Activated Carbon as An Adsorbent: A Review

Mamatha M

Assistant Professor, Department of Physics, Government First Grade College, Sira, Tumkur district, Karnataka, India.

Abstract

Activated carbon is highly porous with a large surface area for activity, thus making it highly adsorption efficient, and is usually derived from waste products. The proximate and ultimate analysis of agricultural waste material and chemical compositions such as hemicelluloses, cellulose, and lignin contents were also discussed. The authors reviewed chemical activators such as alkali hydroxides, KOH, phosphoric acid, zinc chloride, potassium carbonate, and NaOH used to produce activated carbon. A detailed explanation of the characterization techniques (SEM, FTIR, EDAX, BET, XRD etc.) for precursors and activated carbons are discussed. The effect of various parameters on adsorption efficiency of activated carbon is discussed. Wastewater containing different toxic dye contaminants causes serious environmental problems. Removal of various pollutants (SO_2, NO_2, H_2S, CO_2 etc.) using activated carbon were reviewed. In addition, the equilibrium adsorption data were fitted to Isotherm models for the determination of constants correlated to the adsorption phenomena was reviewed.

Keywords: Agricultural wastes, Activated carbon, Chemical activation, Adsorption

Introduction

Activated carbon (AC) is a dark solid, highly porous with a large surface area for activity, thus making it highly adsorption efficient, and is usually derived from waste products. Preparing AC from useless and throw-away materials such as agricultural byproducts became a challenge. The characterization of AC reveals the topography and surface area of the AC. The efficiency of AC depends on its adsorption capacity. The preparation of AC from agro-waste materials has led to pollution control and has a wide application. AC was characterized for surface properties and adsorption efficiency was studied using dyes and heavy metals. The synthesis of AC from waste materials has wide applications and its characterization using techniques such as SEM, EDAX, XRD, and BET analysis were studied. The adsorption efficiency of AC was studied using dyes, heavy metals, etc. Preparation of AC from waste materials which has no commercial values decreases environmental pollution. AC is subjected to remove toxic dyes, heavy metals, organic pollutants, etc. by adsorption technique.

Preparation of activated carbon from agricultural wastes

Mohd Adib Yahya et al. reviewed the synthesis of AC from agricultural waste material. The proximate and ultimate analysis of agricultural waste material and chemical compositions such as cellulose, hemicelluloses, and lignin contents were also discussed. The effects of carbonization and activation temperature, activation time, types of activating agents, and impregnation ratio were discussed. The effects on the textural properties, such as surface area and pore volume, were reviewed. The authors reviewed the use of AC derived from agricultural residues in many fields. They studied the reaction kinetic modeling of the pyrolysis and activation of agricultural wastes [1]. Mohd Adib Yahya et al. discussed the preparation of AC from agricultural waste products by physical and chemical activation. The effects of activating agents, temperature, and impregnation ratio were also discussed. The applications of AC from agricultural waste products were reviewed. Therefore, inexpensive and renewable resources of agricultural waste were found to be effectively converted into useful materials [2].

Kulumkan Sartova et al. prepared AC from cotton (Gossypium Malvaceae) processing waste materials. Carbonization was carried out at 500–800 °C, with subsequent activation at 800 °C by a water stream. Characterization was studied using an Electronic Microscope and FT-IR. AC showed high adsorptive abilities for iodine, chlorine, and sulfur dioxide. The results suggested that the high-quality AC from cotton biomass waste materials can be used as an adsorbent to remove pollutants [3].

Mansooreh Soleimani et al. synthesized AC from agricultural wastes (such as bagasse, apricot stones, almond shells, walnut shells and hazelnut shells) using chemical activation with phosphoric acid. The results reveal that AC from the hard shells of apricot stones showed best adsorption properties, highest surface area and could be used to remove metal ions from wastewater [4].

Junichi Hayashi et al. prepared AC from lignin by chemical activation with $ZnCl_2$, H_3PO_4, and some alkali metal compounds. The effect of carbonization and activating reagents on the pore structure of the AC was studied, and the maximum surface areas were obtained at the carbonization temperature of 600 ^{0}C with $ZnCl_2$ and H_3PO_4 activation. In alkali metal activation, the maximum surface areas were obtained at the carbonization temperature of 800 ^{0}C [5].

