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Review Article

Multipurpose applications of bamboo as an activated carbon: An overview

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Abstract
Bamboo is a versatile resource for the synthesis of activated carbon. Low-cost precursors owing to a high growth rate and high carbon content in bamboo have consolidated its suitability as a renewable and notable alternative resource to activated carbon production. The attractiveness of bamboo activated carbon is due to its microcrystalline structure with a high porosity, fast absorption, and highly active surface area. Bamboo activated carbon can be synthesised via carbonisation and activation processes. The carbonisation process produces a substance with a colossal surface area to the mass ratio, which effective in holding various materials, minerals, humidity, odours, etc. Activation process involves the establishment of typical structures and advanced porosity to devise the high porosity of the solid activated carbon. Bamboo activated carbon can be used for energy-related reasons in environmental conservation, agriculture, soil amendment, animal feed additions, and wastewater treatment. It can also be used as a supplement in the composting and fermentation processes, utilised as a tar reduction catalyst in pyrolysis and gasification, as a pelletised fuel, and as a hydrogen production substrate. Numerous studies on activated carbon produced by diverse feedstocks are published in the areas of production, characterisation and possible uses and applications. Bamboo activated carbon is safeguarding its sphere of importance in today's era due to its multipurpose uses. The bamboo activated carbon is mostly used in the industrial, agricultural, and natural environment-related sectors. This paper presents a brief overview of the applications of bamboo activated carbon in numerous areas.

Keywords: Activated carbon, Adsorbent, Bamboo carbonisation, Pyrolysis

INTRODUCTION

Bamboo is a member of the *Poaceae* family of grasses (Ridara *et al.*, 2020). Bamboo is a fast-growing perennial, evergreen, and arborescent grass family that belongs to the Bambusoideaeae subfamily (Kigomo, 1988; Nfornkah *et al.*, 2020). The herbaceous bamboo (*Olyreae* tribe) and the woody bamboo (*Bambuseae* tribe) are both members of the Bambusoideae subfamily (Ramanayake *et al.*, 2007). Both differ from one another in terms of the existence of abaxial ligules (Zhang and Clark, 2000). The most current classification systems have divided 67 genera of woody bamboo into nine subtribes, based primarily on floral characteristics (Li, 1997).
Approximately more than 1,400 different species of bamboo are reported worldwide. In an altitude range ranging from just above sea level to 4,000 m, bamboo can grow up to 4,000 m tall (Behari, 2006). Bamboo distribution covers approximately 14 million hectares of the earth's surface. Approximately 80% of the total bamboos can be found in Asia (Tewari, 1992). The

largest diversity of species is located in Asia-Pacific, followed by South America, while the least diversity is found in Africa (Bystriakova *et al*., 2003; Du *et al.*, 2018). Du *et al.* (2018) reported that the entire bamboo forest area covers approximately 30538.35 $\times$ 10^3 hectares, with a low root-mean-square error (RMSE) of 611.10 $\times$ 10^3 hectares of the earth's surface.

Since 2005, 11,361 ha has been planted with bamboo, with 1,754 ha being privately held. Herbaceous bamboo is found primarily in the neotropics of Brazil, Paraguay, Mexico, and the West Indies, with roughly 110 species. The natural bamboo forest, known in Brazil as "Tabocais" and in Peru as "Pacales," encompasses over 600,000 hectares in Brazil, Peru, and Bolivia (Filgueiras and Goncalves, 2004; Das *et al*., 2008). There are around 1,680 species in the *Bambuseae* tribe, with nearly 127 genera, which are divided into three primary groupings (Clark and Oliveira, 2018). In the tropical and subtropical regions, the Paleotropical woody bamboo can be found in Africa, Madagascar, Sri Lanka, India, South Japan, Southern China, and Oceania. (Das *et al*., 2008). As highlighted by Liu *et al.* (2020), most of the Paleotropical woody bamboos are hugely valuable from the perspectives of economy, culture and ecology. Bamboo grows well in both cold-tolerant woodlands and hot, humid rainforests. It can endure and grow in cold temperatures of around -20°C. It can also withstand heavy rainfall of 32 to 50 inches (Goyal *et al*., 2005). Azeem *et al.* (2020) indicated that the bamboo can tolerate 700 to 4,500 mm of yearly rainfall although the optimal value is 1,200 to 2,500 mm.

