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ORIGINAL RESEARCH ARTICLE

CONVERSION OF BIOMASS TO ADSORBENT: A REVIEW

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ABSTRACT

Tons of biomass are produced every year including organic agricultural and forestry by-products but they are of limited value. Mostly, in the developing countries, the biomasses are considered as waste and are being burnt or thrown to liter the environment as part of teaming solid waste. Presently, there are no sustainable long-term management strategies to use biomass. The utilization of biomass to produce activated carbon is a good approach that is industrially useful and environmentally benign materials. The adsorption technique is using adsorbents in the removal of heavy metals from water therefore, biomass can be converted to the adsorbent and utilized as a waste-to-wealth commodity in water purification. In this review, the suitable process for conversion of biomass to cheap and simple means of obtaining activation carbon as adsorbent is presented. The potential uses of biomass and the conversion stages including carbonization, pyrolysis, gasification, and activation were discussed. This work depicts that the issue of solid waste utilization to solve existing issues with locally available and cheap materials is beneficial to man and the environment.

1.0 Introduction

Water is a basic source for existence of life on earth. The increase in industrialization and modernization has contributed negatively to clean water resources. Many substances such as heavy metals, dyes, pharmaceuticals, surfactants, pesticides, personal care products and others have contaminated the water resources (Rasheed *et al.*, 2020). These pollutants are environmentally hazardous to human beings and animals (Siyal *et al.*, 2018). Biomass is available from several sources all over the world and has numerous roles to play for sustainable development. In addition to being a food source to animals and renewable raw material, biomass can be used for energy production, carbon sequestration and as activated carbon (Cheng *et al.*, 2009; Jain *et al.*, 2016).

Utilization of biomass to produce activated carbon is a good approach in pollution control strategy in two ways. Firstly, it can fix the carbon of biomass that prevents the production of CO_2 or CH_4; and secondly, it produces activated carbon which is industrially useful and environmentally benign materials that can go into the soil and enter natural carbon cycle process (Danish and Ahmad, 2018). Hong *et al.*, (2020) reported that heavy metals in excess of the stipulated minimum are harmful to human health and aquatic life due to their toxicity and bioaccumulation. Excessive concentration of heavy metals such as, Lead (Pb) and Cadmium (Cd in water could cause irritation of central nerve system and damage to kidney and liver) and many other diseases (Genchi *et al.*, 2020; Siyal *et al.*, 2018). Trace metals are those having density greater than 5 gcm^{-3}. Most often this term denotes metals that are toxic. These include Al, As, Cd, Cr, Co, Pb, Hg, Ni, Se, and Zn which could be discharged from industries, farmlands, municipal urban water runoffs, and agricultural activities into surface water and can cause pollution (Maitera *et al*., 2011).

Previous literature published those conventional technologies for the treatment of contaminated water, such as precipitation, electrochemical treatment, ion exchange, membrane separation, and adsorption have been used globally for the removal of heavy metals from aqueous solution (Chakraborty *et al*., 2020). Among the treatment processes, adsorption has been proven to be one of the most suitable and universal methods, which offer remarkable advantages such as fast, ease of operation, availability, and efficiency (Ni *et al*., 2019). Various adsorbents have been employed, ranging from natural products to synthetic materials which would directly determine the removal efficiency via adsorption. Carbon materials, such as activated carbon, graphene, and fullerene, were found to be promising adsorbents for removing heavy metals from aqueous solution due to their stability and large surface area (Ni *et al*., 2019). Date Palm fibers are lignocellulosic materials, which consist of three vital components: Cellulose (40-50%), hemicellulose (20-35%) and lignin (15-35%) (Shafiq *et al*., 2018) and may be used as adsorbent to remove heavy metal ion from water.

Each date tree produces 20kg of dry leaves yearly (Ismail, 2012) and there are about 105 million trees available worldwide on an area of over a million hectares (Ahmad and Danish, 2012). The area under date palm cultivation in Nigeria was estimated over 1,466.00 ha and an estimated annual production of nearly 20,000 tones date fruit per annum (Abdullahi, 2015). The date tree leaves, stems, and branches are considered as waste and are being burnt.

This study reviews biomass as a potential waste to wealth material with regards to conversion into activated carbon and utilization as adsorbent. The Date Tree Leaf (DTL) is reviewed as the potential biomass source in production the of activated carbon.

2. Biomass

Organic materials originating from living matter or complexes of organic and inorganic materials are collectively referred to as biomass. Biomass includes but not limited to only living organisms, such as plants and animals, but also the excrement of animals, sludge, and waste wood (Cha *et al*., 2016). Sometimes, it is referred to as stored energy, a renewable organic material derived from plants and animals that can serve as sources of energy. Biomass is made up of carbohydrate and has less energy storage problems when compared with other renewable sources such as solar and wind (Schlemmer *et al*., 2021). Wastes such as agricultural/agro-industries wastes and municipal wastes and purposely grown energy crops such as sugarcane, corn, wheat, etc. are the main sources of biomass (Abioye and Nasir, 2015).

Biomass can be converted into several useful forms of energy using different processes briquette and bio-char. There are several factors which could affect the choice of conversion process; these can include (Adams *et al*., 2018): the type of usage, quantity, and characteristics of biomass feedstock, the desired form of the energy environmental. In addition to being a food source to animals, and renewable raw material, it can be used for energy production, carbon sequestration and, as an essential element to produce hydro chars and activated carbons (Jain *et al*., 2016). Figure 1 shows a biomass-to-power supply system.

