



Potentials of activated carbon produced from biomass materials for sequestration of dyes, heavy metals, and crude oil components from aqueous environment

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Abstract

Carbon adsorbents derived from biomass (agricultural and household residues) have been widely used in the sequestration of hazardous substances from the environment due to their distinctive qualities of large internal surface area, mechanical integrity, and regeneration. The need for carbon adsorbents for sequestration of dyes, heavy metals, and crude oil components has increased because of environmental concerns. This has led to studies of carbon adsorbents derived from agricultural and household biomass residues. These adsorbents have been used to remove pollutants. Although numerous reviews have been published before, analogy of results obtained using different adsorbents is hard due to dissimilarities in research data. Against this backdrop, the purpose of the research survey was to review the contemporary publications regarding the production of activated carbon from biomass sources highlighting specifically its utilization in removing toxic wastes from water solution such as oil spill, dyes, and sundry hazardous substances. Also the work focuses on the methods for the restoration of the spent adsorbents and their end use.

Keywords Activated carbon · Biomass · Sorption · Regeneration · Environment · Pollutants

Introduction

Carbon adsorbents are highly porous, made up of mostly sp²-hybridized carbon, and have large internal surfaces. Also, the other properties of a good adsorbent include having sufficient pores sizeable to pass the molecules, be regenerable, not degrade rapidly from constant usage, and withstand vibration from industrial units (Gupta and Tai 2016). There are, however, other adsorbents in commercial use.

The adsorbents in commercial use in the industry with their uses are silica gel for drying of gases, activated alumina for HCl removal, carbons for decolorization of syrups

and (waste) water, and zeolites for the separation of normal paraffins from branched paraffins. Other adsorbents in use include polymers and resins for water purification and clays for edible oil treatment (Richardson et al. 2010):

Agricultural by-products including shells of almonds, hazelnut, and coconut and seeds of olive, apricots, and peach fruits have been used for activated carbon (AC) production (Amaya et al. 2007; Ioannidou and Zabani-otu 2007).

There are two fundamental steps for producing activated carbon adsorbents (Alaya et al. 2000; Zondlo and Velez 2007): “the pyrolysis of the raw material below 800 °C, and physical or chemical activation of the carbonized material.”

There have been studies in some treatment methods. These include coagulation, ultrafiltration, electrochemical adsorption, photo-oxidation, and ion exchange. The adsorption technique was found to be most suitable because it removes pollutants at very low concentrations (Sharma et al. 2012). Furthermore, adsorption requires less land area (half to quarter of what is needed in biological method). When a solid surface makes contact with a liquid or gas medium, the molecules from the mass of the fluid phase have the

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likelihood to adsorb on the solid (Otowa et al. 1997; Bansal et al. 1988). “An adsorption process depends on solid–liquid equilibrium and the rate of mass transfer” (Gupta et al. 2007).

Oil pollutants were formerly removed from water using synthetic materials. This practice went on until it was discovered that dispersants like Corexit could contaminate water, leading to the search for alternative material. Converting agricultural by-products into activated carbon provides another disposal method which minimizes environmental pollutions. A country generates its agricultural byproduct based on its agriculture (Ezechi et al. 2017). “In Malaysia about 1.2 million tons of agricultural waste is generated yearly” (Billy et al. 2013). Agro-waste is incinerated which can pollute the atmosphere. The common waste management technology in India is land filling (70–90%). “In Berlin the waste management technology is incineration and land filling which can lead to methane emissions.” The Nigerian agriculture produces huge amount of corn, rice, and groundnut residues, most of which remain unused (Rosenkranz et al. 2011).

Table 1 presents some review articles on wastewater decontamination by economical adsorbents, published in 2013–2019.

Bhatnagar et al. (2015) explored the use of agro-waste peels (e.g., orange, pomelo, grapefruit, lemon, banana, cassava, and jackfruit) as sorbents for the decontamination of pollutants from contaminated water. The sorption capacities of waste peel biosorbents for organic and inorganic

pollutants were reviewed. Different modification methods which have been employed to develop modified peel-based adsorbents were also presented to highlight and discuss the key advancements in the preparation of novel adsorbents using agro-waste peels. Adsorption mechanisms responsible for pollutant removal by peel-based adsorbents have also been discussed. Future research needs in this field were proposed. Several gaps which need more attention were enumerated by the authors, such as enhancement of biosorption capacity through modification of biosorbent, assessment of biosorbents under multicomponent pollutants, investigation of these materials with real industrial effluents, recovery of metal ions, regeneration studies, and continuous flow studies.

