Chapter 5
Thermochemical Conversion of Biomass into Value-Added Materials for Effluent Treatment Applications

Nethaji Sundarabal, Vairavel Parimelazhagan, Suganya Josephine Gali Anthoni, Praveen Kumar Ghodke, and Sivasamy Arumugam

Abstract Lignocellulosic biomass has been explored for the synthesis of various value-added materials due to its wide availability and environment-friendly nature. Apart from being studied as a potential feedstock for the synthesis of fine chemicals and generation of biofuels, these biomasses have also shown a wide range of applications in effluent treatment processes. Many agricultural waste biomasses had shown potential in effluent treatment, even in their raw form. Activated carbon prepared by the pyrolysis of biomass has yielded promising results as adsorbents and catalysts support the removal of both conventional and priority pollutants from effluents. Moreover, composite materials including metal oxide composites, magnetic materials, catalyst supports, polymer composites, and graphene composites prepared by the thermochemical conversion of biomass are being explored in tertiary treatment processes for the removal of targeted pollutants from the aqueous phase. Hence, this chapter is aimed to discuss the application of biomass-based value-added materials for effluent treatment applications.

N. Sundarabal (✉) · V. Parimelazhagan
Department of Chemical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India
e-mail: nethaji.s@manipal.edu

S. J. Gali Anthoni
Department of Chemistry, Aarupadai Veedu Institute of Technology—Vinayaka Mission Research Foundation, Rajiv Gandhi Salai, Paiyanoor, Kanchipuram, Tamil Nadu, India

P. K. Ghodke
Department of Chemical Engineering, National Institute of Technology Calicut, Kozhikode, Kerala, India
e-mail: praveenkg@nitc.ac.in

S. Arumugam
Catalysis Science Laboratory, CSIR-Central Leather Research Institute (CSIR-CLRI), Chennai, Tamil Nadu, India

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Abbreviations

AC	Activated carbon
BiOBr	Bismuth oxybromide
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
EIA	Energy Information Administration
TDS	Total suspended solids

5.1 Introduction

Humanity dates back to not a decade or a century but a millennium. Since existence began, the production of wastes in many forms originated particularly from natural sources. The most popular form of waste would be wood or of plant origin. In general, the term “Biomass is defined as matter originating from living plants, including tree stems, branches, leaves as well as residues from agricultural harvesting and processing of seeds or fruits” (Pang 2016). Biomass is considered to carry energy in the form of chemical bonds among hydrogen, carbon, and oxygen moieties (Pang 2019). The sources of biomass are plant products, the residue of crop farming and processing industries, fruit and vegetable waste, agro-industrial waste, household waste, urban waste, and animal waste (Wormeyer et al. 2011). Figure 5.1 shows the classification of biomass resources. They include materials consisting of cellulose, hemicellulose, and lignin (Mohan et al. 2006). As for the elementary composition, 90% of the typical biomass contains 51% carbon, 42% oxygen, and trace amounts of hydrogen, nitrogen, and chlorine (Mandapati and Ghodke 2021b). The biomass resources were calculated to be 146 billion tonnes/annum. Tropical countries like India contribute to the production of about 500 million metric tonnes/year of biomass. This natural carbonaceous resource is mostly used or exploited as a source of fuel.

5.2 Biomass as a Source of Fuel

The rapid consumption of fossil fuel has led to its depletion (Mandapati and Ghodke 2021a; Agrawal and Verma 2022; Kumar and Verma 2021a). Various renewable resources which include biomass-based reserves, wind, solar, and geothermal resources have been explored as alternative fuels. Among these renewables,

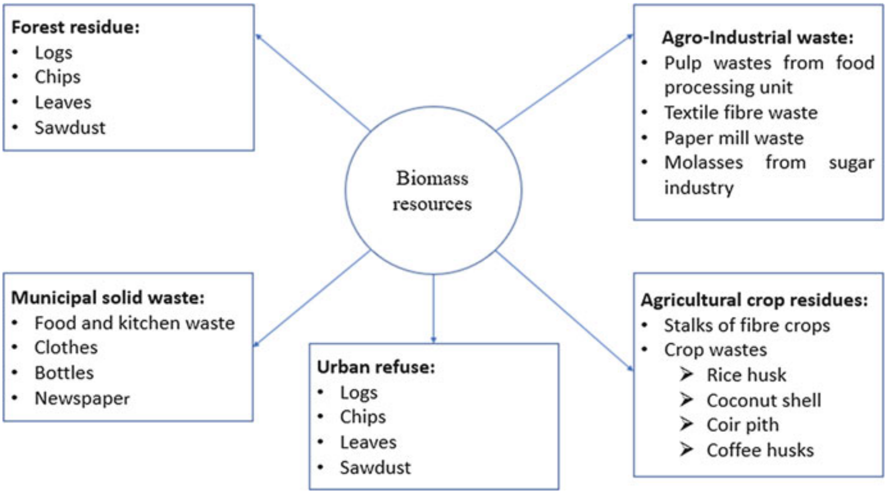

Fig. 5.1 Classification of biomass resources

bioenergy is renewable energy sourced from biomass that is abundant and has a high utilization potential to produce energy (Pang 2019; Kumar et al. 2020; Kumar and Verma 2021b). If 10% of the biomass is exploited for energy production with 50% efficiency, it may have the potential to churn out 3.1 trillion tonnes of oil equivalent energy. This would account for the availability of 200 times the energy consumed worldwide currently (Energy Information Administration, EIA, 2017). On the other hand, the utilization of 10% of biomass for organic chemical synthesis at a 10% conversion rate will lead to the production of 1.6 billion tonnes of chemical feed materials (Pang 2019). Generally, in developing countries, 38% of the energy consumed is primarily from bioenergy produced from biomasses (Sarkar and Praveen 2017).

Biomass is a clean energy source is produced by plants by consuming CO_2 from the atmosphere through photosynthesis (Tekin et al. 2014). Moreover, these biomasses are produced in short duration ranging from months to years when compared to unsustainable fossil fuels which usually require millions of years (Collard et al. 2012). Hence, renewable energy from biomasses proves to be a sustainable source of energy supply that can also address environmental concerns.

5.3 Value-Added Pathway from Biomass for Different Applications

Biomass conversion pathways through various processes are shown in Fig. 5.2. The widely used thermochemical conversion technologies for the conversion of biomasses include but are not limited to gasification, pyrolysis, hydrothermal

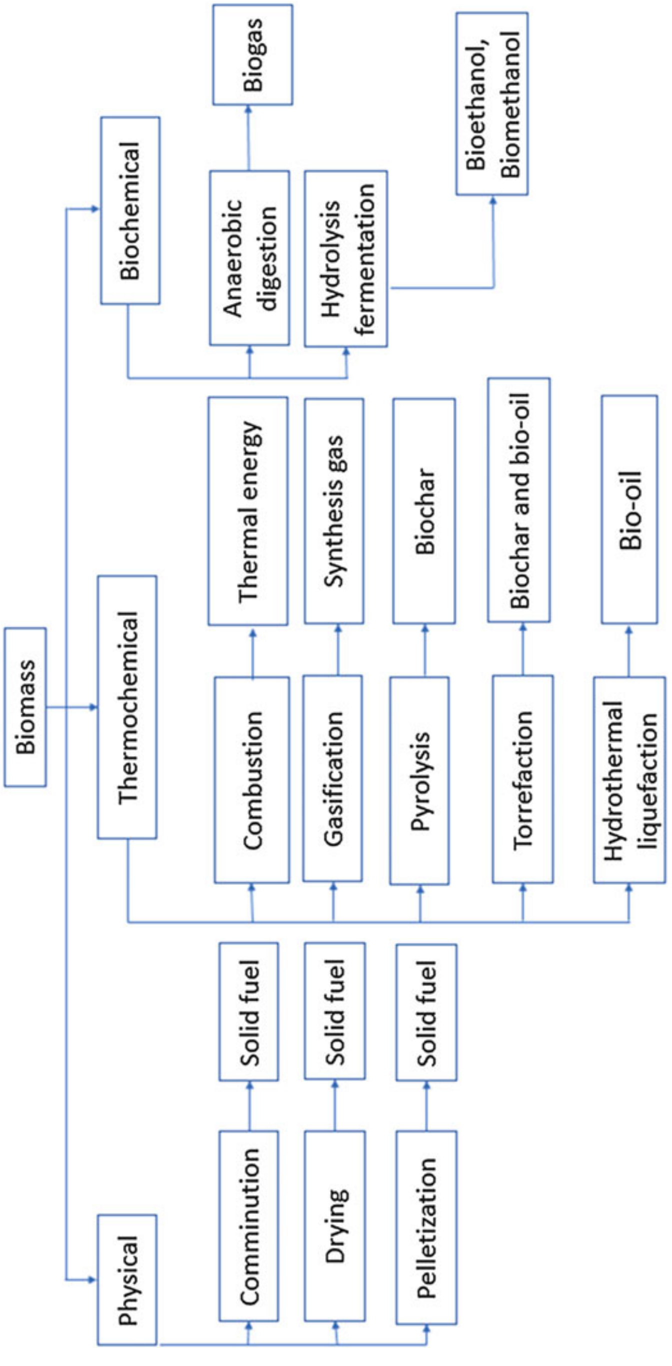

Fig. 5.2 Biomass conversion pathways

liquefaction, and torrefaction (Goswami et al. 2020, 2021a). Torrefaction is a thermal pre-treatment process used in the combustion, pyrolysis, gasification, and liquefaction of biomass (Ghodke and Mandapati 2019). Pyrolysis is heating the biomass at elevated temperatures (573–973 °K) to obtain biochar and bio-oil. The hydrothermal liquefaction process is operated between 523 and 647 °K within the pressure range of 4–22 MPa for the production of bio-oil. Gasification involves the conversion of biomass into syngas at temperatures higher than 973 K.