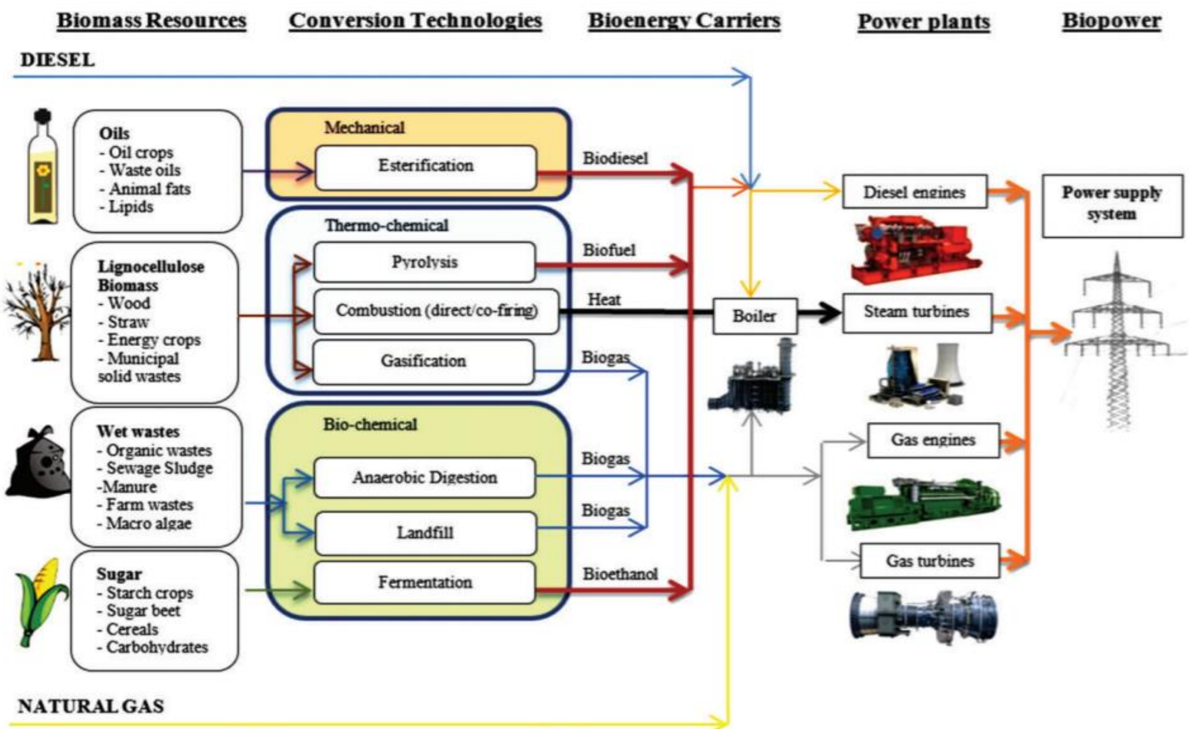

Figure 1: Biomass-to-power supply system (Heidari *et al*., 2018)

Due to the potential reduction in greenhouse gas (GHG) emissions, society has recognized the usage of waste biomass as a sustainable resource. According to Ahmed *et al*., (2019), by balancing the production of plant biomass and its utilization in the future, it is possible that zero GHG emissions can be achieved. For energy recovery, diverse methods of utilization of biomass have been found environmentally friendly and economically viable. The major chemical constituents of biomass are hemicellulose, cellulose, and lignin; and minor chemical components are protein and oil. On an average, the quantitative proportion of hemicellulose, cellulose, and lignin in biomass are observed in the range of 20–35, 40–50, and 15–35%, respectively (Danish and Ahmad, 2018).

It has been reported by Abioye and Nasir, (2015) that the constituents of lignocelluloses are strongly intermeshed and are chemically bonded by either non-covalent forces or covalent linkage, and their composition varies from one plant species to another. Biomass can be converted to biofuels and bioproducts via thermochemical processes, such as pyrolysis and gasification. The net carbon dioxide emissions from biofuel use are considered zero or negative because the released of CO_2 is recycled from the atmosphere captured during photosynthesis (Qian, *et al*., 2015). In addition, since biomass contains a low amount of sulphur and nitrogen, its combustion as a source of energy may result to lower emissions of harmful gas, such as nitrous oxides (NO_x) and sulphur dioxide (SO_2) compared to most of fossil fuels. Such advantages of biomass make it a promising renewable energy resource.

The use of agricultural by-products as bio sorbent material were found to (Chakraborty *et al*., 2020) purify heavy metal contaminated water and has become increasingly popular through the past decade, because they are less expensive, biodegradable, abundant and efficient. Cost is an important parameter for comparing the sorbent materials. The expense of individual sorbents varies depending on the degree of processing required and local availability (Saka and Mas, 2012).

It is stated that an adsorbent can be termed as a low-cost adsorbent if it requires little processing, is abundant in nature, or is a by-product or waste material from some selected industries (Chakraborty *et al*., 2020). Thus, there is an urgent need that all possible sources of agro-based inexpensive adsorbents should be explored and their feasibility for the removal of heavy metals should be studied in detail (Saka and Mas, 2012).

The generation of bioenergy in terms of liquid, gaseous, and solid fuels from biomass wastes has been an important field in research and development. Low-cost, abundance, renewability, and high lignocellulosic content of agricultural biomass make them promising precursors for cost-effective activated carbons (Ahmed, 2016). Biomass can be classified based on the types existing in nature, which include wood and woody biomass, herbaceous biomass, aquatic biomass, animal and human waste biomass, and biomass mixtures (Jekayinfa and Orisaleye, 2020).