Activation of raw materials by physical activation or chemical activation

Heidarinejad et al. reviewed that AC refers to a wide range of carbonized materials with a high degree of porosity and a large surface area. The authors reviewed chemical activators such as alkali hydroxides, KOH, phosphoric acid, zinc chloride, potassium carbonate, and NaOH used to produce AC. Activation with phosphoric acid is commonly used for lignocellulose material at lower temperatures, whereas Zinc chloride generates more surface area than phosphoric acid but is used less due to its toxicity. The comparison of the physical activation and the impregnation method activation with alkali metals indicates that the AC obtained through physical mixing had a higher porosity than that produced by the impregnation method [6]. Samah Zaki Naji et al. review the preparation and modification of AC, which involves precursor treatments, carbonization, and physical and/or chemical activation. The temperature, activation time, and impregnation ratio of the activating agent to the precursor were found to have a significant influence on the surface morphology of the AC during the activation process. The effect of AC yield, BET surface area, and pore volume during synthesis from various raw materials are reviewed. This could serve as a guideline for designing a high-performance AC-based catalyst for biofuel production [7].

M. Olivares-Marín et al. prepared AC from cherry stones by chemical activation using $ZnCl_2$. The influence of carbonization temperature and impregnation ratio on the textural and chemical-surface properties of the products obtained was studied and characterized texturally by the adsorption of N_2 at −196 °C. The presence of functional groups on the surface of AC was studied by FT-IR spectroscopy. With a 4:1 impregnation ratio, the specific surface area of the resultant AC is as high as 1971 m^2g^{-1}. The effect of the increase in the impregnation ratio on the porous structure of AC is effective than that of the increase in the carbonization temperature, whereas the reverse applies to the effect on the surface functional groups and structures [8].

Chiung-Fen Chang et al. prepared AC from corn cob using physical activation by gasifying agents such as CO_2 and steam. With 50 wt% burn-off, the results reveal that the BET surface area, pore volume, and average pore diameter of the resulting AC generally increase with the extent of burn-off in both gasifying agents and at both temperatures (1073 and 1173 K). The BET surface areas of the AC after steam activations at 1173 K are 1705 and 1315 m^2/g, respectively, indicating high adsorption capacities with microporous structures [9].

Kang, HY et al. synthesized AC using paper mill sludge from pyrolysis, which was chemically activated with KOH. The effects of activation agent ratio, activation temperature, and activation time on the properties of the char were carried out in a rotary kiln reactor. The AC was characterized by measuring iodine and methylene blue numbers and specific surface areas. The AC in this study had maximum iodine and methylene blue numbers of 726.0 mg/g and 152.0 mg/g, respectively, and a specific surface area of 1,002.0 m^2/g. Freundlich isotherms yield a fairly good fit to the adsorption data, indicating monolayer adsorption of metals onto AC prepared from the char of paper mill sludge using potassium hydroxide as the activating agent [10].

Characterization of activated carbon by SEM, XRD, BET method, and EDAX techniques

Author González-García reviewed the methods of synthesis of AC from lignocellulosic precursors. Special attention must be given to the precursor characteristics, the final microstructure and properties of carbon. A detailed description of the characterization techniques for precursors and AC, comprising physicochemical, micro/nanostructural, surface chemistry, textural, and adsorption capacity features, is presented. The application of AC in the adsorption of heavy metals, dyes, volatile organic compounds, gas storage, and electrochemical capacitors is also included [11]. Ahmad, A.A. et al. Prepared AC from biosolids as adsorbents for pollutant removal. Both physical and chemical characterizations provide basic knowledge for pollutant removal. The literature illustrates that chemical activation with KOH is found to be the most effective technique for producing a high BET surface area on AC prepared from biosolid is 1,882 m^2/g. In this review, the results reveal that the bio-solid AC is comparable with commercially AC [12].

Turgay Tay et al. synthesized AC from the pyrolysis of soybean oil cakes at 600 °C and 800 °C by chemical activation using K_2CO_3 and KOH. The effect of temperature and chemical reagents on porosity development was investigated and discussed. K_2CO_3 as a chemical reagent was found to be more effective than KOH under identical conditions (in terms of porosity development and yield of the AC). The maximum surface area (1352.86 m^2 g^{-1}) was obtained at 800 °C with K_2CO_3 activation, which was in the range of commercial AC. Elemental analyses of the AC indicate insignificant sulfur content. The ash and sulfur contents of the AC prepared with chemical activation by K_2CO_3 were lower than those prepared with chemical activation by KOH [13].

R.M. Suzuki et al. studied the preparation of rice bran AC with and without an acid treatment step before the activation process. The effect of activation time on the structure of the AC was evaluated. The acid treatment had a significant positive influence on the adsorption properties of AC. The BET surface area and pore volume of rice bran-AC were 652 m^2 g^{-1} and 0.137 cm^3 g^{-1} respectively, with mesoporous predominance (ca. 55%). The study results indicate that the potential use of rice bran as a precursor in the preparation of AC is an economically promising material [14].