5.4 An Alternate Strategy for the Utilization of Waste Biomass

Biomass has a great potential to be used as a source of biofuel (Bhardwaj et al. 2021). The total biomass power generation potential of India is estimated to be 17,500 MW. However, at present, only 2665 MW of power is being generated (Kumar et al. 2015). Hence, due to the availability of abundant waste biomass materials, the management or disposal of these substances is itself a major task for environmentalists. In the global arena, "Waste to Wealth" is a term coined to utilize waste material for useful resources. Since the resource is inexpensive, green, and renewable, environmentalists focus on such processes to reduce pollution. There are several studies, where the waste biomass and its derivatives were used as a precursor material for effluent treatment processes. The biomass could be converted into a base material for catalyst preparation in the form of support or as an adsorbent material. They can be utilized for the treatment of effluents by the process of adsorption or by using an advanced oxidation process (AOP). Wherein the preparation of heterogeneous catalyst by supporting the active material on carbon support derived from biomass reduces the cost of the effluent treatment process. Hence, this chapter is aimed to discuss the thermochemical conversion of biomass into value-added materials for effluent treatment applications.

5.5 Biomass for Effluent Treatment Processes

It has been reported that every day two million tons of waste from various sources are discharged into water bodies worldwide. This created an impact that one in eight people worldwide are deprived of safe and clean drinking water as reported in World Water Assessment Programme, World Water Development Report1: "Water for People, Water for Life," Paris (2003). Water pollution is found to be the major reason for diseases and subsequently deaths worldwide (Vairavel and Murty 2020; Goswami et al. 2021b). In India alone, it has been estimated that approximately 580 people die due to water pollution-related illnesses every day (Clark et al. 1996). Major contaminants found in wastewater include but are not limited to dyes and pigments, heavy metals, phenolic compounds, pharmaceuticals, agrochemicals, and endocrine disruptors (Akhil et al. 2021; Kumar et al. 2019; Kumar et al. 2021). Effluent treatment plants comprise physical, chemical, and biological treatment systems. Generally, all these treatment methods are grouped under primary, secondary, tertiary, and advanced treatment processes. Primary treatment processes aim to remove contaminants by the physicochemical processes like primary clarification (gravity settling) and coagulation/flotation. The secondary treatment processes work on the removal of the residual organics. The secondary treatment processes employ various microorganisms for reducing the COD and BOD of the effluent. Activated sludge treatment methods such as aerobic and anaerobic digestion are some of the secondary wastewater treatment methods. Tertiary treatment methods include membrane separation processes, electrodialysis, advanced oxidation processes, adsorption, biosorption, bioaccumulation, and ion exchange (Sonune and Ghate 2004). Most of these treatment processes like adsorption, biosorption, and advanced oxidation processes utilize functional materials for their operation. These functional materials like adsorbents and catalysts in case of adsorption and oxidation processes respectively are of chemical origin, which leads to secondary pollution. However, the waste biomasses and their derivatives proved to be environmentally friendly precursor materials for the synthesis of adsorbents and catalysts support materials. A simple thermochemical modification of the lignocellulosic waste materials could yield highly functional materials for wastewater treatment processes (Liu et al. 2015).

5.6 Application of Raw Biomass in the Effluent Treatment Process

Adsorption is the most widely used effluent treatment technique This is because, the used adsorbent materials have the potential for regeneration, recovery, and recycling which proved to be an added advantage at the industrial scale of operations. It is not only used for the removal of contaminants but also could be used for the recovery of precious and costly entities from the effluents (Crini et al. 2019). The physicochemical properties of the adsorbent have a major influence on the efficacy of the adsorption process. The chosen or prepared adsorbent should be easily available, economical, non-toxic, and should have good surface characteristics. They must also have high mechanical and thermal stability (Reddy et al. 2017). The lignocellulosic waste biomasses, in their raw or modified form, proved to be potential candidates for the preparation of economical and sustainable adsorbents for effluent treatment (Bhatnagar et al. 2015). Plant and agricultural waste products have earned increased interest for dye and heavy metals removal by adsorption from the aqueous solution because of their natural availability and higher removal efficiency (Garg et al. 2019; Agrawal and Verma 2021). The inexpensive waste products, after basic cleaning or some minor treatment, were explored as adsorbents. Agricultural by-products especially those containing cellulose exhibit good adsorption potential for removing various toxic pollutants from effluents. There are numerous studies reporting the application of raw lignocellulosic materials like rice husk, oil cakes, banana peel, sugarcane bagasse, powdered leaves, etc. for the removal of different types of dyes, heavy metals, and other priority pollutants. This method of exploiting raw biomass as functional adsorbent materials proved to solve disposal problems associated with the abundant availability of these waste biomasses (Moorthy Rajendran et al. 2020). Few of the studies which deal with the application of these raw biomass materials for effluent treatment is tabulated in Table 5.1.

5.7 Biomass-Derived Activated Carbon for the Effluent Treatment Process

Many studies reported raw agricultural biomass as an adsorbent for the removal of organics and inorganics from simulated effluents. However, most of these raw biomasses were found to lack desired adsorption efficiency and were mechanically unstable. The efficiency of these biomasses could be enhanced by carbonization and activation using thermal and chemical treatment methods. The physical treatment includes carbonizing the material at a temperature of around 500 °C under an inert atmosphere using nitrogen or argon supply. The carbonized material is then activated at higher temperatures using suitable activating agents like steam or CO_2. The chemical treatment method involves the impregnation of the cellulosic biomass with various strong acids and bases like NaOH, KOH, HCl, H_2SO_4, $ZnCl_2$, etc. The impregnated material is then carbonized at higher temperatures at around 500 °C to obtain activated carbon (AC) (Rodríguez-Reinoso and Molina-Sabio 1992). The schematic for the preparation of AC through physical and chemical methods is presented in Fig. 5.3. AC is proved to have superior adsorptive and mechanical properties when compared to raw biomasses owing to increased surface area and porosity (Zhang et al. 2019). AC derived from different biomass has varying properties. The properties of AC depend on the precursor material, type of carbonization and activation, and activation temperature and duration. AC is the widely studied adsorbent material for treating effluents which contain all types of pollutants including the emerging contaminants from effluents (Yahya et al. 2015). Moreover, AC also finds its application as catalyst support in many reported studies in advanced oxidation processes which are discussed in Sect. 5.8.4. The application of biomass-derived AC is not limited to effluent treatment methods, and thus they are used in various fields such as gas purification (Ma et al. 2008), supercapacitors (Yang et al. 2014), and medicinal applications (Lakshmi et al. 2018). Few of the studies on the application of biomass-derived activated carbon for water and wastewater treatment is summarized in Table 5.2.

Table 5.1 Application of raw biomass for effluent treatment

Raw biomasses	Target pollutants	Maximum monolayer adsorption capacity “q_m” (mg/g)	References
Dyes			
Guava leaves	Remazol brilliant blue-R	93.12	Debamita et al. (2020)
Coffee husks	Congo red	38.65	Vairavel et al. (2021)
Neem leaf powder	Coomassie violet	39.64	Divya et al. (2020)
Sugar cane bagasse	Congo red	38.20	Zhang et al. (2011a, b)
Almond shells	Direct red 80	22.42	Ardejani et al. (2008)
Jujuba seeds	Congo red	55.55	Reddy et al. (2012)
Jackfruit peel	Methylene blue	285.71	Hameed (2009)
Lotus leaf	Congo red	45.89	Meghana et al. (2020)
Heavy metals			
Neem leaf	Cd(II)	157.80	Sharma and Bhattacharyya (2005)
Cucumis melo rind	Fe(II)	4.98	Othman and Asharuddin (2013)
Coffee residues	Cd(II)	39.52	Boonamnuayvitaya et al. (2004)
Coconut husk	Pb(II)	2.75	Abdulrasaq and Basiru (2010)
Durian shell	Cr (VI)	117	Edokpayi et al. (2015)
Sugarcane bagasse	Cd(II)	189	Karnitz et al. (2007)
Cassava tuber bark waste	Zn(II)	83.3	Horsfall et al. (2006)
Wheat bran	Cd(II)	101	Ozer and Pirincci (2006)
Phenol			
Tea waste	Phenol	154.39	Pathak et al. (2020)
Garlic peel	Phenol	14.48	Muthamilselvi et al. (2016)
Rice straw	Phenol	5.78	Sarker and Fakhruddin (2017)
Lantana camara	Phenol	112.5	Girish and Murty (2014)
Vegetal cords	Phenol	6.21	Cherifi et al. (2009)
Endocrine disruptors			
Barley husk	Bisphenol A	19.94	Balarak (2016)
Walnut shell	Bisphenol A	38.5	Dovi et al. (2021)
Raw fibric peat	Bisphenol A	6.48	Zhou et al. (2011)

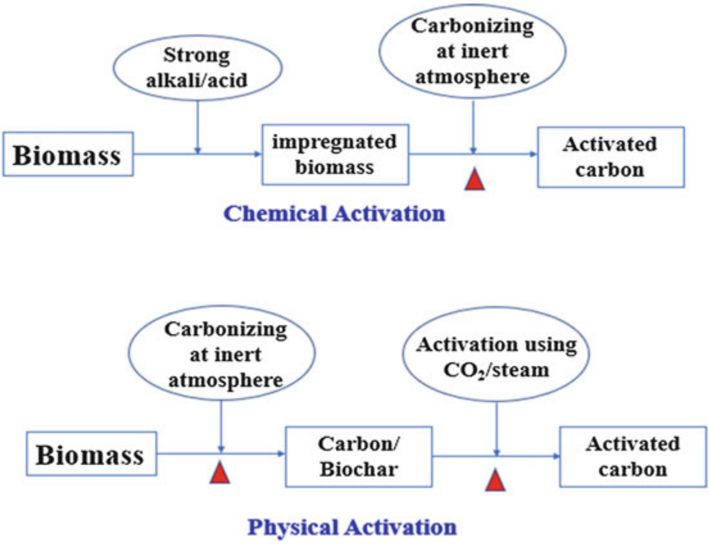

Fig. 5.3 Chemical and physical activation methods for the preparation of biomass-derived activated carbon

5.8 Biomass-Based Composite Materials for Effluent Treatment

Biomass-based materials either in their raw form or with thermal and chemical modification demonstrated to be an efficient low-cost material for the adsorption of various organics and inorganics from simulated effluents. Furthermore, recent studies suggest that these biomasses can also be fused with other functional materials and could be actively applied in various treatment processes. These biomass-based composites include but are not limited to metal oxide composites, magnetic materials, polymeric materials, and graphene-based composites. The schematic representation of the same is presented in Fig. 5.4.