Although numerous reviews have been published before, Gautam et al. (2014) carried out analysis of results obtained using a wide range of locally available non-conventional low-cost biosorbents for the removal of heavy metals as metal ions, viz Cd, Ni, Cr, Zn(II), Se(IV), and organometallic compounds from industrial effluents. Various adsorption models used to study the mechanism of adsorption such as isotherm, kinetics, and thermodynamic models and biosorption technologies (e.g., batch, column, and reactor) were also discussed. Further the authors cited that a direct comparison of data obtained using different biosorbents is difficult because of inconsistencies in the data presentation.

Thus, taking this situation into account the aim of this study was to analyze the contemporary research reports regarding the beneficiation of agricultural and household

Table 1 Some review articles concerning wastewater decontamination by economical adsorbents published in 2013–2019

References	Purpose	Adsorbent(s)	Pollutant(s)
Anastopolous et al. (2019)	The review is focused on the use of agricultural biomasses for the removal of toxic metal(oid)s from contaminated aqueous solutions	Biomass	Toxic metal(oid)s
Wei et al. (2019)	Treatment technologies in petrochemical wastewater and produced water from oil and gas production are reviewed	Chitosan-activated montmorillonite, nutshell filters, etc	Petrochemical wastewater and produced water from oil and gas
Doshi et al. (2018)	This is an investigation carried out by researchers in the recovery of spilled oils using biomass and polymers, as sorbents or separators	Biomass	Diesel, crude oil, gasoline, waste lubricating oil, etc
Wong et al. (2018)	The review focused on the use of ACs prepared from magnetic materials and nanoparticles in wastewater purification compared to biochars derived from biowaste.	Biomass	Dyes; heavy metals
Amirza et al. (2017)	The study focused on dye removal using activated carbons from woody and non-woody materials	Biomass	Dyes
Bhatnagar et al. (2015)	The review summarized the study of adsorption capabilities for pollutants removal using different peel-based adsorbents.	Biomass	Dyes; heavy metals
Gautam et al. (2014)	The work gave a detailed assessment of the modeling of some biosorption processes	Biomass	Heavy metals
Nguyen et al. (2013)	The paper analyzed the possible use of agro-waste to prepare adsorbents for heavy metals sequestration	Biomass	Heavy metals

wastes for the production of efficient adsorbent using uncomplicated and economical methods. The objectives of the paper were to: compare and contrast the production and characterization of activated carbon from various sources, review the properties and adsorption capabilities of different biomass waste sorbents in oil spill recovery, highlight the major properties and sorption capabilities of different biomass waste sorbents for dyes recovery from wastewater, provide an overview of the major properties and adsorption capabilities of different biomass waste sorbents for removing sundry pollutants, and carefully highlight the reusability of activated carbon adsorbents and their end of life.

Production and characterization of activated carbon from different sources

As was presented earlier, the two main steps used to produce activated carbon adsorbents were: the pyrolysis of a carbon-rich raw material below 800 °C and activation of the carbonized material by physical or chemical method (Zhang et al. 2004; Zondlo and Venez 2007; Ani et al. 2019). The carbon-rich raw materials for producing activated carbon are cleaned, washed, and dried before physical or chemical activation is applied.

Physical activation also called thermal activation occurs in two steps (Jiazhen et al. 2018). It involves carbonization at the temperature range of 500–600 °C of a carbon-rich product with the activation of the charcoal between 800 and 1100 °C in the presence of oxidizing agents such as CO₂, steam, air, or their mixtures. Kumar and Namasivayam (2009) prepared activated carbon by steam activation. In their work, washed, dried, and pulverized jatropha husk (450 g) in 100 ml of water in a tightly covered steel container was carbonized in a muffle furnace for 1 h at 800 °C. Ioannidou and Zabaniotou (2007) had reported in a review paper that corn cob, oak, corn husks, corn stover, rice straw, rice husks, pecan shells, peanut husks, and almond shells have been used to prepare activated carbon by physical method. Sulaiman et al. (2011) investigated the differences in ash content between oil palm wastes namely shell, frond and trunk; by soaking 100.0 g of precursor in 5.0 l tap water then leaving it for 10 min which is now with the unwashed biomass. Their findings show that the ash content in palm shell, frond and trunk declined to approximately 43.16, 52.18, and 7.42%, respectively upon water-washing.