Donni Adinata et al. prepared activated carbon from Palm shells using potassium carbonate (K_2CO_3) as an activating agent by chemical activation. The effect of carbonization temperatures (600–1000 °C) and impregnation ratios (0.5–2.0) of the prepared AC were studied. The Results revealed that with an increase in the carbonization temperature and impregnation ratio, the yield decreased whereas the adsorption of CO_2 increased progressively. The specific surface area of AC was maximum (1170 m^2/g) at 800 °C with an activation period of 2 hours and an impregnation ratio of 1.0 [15].

Adsorption of pollutants on activated carbon

Author Ayhan Demirbas reviewed several different agricultural waste adsorbents and types of dyes. Wastewater containing various dye contaminants causes serious environmental problems. Recently, growing research interest in the production of AC has been focused on agricultural by-products. Low-cost adsorbents derived from agricultural wastes have proven to have outstanding capabilities for the removal of dyes from wastewater. The inexpensive and eco-friendly adsorbents have been studied as an alternative substitution for the removal of dyes from wastewater. The adsorption efficiency of dye on agricultural waste adsorbents depend on the characteristics of the individual adsorbent, the extent of surface modification, and the initial concentration of adsorbate [16]. Mustafa T. et al. reviewed the application of adsorption in the removal of toxic dyes from aqueous solutions. The article provides extensive literature information about dyes, their classification and toxicity, various treatment methods, and dye adsorption characteristics by various adsorbents. AC from biomass has the advantage of non-renewable coal-based granular AC, provided that it has better adsorption efficiency. The effective adsorption factors of dye, such as solution pH, initial dye concentration, adsorbent dosage, and temperature, and the applicability of various adsorption kinetic models and isotherm models for dye removal by a wide range of adsorbents are also reported here [17].

Santhy et al. investigated the adsorption efficiency of AC prepared from coir pith using reactive dyes in the textile industry. The results show that the adsorption of dyes increased with an increase in contact time and carbon dose. Maximum adsorption of all the dyes was observed at an acidic pH. The adsorption of dyes was fitted with the Freundlich model. Kinetic studies showed that the adsorption followed first order. The carbon could be regenerated and used with 1.0 M NaOH. The coir pith-AC was effective in removing color and also significantly reduced COD levels in the textile wastewater [18].

Prastuti, O. P., et al. studied the removal of dyes and heavy ions from textile waste using banana peel-AC. Banana peel-AC was characterized using SEM to obtain morphology. Adsorption studies of Cu^{2+} and Cr^{6+} on AC were obtained using spectrophotometric UV-Vis analysis with a wavelength of 635 nm for copper (Cu) and 469 nm for chromium (Cr). The results of the atomic absorption spectroscopy analysis of AC show that it can reduce copper and chromium ion content by 55.5% and 61%, respectively. Therefore, when AC was used as an adsorbent for dyes in wastewater (textile waste), the average absorption capacity of the dye ion was 12.21% during the contact time of adsorption of 120 minutes [19].

Tsang, D.C.W., et al. studied the adsorption of basic dyes (methylene blue), acid dyes (acid blue 25 and acid red 151), and reactive dyes (reactive red 23) using waste wood pallets and AC. The results reveal that phosphoric acid concentration, impregnation ratio, activation temperature, and activation time could maximize the surface area and pore volume of AC. The characterization of the carbon surface chemistry using Fourier-transform infrared spectroscopy revealed a decrease in the amount of several functional groups with increasing activation temperature. The kinetics and high capacity of dye adsorption on waste wood AC suggest that the production of AC from different types of wood waste should value further investigation [20].

Applications of activated carbon

Norhusna Mohamad Nor et al. studied the preparation of activated carbon from lignocellulosic biomass and its applications in air pollution control. The effects of carbonization and activation parameters such as temperature, heating rate, gas flow rate, activating agent, and residence time on the properties of activated carbon were discussed. Removal of SO_2, NO_2, and H_2S, simultaneous removal of SO_2 and NO_X, and removal of VOC using AC were reviewed. Converting lignocellulosic biomass into AC could decrease environmental problems such as agricultural waste and air pollution [21]. Reza, Md. Sumon, et al. reviewed the preparation of biomass-AC. Fresh water is being polluted by industrial and agricultural activities, pharmaceuticals, technocratic civilization, pesticides, garments, global changes, etc. Environmental pollution and global warming are due to the greenhouse gases and harmful gases generated from the dumping and burning of fossil fuels. The synthesis of AC is an easy and safe process, mainly from the pyrolysis or gasification of biomass with heat and/or chemicals. The recycling and regeneration of AC are also necessary for resource maintenance and environmental safety [22].