5.8.1 Biomass-Based Magnetic Materials for Effluent Treatment

Generally, nanoparticles have promising potential to be used in various effluent treatment technologies. However, the application of these nanoparticles in water and wastewater purification is limited. This is due to the fact that, the spent nanomaterials after application tends to escape into the aquatic environment causing secondary pollution. The removal and recovery of the spent materials in their nanoform is not economical. Recently, materials coated with magnetite nanoparticles are considered

Table 5.2 Biomass-derived activated carbon for effluent treatment

Biomass-derived activated carbon	Target pollutants	Activation of adsorbents				Maximum monolayer adsorption capacity “q_m” (mg/g)	References
		Physical		Chemical			
		Temperature (K)	Activating agent	Temperature (K)	Chemicals used		
Dyes							
Pomegranate peel	Direct blue 106	–	–	773	$ZnCl_2$, H_3PO_4,	54.05	Amin (Amin 2009)
Orange peel	Direct navy blue 106	–	–	393	H_2SO_4	107.53	Khaled et al. (Khaled et al. 2009)
Pineapple waste	Methylene blue	–	–	773	$ZnCl_2$	288.34	Mahamad et al. (2015)
Rice husk	Acid yellow 36	373	steam	–	–	86.9	Malik (2003)
Sugarcane bagasse pith	Reactive orange	–	–	873	H_3PO_4	3.48	Amin (2008)
Grape processing waste	Methylene blue, Metanil yellow	–	–	873	$ZnCl_2$ $ZnCl_2$	417 386	Saygili et al. (2015)
Apple pulp and peel	Methylene blue	–	–	–	H_3PO_4	278	Hesas et al. (2013)
Palm flower	Amido black 10B	–	–	413	H_2SO_4	4.03	Nethaji and Sivasamy (2011)
Heavy metals							
Dairy waste Sugar beet	Pb(II) Pb(II)	873 873	– –	– –	– –	248 197	Inyang et al. (2012)
Hazelnut shell	Ni(II)	–	–	423	H_2SO_4	11.64	Demirbas et al. (2002)
Canna indica	Cd(II)	–	–	873	HCl	189	Cui et al. (2016)

Corn straw	Cu(II) Zn(II)	– –	– –	873 873	– –	12.5 11.0	Chen et al. (2011)
Pine bark Oak bark	Pb(II) Pb(II)	723 723	– –	– –	– –	3.0 13.1	Mohan et al. (2007)
Peanut shell	Pb(II)	–	–	823	H_3PO_4, HNO_3	35.5	Xu and Liu (2008)
Corn stalk	Cd(II)	–	–	873	$ZnCl_2$	32.4	Youssef et al. (2004)
Phenols							
Bamboo charcoal	Phenol	473	–	–	–	24.96	Ma et al. (2013)
Banyan root	Phenol	–	–	773	KOH	26.95	Nirmala et al. (2019)
Date-pit	Phenol	1173	CO_2	–	–	262.3	El-Naas et al. (2010)
Rattan saw dust	Phenol			973	KOH	149.25	Hameed and Rahman (2008)
Dates' stones	Para-chlorophenol	–	–	773	$ZnCl_2$	102.04	Aldoury and Sabeeh (2014)
Corn husk	Phenol Para-nitrophenol	– –	– –	773 773	$FeCl_3$ $FeCl_3$	8.445 11.668	Mishra et al. (2019)
Pharmaceutical wastes							
Pine sawdust	Sulfamethoxazole	–	–	923	$FeCl_2$, KOH, KNO_3	`19.09	Reguyal and Sarmah (2018)
Tea waste	Sulfamethazine	973	Steam	–	–	10	Rajapaksha et al. (2016)
Giant reed	Amoxicillin	973	Microwave	–	–		Chayid and Ahmecd (2015)

(continued)

Table 5.2 (continued)

Biomass-derived activated carbon	Target pollutants	Activation of adsorbents				Maximum monolayer adsorption capacity “q_m” (mg/g)	References
		Physical		Chemical			
		Temperature (K)	Activating agent	Temperature (K)	Chemicals used		
Cassava waste	Oxytetracycline	–	–	773	KOH	3.33	Luo et al. (2018)
Olive stones	Paracetamol	–	–	773	H_3PO_4	108.3	Garcia-Mateos et al. (2015)
Moringa seed	Diclofenac	–	–	723	H_3PO_4	121.112	Bagheri et al. (2020)
Cauliflower roots	Chlortetracycline	773	–	–	–	81.30	Qin et al. (2017)
Wheat straw	Ketoprofen	–	–	973	HCl	72.46	Wu et al. (2018)
Endocrine disruptors							
Agave Americana leaf fibers in combination with tannin	Tetracycline	1173	–	–	–	87.21	Selmi et al. (2018)
Argun nut shells	Diuron	573	–	–	–	833.33	Zbair et al. (2020)
Argun nut shells	Bisphenol A	573	–	–	–	1162.79	Zbair et al. (2020)
Pistachio nut shells	Caffeine	–	–	493	HNO_3	22.6	Roman et al. (2018)
Montmorillonite/rice husk hydrochar	17α-ethynyl estradiol	–	–	452	Methanol	138	Tian et al. (2018)
Sawdust hydrochar	Tetracycline	–	–	1073	KOH	423.7	Chen et al. (2017)

Potato peel hydrochar	Pramipexole	–	–	473	KOH	66	Kyzas and Deliyanni (2015)
	Dorzolamide	–	–	473	KOH	60	
Rice straw hydrochar	Tetracycline	–	–	573	K_2CO_3	714	Liu et al. (2014)

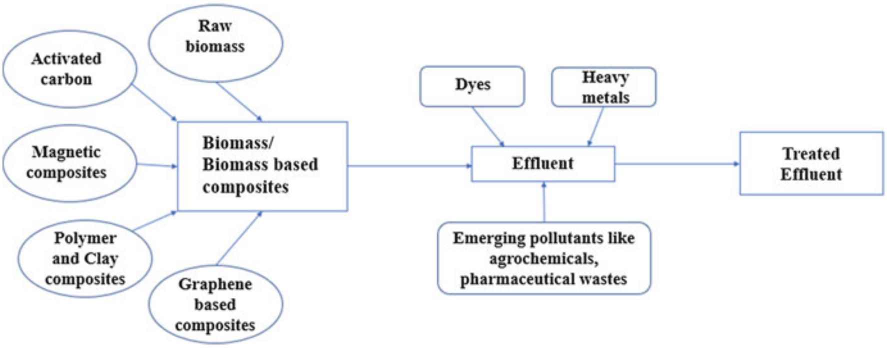

Fig. 5.4 Biomass-based composites for effluent treatment

very promising in the environmental remediation process. Since the magnetic particles are superparamagnetic (they are magnetized only with the external magnetic field), they can be recovered easily by the external magnetic field and reused without any loss of the functional materials (Nethaji et al. 2013). Hence, magnetic materials like iron oxide nanoparticles are extensively studied as functional materials for their application in water treatment owing to their magnetic properties. However, these iron oxide nanoparticles tend to agglomerate in the solution, thereby decreasing their efficiency. Hence, biomass-based materials supported by iron oxide nanocomposites were studied and successfully applied to overcome these drawbacks (Mehta et al. 2015). Biomass-based magnetic composites are mainly used in the adsorption process, and there are few studies which deals on the application of these materials in photocatalytic oxidation (Pang et al. 2016). Though several methods like hydrothermal reactions, sol-gel methods were reported, the co-precipitation method is most commonly employed for the preparation of magnetic composites. In the co-precipitation method, the biomass, or biomass-derived materials like activated carbon (AC) are dispersed along with the iron precursors like ferric chloride or ferrous sulfate. The iron salt in the precursors is then reduced using various reducing agents under continuous stirring, thus depositing the iron oxide nanoparticles onto the matrix of the raw biomass or AC derived from the biomass (Nethaji et al. 2013). The efficiency of these magnetic composites expended for the adsorptive/oxidative treatment of various pollutants from the aqueous phase along with the experimental conditions are shown in Table 5.3. The application of magnetized adsorbents derived from raw biomass and AC is presented in Fig. 5.5. Most of the studies reported an enhanced removal efficiency of the magnetic nanocomposites in comparison with the unmagnetized materials. Few adsorption studies reported a slight decrease in the efficiency, owing to the reduction in the available surface area due to the impregnation of iron oxide particles into the matrix of the biomass. Nevertheless, the ease of separation of the functional material improved considerably, thereby aiding in the regeneration and reusability of the nanocomposite materials.

Table 5.3 Biomass-based magnetic composites for effluent treatment

Biomass-based magnetic adsorbents	Precursor biomass materials	Target pollutants	Surface area (m^2/g)	Maximum monolayer adsorption capacity "q_m" (mg/g)	Inferences	References
Dyes						
Magnetic Corn cob-derived carbon (MCA)	Corn cob	Methylene Blue	153.89 (MCA) 69.45 (unmagnetized carbon)	163.93 (MCA) 103.09 (unmagnetized carbon)	The efficiency of the magnetized and unmagnetized adsorbent derived from corn cob was compared. The magnetized carbon possessed better surface area and adsorption efficiency for the sorption of methylene blue dye.	Ma et al. (Ma et al. 2015)
Magnetic graphene oxide-biomass activated carbon composite	Palm Kernel Shell (PKS)	Acid Blue 113	280.39	32.2	The adsorbent had the saturation magnetization value of 33.74 emu/g as characterized by a Vibrating Sample Magnetometer. A comparison study was also carried out to prove that the magnetized graphene oxide-PKS-derived carbon composites had better removal efficiency than the raw precursor and graphene oxide.	Ying et al. (2020)
Magnetic activated carbon from peanut shell	Peanut shell	Malachite Green	722.34 (CO_2 activation) 448.70 (Without CO_2 activation)	747.03 (CO_2 activation) 270.28 (Without CO_2 activation)	Studies were performed by increasing the iron oxide content in the matrix of the carbon derived from the peanut shell. The surface area, porosity, and adsorption efficiency increased with the increase in the iron oxide impregnation proving that the degree of magnetization is one of the most important parameters.	Guo et al. (2018)

(continued)

Table 5.3 (continued)