For the chemical process, the two steps involving carbonization and activation are performed at the same time, with the raw material being mixed with some chemicals, as dehydrating agents and oxidants (Gupta et al. 2008; Mittal et al. 2008; Hai et al. 2017). Also Kumar and Namasivayam (2009) used concentrated acids such as H₂SO₄, HCl, HNO₃, and H₃PO₄ for chemical activation. One hundred grams (100 g) of dried jatropha husk was combined

with 2.8 parts by mass of concentrated acid and left in the oven at 185 ± 5 °C for 24 h. The carbonized product was washed with 500 ml distilled water four times and with 1% NaHCO₃ solution. The final product was soaked overnight in 1% NaHCO₃ solution to remove excess acid. The product was washed with water to pH 7, dried at 105 ± 5 °C for 8 h and sieved to 250–500 μm size. Rios et al. (2003) described a simple and versatile method for the introduction of heteroatoms such as sulphur and nitrogen containing molecules onto carbon surface which therefore improved its adsorption capability of Pb⁺², Cu⁺² and Ni⁺².

The scanning electron micrograph (SEM) showed that when the jatropha husk was treated with activating chemicals, the pores in the surface of the char were wider, due to the removal of volatile compounds by chemical activation. The resulting morphology was not the same for all activating reagents, because the chemicals possess different properties. Furthermore, the acid-activated carbons produced higher yields than the steam-, ZnCl₂-, and NaOH-activated carbons.

The properties and adsorption capabilities of different biomass waste sorbents in oil spill recovery

The influence of acetylation on oil sorption capability of corncobs, found around Enugu, Nigeria, was investigated by Nwadiogbu et al. (2016). In the study, the corncobs were treated with acetic anhydride to enhance the hydrophobic properties and also improve the adsorption in water. It was observed that acetylated corncobs were suitable for the sorption of crude oil from water.

“A good source of non-toxic magnetic sorbent that has potential in oil pollution treatment is coco peat powder (CPD) which is a byproduct of coconut palm. CPD is abundant in many countries, including China, Malaysia, Philippines and Thailand” (Owolabi et al. 1985; Keerthika et al. 2016). Yang et al. (2017) used mussel-inspired polydopamine to immobilize Fe₃O₄ nanoparticles on coco peat powder which was chemically modified by low-surface-energy octadecylamine to prepare a novel magnetic coco peat powder (MCPD) for selective oil–water separation. Table 2 presents the major properties and adsorption capabilities of different biomass wastes in oil spill recovery.

Some characteristics of biomass waste sorbents for removing dyes pollutants from wastewater

Some industries including textiles, rubber, plastics, printing, leather, cosmetics, etc., use large quantities of dyes to color their products. Dye-polluted wastewater is therefore generated. “Dye-bearing wastewater in natural streams and rivers causes severe pollution problems to the aquatic life,