It has been widely reported that the thermal degradation characteristics of lignocellulosic materials are profoundly influenced by their chemical composition (cellulose, hemicellulose, and lignin), and TG and DTG curves provide semi- quantitative understanding of the thermal degradation processes occurring during thermochemical conversion under various atmospheres (Roma, *et al*., 2009). Furthermore, Mudryk *et al*., (2021) found that the processes of thermal processing of herbaceous biomass generate significant amounts of waste in the form of ashes. Figure 2 shows the contributions of biomass sources to the overall technical potential.

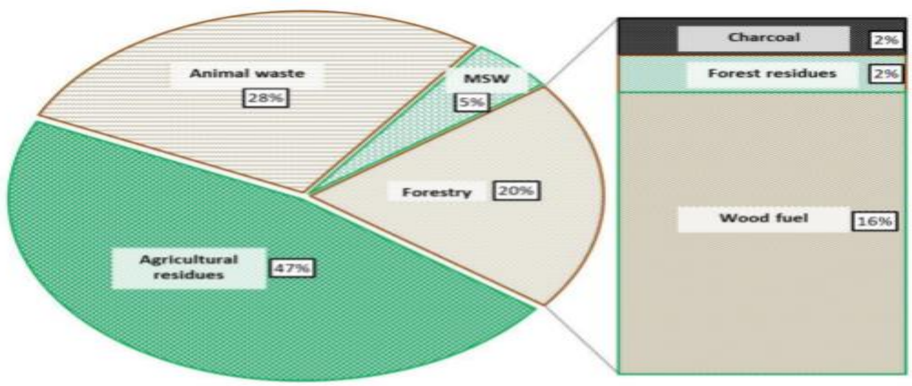

Figure 2: Contributions of biomass sources (Jekayinfa and Orisaleye, 2020)

2.1. Types of Biomass

Woody biomass includes components whose major constituents are carbohydrates and lignin including live trees, forest and manufacturing residues, or consumer waste materials (Jekayinfa and Orisaleye, 2020). Another type of biomass is the herbaceous biomass which is obtained from plants with a non-woody stem which dies at the end of the growing season (Picchio *et al*., 2020). It includes grain and seed crops from the food processing industry and their by-products. Herbaceous crops can be sub-divided into agricultural residues and energy crops (Jekayinfa and Orisaleye, 2020).

Aquatic biomass includes algae and emerging plants. These include marine or freshwater algae, macroalgae or micro algae, seaweed, kelp, lake weed, and water hyacinth (Heidari *et al*., 2018). Aquatic weeds have exceptionally high reproduction rates and are rich in cellulose and hemicellulose with a very low lignin content, which makes them efficient as biofuel crops. The three common fast-growing aquatic weeds in Nigeria are water hyacinth, water lettuce, and bracken fern (Jekayinfa and Orisaleye, 2020). Municipal solid waste refers to classes of wastes considered as trash (Srinilta, 2019). They are found to be highly nonhomogeneous, being a mixture of residential, commercial, and industrial wastes (Conti *et al*., 2020; Ferrari *et al*., 2020). Globally, and particularly in developing countries, the management of municipal solid waste constitutes an important environmental concern (Maalouf, 2020).

2.2. Date Tree Leaves (DTL) Biomass

Date palm is a soft edible fruit (Alam *et al*., 2021) and its fruits are popular among the people of northern Nigeria, it was found that the date palm tree is an economic crop which is grown in the arid region of Northern Nigeria from latitude 10° N in the Sudan savannah and the Sahel region (Dada *et al*., 2012). It is originated from the Middle East and North Africa and was introduced to Nigeria from North Africa during the Trans-Saharan trade by pilgrims and traders from the Middle East (Abdullahi, 2015). The date fruit is a good source of food providing, fiber, carbohydrates, minerals, and vitamins besides having anti-mutagenic and anti-carcinogenic properties, it is antioxidant and anti-inflammatory and provides protection to the liver, stomach, and kidney (Al-Abdoulhadi *et al*., 2011; Kamarubahrin and Haris, 2020).

Based on literature, (Ahmed, 2016), an adult date palm tree has a trunk or stem of 15-25 m high and fronds or leaves that look like feathers with 3-5 m long, there are about 150 leaflets in each frond which can be up to 30 cm in length and 2cm in breadth, while the full span of the crown of the palm tree is about 6-10 m height. It is a feather palm, characterized by compound leaves with a series of leaflets on each side of a common petiole, originating from one growing point at the apex (Ahmad and Danish, 2012). However, (Ismail, 2012) discovered that date palm tree produces large quantity of agricultural waste. For example, each date tree produces about 20 kg of dry leaves yearly.

DTL are lignocellulosic materials, which consist of three vital components: Cellulose (40-50%), hemicellulose (20-35%) and lignin (15-35%) also, lignin is the most important constituent and has complex chemical constituents within the DTL waste material, as it is a three-dimensional polymer of phenyl propane units linked together by C–C or C–O–C bonds (Shafiq and Alazba, 2018; Parthasarathy and Narayanan, 2014). DTL waste has been used in various forms for different heavy metals removal from wastewater. The removal of Pb^{2+}, for example, has been investigated using DT trunk, DT leaves, DT leaves ash, and palm leaf base (the petiole) (Yadav *et al*., 2013). Several naturally available materials like plant wastes and agricultural products have been tried as adsorbents for the removal of metals. The advantages associated with the use of plant materials are little processing, good uptake capacity, free availability, the minimization of chemical or biological sludges and easy regeneration (Rajamohan *et al*., 2014). Figure 3 shows the DTL biomass.