Biomass-based magnetic adsorbents	Precursor biomass materials	Target pollutants	Surface area (m^2/g)	Maximum monolayer adsorption capacity "q_m" (mg/g)	Inferences	References
Heavy metals						
Magnetic biochar composites (MB)	Phoenix tree leaves	Chromium (VI)	83.6	55 (Magnetized Biochar) 39.8 (Unmagnetized Biochar) 26.5 (Fe_3O_4 nanoparticles	Magnetized biochar was prepared by hydrothermal method. The O_2 containing groups on the surface of the biochar provided growth sites for Fe_3O_4 nanoparticles.	Liang et al. (Liang et al. 2019)
Magnetic nanoparticle (Fe_3O_4) impregnated onto tea waste	Tea waste	Nickel (II)	22.3 (tea waste) 27.5 (magnetized tea waste)	38.3	This study does not involve the preparation of activated carbon from tea waste. Tea waste is directly incorporated with Fe_3O_4 nanoparticles. The incorporation of iron oxide nanoparticles had a negligible impact on the surface area.	Panneerselvam et al. (2011)
EDTAD-modified magnetic baker's yeast biomass (EMB)	Baker's yeast	Lead (II)/cadmium (II)	–	89.21 (Pb^{2+}) 41 (Cd^{2+})	EMB could be regenerated using both HCl and EDTA with an efficiency of greater than 90% without disturbing the morphological characteristics.	Zhang et al. (2011a, 2011b)
Emerging contaminants						
Fe_3O_4/Douglas fir biochar	Douglas fir	Caffeine (stimulant) Ibuprofen (Inflammatory drug) Acetylsalicylic	468.2 (Douglas fir biochar) 322.0 (Fe_3O_4/Douglas fir biochar)	**Caffeine**: 23.9 (Douglas fir biochar) 73.1 (Fe_3O_4/Douglas fir biochar) **Ibuprofen:** 15.5 (Douglas fir	It was observed that the unmagnetized adsorbent exhibited better surface area when compared to the magnetized Douglas fir biochar. However, the adsorption of all the three pharmaceuticals were better	Liyanage et al. (2020)

		acid (Inflammatory drug)		biochar) 32 (Fe_3O_4/Douglas fir biochar) **Acetylsalicylic acid:** 89 (Douglas fir biochar) 126 (Fe_3O_4/Douglas fir biochar)	using the magnetized adsorbent compared to the unmagnetized char.	

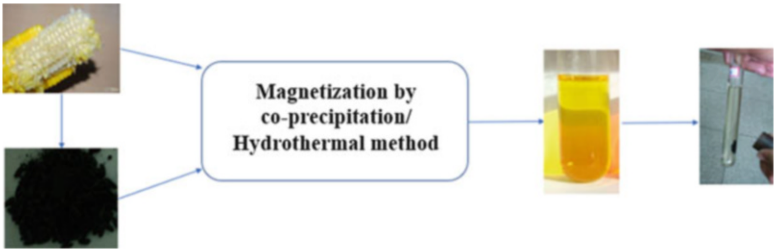

Fig. 5.5 Biomass-derived magnetic composites for effluent treatment

5.8.2 *Biomass-Based Polymer and Clay Composites for Effluent Treatment*

The efficiency of a functional material in the effluent treatment mainly depends upon its available surface area and surface functionality for adsorptive removal, and oxidative potential in case of advanced oxidation processes. Hence, polymeric materials are potential candidates to be used in the adsorption process, owing to their tunable surface properties (Pan et al. 2009). Naturally occurring biopolymers such as starch, cellulose, chitosan, and alginate were widely explored for their adsorption potential due to their high surface area and variable surface functionality. Among all the above-mentioned biopolymers, chitosan is widely explored for the removal of contaminants from simulated wastewater. It is more preferred since it contains -NH_2 and -OH functional groups on its surface which can act as chelating sites for concentrating organic and inorganic moieties (Wang and Zuang 2018). However, most of these naturally occurring biopolymers exhibit weak thermal and mechanical properties. Moreover, these biopolymers exhibit swelling phenomena when exposed to the aqueous environment. Hence, most of the studies deal with crosslinking these biopolymers with mechanically strong materials like biochar, biomass-derived AC, or clay composites. Natural clay materials like bentonite, montmorillonite, kaolinite, zeolite, etc. are mostly aluminosilicates with the presence of sodium, potassium, magnesium, and calcium. The layered morphology of these clay materials with the charged surface is ideal for the adsorption of ionic contaminants from the effluent. However, these clay minerals have poor potential for the removal of non-ionic contaminants. Nevertheless, they possess strong mechanical and thermal stability. Hence, the biopolymers are generally cross-linked with clay minerals to overcome the shortcomings of both clay and biopolymers (Unuabonah and Taubert 2014). Hence, biopolymers supported with biochar, AC, and clay minerals exhibited superior adsorption efficiency with better thermal and mechanical stability as shown in Table 5.4.

Table 5.4 Biomass-based polymer and clay composites for effluent treatment

Biomass-based adsorbent	Biomass precursors	Target pollutants	Surface area (m^2/g)	Maximum monolayer adsorption capacity "q_m" (mg/g)	Inference	References
Biopolymer composites						
Zeolite derived from chitin	Chitin	Crystal violet, methylene blue, basic fuchsin	–	124 (Crystal violet), 87.45 (methylene blue), 789.10 (basic fuchsin)	The zeolite was synthesized using biopolymer chitin as a mesoporosity agent by the hydrothermal method	Briao et al. (Briao et al. 2018)
Bacteria-derived poly(γ-glutamic acid) (γ-PGA)	*B. subtilis var.* (natto)	Auramine O, rhodamine B, safranin O	–	0.05 dm^3/mg (auramine O), 0.02 dm^3/mg (rhodamine B), 0.19 dm^3/mg (safranin O)	The kinetic data were well in agreement with Boyd's ion-exchange model	Inbaraj et al. (2006)
Chitosan/activated carbon/iron bio-nanocomposite	Chitosan from shrimp shell, activated carbon from grape stalks	Cadmium	834 (activated carbon) 11.6 (chitosan) 419.20 (chitosan/activated carbon/iron bio-nanocomposite)	322.58	The study indicated better interactions between oxygen functional groups of AC, iron ions, and amine groups of chitosan	Sharififard et al. (2018)
Zerovalent iron encapsulated chitosan nanospheres (CIN)	Chitosan	Arsenic (V) and (III)	69 (CIN) 26 (zerovalent iron)	–	The study shows that the adsorbent is porous in nature and iron particles exist in zerovalent state and there exists a complexation reaction among iron, chitosan, and arsenic	Gupta et al. (2012)
Biopolymer clay composites						
Cellulose-montmorillonite composite	Cellulose	Chromium (VI)	87.09	22.2	The interaction between cellulose and montmorillonite has proved the potential application	Kumar et al. (2011)

(continued)

Table 5.4 (continued)

Biomass-based adsorbent	Biomass precursors	Target pollutants	Surface area (m^2/g)	Maximum monolayer adsorption capacity "q_m" (mg/g)	Inference	References
					of the material for the effective adsorption of chromium. The XRD peaks signified the ordered distribution of clay layers in the biopolymer composite	
Montmorillonite-alginate beads	Alginate	Paraquat herbicides	46	0.321 mmol/g	TGA was used to determine the thermal stability of the beads. The results proved that the thermal stability of montmorillonite-alginate beads was much better than alginate beads	Etcheverry et al. (2017)
Guar gum /bentonite bio-nanocomposites	Guar gum	Lead (II), crystal violet (CV) dye	5.533	187.08 (Pb^{2+}) 167.92 (CV)	The TGA results proved increased thermal stability of biocomposites in comparison with guar gum. FT-IR suggested the electrostatic interaction or chelation via hydrogen bond formation between Pb^{2+} or CV and active sites of bio-nanocomposites.	Ahmad and Mirza (2018)

5.8.3 Biomass-Based Graphene Composites for Effluent Treatment

Graphene is composed of single layers of carbon atoms densely packed which attracted tremendous attraction in late 2004. It is a “single layer of carbon atom densely packed in a honeycomb crystal lattice” (Li et al. 2019). Because of its good chemical stability and graphitized basal plane structure, graphene-based materials are widely used in different applications including supercapacitors, fuel cells, batteries, and as adsorbents in effluent treatment systems (Novoselov et al. 2012). Graphene or reduced graphene oxide is mostly synthesized by using Hummers or modified Hummers method. Various functional groups present on the edges of the graphitic planes aid in the interaction of the graphene sheets with the charged contaminants present in the wastewater. However, the graphene sheets generally suffer from stacking and agglomeration problems due to π–π interactions and van der Waals forces in the aqueous phase. Hence, to overcome these limitations and to exploit the desirable properties of the graphene-based materials, various biomass-based graphene composite materials were reported for the removal of organic and inorganic compounds from simulated effluents (Nethaji and Sivasamy 2017). Biomass-derived materials like biochar, AC, and other cellulosic waste biomass were used as composite materials by crosslinking with the honeycomb structure of graphene oxides. There are also studies which had reported on the utilization of iron oxide nanomaterials for acquiring the magnetic properties reducing the stacking problem of graphene layers. The application of these biomass-based graphene composite materials for the removal of organic and inorganic moieties is presented in Table 5.5.

5.8.4 Biomass-Based Metal Oxides Composites such as Catalyst and Catalyst Supports

Heterogeneous catalysis involving metal oxides is a good example of an advanced oxidation process. Literature shows a number of methods for the enhancement of catalyst activity alongside cost reduction and efficiency maximization. Though many paths are sorted for catalyst modification, synthesis of a catalyst supported on materials with a higher surface area without diminishing the activity is a greater concern. Hence, the choice of the support material comes into the picture, wherein it must be cheap, green, and environmentally friendly with enhanced activity. Hence, carbon as catalyst support derived from biomass is a better option. Wherein, the disposal problem of the biomass itself is minimized and the resulting carbon could be used efficiently. However, activated carbon in itself has been used as a catalyst. Juhola et al. (2021) had prepared biomass–metakaolin as granular composite materials for application as a catalyst for the treatment of effluents.