Table 2 Some characteristics of biomass waste sorbents for oil–water separation

Adsorbent		Test					Refs.		
Type	Synthesis/properties	Pollutants removed	Adsorbent dose	Initial pollutant concentration range	Period	Temp	pH	Amount adsorbed	
Modified coco peat powder	A novel modified coco peat powder was produced using octadecylamine by immobilized Fe_3O_4 nanoparticles coupled with mussel- inspired polydopamine.	Paraffin oil Silicone oil Chloroform Cottonseed oil Machine oil	0.1 g	n/a	n/a	25 °C	3–11	5.14 g/g 6.19 g/g 8.57 g/g 5.91 g/g 5.49 g/g	Yang et al. (2017)
Banana peels	Irregular morphology and a porous surface (SEM); C=O (hemicelluloses), C-O stretching (lignin)—FTIR	Gas oil 1-day weathered crude oil	0.5–2.5 g	n/a	5–60 min	20–45 °C	n/a	5.31 g/g 6.35 g/g	El-Din et al. (2017)
Mucor rouxii	pH=6.4, Surface area = 20.55 m ² /g	7-day weathered crude oil						6.63 g/g	
Absidia coerulea	pH=4.5, Surface area = 0.68 m ² /g	Standard mineral oil Canola oil Bright-Edge 80	0.2 g/100 ml	200 mg/l	6 h	n/a	5.0 and 7.6	77.2 mg/g 92.5 mg/g 84.0 mg/g	Srinivasan and Viraraghavan (2010)
Chitosan	pH=6.8, Surface area = 0.65 m ² /g for Sigma C3646	Standard mineral oil Canola oil Bright-Edge 80	0.2 g/100 ml	200 mg/l	6 h	n/a	5.0 and 7.6	72.0 mg/g 91.0 mg/g 80.0 mg/g	
Walnut shell	pH=7.5, Surface area = 0.17 m ² /g	Standard mineral oil Canola oil Bright-Edge 80	0.2 g/100 ml	200 mg/l	6 h	n/a	5.0 and 7.6	99.0 mg/g 99.0 mg/g 97.0 mg/g	
Hydrogel of chitosan-based polyacrylamide	Melt temperature = 86.8 °C	Crude oil	1 g/l	0.5–30 g/l	1–6 h	25 °C	3 7 9	83.0 mg/g 96.0 mg/g 96 mg/g 2.4 g/g 2.0 g/g 1.6 g/g	Sokker et al. (2011)

Table 2 (continued)

Adsorbent	Test						Refs.		
	Synthesis/properties	Pollutants removed	Adsorbent dose	Initial pollutant concentration range	Period	Temp		pH	Amount adsorbed
Oil palm leaves	FTIR showed strong band at 3400 cm^{-1} , is attributed to the intra- and intermolecular hydrogen-bonded (O–H) stretching that occurs in cellulose. Two peaks observed between 2970 and 2855 cm^{-1} were attributed to the presence of C–H asymmetric stretching of CH_3 and CH_2 groups. The broad peaks at approximately 1103 and 1060 cm^{-1} show the C–O–C stretching vibration of lignin and C–O stretching of cellulose and hemicellulose.	Crude oil	0–52 g/l	0–6400 mg/l	10–60 min	303–323 K	2–11	1176 ± 12.92 mg/g at 303 K	Sidik et al. (2012)
Bagasse Rice hull	Mesh—14–18 and 18–45 Mesh—10–14	Gas oil No. 1 Gas oil No. 2 Light crude oil Heavy crude oil	1000 g	10–30 g/400 ml	5 min	n/a	n/a	3–5 g/g	Bayat et al. (2005)
Raw rice husks (RRH) White rice husks ash (Pyrolyzed RRH in presence of air) Black rice husks ash (Pyrolyzed RRH in N_2 inert medium)	Specific surface area = 1 m^2/g Specific surface area = 228 m^2/g Specific surface area = 241 m^2/g	Crude oil Diesel fuel	1 g	n/a	0–20 min	20 °C	n/a	2.8 g/g 5.0 g/g	Vlaev et al. (2011)

Table 2 (continued)

Adsorbent Type	Test				Refs.				
	Synthesis/properties	Pollutants removed	Adsorbent dose	Initial pollutant concentration range	Period	Temp	pH	Amount adsorbed	
Grafted raw bagasse	Excess raw bagasse was mixed with stearic acid, water and some bases for 8 h and dried in vacuum at 60 °C for 20 h.	Used Caltex Valor 100 motor oil	n/a	n/a	10/15 min	n/a	n/a	3.0 g/g	Said et al. (2009)
Corncobs	Porosity = 81.5%	Crude oil	1 g	5 g/100 ml	2 h	26 °C	n/a	2.08 g/g	Nwadiogbu et al. (2016)

food web and also causes damage to the aesthetic nature of the environment” (Bharati and Ramesh 2013).