Figure 3: Date Tree Leaves (DTL) biomass

2.3. Carbonization, Pyrolysis and Gasification of Biomass

Because of the diversity of raw biomass and biofuel, there are many ways to improve biomass fuel quality and achieve extensive utilization and higher efficiency such like the thermo-chemical upgrading of biomass fuel, which includes torrefaction, carbonization, pyrolysis, gasification and liquefaction (Qi *et al*., 2018). Carbonization involves the conversion of organic containing residue into carbon or a carbon containing residue through pyrolysis, furthermore, the process is carried out in an oxygen free environment at a temperature of about 500°C-700°C (Bones *et al*., 2019). According to Ahmed, (2016), the carbonization is a phase to enriching carbon content in carbonaceous material by eliminating non-carbon species using thermal decomposition while in the process, the temperature has the most significant effect, followed by heating rate, nitrogen flow rate, and finally, residence time.

Carbon is a raw material for several industrial products and their production from various bio-resources is an active area of research, (Ahmed *et al*., 2019). The char is a solid carbonaceous residue with a high content in fixed carbon (>75%), which can be used directly as fuel, as briquettes or as precursor for activated carbons production (Roma *et al*., 2009). Effective utilization of biochar is critical for improving economic viability and environmental sustainability of biomass thermochemical technologies (Qian *et al*., 2015). Normally, higher temperatures (600–700 °C) result in reduced yield of char while increasing the liquid and gases release rate, however, the obtained char usually exhibits little adsorption capability, and an activation step is required to expand initial porosity created by carbonization (Ahmed, 2016). Figure 4 depicts the preparation of the biomass-derived porous carbon.

Figure 4: Preparation of the biomass-derived porous carbon

The word pyrolysis is derived from the Greek words' 'pyro' meaning fire and 'lysis' meaning decomposition or breaking down into constituent parts. It is a process for decomposing organic materials thermally under oxygen-free conditions in the temperature range, 300-900 °C (Adams *et al*., 2018). During thermal decomposition, cellulose, hemicellulose and lignin that comprise biomass undergo their own reaction pathways, including cross-linking, depolymerization and fragmentation at their own temperature, producing solid, liquid and gaseous products (Cha *et al*., 2016).

Earlier, Adams *et al*., (2018) stated that pyrolysis operates in anaerobic conditions where heat is usually provided externally and the constituents of biomass are thermally cracked to gases and vapors which usually undergo secondary reactions, thereby giving a broad spectrum of products.

On the other hand, three phases are produced when biomass is subjected to pyrolysis processes: char, liquid, and gas (Roma *et al*., 2009). Pyrolysis has over the years been the most efficient route, by which bio-waste can be thermally degraded at 400–500 °C in the presence of inert gases to produce biochar (solid), bio-oil (liquid), and gaseous fuel (CO, CH_4, and H_2) as products (Bharath *et al*., 2020). Figure 5 shows the flow diagram of the simplified pyrolysis process.

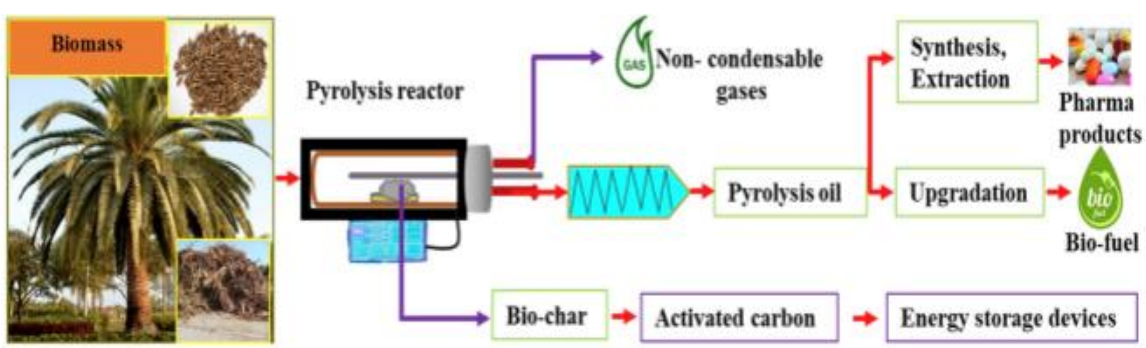

Figure 5: Flow diagram of the simplified pyrolysis process (Bharath *et al*., 2020)

The solid product obtained in pyrolysis process is known as char/biochar or charcoal and contains around half of the carbon of the original organic matter and, based on the heating rate applied to the biomass to reach the intended pyrolysis temperature, pyrolysis is classified into slow pyrolysis and fast pyrolysis (Mulabagal *et al*., 2017). The solid and liquid products are referred to as char and bio-oil, respectively, whereas the gaseous mixture containing CO, CO_2, H_2, and C_1-C_2 hydrocarbons are called syngas (Cha *et al*., 2016).

Gasification transforms biomass into primarily a gaseous mixture (syngas containing CO, H_2, CO_2, CH_4, and smaller quantities of higher hydrocarbons) by supplying a controlled amount of oxidizing agent under high temperature (greater than 700) (Qian *et al*., 2015). According to Adams *et al*., (2018), the gasification process thermo-chemically converts an organic feedstock (e.g., liquid, or solid fuel) into its gaseous components which depend on the gasification temperature.