Table 5.5 Biomass-based graphene composites for effluent treatment

Biomass-based graphene composites	Biomass precursors	Target pollutants	Surface area (m^2/g)	Maximum monolayer adsorption capacity "q_m" (mg/g)	Inference	References
Graphene oxide-based carbonaceous nanocomposites	Rice husk	Methylene blue	936	1591	Graphene oxide/ordered mesoporous carbon was prepared from rice husk using mesoporous silica as a template source	Liou and Wang (2020)
Graphene oxide/silica nanocomposites	Rice husk	Rhodamine B	625	147.06	Silica was extracted from rice husk. The hybrid material was prepared by hydrothermal method. The study also claims that the composites not only aid in recycling agricultural waste but also help in the recovery of graphene oxide from the aqueous phase	Liou et al. (2021)
Graphene/activated carbon composite	Glucose	Lead (II)	2012	217.6	Mesoporous graphene/activated carbon composite was prepared from graphene oxide and glucose. The prepared composite had a higher adsorption capacity for Pb^{2+} when compared to the reported literature	Saeidi et al. (2015)
Nitrogen-containing carbon nano-onions-like and graphene-like materials	*Lentinus edodes*	Phenol	35.40	–	Nitrogen-containing carbon materials with different morphologies were prepared using $Fe(NO_3)_3$ through a hydrothermal method. The prepared material was used for both adsorption and photocatalytic oxidation of phenol. The photoelectrons transformed by graphite claim to be reacted with O_2 molecules to form the superoxide radicals ($^{\cdot}O_2$) for the degradation of phenol	Han et al. (2021)

Since the development of nano metal oxides as a photocatalyst under visible light irradiation for environmental remediation (Fujishima and Honda 1972). Various research has been focused on the modification of metal oxides for maximum efficiency. The preparation of metal oxide on catalyst support is highly researched. While a choice for support material activated carbon prepared from biomass is widely preferred. Devagi and Soon (2018) have reported a TiO_2/modified sago bark (biomass) for treating the sago wastewater effluent. The author chose the effluent as it had a higher chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TDS), and was acidic. The sago bark was chosen as a precursor as it is a major waste during the debarking step of the starch extraction. The modified biomass TiO_2 mixture was used as a photocatalyst for 64.92% removal with 0.2 g/L TiO_2/1% MSB (120 min of irradiation). Poudel et al. (2020) has removed As(III) from water by using agro-waste-based biomass impregnated with $TiO_{2.}$

ZnO incorporation on biomass-derived activated carbon has been widely researched by various research groups. Cruz et al. (2018) had prepared a ZnO/activated carbon (biomass derives) nanocomposite for the treatment of methylene blue dye. The ZnO nanoparticles were evenly distributed on the surface of the activated carbon. Ramya et al. (2018) has worked on the preparation of activated carbon from tannery sludge biomass. The acquired biomass was used as support material for ZnO-based nanocomposite preparation. The material was used for Cr (VI) removal from the aqueous phase. Supported biomass-based activated carbon for dye degradation has been prepared by hydrothermal technique. Waste biomass was used by Vinayagam et al. (2018) for activated carbon preparation as carbon support. Akpomie et al. (2020) recently prepared a ZnO nanoparticle along with biomass for the treatment of celestine blue dye.

Hybrid bifunctional materials have also been synthesized by various research groups comprising AC and nanomaterials which would serve both as an adsorbent and photocatalytic material. Our group has also worked in this area (Nethaji et al. 2018) and we have reported a bismuth oxybromide (BiOBr)/activated carbon hybrid material as a bifunctional nanomaterial for effluent treatment. It was a good adsorbent material and it even degraded malachite green dye under visible light irradiation. The source of AC was waste polyurethane foam trash from used car seats. The composition of the foam was a polyol with a toluene diisocyanate blend. A simple hydrothermal process was used for the preparation of the bifunctional material.

5.9 Conclusions

Biomass materials are mostly explored for their potential to be used as biofuel. However, the consumption of this biomass for the production of biofuel accounts for less than 10% of the available lignocellulosic materials. Owing to its abundant availability, most of the agricultural waste biomass is considered waste and requires a separate disposal method or a process for the same. But the utilization of these types of wastes and naturally available renewable material as a source for the production of materials for the effluent treatment itself is a boon to the environment. Most of the studies suggest that these biomasses either in their raw form or modified form proved to be an effective replacement for the synthetic materials conventionally used in effluent treatment operations. Moreover, the hybrid materials which include biomass-based composites could effectively overcome the shortcomings of their synthetic counterparts. The biomass-derived activated carbon was effectively used in various adsorptive and catalytic applications as adsorbent and catalyst support, respectively. The compatible and environmentally friendly nature of the biomasses could be explored for applications in various other unit operations in effluent treatment plants. Hence, these materials derived from the biomasses can be coined as “waste to wealth” and thus prove to be environment-friendly substitutes to treat and overcome effluent treatment problems.

Competing Interests All the authors declare that they have no competing interests.

References

Abdulrasaq O, Basiru OG (2010) Removal of copper (II), iron (III) and lead (II) ions from mono-component simulated waste effluent by adsorption on coconut husk. Afr J Environ Sci Technol 4:382–387. https://doi.org/10.5897/AJEST09.224

Agrawal K, Verma P (2021) Removal of refractory pollutants from wastewater treatment plants: phytoremediation for the treatment of various types of pollutants: a multi-dimensional approach. In: Shah MP (ed) Removal of refractory pollutants from wastewater treatment plants. CRC Press, pp 233–248

Agrawal K, Verma P (2022) An overview of various algal biomolecules and its applications. an integration of phycoremediation processes in wastewater treatment. Elsevier, pp 249–270. https://doi.org/10.1016/B978-0-12-823499-0.00006-7

Ahmad R, Mirza A (2018) Synthesis of Guar gum/bentonite a novel bionanocomposite: Isotherms, kinetics and thermodynamic studies for the removal of Pb (II) and crystal violet dye. J Mol Liq 249:805–814. https://doi.org/10.1016/j.molliq.2017.11.082

Akhil D, Lakshmi D, Kumar PS, Vo DN, Kartik A (2021) Occurrence and removal of antibiotics from industrial wastewater. Environ Chem Lett 19:1477–1507. https://doi.org/10.1007/s10311-020-01152-0

Akpomie KG, Conradie J (2020) Synthesis, characterization, and regeneration of an inorganic–organic nanocomposite (ZnO@biomass) and its application in the capture of cationic dye. Sci Rep 10:14441. https://doi.org/10.1038/s41598-020-71261-x

Aldoury MMI, Sabeeh NN (2014) Phenol and parachlorophenol removal using granular activated carbon. Int J Petroleum Technol 1:48–60. https://doi.org/10.15377/2409-787X.2014.01.02.4

Amin NK (2008) Removal of reactive dye from aqueous solutions by adsorption onto activated carbons prepared from sugarcane bagasse pith. Desalination 223:152–161. https://doi.org/10.1016/j.desal.2007.01.203

Amin NK (2009) Removal of direct blue 106 dye from aqueous solution using new activated carbons developed from pomegranate peel: adsorption equilibrium and kinetics. J Hazard Mater 165:52–62. https://doi.org/10.1016/j.jhazmat.2008.09.067

Ardejani FD, Badii K, Limaee NY, Shafaei SZ, Mirhabibi AR (2008) Adsorption of direct red 80 dye from aqueous solution onto almond shells: effect of pH, initial concentration and shell type. J Hazard Mater 151:730–737. https://doi.org/10.1016/j.jhazmat.2007.06.048

Bagheri A, Abu-Danso E, Iqbal J, Bhatnagar A (2020) Modified biochar from Moringa seed powder for the removal of diclofenac from aqueous solution. Environ Sci Pollut Res 27:7318–7327. https://doi.org/10.1007/s11356-019-06844-x

Balarak D (2016) Kinetics, isotherm and thermodynamics studies on bisphenol A adsorption using barley husk. Int J ChemTech Res 9:681–690

Bhardwaj N, Agrawal K, Kumar B, Verma P (2021) Role of enzymes in deconstruction of waste biomass for sustainable generation of value-added products. In: Thatoi H, Mohapatra S, Das SK (eds) Bioprospecting of enzymes in industry, healthcare and sustainable environment. Springer, Singapore, pp 219–250. https://doi.org/10.1007/978-981-33-4195-1_11

Bhatnagar A, Sillanpaa M, Krowiak AW (2015) Agricultural waste peels as versatile biomass for water purification: a review. Chem Eng J 270:244–271. https://doi.org/10.1016/j.cej.2015.01.135

Boonamnuayvitaya V, Chaiya C, Tanthapanichakoon W, Tarudilokkul S (2004) Removal of heavy metals by adsorbent prepared from pyrolyzed coffee residue and clay. Sep Purif Technol 35:11–12. https://doi.org/10.1016/S1383-5866(03)00110-2

Briao GV, Jahn SL, Foletto EL, Dotto GL (2018) Highly efficient and reusable mesoporous zeolite synthetized from a biopolymer for cationic dyes adsorption. Colloids Surf A Physicochem Eng Asp 556:43–50. https://doi.org/10.1016/j.colsurfa.2018.08.019

Chayid MA, Ahmecd MJ (2015) Amoxicillin adsorption on microwave prepared activated carbon from *Arundo donax* Linn: isotherms, kinetics, and thermodynamics studies. J Environ Chem Eng 3:1592–1601. https://doi.org/10.1016/j.jece.2015.05.021

Chen X, Chen G, Chen L, Chen Y, Lehmann J, McBride MB, Hay AG (2011) Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresour Technol 102:8877–8884. https://doi.org/10.1016/j.biortech.2011.06.078

Chen SQ, Chen YL, Jiang H (2017) Slow pyrolysis magnetization of hydrochar for effective and highly stable removal of tetracycline from aqueous solution. Ind Eng Chem Res 56:3059–3066. https://doi.org/10.1021/acs.iecr.6b04683

Cherifi H, Hanini S, Bentahar F (2009) Adsorption of phenol from wastewater using vegetal cords as a new adsorbent. Desalination 244:177–187. https://doi.org/10.1016/j.desal.2008.05.022

Clark R, Lawrence A, Foster SSD (1996) Groundwater a threatened resource. UNEP Environ Library 15:1–36

Collard FX, Blin J, Bensakhria A, Valette J (2012) Influence of impregnated metal on the pyrolysis conversion of biomass constituents. J Anal Appl Pyrolysis 95:213–226. https://doi.org/10.1016/j.jaap.2012.02.009