Some biomasses are being studied for removal of different dyes pollution by adsorption. Table 3 gives the properties and other qualities of biomass sorbent for removing dye from water. Garg et al. (2003) used rosewood sawdust to remove malachite green dye from water solution. Also to improve its efficiency, the adsorbent was treated with formaldehyde and sulfuric acid.

Further, Stavropoulos and Zabaniotu (2005) studied the potential of olive waste residue as adsorbent for removal of methylene blue pollution from water solution. It showed that the biomass has good potential.

Some adsorption characteristics of biomass waste sorbents for removing sundry pollutants

The biomass waste from rice husk ash (Mbui et al. 2002), olive seed waste (Stavropoulos and Zabaniotou 2005), cassava peels (Owamah 2014), waste bamboo (Ademiluyi et al. 2009), sugarcane bagasse and corn husk (Billy et al. 2013), cashew nut shell (Ponnusamy et al. 2011), corn-cob (El-Sayed et al. 2014), groundnut shell (Malik et al. 2007), walnut shell (Aygun et al. 2003), kenaf core fiber (Shamsudinn et al. 2016), rice shell (Aydin et al. 2008), rice husk (Ding et al. 2014; Xu et al. 2015; Yadav et al. 2015), *Typha orientalis* (cattail) leaves (Anisuzzaman et al. 2015), activated bone and wood (Okafor and Aneke 2006), wood derived biochar (Kizito et al. 2015), potato peel (Aman et al. 2008), and microwave-activated carbon coconut shells (Pillai et al. 2014) have been studied for removing pollutants from wastewater.

Stavropoulos and Zabaniotou (2005) studied the production of activated carbon from olive seed waste using KOH. The product was initially pulverized and sieved to 125–160 µm and subsequently dried at 110 °C for 24 h. To prepare the charcoal, pyrolysis of the olive seed waste was carried out at 800 °C for 1 h in inert atmosphere using a tubular fixed bed reactor.

Ademiluyi et al. (2009) performed batch and column tests for removing organic compounds from petroleum refinery effluent using granular activated carbon from Nigerian waste bamboo. The produced activated carbon was characterized by bulk density, porosity, pore volume, ash content, average particle size, moisture content, and pH. Granulated activated carbon from the biomass was used for the removal of organic pollutants from a refinery wastewater sample, after mechanical and biological treatment.

Anisuzzaman et al. (2015) investigated the production of activated carbon from *Typha orientalis* (cattail) leaf using muffle furnace. The work also evaluated the adsorption capability of the produced activated carbon by adsorbing Pb(II) in aqueous solution. The maximum BET surface