2.3.1. Hydrothermal carbonization

Hydrothermal carbonization is an effective technology to carbonize wet biomass to evade the energy concentrated pre-drying step. Normally, in the HTC procedure, the wet biomass remains heated in a high-pressured container at comparatively lower temperatures i.e., 150–350 °C. The HTC process has been introduced successfully and applied practically (Ahmed *et al*., 2019). Feedstocks with high moisture and ash content are particularly reported to be suitable for hydrothermal processing and include feedstocks such as manures, sewage sludge, DDGS, food waste, municipal wastes, and aquatic biomass such as micro- and macroalgae (Adams *et al*., 2018). During hydrothermal carbonization, water acts as a solvent and as a catalyst that facilitates hydrolysis and cleavage of lignocellulosic biomass, water possesses high ionization constant at high temperatures and is responsible for hydrolysis of organics which can further be catalyzed by acids or bases (Jain *et al*., 2016). The hydrothermal conversion is a promising biomass-to-oil approach (Liu and Zhang, 2009). Figure 6 is a graphic diagram of biomass applications.

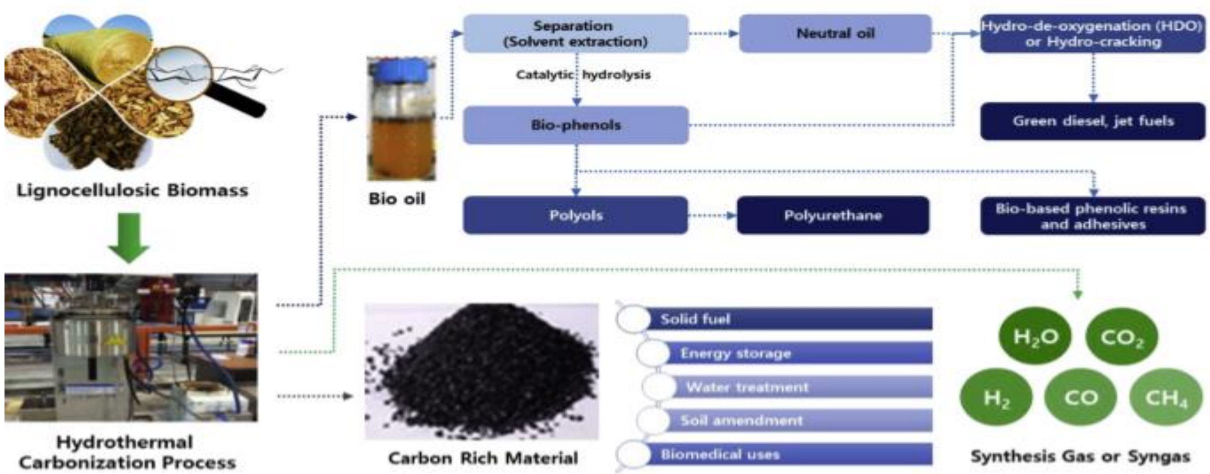

Figure 6: Graphic diagram of biomass applications (Khan *et al*., 2019)

3. Activated Carbon

Activated carbon (AC) is a microcrystalline form of carbon with high porosity and surface area for removal of impurities from soil, liquids, gases, and solids. the processes involved in carbon activation following raw materials preparation, low temperature combustion, and activation (Le and Nguyen, 2020). The raw material in this case could be coal, wood, carbon materials, coconut shell, fruits shells, derived biomass, etc. Due to the pore structure characteristics of straw AC, it has potential in the application of wastewater treatment and air purification, several studies have described the manufacturing processes of AC (Bones *et al*., 2019; Danish and Ahmad, 2018; Le and Nguyen, 2020; Silas *et al*., 2019) AC is a porous, black carbonaceous material that is prepared by physical or thermal activation and chemical activation (Bones *et al.*, 2019).

It was found that (Danish and Ahmad, 2018) the high surface area, well-organized macro, meso, and micro-pores, and a wide range of chemical functional groups present on the surface of activated carbon make it a versatile material which has numerous applications. The AC prepared from rice husk and sugarcane bagasse by Liu and Zhang, (2009) had good adsorption capacities with respect to arsenic, humic acid and phenol, the promising results were obtained when carbonaceous material prepared from coconut shell was utilized as adsorbent for wastewater treatment. Ni *et al.*, (2019) produced activated carbons from nutshell and removed almost 100% of Pb (II), 90-95% of Cu (II) and 80-90% of Zn (II) from water.

Activation is a process of converting carbonaceous materials into activated carbon by thermal decomposition in a furnace (convectional heating) or a microwave using a controlled atmosphere and heat. Physical activation, chemical activation, combined chemical and physical (Physiochemical) activation and microwave-induced activation are the methods being employed for the preparation of activated carbon (Abioye and Nasir, 2015).

3.1 Physical Activation

Physical activation, also called gas activation, uses gas, such as steam, CO_2, and ozone, to activate biochar at temperatures above 700 °C (Qian *et al.*, 2015). Physical activation can be divided into two steps. In the first step, the unstructured parts of the carbonized material are decomposed selectively while fine pores enclosed in the carbon structure are opened, thereby increasing the internal surface area (Cha *et al.*, 2016).

The development of porosity is the major function of the activating agent during the activation process, and this is usually accomplished through a controlled carbon burn-off and elimination of volatile matters (Abioye and Nasir, 2015). The authors further reported that the level of carbon burn-off greatly depends on the temperature and duration of activation as well as other experimental parameters such as gas flow and furnace type and ultimately determine the quality of the activated carbon.