Cheol-Soo Yang et al. prepared Bamboo-based AC with or without KOH activation by simple heat treatment and characterized it for energy storage applications. The KOH AC has large surface area (more than 3000 $m^2\ g^{-1}$) resulting in high specific capacitance, energy density, and power density in an aqueous electrolyte. The specific capacitance retention after 3000 cycles is more than 91% of the original capacitance, proving outstanding cyclic stability for supercapacitor applications. The results indicate that the natural resource of common bamboo could be an essential raw material for energy storage devices [23].

Ana Lea Cukierman et al. discussed the applications of AC cloths, which have received growing attention because they offer comparative advantages over the traditional powdered or granular forms of this well-known adsorbent, providing further potential uses for technological innovations in several fields. Some fabrics and textile wastes used as precursors and activation process variables affect the development and physicochemical, mechanical, and/or electrical properties of the resulting AC cloths. Then the removal of water and air pollutants by adsorption onto AC cloths, including advances towards optimizing their regeneration after organic vapor saturation, is discussed [24].

Alberto Adan-Mas et al. prepared AC from spent coffee ground second waste, after polyphenol extraction, using a hydrothermal process followed by physical or chemical activation. The resulting AC showed microporous structures with a total specific area between 585 and 2330 m^2g^{-1}. Scanning electron microscopy revealed a highly porous microstructure with chemically AC where as physical activation led to a cracked, micro-sized morphology. After chemical activation, the AC displayed a capacitance of 84 $F{\cdot}g^{-1}$ at 1 $A{\cdot}g^{-1}$ in a 1.9 V voltage window, with 70% capacitance retention at 10 Ag^{-1} and 85% retention after 5000 cycles of continuous charge-discharge [25].

Conclusion

The preparation of AC from useless and throwaway materials such as agricultural byproducts became a challenge. Therefore, inexpensive and renewable resources from agricultural waste were found to be effectively converted into useful materials. The temperature, impregnation time, and impregnation ratio of the activating agent to the precursor were found to have a significant influence on the surface morphology of the AC during the activation process. The characterization technique for precursors and activated carbons was discussed. The various parameters such as, solution pH, initial dye concentration, adsorbent dosage, and temperature, and the applicability of various adsorption kinetic models and isotherm models for dye removal by a wide range of adsorbents are also reported here. Removal of SO_2, NO_2, and H_2S, simultaneous removal of SO_2 and NO_X, and removal of VOC using AC were reviewed. The recycling and regeneration of AC are also important to preserve the natural resource and decrease the pollution.

Acknowledgement
The authors thank the Department of Physics, Government First Grade College, Sira, Tumkur district, Karnataka, India.

References

1. Mohd Adib Yahya., Z. Al-Qodah., C.W. Zanariah Ngah., "Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production", Renewable and Sustainable Energy Reviews, 2015, 46, 218-235.
2. Mohd Adib Yahya., Muhammad Humaidi Mansor., Wan Amani Auji Wan Zolkarnaini., Nurul Shahnim Rusli., Anisah Aminuddin., Khalidah Mohamad., Fatin Aina Mohamad Sabhan., Arif Abdallah Aboubaker Atik., Lailatun Nazirah Ozair., "A brief review on activated carbon derived from agriculture by-product", AIP Conference Proceedings 1972, 2018.
3. Kulumkan Sartova., Emil Omurzak., Gulnara Kambarova., Isaak Dzhumaev., Bakyt Borkoev., Zhypargul Abdullaeva., "Activated carbon obtained from the cotton processing wastes", Diamond and Related Materials, 2019, 91, 90-97.
4. M. Soleimani., T. Kaghazchi., "Agricultural Waste Conversion to Activated Carbon by Chemical Activation with Phosphoric Acid", Chem. Eng. Technol, 2007, 30(5), 649-654.
5. Hayashi Junichi., Kazehaya Atsuo., Muroyama Katsuhiko., Watkinson Paul., "Preparation of activated carbon from lignin by chemical activation", Carbon, 2000, 38(13) 1873-1878.
6. Heidarinejad, Zoha Dehghani., Mohammad Hadi Heidari., Mohsen Javedan., Gholamali Ali., Imran Sillanpaa Mika., "Methods for preparation and activation of activated carbon: a review", Environ Chem., 2020, 393–415.
7. Samah Zaki Naji., Ching Thian Tye., "A review of the synthesis of activated carbon for biodiesel production: Precursor, preparation, and modification", Energy Conversion and Management: X, 2022, 13.
8. M. Olivares-Marin., C. Fernandez-Gonzalez., A. Macias-Garcia., V. Gomez-Serrano., "Preparation of activated carbon from cherry stones by chemical activation with $ZnCl_2$", Applied Surface Science, 2006, 252(17) 5967-5971.
9. Chiung-Fen Chang., Ching-Yuan Chang., Wen-Tien Tsai., "Effects of Burn-off and Activation Temperature on Preparation of Activated Carbon from Corn Cob Agrowaste by CO_2 and Steam", Journal of Colloid and Interface Science, 2000, 232(1), 45-49.
10. Kang H. Y., Park S. S., Rim Y. S., "Preparation of activated carbon from paper mill sludge by KOH-activation", Korean J. Chem. Eng., 2006, 23, 948–953.
11. P. Gonzalez-Garcia., "Activated carbon from lignocellulosics precursors: A review of the synthesis methods, characterization techniques and applications", Renewable and Sustainable Energy