Activated carbon (C) is thought to have originated in Ancient Egypt (1500 BC), where the Egyptians employed its adsorbent capabilities for water purification and medical uses. Over the last few years, a Swedish chemist named Karl Wilhelm discovered and revealed that gas can be absorbed by utilising charcoal (Cameron Carbon Incorporated (CCI), 2006). In recent decades, activated C has been employed as a decolorising agent in various sectors. However, the potential utility of activated C was really capitalised on during the First World War, when activated C was put into personal protective masks against hazardous gases during wars. As a result, granular activated C was employed throughout World War I and is still used today (Leimkuehler, 2010). At present, the granular activated C is typically applied as a water treatment material to eliminate pollutants (Brunner *et al*., 2020) effectively.

Activated C is a porous substance that is frequently utilised as an adsorbent in several industries (Cazetta *et al*., 2011). The porosity, pore-volume, and surface area are high (Hadoun *et al*., 2013). It also has a high degree of adsorption, high thermal stability, quick adsorption kinetics, strong chemical stability, and ease of regeneration (Gao *et al*., 2015). Due to the rapid expansion of society and the emphasis on tight environmental control, the production and usage of activated C surged during the 20th century. Environmental pollution has become a critical issue since the turn of the 21st century, where most of the pollution is caused by dyes, heavy metal ions, and etc. (Mallakpour and Behranvand, 2020; Moosavi *et al*., 2020). Activated C is a filtering material used to remove dangerous chemical components from exhaust gases, purify household drinking water, and treat waste water. Hence, the demand for activated C continues to increase due to its wide range of uses (Elisabeth *et al*., 2007; Im *et al*., 2019).

The chemical bondings and surface functional groups of heteroatoms define the chemical properties of an activated C. Properties such as intensity of polarisation, degree of hydrophobic, pH, and adsorption kinetics are influenced by the surface functional groups. The optimum temperature of activation is also influenced by the physico-chemical and biomass properties, the content of oxygen, electrical conductivity property, catalytic activity, and the targeted pollutant (Chand Bansal and Goyal, 2005).

Physical activation, chemical activation, and a mixture of the two approaches can activate activated C in theory (Ceyhan *et al*., 2013; Negara *et al*., 2020). Pyrolysis, a carbonising process undertaken in the absence or limited presence of oxygen and activation are the two basic techniques involved in the creation of activated C (Rovani *et al*., 2016). To begin, carbonaceous materials are pyrolysed at temperatures between 500 and 1,000°C to remove the O_2 and H_2 elements. Following the pyrolysis process, thermal activation takes place (Jawad and Abdulhameed, 2020) in an oxidising atmosphere at or above the pyrolysis temperature or in the presence of activating chemicals such as water vapour, CO_2, O_2, or any gas combinations (Bouchelta *et al*., 2008). Chemical activation is another process for activating the activated C. It can either be performed using one- or two-step techniques. When a precursor is combined with a dehydrating agent (for example, KOH, NaOH, H_2SO_4, HCl), the pyrolysis and carbon activation processes are carried out simultaneously in a one-step activation process (Sujiono *et al*., 2022).

On the other hand, the two-step activation involves carbonising a precursor and then activating the resulting char with an activating agent (Hadoun *et al*., 2013). The amount of ash generated is the fundamental distinction between one-step and two-step activations. The latter produces less ash than the former because the activator reacts primarily with carbon and not with biomass. As a result of the pores created by the ashes, the activated C produced by two-step activation has a higher degree of adsorption capacity and surface area (Thotagamuge *et al*., 2021). Furthermore, KOH is the most commonly utilised activator for high-quality activated C production, and it is the most important alkaline salt for activated C production (Chandra *et al*., 2009).

Carbonisation, and trailing by the activation are two different processes used to synthesize the bamboo into activated C (Mui *et al*., 2010). The carbonisation process boosts the carbon content and forms initial porosity. On the other hand, the activation process improves the pore structure and elevates the adsorption properties. The pre-prepared bamboos are cut into small pieces, washed and air-dried to eliminate moisture for the carbonisation process with a high heating rate of at least 600 to 800°C in the absence of air (Oss *et al*., 2022). As a common practice, the carbonisation process takes place in an oven. The residue generated by the carbonisation process acts as the core substance for the activation process. The activation process is set at different times and temperatures to activate the activated C as soon as the carbonisation is completed. Activation is deemed indispensable in the production of activated C as it enhances the material volume, disintegrates some bonds of turbostratic carbon structures that constitute surface functional groups and eradicate non-crystallized carbons from the bamboo activated C.

