze its absorption capacity towards pollutants [132].

The analysis of the activated carbon sample generated from rubber seed shell has been conducted to observe the surface morphology of the produced bio-char under optimal pyrolysis conditions using FESEM (Fig. 5). The BET surface area of the bio-char was calculated to be 175.95 m^2/g, accompanied by a total pore volume of 0.12 cm^3/g and an average pore diameter of 2.66 nm [139].

Based on Table 5, activated carbon derived from rubber shell biomass exhibits the highest surface area, measuring at 889 m^2/g, with a pore volume of 0.65 nm, and an adsorption capacity of 271.95 mg/g. Activated carbon continues to be applied as an adsorbent for phenol, dye waste, and other organic compounds such as benzene. These findings underscore the ongoing advancements in activated carbon, reinforcing its potential as a future, durable and widely applied adsorbent for an effective environmental adsorbent [131].

■ CONCLUSION

This review highlighted various studies on phenol contaminant removal using adsorption method as it stands out due to its cost-effectiveness, especially when utilizing waste materials as the adsorbent. Activated carbon derived from agricultural waste has appeared as an effective and sustainable source of adsorbent for the phenol removal. This review has highlighted that activated carbons derived coconut palm shells, candlenut shells, and rubber shells, have promising adsorption capabilities due to their superior porous structure and higher surface area. In addition, it offers flexibility in adjusting the adsorbent capacity to accommodate different concentrations of contaminants. However, challenges on expensive production costs and limited selectivity, and adsorption saturation need to be addressed for further application. Modification on the activation procedure and the functionalization on the activated carbon surface are expected to provide optimized pore structures and thus leading to higher adsorption capacity. Future studies should focus on optimizing synthesis conditions, developing improved regeneration process, and long-term adsorption performance evaluation. Additionally, the synergy adsorption with supporting treatment technology will further increase the effectiveness of phenol removal. Overall, activated carbons derived from coconut palm shells, candlenut shells, and rubber seed shells possess distinct characteristics and exhibiting comparable levels of adsorption efficiency compared to other biomass derived activated carbon. Despite their differences, these adsorbents were found to be viable materials for the premoval of phenol contaminants.

■ ACKNOWLEDGMENTS

The authors express their deepest gratitude to Mr. Arif Setiajaya, lecturer at Institut Teknologi Sumatera and Universitas Malahayati, for his invaluable guidance and insightful contributions during the initial conceptualization of this article. The authors also extend their sincere appreciation to Ms. Annur Valita Sindiani, Master of Chemistry student at Universitas Lampung, for her meticulous assistance in refining the manuscript during the revision process.

■ CONFLICT OF INTEREST

The authors state that they have no conflict of interest.

■ AUTHOR CONTRIBUTIONS

Annisaa Siti Zulaicha was responsible for conceptual and writing the original draft. Agung Abadi Kiswandono contributed to the writing, reviewing, and editing paper. Buhani was responsible for reviewing the paper. Suharso contributed to the data curation and research design. Fidelis Nitti contributed to the writing, editing, and reviewing paper. Rinawati did the supporting the study and revising the substantial content.

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