Table 3 Some characteristics of biomass waste sorbents for dyes recovery

Sorbent	Test							Refs.	
	Properties	Pollutants removed	Adsorbent dose	Initial pollutant concentration range	Period	Temp	pH		Amount adsorbed
Olive seed waste residue	Specific surface area = 3049.0 m ² /g	Methylene blue	0.01–0.03 g/200 cm ³	500 mg/l	n/a	n/a	n/a	262.0 mg/g	Stavropoulos and Zabaniotu (2005)
AC-Corn cob	Specific surface area = 700 m ² /g	Methylene blue	1–5 g/l	5–50 mg/l	120 min	25 °C	2–10	28.65 mg/g	El-sayeed et al. 2014
AC-Coconut shell	IR spectra: 3500 cm ⁻¹ (hydroxyl group), 2220 cm ⁻¹ (alkyne group), 1612 cm ⁻¹ (carbonyl group)	Maxilon blue dye	(0.005–0.5) g/100 ml	2–16 mg/l	120 min	20 °C	3–10	62.06 mg/g	Aljeboree et al. (2017)
A C-Cashew nut shell	Specific surface area = 984 m ² /g	Methylene blue	2.1846 g/l	50 mg/l	62.8693 min	n/a	10	n/a	Subramaniam and Ponnusamy (2015)
Prickly bark of cactus fruit (PBCF)	n/a	Methylene blue	0.1 g/25 ml	90–2000 mg/l	60 min	20–40 °C	≥ 8	222.22 mg/g	Abdelkarim et al.(2017)
AC-leather shaving waste	Specific surface area = 800.4 m ² /g	Acid black 210	0.05–7.00 g/l	800 mg/l	72 h	20–50 °C	2–10	573.9 mg/g	Manera et al. (2018)
AC-leather shaving waste	Specific surface area = 800.4 m ² /g	Acid red 357	0.05–7.00 g/l	800 mg/l	72 h	20–50 °C	2–10	204.4 mg/g	Manera et al. (2018)
AC-rice husk	Specific surface area = 281.7 m ² /g	Methylene blue	0.01–0.1 g	50 mg/l	240 min	25 °C	2–12	72.4 mg/g	Ratan et al. (2018)
AC-wheat straw	Specific surface area = 282.1 m ² /g	Methylene blue	0.01–0.1 g	50 mg/l	240 min	25 °C	2–12	90.9 mg/g	Ratan et al. (2018)
AC-Hazelnut shell (ACH)	Specific surface area = 793.0 m ² /g	Basic blue 9	n/a	n/a	24 h	n/a	n/a	8.82 mg/g	Aygun et al. (2003)
Calcined bones	Specific surface area = 85 m ² /g	Direct red 75	0.6–1.6 g/200 ml	25–100 mg/l	60 min	20–50 °C	2–12	24.56 mg/g	Haddad et al. (2013)
Calcined bones	Specific surface area = 85 m ² /g	Direct red 80	0.6–1.6 g/200 ml	25–100 mg/l	60 min	20–50 °C	2–12	22.54 mg/g	Haddad et al. (2013)
AC-rice straw	FTIR show bands characteristic of surface hydroxyl groups and chemisorbed water at 3427.85 cm ⁻¹ . The peak at 1071.26 cm ⁻¹ is due to Si–O–Si bond.	Brilliant green dye	3.75 g/l	20–100 mg/l	15–180 min	25 °C	n/a	30.675 mg/g	El-Chaghaby et al. (2018)

Table 3 (continued)

Sorbent	Test						Refs.		
	Properties	Pollutants removed	Adsorbent dose	Initial pollutant concentration range	Period	Temp		pH	Amount adsorbed
AC-rice straw ash	FTIR shows bands characteristic of surface hydroxyl groups and chemisorbed water at 3444.24 cm^{-1} . The peak at 1093.24 cm^{-1} is due to Si-O-Si bond.	Brilliant green dye	3.75 g/l	20–100 mg/l	15–180 min	25 °C	n/a	11.628 mg/g	El-Chaghaby et al. (2018)
Rice husk carbon (RHC)	Specific surface area = 272.5 m^2/g	Acid yellow 36 (C.I. 13,065)	n/a	n/a	180 min	30 °C	3.0	86.9 mg/g	Malik et al. (2007)

area of the *Typha orientalis* (cattail) leaf was 1, 238 m^2/g . The morphology showed that the produced activated carbon had clear burnout pore that had honeycomb-like structure. “The functional groups found in the activated carbon included C–O, C=O, O–H, C=C.” The Langmuir and Freundlich isotherms were used to model the equilibrium data of Pb(II) adsorption on *Typha orientalis* (cattail) leaf. The Langmuir isotherm having a correlation coefficient (R^2) = 0.9999 described the adsorption process better than the Freundlich isotherm. The kinetic data gave a pseudo-second-order rate equation (R^2 = 0.9999) better than the pseudo-first-order model.

Reusability and end of life of sorbent material

Exhausted activated carbon can be recovered by various techniques with the objective to desorb accumulated adsorbates and restore the original porous structure with little or no damage to the carbon (Salil and Ralph 1998). Apart from being restored for reuse the regenerated carbon is also safe for disposal due to stringent environmental regulations. The ease of regeneration depends on if the adsorption is physical or chemical. In physical adsorption, the shift of equilibrium from adsorption to desorption is accomplished by heating, lowering the pressure. In the case of chemical adsorption, a supply of energy greater than the adsorptive force is required to break the strong ionic or covalent bonds. The regeneration of spent activated carbons includes thermal process, wet air oxidation, and chemical and solvent regeneration. Furthermore, the recovery of used activated carbon is dependent on the characteristics of the base material, the activation process, and the type or types of adsorbates (Girgis and El-Hendawy 2002).