3.2 Chemical Activation

Chemical activation is a step process in which the carbonization and activation are carried out simultaneously and usually in the temperature range of 300–95 °C thus influencing the pyrolytic decomposition and, therefore, resulting in the development of a better porous structure and increased carbon yield while Potassium hydroxide (KOH) and zinc chloride ($ZnCl_2$) are the most used activating agents (Abioye and Nasir, 2015). Cha *et al.,* (2016) found that in chemical activation, char is doped with a chemical agent and micropores are formed by subsequent dehydration and oxidation. Activated carbons prepared by pyrolysis of mixtures of carbon precursor/alkaline hydroxide were investigated. It was reported that NaOH is more efficient in the activation of low structural ordered materials, whereas KOH is more effective for the highly ordered materials, which indicates differences in the activation performance of both hydroxides (Tay *et al.*, 2009). Several studies are published on the utilization of biomass as adsorbents as shown in Table 1.

Table 1: Reviews on adsorption from previous studies

Objective	Method of synthesis	Characterization	Findings	Reference
Study of leaves of populous tree for adsorptive removal of MO in aqueous medium	Impregnation	FTIR, XRD, SEM	Populous leaves, is an excellent alternative in the removal of MO dye from aqueous solution	(Shah *et al.*, 2021)
Synthesized magnetized mesoporous activated carbon and its application for the removal of MB and MO from dye solutions.	wetness impregnation method	FTIR, XRD, SEM, BET	The adsorbent shows efficient adsorption ability for an anionic dye	(Azam *et al.*, 2020)
adsorption capability of the prepared Ct-PAC hybrid beads using a cationic surfactant.	Impregnation	FTIR, SEM,	Ct-PAC-HDA is a promising adsorbent for the elimination of reactive dyes.	(Vakili *et al.*, 2020)

4. Conclusion and Recommendation

The carbonaceous adsorbents in the treatment of wastewater such as activated carbon from biomass were found to have advantages like, high pollutant removal capacity, adequate sensitivity, productivity, simple synthesis, and cost-effective (waste to wealth). Therefore, the utilization of biomass such as the Date Tree Leaf is a suitable strategy for the decontamination of heavy metals from contaminated waters. Many researchers reported the prevalent of heavy metals in water in Maiduguri, Borno State, yet there are plantations of date palm where the leaves are considered as solid waste and mostly burnt therefore, this study recommends the utilization of DTL for the treatment of heavy metals which are harmful to human after a thorough investigation of the adsorbent's characteristics, effects, and safe use of treatment of contaminated water.

References

Abdullahi, M. 2015. The potentials of esterblishing date palm plantation in sudano sahelian region of Nigeria. Conference: Farm Management Association of Nigeria (FAMAN) At: general studies auditorium, Federal University Dutse, Jigawa State Nigeria.

Abioye, AM. and Nasir, F. 2015. Recent development in the production of activated carbon electrodes from agricultural waste biomass for supercapacitors: A review. Renewable and Sustainable Energy Reviews, *52*: 1282–1293. https://doi.org/10.1016/j.rser.2015.07.129.

Adams, P., Bridgwater, T., Ross, A. and Watson, I. 2018. Biomass conversion technologies. Chapter 8. Greenhouse Gases Balance of Bioenergy Systems. (Thornley, P. and Adams, P., Eds.). Cambridge: Academic Press, 107-139. https://doi.org/10.1016/B978-0-08-101036-5.00008-2.

Ahmad, T. and Danish, M. 2012. The use of date palm as a potential adsorbent for wastewater treatment: A review. Environmental Science and Pollution, 19: 1464–1484. https://doi.org/10.1007/s11356-011-0709-8.

Ahmed, T., Sajidah, A., Jamari, S. S., Hasbi, M., Rahim, A., Park, J. and Kim, H. 2019. Biomass and Bioenergy Hydrothermal carbonization of lignocellulosic biomass for carbon rich material preparation : A review.

Biomass and Bioenergy, 130: 1-14. https://doi.org/10.1016/j.biombioe.2019.105384.

Ahmed, MJ. 2016. Preparation of activated carbons from date (*Phoenix dactylifera* L.) palm stones and application for wastewater treatments: Review. Safety and Environmental Protection Process, 102*: 168-182*. https://doi.org/10.1016/j.psep.2016.03.010.

Al-Abdoulhadi, IA., Dinar, HA., Ebert, G. and Büttner, C. 2011. Effect of salinity on leaf growth, leaf injury and biomass production in date palm (*Phoenix dactylifera L.*) cultivars. Indian Journal of Science and Technology, 4(11): 1542–1546. https://doi.org/10.17485/ijst/2011/v4i11/30283.

Alam, MZ., Alhebsi, MSR., Ghnimi, S. and Kamal-eldin, A. 2021. Inability of total antioxidant activity assays to accurately assess the phenolic compounds of date palm fruit (*Phoenix dactylifera L.*). NFS Journal, 22:32–40. https://doi.org/10.1016/j.nfs.2021.01.001

Azam, K., Raza, R., Shezad, N., Shabir, M., Yang, W., Ahmad, N. and Hussain, M. 2020. Development of recoverable magnetic mesoporous carbon adsorbent for removal of methyl blue and methyl orange from wastewater. Biochemical Pharmacology, 8: 1–20. https://doi.org/10.1016/j.jece.2020.104220.

Bharath, G., Hai, A., Rambabu, K., Banat, F., Jayaraman, R., Taher, H. and Ejbye, J. 2020. Biomass and bioenergy systematic production and characterization of pyrolysis-oil from date tree wastes for bio-fuel applications. Biomass and Bioenergy, 135: 1-33. https://doi.org/10.1016/j.biombioe.2020.105523.