Crini G, Lichtfouse E, Wilson LD, Morin-Crini N (2019) Conventional and non-conventional adsorbents for wastewater treatment. Environ Chem Lett 17:195–213. https://doi.org/10.1007/s10311-018-0786-8

Cruz GJF, Gómez MM, Solis JL, Rimaycuna J, Solis RL, Cruz JF, Rathnayake B, Keiski RL (2018) Composites of ZnO nanoparticles and biomass based activated carbon: adsorption, photocatalytic and antibacterial capacities. Water Sci Technol 2:492–508. https://doi.org/10.2166/2018/176

Cui X, Fang S, Yao Y, Li T, Ni Q, Yang X, He Z (2016) Potential mechanisms of cadmium removal from aqueous solution by *Canna indica* derived biochar. Sci Total Environ 562:517–525. https://doi.org/10.1016/j.scitotenv.2016.03.248

Debamita C, Rampal N, Gautham JP, Vairavel P (2020) Process optimization, isotherm, kinetics, and thermodynamic studies for removal of Remazol Brilliant Blue-R dye from contaminated water using adsorption on guava leaf powder. Desalin Water Treat 185:318–343. https://doi.org/10.5004/dwt.2020.25395

Devagi K, Soon PW (2018) Photocatalytic efficiency of TiO_2-biomass loaded mixture for wastewater treatment. J Chem 12:1–14. https://doi.org/10.1155/2018/4314969

Demirbas E, Kobya M, Oncel S, Sencan S (2002) Removal of Ni(II) from aqueous solution by adsorption onto hazelnut shell activated carbon: equilibrium studies. Bioresour Technol 84: 291–293. https://doi.org/10.1016/S0960-8524(02)00052-4

Divya JM, Palak K, Vairavel P (2020) Optimization, kinetics, equilibrium isotherms, and thermodynamics studies of Coomassie violet dye adsorption using *Azadirachta indica* (neem) leaf adsorbent. Desalin Water Treat 190:353–382. https://doi.org/10.5004/dwt.2020.25706

Dovi E, Kani AN, Aryee AA, Ma J, Li JJ, Li ZH, Qu LB, Han RP (2021) Decontamination of Bisphenol A and Congo red dye from solution by using CTAB functionalized walnut shell. Environ Sci Pollut Res 28:28732–28749. https://doi.org/10.1007/s11356-021-12550-4

Edokpayi JN, Odiyo JO, Msagati TA, Popoola EO (2015) A novel approach for the removal of lead (II) ion from wastewater using mucilaginous leaves of *Diceriocaryum eriocarpum* plant. Sustainability 7:14026–14041. https://doi.org/10.3390/su71014026

El-Naas MH, Al-Zuhair S, Alhaija MA (2010) Removal of phenol from petroleum refinery wastewater through adsorption on date-pit activated carbon. Chem Eng J 162:997–1005. https://doi.org/10.1016/j.cej.2010.07.007

Etcheverry M, Cappa V, Trelles J, Zanini G (2017) Montmorillonite-alginate beads: natural mineral and biopolymers-based sorbent of paraquat herbicides. J Environ Chem Eng 5:5868–5875. https://doi.org/10.1016/j.jece.2017.11.018

Fujishima A, Honda K (1972) Electrochemical photolysis of water at a semiconductor electrode. Nature 238(5358):37–38. https://doi.org/10.1038/238037a0

Garcia-Mateos FJ, Ruiz-Rosas R, Marques MD, Cotoruelo LM, Rodriguez-Mirasol J, Cordero T (2015) Removal of paracetamol on biomass-derived activated carbon: modeling the fixed bed breakthrough curves using batch adsorption experiments. Chem Eng J 279:18–30. https://doi.org/10.1016/j.cej.2015.04.144

Garg D, Majumder CB, Kumar S, Sarkar B (2019) Removal of direct blue-86 dye from aqueous solution using alginate encapsulated activated carbon (PnsAC-alginate) prepared from waste peanut shell. J Environ Chem Eng 7:103365. https://doi.org/10.1016/j.jece.2019.103365

Ghodke P, Mandapati RN (2019) Investigation of particle level kinetic modeling for babul wood pyrolysis. Fuel 236:1008–1017. https://doi.org/10.1016/j.fuel.2018.09.084

Girish CR, Murty VR (2014) Adsorption of phenol from aqueous solution using *Lantana camara*, forest waste: kinetics, isotherm, and thermodynamic studies. Int Scholar Res Notices 2014:1–16. https://doi.org/10.1155/2014/201626

Goswami RK, Agrawal K, Mehariya S, Molino A, Musmarra D, Verma P (2020) Microalgae-based biorefinery for utilization of carbon dioxide for production of valuable bioproducts. CRC Press, Hoboken, NJ, pp 203–228. https://doi.org/10.1201/9780429317187-11

Goswami RK, Agrawal K, Verma P (2021a) Microalgae-based biofuel-integrated biorefinery approach as sustainable feedstock for resolving energy crisis. Springer, Singapore, pp 267–293. https://doi.org/10.1007/978-981-16-1190-2_9

Goswami RK, Agrawal K, Shah MP, Verma P (2021b, 2021) Bioremediation of heavy metals from wastewater: a current perspective on microalgae-based future. Lett Appl Microbiol:13564. https://doi.org/10.1111/lam.13564

Guo F, Li X, Jiang X, Zhao X, Guo C, Rao Z (2018) Characteristics and toxic dye adsorption of magnetic activated carbon prepared from biomass waste by modified one-step synthesis. Colloids Surf A Physicochem Eng Asp 555:43–54. https://doi.org/10.1016/j.colsurfa.2018.06.061

Gupta A, Yunus M, Sankararamakrishnan N (2012) Zerovalent iron encapsulated chitosan nanospheres—a novel adsorbent for the removal of total inorganic arsenic from aqueous systems. Chemosphere 86:150–155. https://doi.org/10.1016/j.chemosphere.2011.10.003

Hameed BH (2009) Removal of cationic dye from aqueous solution using jackfruit peel as non-conventional low-cost adsorbent. J Hazard Mater 162:344–350. https://doi.org/10.1016/j.jhazmat.2008.05.045

Hameed BH, Rahman AA (2008) Removal of phenol from aqueous solutions by adsorption onto activated carbon prepared from biomass material. J Hazard Mater 160:576–581. https://doi.org/10.1016/j.jhazmat.2008.03.028

Han L, Zhang P, Li L, Lu S, Su B, An X, Lei Z (2021) Nitrogen-containing carbon nano-onions-like and graphene-like materials derived from biomass and the adsorption and visible photocatalytic performance. Appl Surf Sci 543:148752. https://doi.org/10.1016/j.apsusc.2020.148752

Hesas RH, Araminiya A, Daud AW, Sahu JN (2013) Preparation and characterization of activated carbon from apple waste by microwave-assisted phosphoric acid activation: application in methylene blue adsorption. Bioresources 8:2950–2966

Horsfall MJ, Abia AA, Spiff AI (2006) Kinetic studies on the adsorption of Cd^{2+}, Cu^{2+} and Zn^{2+} ions from aqueous solutions by cassava (*Manihot esculenta* Crantz) tuber bark waste. Bioresour Technol 97:283–291. https://doi.org/10.1016/j.biortech.2005.02.016

Inbaraj BS, Chien JT, Ho GH, Yang J, Chen BH (2006) Equilibrium and kinetic studies on sorption of basic dyes by a natural biopolymer poly(γ-glutamic acid). Biochem Eng J 31(3):204–215. https://doi.org/10.1016/j.bej.2006.08.001

Inyang M, Gao B, Yao Y, Xue Y, Zimmerman AR, Pullammanappallil P, Cao X (2012) Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. Bioresour Technol 110:50–56. https://doi.org/10.1016/j.biortech.2012.01.072

Juhola R, Heponiemi A, Tuomikoski S, Hu T, Huuhtanen M, Bergna D, Lassi U (2021) Preparation of granulated biomass carbon catalysts–structure tailoring, characterization, and use in catalytic wet air oxidation of Bisphenol A. Catalysts 11:251–270. https://doi.org/10.3390/catal11020251

Karnitz O, Gurgel LVA, Melo JCPD, Botaro VR, Melo TMS, Gil RPF, Gil LF (2007) Adsorption of heavy metal ion from aqueous single metal solution by chemically modified sugarcane bagasse. Bioresour Technol 98:1291–1297. https://doi.org/10.1016/j.biortech.2006.05.013

Khaled A, Nemr AE, El-Sikaily A, Abdelwahab O (2009) Removal of direct N blue 106 from artificial textile dye effluent using activated carbon from orange peel: adsorption isotherm and kinetic studies. J Hazard Mater 165:100–110. https://doi.org/10.1016/j.jhazmat.2008.09.122

Kumar B, Verma P (2021a) Techno-economic assessment of biomass-based integrated biorefinery for energy and value-added product. Springer, Singapore, pp 581–661. https://doi.org/10.1007/978-981-15-9593-6_23

Kumar B, Verma P (2021b) Life cycle assessment: blazing a trail for bioresources management. Energy Convers Manage X 10:100063. https://doi.org/10.1016/j.ecmx.2020.100063

Kumar ASK, Kalidhasan S, Rajesh V, Rajesh N (2011) Application of cellulose-clay composite biosorbent toward the effective adsorption and removal of chromium from industrial wastewater. Ind Eng Chem Res 51(1):58–69. https://doi.org/10.1021/ie201349h

Kumar A, Kumar N, Baredar P, Shukla A (2015) A review on biomass energy resources, potential, conversion, and policy in India. Renew Sust Energ Rev 45:530–539. https://doi.org/10.1016/j.rser.2015.02.007

Kumar B, Agrawal K, Bhardwaj N, Chaturvedi V, Verma P (2019) Techno-economic assessment of microbe-assisted wastewater treatment strategies for energy and value-added product recovery. In: Arora P (ed) Microbial technology for the welfare of society. Microorganisms for sustainability. Springer, Singapore, pp 147–181. https://doi.org/10.1007/978-981-13-8844-6_7