Thermal regeneration of granular activated carbon involves three steps: drying (200 °C), pyrolysis of adsorbates (400–600 °C), and reactivation (oxidation of the residue from the adsorbate which is carried out at 870–1000 °C). Thermal desorption has an advantage that it can be used for carbon which contain a heterogeneous mixture of adsorbates. The demerits of thermal regeneration include loss of adsorption capabilities due to changes in the pore structure of the carbon, high energy requirements, air pollution problems associated with off gases, and incompatibility of some adsorbates with high-temperature operations.

Wet air oxidation is an aqueous phase oxidation process that uses molecular oxygen as an oxidant. Mundale et al. (1991) studied the regeneration of activated carbon with phenol. Applying a wet air oxidation process, experiments were conducted at temperatures of 150–185 °C and an oxygen partial pressure of 0.5 MPa. They reported 5–10% losses, respectively, at temperatures of 185 and 150 °C. The loss of adsorption capacity was attributed to surface oxidation and

the formation of carbon–oxygen complexes on the surface of the carbon.

Two types of reagents are used in chemical regeneration: those with oxidizing ability and those with solubilizing property. Subsequent washing with water is required to remove the regenerating agent. Chemical regeneration exhibits a number of advantages over thermal regeneration. The process can be done in situ which eliminates losses due to pumping, transport, and repacking. Also, carbon loss due to burn-off is eliminated, and recovery of adsorbate is achievable by using subsequent treatment methods such as distillation. The disadvantages associated with chemical regeneration include the high cost of reagents, danger of pollution from hazardous chemicals, and incomplete regeneration. The extent of regeneration depends on the solubility of the adsorbate in the regenerant solution. Furthermore, since most industrial wastewater contains a heterogeneous mixture of adsorbates, multiple regenerants are required.

In solvent regeneration process, a solvent is passed through a bed of spent carbon material to extract the adsorbate. Salvador and Sanchez (1996) studied supercritical water regeneration (300 °C and 12.2 MPa) of three types of carbon exhausted with phenols, textile dyes, and pesticides. They reported that phenol desorbs at low temperature (155 °C), dyes (sirus red) at medium temperature (263 °C), and carbofuran, a pesticide, at temperature range of 100–250 °C. Sanchez-Montero et al. (2018) suggested the regeneration of exhausted activated carbon using supercritical carbon dioxide as an alternative to conventional thermal regeneration at critical temperature 400 °C and critical pressure 225 bar.

Salman et al. (2011) studied the desorption of bentazon from spent activated carbon prepared from branches of pomegranate trees using 100 ml of 95 vol% ethanol. The desorption was repeated for four cycles while regeneration efficiency was found to be 92–96% indicating that the exhausted adsorbent can be reused.

El-din et al. (2017) studied the recovery of used banana peel-based adsorbent to separate gas oil, 1-day weathered crude oil, and 7-day weathered crude oil from aqueous solution. Mechanical pressing and chemical reagent (n-hexane) were used to recover the exhausted adsorbent. The investigation revealed that for gas oil, about 90% of the initial sorption capacity remained after 10 cycles of applying mechanical action 20 times.

Yang et al. (2017) studied the desorption of oil from coco peat powder and found out that the percent removal of adsorption for cotton seed oil, paraffin oil, machine oil, and silicone oil were 11.98%, 11.63%, 10.63%, and 15.32%, respectively, after 11 cycles.

According to Vlaev et al. (2011), black rice husk ash saturated with crude oil, diesel fuel, or different hydrocarbons characterized by high calorific value can be burnt in incinerators, industrial ovens, or steam generators, after cycles of

regeneration. Therefore, the rice husk ash is useful. “Grafted bagasse material containing oil can be used as fuel in the production of sugar cane or other industrial heating processes” (Said et al. 2009).

Conclusions

Based on the far-reaching literature studied, the following are the conclusions:

Activated carbon prepared from biomass wastes has been found to be useful in removing pollutants from aqueous media. Data presentations were found to be dissimilar which makes it difficult to compare the results. The work confirmed the regeneration of the novel adsorbents and also their end of life.

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Compliance with ethical standards

Conflict of interest The authors declare that the research was conducted without any conflict of interest.

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