Bones, H., Sunday, NJ., Okechukwu, NS., Elom, N., Anthony, O. and Michael, PT. 2019. Quantitative characterization of activated carbon from cow, donkey, chicken and horse bones from Ezzangbo in Ebonyi State, Nigeria. American Journal of Applied Chemistry, 6(5): 169-175. https://doi.org/10.11648/j.ajac.20180605.12.

Cha, JS., Park, SH., Jung, S., Ryu, C., Jeon, J., Shin, M. and Park, Y. 2016. Production and utilization of biochar: A review. Journal of Industrial And Engineering Chemistry, 40(25): 1-15 https://doi.org/10.1016/j.jiec.2016.06.002

Chakraborty, R., Asthana, A., Singh, AK. and Jain, B. 2020. Adsorption of heavy metal ions by various low-cost adsorbents: A review. International Journal of Environmental Analytical Chemistry, 2020: 1–38. https://doi.org/10.1080/03067319.2020.1722811.

Cheng, WP., Yang, JG. and He, MY. 2009. Evaluation of crystalline structure and SO_2 removal capacity of a series of MgAlFeCu mixed oxides as sulfur transfer catalysts. Catalysis Communications, 10(6): 784–787. https://doi.org/10.1016/j.catcom.2008.11.038.

Conti, F., Toor, SS., Pedersen, TH., Seehar, TH. and Nielsen, AH. 2020. Valorization of animal and human wastes through hydrothermal liquefaction for biocrude production and simultaneous recovery of nutrients. Energy Conversion and Management, 216: 1–25. https://doi.org/10.1016/j.enconman.2020.112925.

Dada, M., Nwawe, CN., Okere, RA. and Uwubanmwen, IO. 2012. Potentials of date palm tree to the Nigerian economy. World Journal of Agricultural Sciences, 8(3): 309–315.

Danish, M. and Ahmad, T. 2018. A review on utilization of wood biomass as a sustainable precursor for activated carbon production and application. Renewable and Sustainable Energy Reviews, 87: 1–21. https://doi.org/10.1016/j.rser.2018.02.003.

Ferrari, F., Striani, R., Minosi, S., Fazio, R. De, Visconti, P., Patrono, L., Greco, A. 2020. An innovative IoToriented prototype platform for the management and valorisation of the organic fraction of municipal solid waste. Journal of Cleaner Production, 247:1–18. https://doi.org/10.1016/j.jclepro.2019.119618.

Genchi, G., Sinicropi, MS., Lauria, G. and Carocci, A. 2020. The effects of Cadmium toxicity. International Journal of Environment Resources And Public Health, 17(3782): 1–24.

Heidari, A., Hajinezhad, A. and Aslani, A. 2018. A sustainable power supply system, Iran' s opportunities via bioenergy. Environmental Progress & Sustainable Energy, 38(1):1–18. https://doi.org/10.1002/ep.12937.

Hong, Y., Liao, W., Yan, Z., Bai, Y., Feng, C., Xu, Z. and Xu, D. 2020. Progress in the research of the toxicity effect mechanisms of heavy metals on freshwater organisms and their water quality criteria in China. Journal of Chemistry, 2020: 1-17.

Ismail, ZZ. 2012. Kinetic study for phosphate removal from water by recycled date-palm wastes as agricultural by-products. International Journal of Environment, 69(1):37–41. https://doi.org/10.1080/00207233.2012.656975.

Jain, A., Balasubramanian, R. and Srinivasan, MP. 2016. Hydrothermal conversion of biomass waste to activated carbon with high porosity: A review. Chemical Engineering Journal, 283: 789–805. https://doi.org/10.1016/j.cej.2015.08.014.

Jekayinfa, SO. and Orisaleye, JI. 2020. An assessment of potential resources for biomass inergy in Nigeria. Resource, 98(2):1–41.

Kamaraj, M., Srinivasan, NR., Assefa, G., Adugna, AT. and Kebede, M. 2020. Facile development of sunlit ZnO nanoparticles-activated carbon hybrid from pernicious weed as an operative nano-adsorbent for removal of methylene blue and chromium from aqueous solution: Extended application in tannery industrial wastewater. Environmental Technology and Innovation, 17: 10–40. https://doi.org/10.1016/j.eti.2019.100540.

Kamarubahrin, AF. and Haris, A. 2020. Nutritional and potential planting of date palm: review of recent trends and future prospects in Malaysia. International Journal of Fruit Science, 20(sup 3): 1–13. https://doi.org/10.1080/15538362.2020.1775160.

Khan, TA., Anisah, SS., Mohd, HA., Hyun-Joong, K. 2019. Hydrothermal carbonization of lignocellulosic biomass for carbon rich material preparation: A review. Biomass and Bioenergy, 130:1-14. https://doi.org/10.1016/j.biombioe.2019.105384.

Le, P. and Nguyen, V. 2020. Materials porous carbon materials derived from areca palm leaves for high performance symmetrical solid-state supercapacitors. Journal of Materials Science, 55(24): 10751–10764. https://doi.org/10.1007/s10853-020-04693-5.

Liu, Z. and Zhang, F. 2009. Removal of lead from water using biochars prepared from hydrothermal liquefaction of biomass, 167: 933–939. https://doi.org/10.1016/j.jhazmat.2009.01.085.

Maalouf, A. 2020. Global municipal solid waste infrastructure: Delivery and forecast of uncontrolled disposal. Waste Management & Research, 38(9): 1028–1036. https://doi.org/10.1177/0734242X20935170.

Maitera, O., Ogbuaja, O. and Barminas, JT. 2011. Determination of trace metal levels in water and sediments of River Benue in Adamawa state, Nigeria. Journal of Ecology and the Natural Environment, 4: 149-156.