Reviews, 2018, 82, 1393-1414.

12. A.A. Ahmad., A. Idris., “Preparation and characterization of activated carbons derived from bio-solid: areview", Desalination and Water Treatment, 2014, 52(25-27), 4848-4862.
13. Tay T., Ucar S., Karagoz S., “Preparation and characterization of activated carbon from waste biomass", Journal of Hazardous Materials, 2009, 165(1-3), 481-485.
14. R.M. Suzuki., A.D. Andrade., J.C. Sousa., M.C. Rollemberg., “Preparation and characterization of activated carbon from rice bran", Bioresource Technology, 2007, 98(10), 1985-1991.
15. Donni Adinata., Wan Mohd Ashri Wan Daud., Mohd Kheireddine Aroua., “Preparation and characterization of activated carbon from palm shell by chemical activation with K2CO3", Bioresource Technology, 2007, 98(1), 145-149.
16. A. Demirbas., "Agricultural based activated carbons for the removal of dyes from aqueous solutions: A review", Journal of Hazardous Materials, 2009, 167(1-3), 1-9.
17. Mustafa T. Yagub., Tushar Kanti Sen., Sharmeen Afroze., H.M. Ang., “Dye and its removal from aqueous solution by adsorption: A review", Advances in Colloid and Interface Science, 2014, 209, 172-184.
18. K. Santhy., P. Selvapathy., “Removal of reactive dyes from wastewater by adsorption on coir pith activatedcarbon" Bioresource Technology, 2006, 97(11), 1329-1336.
19. Prastuti O. P., Septiani E. L., Kurniati Y., Widiyastuti, Setyawan H., “Banana Peel Activated Carbon in Removal of Dyes and Metals Ion in Textile Industrial Waste", Materials Science Forum, 2019, 966, 204–209.
20. Tsang Dan., Hu Jing., Liu Mei., Zhang Weihua., Lai Keith., Lo Irene., “Activated Carbon Produced from Waste Wood Pallets: Adsorption of ThreeClasses of Dyes", Water Air Soil Pollut, 2007, 184, 141–155.
21. Mohamad Nor Norhusna., Lau Lee Chung., Lee Keat Teong., Mohamed Abdul., Synthesis of activated carbon from lignocellulosic biomass and its applications in air pollution control—a review", Journal of Environmental chemical Engineering, 2013, 1(4), 658-666.
22. Md Sumon Reza., Cheong Sing Yun., Shammya Afroze., Nikdalila Radenahmad., Muhammad S. Abu Bakar., Rahman Saidur., Juntakan Taweekun., Abul K. Azad., “Preparation of activated carbon from biomass and its applications in water and gas purification, a review" Arab Journal of Basic and Applied Sciences, 2020, 27(1), 208-238.
23. Cheol-Soo Yang., Yun Su Jang., Hae Kyung Jeong., “Bamboo-based activated carbon for super capacitor applications", Current Applied Physics, 2014, 14(12), 1616-1620.
24. Ana Lea Cukierman., “Development and environmental Applications of Activated Carbon Cloths", Hindawi Publishing Corporation ISRN Chemical Engineering, 2013, 2013, 1-31.
25. Alberto Adan-Mas., Lorena Alcaraz., Pablo Arevalo-Cid., Felix. A. Lopez-Gomez., Fatima Montemor., “Coffee-derived activated carbon from second biowaste for super capacitor applications" Waste Management, 2021, 120, 280-289.