Kumar B, Bhardwaj N, Agrawal K, Verma P (2020) Bioethanol production: generation-based comparative status measurements. In: Biofuel Production technologies: critical Analysis for Sustainability. Springer, Singapore, pp 155–201. https://doi.org/10.1007/978-981-13-8637-4_7

Kumar B, Agrawal K, Verma P (2021) Microbial electrochemical system: a sustainable approach for mitigation of toxic dyes and heavy metals from wastewater. J Hazard Toxic, Radioactive Waste 25:04020082

Kyzas GZ, Deliyanni EA (2015) Modified activated carbons from potato peels as green environmental-friendly adsorbents for the treatment of pharmaceutical effluents. Chem Eng Res Des 97:135–144. https://doi.org/10.1016/j.cherd.2014.08.020

Lakshmi SD, Avti PK, Hegde G (2018) Activated carbon nanoparticles from biowaste as new generation antimicrobial agents: a review. Nano-Struct Nano-Objects 16:306–321. https://doi.org/10.1016/j.nanoso.2018.08.001

Li Z, Wang L, Li Y, Feng Y, Feng W (2019) Carbon-based functional nanomaterials: preparation, properties and applications. Compos Sci Technol 179:10–40. https://doi.org/10.1016/j.compscitech.2019.04.028

Liang S, Shi S, Zhang H, Qui J, Yu W, Li M, Gan Q, Yu W, Xiao K, Liu B, Hu J, Hou H, Yang J (2019) One-pot solvothermal synthesis of magnetic biochar from waste biomass: formation mechanism and efficient adsorption of Cr(VI) in an aqueous solution. Sci Total Environ 695: 133886. https://doi.org/10.1016/j.scitotenv.2019.133886

Liou T, Wang P (2020) Utilization of rice husk wastes in synthesis of graphene oxide-based carbonaceous nanocomposites. Waste Manag 108:51–61. https://doi.org/10.1016/j.wasman.2020.04.029

Liou T, Tseng YK, Liu S, Lin Y, Wang S, Liu R (2021) Green synthesis of mesoporous graphene oxide/silica nanocomposites from rich husk ash: characterization and adsorption performance. Environ Technol Innov 22:101424. https://doi.org/10.1016/j.eti.2021.101424

Liu Y, Zhu X, Qian F, Zhang S, Chen J (2014) Magnetic activated carbon prepared from rice straw derived hydrochar for Triclosan removal. RSC Adv 4:63620–63626. https://doi.org/10.1039/c4ra11815d

Liu W, Jiang H, Yu H (2015) Development of biochar-based functional materials: toward a sustainable platform carbon material. Chem Rev 115:12251–12285. https://doi.org/10.1021/acs.chemrev.5b00195

Liyanage AS, Canaday S, Pittman CU Jr, Mlsna T (2020) Rapid remediation of pharmaceuticals from wastewater using magnetic Fe_3O_4/Douglas fir biochar adsorbents. Chemosphere 258: 127336. https://doi.org/10.1016/j.chemosphere.2020.127336

Luo J, Li X, Ge C, Muller K, Yu H, Huang P, Li J, Tsang DCW, Bolan NS, Rinklebe J, Wang H (2018) Sorption of norfloxacin, sulfamerazine and oxytetracycline by KOH-modified biochar under single and ternary systems. Bioresour Technol 263:385–392. https://doi.org/10.1016/j.biortech.2018.05.022

Ma L, Ning P, Zhang Y, Wang X (2008) Experimental and modeling of fixed-bed reactor for yellow phosphorous tail gas purification over impregnated activated carbon. Chem Eng J 137(3): 471–479. https://doi.org/10.1016/j.cej.2007.04.032

Ma Y, Gao N, Chu W, Li C (2013) Removal of phenol by powdered activated carbon adsorption. Front Environ Sci Eng 7:158–165. https://doi.org/10.1007/s11783-012-0479-7

Ma H, Li J, Liu W, Miao M, Cheng B, Zhu S (2015) Novel synthesis of a versatile magnetic adsorbent derived from corncob for dye removal. Bioresour Technol 190:13–20. https://doi.org/10.1016/j.biortech.2015.04.048

Mahamad MN, Zaini MAA, Zakaria ZA (2015) Preparation and characterization of activated carbon from pineapple waste biomass for dye removal. Int Biodeterior Biodegrad 102:274–280. https://doi.org/10.1016/j.ibiod.2015.03.009

Malik PK (2003) Use of activated carbons prepared from sawdust and rice-husk for adsorption of acid dyes: a case study of acid yellow 36. Dyes Pigments 56:239–249. https://doi.org/10.1016/S0143-7208(02)00159-6

Mandapati RN, Ghodke PK (2021a) Kinetic modeling of Indian lignites pyrolysis in the context of underground coal gasification (UCG). Fuel 283:118939. https://doi.org/10.1016/j.fuel.2020.118939

Mandapati RN, Ghodke PK (2021b) Kinetics of pyrolysis of cotton stalk using model-fitting and model-free methods. Fuel 303:121285. https://doi.org/10.1016/j.fuel.2021.121285

Meghana C, Juhi B, Rampal N, Vairavel P (2020) Isotherm, kinetics, process optimization and thermodynamics studies for removal of Congo red dye from aqueous solutions using *Nelumbo nucifera* (lotus) leaf adsorbent. Desalin Water Treat 207:373–397. https://doi.org/10.5004/dwt.2020.26389

Mehta D, Mazumdar M, Singh SK (2015) Magnetic adsorbents for the treatment of water/wastewater—a review. J Water Process Eng 7:244–265. https://doi.org/10.1016/j.jwpe.2015.07.001

Mishra S, Yadav SS, Rawat S, Singh J, Koduru JR (2019) Corn husk derived magnetized activated carbon for the removal of phenol and para-nitrophenol from aqueous solution: interaction mechanism, insights on adsorbent characteristics, and isothermal, kinetic and thermodynamic properties. J Environ Manag 246:362–373. https://doi.org/10.1016/j.jenvman.2019.06.013

Mohan D, Pittman CU, Steele PH (2006) Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 20:848–889. https://doi.org/10.1021/ef0502397

Mohan D, Pittman CU, Bricka M, Smith F, Yancey B, Mohammad J, Steele PH, Alexandre-Franco MF, Gomez-Serrano V, Gong H (2007) Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production. J Colloid Interface Sci 310:57–73. https://doi.org/10.1016/j.jcis.2007.01.020

Moorthy Rajendran K, Chintala V, Sharma A, Pal S, Pandey JK, Ghodke P (2020) Review of catalyst materials in achieving the liquid hydrocarbon fuels from municipal mixed plastic waste (MMPW). Mater Today Commun 24:100982. https://doi.org/10.1016/j.mtcomm.2020.100982

Muthamilselvi P, Karthikeyan R, Kumar BSM (2016) Adsorption of phenol onto garlic peel: optimization, kinetics, isotherm, and thermodynamic studies. Desalin Water Treat 57:2089–2103. https://doi.org/10.1080/19443994.2014.979237

Nethaji S, Sivasamy A (2011) Adsorptive removal of an acid dye by lignocellulosic waste biomass activated carbon: equilibrium and kinetic studies. Chemosphere 82:1367–1372. https://doi.org/10.1016/j.chemosphere.2010.11.080

Nethaji S, Sivasamy A (2017) Graphene oxide coated with porous iron oxide ribbons for 2,4-Dichlorophenoxyacetic acid (2,4-D) removal. Ecotoxicol Environ Saf 138:292–297. https://doi.org/10.1016/j.ecoenv.2017.01.001

Nethaji S, Sivasamy A, Mandal AB (2013) Preparation and characterization of corn cob activated carbon coated with nano-sized magnetite particles for the removal of Cr(VI). Bioresour Technol 134:94–100. https://doi.org/10.1016/j.biortech.2013.02.012

Nethaji S, Tamilarasan G, Neehar P (2018) Visible light photocatalytic activities of BiOBr-activated carbon (derived from waste polyurethane) composites by hydrothermal process. J Environ Chem Eng 6:3735–3744. https://doi.org/10.1016/j.jece.2017.02.037

Nirmala G, Murugesan T, Rambabu K, Sathiyanarayanan K, Show PL (2019) Adsorptive removal of phenol using banyan root activated carbon. Chem Eng Commun 208:831–842. https://doi.org/10.1080/00986445.2019.1674839

Novoselov KS, Falko VI, Colombo L, Gellert PR, Schwab MG, Kim K (2012) A roadmap for graphene. Nature 490:192–200. https://doi.org/10.1038/nature11458

Othman N, Asharuddin SM (2013) Cucumis melo rind as biosorbent to remove Fe(II) and Mn (II) from synthetic groundwater solution. Adv Mater Res 795:266–271. https://doi.org/10.4028/www.scientific.net/AMR.795.266

Ozer A, Pirincci HB (2006) The adsorption of Cd(II) ions on sulfuric acid-treated wheat bran. J Hazard Mater B 137:849–855. https://doi.org/10.1016/j.jhazmat.2006.03.009

Pan B, Zhang W, Lv L, Zhang Q, Zheng S (2009) Development of polymeric and polymer-based hybrid adsorbents for pollutants removal from waters. Chem Eng J 151(1–3):19–29. https://doi.org/10.1016/j.cej.2009.02.036

Pang S (2016) Fuel flexible gas production: Biomass, coal and bio-solid wastes. In: Fuel Flexible Energy Generation. Woodhead Publishing, pp 241–269. https://doi.org/10.1016/B978-1-78242-378-2.00009-2

Pang S (2019) Advances in thermochemical conversion of woody biomass to energy, fuels and chemicals. Biotechnol Adv 37:589–597. https://doi.org/10.1016/j.biotechadv.2018.11.004

Pang YL, Lim S, Ong HC, Ching WT (2016) Research progress on iron oxide-based magnetic materials: synthesis techniques and photocatalytic application. Ceram Int 42(1A):9–34. https://doi.org/10.1016/j.ceramint.2015.08.144

Panneerselvam P, Morad N, Tan KA (2011) Magnetic nanoparticle (Fe_3O_4) impregnated onto tea waste for the removal of nickel(II) from aqueous solution. J Hazard Mater 186(1):160–168. https://doi.org/10.1016/j.jhazmat.2010.10.102