Mudryk, K., Jewiarz, M., Wr, M., Niemiec, M. and Dyjakon, A. 2021. Mechanical and chemical parameters of raw material. Energies, 14(4): 1-8.

Mulabagal, V., Baah, DA., Egiebor, NO. and Chen, W. 2017. Biochar from biomass: A strategy for carbon doxide sequestration, soil amendment, power generation, and CO_2 utilization. Handbook of Cilimate Adaptability. New York: Springers., pp. 1-31. https://doi.org/10.1007/978-3-319-14409-2.

Ni, B., Huang, Q., Wang, C., Ni, T., Sun, J. and Wei, W. 2019. Competitive adsorption of heavy metals in aqueous solution onto biochar derived from anaerobically digested sludge. Chemosphere, 219: 351-357., https://doi.org/10.1016/j.chemosphere.2018.12.053.

Parthasarathy, P. and Narayanan, SK. (2014). Effect of hydrothermal carbonization reaction parameters. Environmental Progress & Sustainable Energy, 33(3): 676–680. https://doi.org/10.1002/ep.

Picchio, R., Latterini, F., Venanzi, R., Stefanoni, W., Suardi, A., Tocci, D. and Pari, L. 2020. pellet production from woody and non-woody feedstocks: A review on biomass quality evaluation. Energies, 13(11): 2937-2957.

Qi, J., Zhao, J., Xu, Y., Wang, Y. and Han, K. 2018. Segmented heating carbonization of biomass: Yields, property and estimation of heating value of chars. Energy, 144: 301–311. https://doi.org/10.1016/j.energy.2017.12.036.

Qian, K., Kumar, A., Zhang, H., Bellmer, D. and Huhnke, R. 2015. Recent advances in utilization of biochar. Renewable and Sustainable Energy Reviews, 42: 1055–1064. https://doi.org/10.1016/j.rser.2014.10.074

Rajamohan, N., Rajasimman, M. and Dilipkumar, M. 2014. Parametric and kinetic studies on biosorption of mercury using modified Phoenix dactylifera biomass. Journal of The Taiwan Institute of Chemical Engineers, 45(5): 2622–2727. https://doi.org/10.1016/j.jtice.2014.07.004.

Rasheed, T., Sha, S., Bilal, M., Hussain, T., Sher, F. and Rizwan, K. 2020. Surfactants-based remediation as an effective approach for removal of environmental pollutants — A review. Journal of Molecular Liquids, 318: 1–15. https://doi.org/10.1016/j.molliq.2020.113960.

Roma, S., Encinar, JM. and Martı, G. 2009. Pyrolysis of various biomass residues and char utilization for the production of activated carbons. Journal of Analytical and Applied Pyrolysis, 85: 134–141. https://doi.org/10.1016/j.jaap.2008.11.035.

Saka, C. and Mas, M. 2012. Applications on agricultural and forest waste adsorbents for the removal of lead (II) from contaminated waters. International Journal of Technology, 9: 379–394. https://doi.org/10.1007/s13762-012-0041-y.

Schlemmer, W., Selinger, J., Andreas, M. and Spirk, S. 2021. Polysaccharides for sustainable energy storage – A review. Carbohydrate Polymers, 265: 1–23. https://doi.org/10.1016/j.carbpol.2021.118063

Shafiq, AA. and Alazba, MA. 2018. Removal of heavy metals from wastewater using date palm as a biosorbent: A comparative review. Sains Malaysiana 47(1): 35–49.

Shah, SS., Sharma, T., Dar, BA., and Bamezai, RK. 2021. Adsorptive removal of methyl orange dye from aqueous solution using populous leaves: Insights from kinetics, thermodynamics and computational studies. Environmental Chemistry and Ecotoxicology, 3:172–181. https://doi.org/10.1016/j.enceco.2021.05.002.

Silas, K., Azlina, W., Ab, W., Ghani, K., and Choong, TY. 2019. Carbonaceous materials modified catalysts for simultaneous SO_2/NOx removal from flue gas: A review. Catalysis Reviews, 61(1): 134–161. https://doi.org/10.1080/01614940.2018.1482641.

Siyal, AA., Shamsuddin, MR., Khan, MI., Rabat, E., Zulfiqar, M., Man, Z. and Azizli, KA. 2018. A review on geopolymers as emerging materials. Journal of Environmental Management, 224: 339-358. https://doi.org/10.1016/j.jenvman.2018.07.046.

Srinilta, C. 2019. Municipal solid waste segregation with CNN. 2019 5th International Conference on Engineering, Applied Sciences and Technology (ICEAST), 1–4. IEEE. DOI:10.1109/ICEAST.2019.8802522.

Tay, T., Ucar, S. and Karagöz, S. 2009. Preparation and characterization of activated carbon from waste biomass. Journal of Hazardous Materials, 165(1–3): 481–485. https://doi.org/10.1016/j.jhazmat.2008.10.011

Vakili, M., Zwain, HM., Mojiri, A., Wang, W., Gholami, F., Gholami, Z. and Salamatinia, B. 2020. Effective adsorption of reactive black 5 onto hybrid hexadecylamine impregnated chitosan-powdered activated carbon beads. Water, 12: 2242- 2256., DOI: 10.3390/w12082242.

Yadav, SK., Singh, DK. and Sinha, S. 2013. Adsorption study of lead(II) onto xanthated date palm trunk: kinetics, isotherm and mechanism. Desalination and Water Treatment, 51(34–36): 6798–6807. https://doi.org/10.1080/19443994.2013.792142