Pathak U, Jhunjhunwala A, Roy A, Das P, Kumar T, Mandal T (2020) Efficacy of spent tea waste as chemically impregnated adsorbent involving ortho-phosphoric and sulphuric acid for abatement of aqueous phenol-isotherm, kinetics and artificial neural network modelling. Environ Sci Pollut Res 27:20629–20647. https://doi.org/10.1007/s11356-019-06014-z

Poudel BR, Aryal RL, Bhattarai S, Koirala AR, Gautam SK, Ghimire KN, Pant B, Park M, Paudyal H, Pokhrel MR (2020) Agro-waste derived biomass impregnated with TiO_2 as a potential adsorbent for removal of As (III). Catalysts 10:1125–1142. https://doi.org/10.3390/catal10101125

Qin TT, Wang ZW, Xie XY, Xie CR, Zhu JM, Li Y (2017) A novel biochar derived from cauliflower (*Brassica oleracea* L.) roots could remove norfloxacin and chlortetracycline efficiently. Water Sci Technol 76:3307–3318. https://doi.org/10.2166/wst.2017.494

Rajapaksha AU, Vithanage M, Lee SS, Seo DC, Tsang DCW, Ok YS (2016) Steam activation of biochars facilitates kinetics and pH-resilience of sulfamethazine sorption. J Soils Sediments 16: 889–895. https://doi.org/10.1007/s11368-015-1325-x

Ramya V, Murugan D, Lajapathirai C, Sivasamy A (2018) Activated carbon (prepared from secondary sludge biomass) supported semiconductor zinc oxide nanocomposite photocatalyst for reduction of Cr (VI) under visible light irradiation. J Environ Chem Eng 6:7327–7337. https://doi.org/10.1016/j.jece.2018.08.055

Reddy MCS, Sivaramakrishna L, Reddy AV (2012) The use of an agricultural waste material, jujuba seeds for the removal of anionic dye (congo red) from aqueous medium. J Hazard Mater 203–204:118–127. https://doi.org/10.1016/j.jhazmat.2011.11.083

Reddy DHK, Vijayaraghavan K, Kim JA, Yun Y (2017) Valorisation of post-sorption materials: opportunities, strategies, and challenges. Adv Colloid Interf Sci 242:35–58. https://doi.org/10.1016/j.cis.2016.12.002

Reguyal F, Sarmah AK (2018) Adsorption of sulfamethoxazole by magnetic biochar: Effects of pH, ionic strength, natural organic matter and 17 alpha-ethinylestradiol. Sci Total Environ 628–629: 722–730. https://doi.org/10.1016/j.scitotenv.2018.01.323

Rodríguez-Reinoso F, Molina-Sabio M (1992) Activated carbons from lignocellulosic materials by chemical and/or physical activation: an overview. Carbon 30(7):1111–1118. https://doi.org/10.1016/0008-6223(92)90143-K

Roman S, Ledesma B, Alvarez A, Herdes C (2018) Towards sustainable micro-pollutants removal from wastewaters: caffeine solubility, self-diffusion and adsorption studies from aqueous solutions into hydrochars. Mol Phys 116:2129–2141. https://doi.org/10.1080/00268976.2018.1487597

Saeidi N, Parvini M, Niavarani Z (2015) High surface area and mesoporous graphene/activated carbon composite for adsorption of Pb(II) from wastewater. J Environ Chem Eng 3(4): 2697–2706. https://doi.org/10.1016/j.jece.2015.09.023

Sarkar A, Praveen G (2017) Utilization of waste biomass into useful forms of energy. In: Biofuels and bioenergy (BICE2016). Springer, Cham. https://doi.org/10.1007/978-3-319-47257-7_12

Sarker N, Fakhruddin ANM (2017) Removal of phenol from aqueous solution using rice straw as adsorbent. Appl Water Sci 7:1459–1465. https://doi.org/10.1007/s13201-015-0324-9

Saygili H, Guzel F, Onal Y (2015) Conversion of grape industrial processing waste to activated carbon sorbent and its performance in cationic and anionic dyes adsorption. J Clean Prod 93:84–93. https://doi.org/10.1016/j.jclepro.2015.01.009

Selmi T, Sanchez-Snachez A, Gaddoneix P, Jagiello J (2018) Tetracycline removal with activated carbons produced from hydrothermal carbonisation of *Agave americana* fibers and mimosa tannin. Ind Crop Prod 115:146–157. https://doi.org/10.1016/j.indcrop.2018.02.005

Sharififard H, Shahraki ZH, Rezvanpanah E, Rad SH (2018) A novel natural chitosan/activated carbon/iron bio-nanocomposite: Sonochemical synthesis, characterization, and application for cadmium removal in batch and continuous adsorption process. Bioresour Technol 270:562–569. https://doi.org/10.1016/j.biortech.2018.09.094

Sharma A, Bhattacharyya KG (2005) *Azadirachta indica* (Neem) leaf powder as a biosorbent for removal of Cd(II) from aqueous medium. J Hazard Mater B125:102–112. https://doi.org/10.1016/j.jhazmat.2005.05.012

Sonune A, Ghate R (2004) Developments in wastewater treatment methods. Desalination 167:55–63. https://doi.org/10.1016/j.desal.2004.06.113

Tekin K, Karagoz S, Bektas S (2014) A review of hydrothermal biomass processing. Renew Sust Energ Rev 40:673–687. https://doi.org/10.1016/j.rser.2014.07.216

Tian S, Liu Y, Liu S, Zeng G, Jiang L, Tan X, Huang X, Yin Z, Liu N, Li J (2018) Hydrothermal synthesis of montmorillonite/hydrochar nanocomposites and application for 17β-estradiol and 17α-ethynylestradiol removal. RSC Adv 8:4273–4283. https://doi.org/10.1039/C7RA12038A

Unuabonah EI, Taubert A (2014) Clay–polymer nanocomposites (CPNs): adsorbents of the future for water treatment. Appl Clay Sci 99:83–92. https://doi.org/10.1016/j.clay.2014.06.016

Vairavel P, Murty VR (2020) Decolorization of Congo red dye in a continuously operated rotating biological contactor reactor. Desalin Water Treat 196:299–314. https://doi.org/10.5004/dwt.2020.25931

Vairavel P, Rampal N, Jeppu G (2021) Adsorption of toxic Congo red dye from aqueous solution using untreated coffee husks: kinetics, equilibrium, thermodynamics and desorption study. Int J Environ Anal Chem. https://doi.org/10.1080/03067319.2021.1897982. (Article as in press)

Vinayagam M, Ramachandran S, Ramya V, Sivasamy A (2018) Photocatalytic degradation of orange G dye using ZnO/biomass activated carbon nanocomposite. J Environ Chem Eng 6(3):3726–3734. https://doi.org/10.1016/j.jece.2017.06.005

Wang J, Zuang S (2018) Removal of various pollutants from water and wastewater by modified chitosan adsorbents. Crit Rev Environ Sci Technol 47:2331–2386. https://doi.org/10.1080/10643389.2017.1421845

Wormeyer K, Ingram T, Saake B, Brunner G, Smirnova I (2011) Comparison of different pre-treatment methods for lignocellulosic materials. Part II: Influence of pre-treatment on the properties of rye straw lignin. Bioresour Technol 102:4157–4164. https://doi.org/10.1016/j.biortech.2010.11.063

Wu L, Yang NW, Li BH, Bi EP (2018) Roles of hydrophobic and hydrophilic fractions of dissolved organic matter in sorption of ketoprofen to biochars. Environ Sci Pollut Res 25:31486–31496. https://doi.org/10.1007/s11356-018-3071-2

Xu T, Liu XQ (2008) Peanut shell activated carbon: characterization, surface modification and adsorption of Pb^{2+} from aqueous solution. Chin J Chem Eng 16:401–406. https://doi.org/10.1016/S1004-9541(08)60096-8

Yahya M, Al-Qodah Z, Ngah CWZ (2015) Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: a review. Renew Sust Energ Rev 46:218–235. https://doi.org/10.1016/j.rser.2015.02.051

Yang C, Jang YS, Jeong HK (2014) Bamboo-based activated carbon for supercapacitor applications. Curr Appl Phys 14:1616–1620. https://doi.org/10.1016/j.cap.2014.09.021

Ying TY, Raman AAA, Bello MM, Buthiyappan A (2020) Magnetic graphene oxide-biomass activated carbon composite for dye removal. Korean J Chem Eng 37:2179–2191. https://doi.org/10.1007/s11814-020-0628-9

Youssef AM, El-Nabarawy T, Samra SE (2004) Sorption properties of chemically-activated carbons: 1. Soprtion of Cadmium (II) ions. Colloids Surf A Physicochem Eng Asp 235:153–163. https://doi.org/10.1016/j.colsurfa.2003.12.017

Zbair M, Bottlinger M, Ainassaari K, Ojala S, Stein O, Keiski RL, Bensitel M, Brahmi R (2020) Hydrothermal carbonization of Argan nut shell: Functional mesoporous carbon with excellent performance in the adsorption of Bisphenol A and Diuron. Waste Biomass Valorization 11:1565–1584. https://doi.org/10.1007/s12649-018-00554-0

Zhang ZYL, Moghaddam ZY, O'Hara IM, Doherty WOS (2011a) Congo red adsorption by ball-milled sugarcane bagasse. Chem Eng J 178:122–128. https://doi.org/10.1016/j.cej.2011.10.024

Zhang Y, Zhu J, Zhang L, Zhang Z, Xu M, Zhao M (2011b) Synthesis of EDTAD-modified magnetic baker's yeast biomass for Pb^{2+} and Cd^{2+} adsorption. Desalination 278(1–3):42–49. https://doi.org/10.1016/j.desal.2011.05.003

Zhang W, Cheng H, Niu Q, Fu M, Huang H, Ye D (2019) Microbial targeted degradation pretreatment: a novel approach to preparation of activated carbon with specific hierarchical porous structures, high surface areas, and satisfactory toluene adsorption performance. Environ Sci Technol 53(13):7632–7640. https://doi.org/10.1021/acs.est.9b01159

Zhou Y, Chen L, Lu P, Tang X, Lu J (2011) Removal of bisphenol A from aqueous solution using modified fibric peat as a novel biosorbent. Sep Purif Technol 81:184–190. https://doi.org/10.1016/j.seppur.2011.07.026