In terms of energy-related activities, bamboo activated C can be implemented and used in environmental conservation and agriculture. The number of activated C uses continues to grow, mostly in the industrial and agricultural sectors and in natural environment-related areas. Bamboo activated C can be used in a variety of ways, including as a soil amendment, animal feed additions, and wastewater treatment (Malinska, 2015; Pereira *et al*., 2014). Bamboo activated C can also be utilised for soil contaminant immobilisation and sewage waste treatment. Bamboo activated C can also be used as a supplement in the composting and fermentation processes (Tang *et al*., 2013; Mohan *et al*., 2014; Steiner *et al*., 2010; Malinska *et al*., 2014; Malinska and Dach, 2015; Wang *et al*., 2016; Li et al., 2017; Li *et al*., 2019; Yin *et al*., 2021). For instance, a study by Yin *et al.* (2021) demonstrated that application of bamboo activated C in the composting process altered the co-occurrence patterns of the bacterial communities that exerted high capacities for degrading carbon source, resulting in the increase in the activities of cellulase and urease. A composting study done by Li *et al.* (2017) indicated that 10% of bamboo activated C supplementation is appropriate for reducing antibiotic resistance genes in chicken manure compost. In another study by Li *et al.* (2019), the use of bamboo charcoal in composting process as a separating material could be used as an alternative strategy to the traditional composting method due to its effectiveness in reducing the NH_3 emissions and N loss. In addition, a study by Wang *et al.* (2016) indicated that bamboo charcoal incorporation enhanced the removal of antibiotics during manure composting, thus reducing the risk of antibiotic residue runoff when composts are used in agriculture.

Furthermore, bamboo activated C is utilised as a tar reduction catalyst in pyrolysis and gasification, as a pelletised fuel, and as a hydrogen production substrate (Paethanom *et al*., 2013; Bartocci *et al*., 2016; Yang *et al*., 2016; Bartocci *et al*., 2018; Liu *et al*., 2018; Kurniawansyah *et al*., 2020; Zhang *et al*., 2021; Guo *et al*., 2021). In a study by Zhang *et al.* (2021), a bamboo charcoal catalyst was applied to the co-pyrolysis of straw and polyethylene to produce H_2 and was found to increase H_2 production. Another study by Guo *et al.* (2021) found that the productivity of catalyst with bamboo-based activated C as catalyst carrier after thermal treatment in N_2 and CO_2 was significantly increased by 14 and 20%, respectively. Next, a research study by Kurniawansyah *et al.* (2020) utilized bamboo and converted it to activated C through carbonization at 773 K, followed by activation using an acidic solution. The activated C was used as catalyst support and glucose was successfully converted to polyols with an overall yield of approximately 3 wt% from the total products. In addition, a study by Liu *et al.* (2018) discovered that bamboo charcoal-based magnetic solid base catalyst possesses a mesoporous structure and high specific surface area, which can maintain high catalytic activity with potential applications in biodiesel production.

There are numerous published works and findings on activated C produced by various feedstocks regarding its production, characteristics and possible applications. Recent notable studies on activated C were done by Lütke *et al.* (2019), Naushad *et al.* (2019), Sharma *et al.* (2019), Wei *et al.* (2019), Alkherraz *et al.* (2020), to list a few. To explain, Lütke *et al.* (2019) produced an activated C from black bark waste to adsorb phenol. Naushad *et al.* (2019) studied the removal of cationic dye by arginine modified activated C. Sharma *et al.* (2018) introduced an adsorbent for decontamination of hexavalent chromium. The adsorbent was developed by integrating the ZnO tetrapods and activated C. Meanwhile, Wei *et al.* (2019) developed an inexpensive activated C created from agricultural wastes serving as a supercapacitor. Alkherraz *et al.* (2020) investigated the equilibrium and thermodynamics of the bioabsorption of lead, zinc, copper, and cadmium based on the olive branch-based activated C. This review paper attempts to compile and provide an overview of bamboo activated C applications in industry, agriculture, and operations associated with the natural environment.

BAMBOO ACTIVATED C IN ADSORBING HEAVY METALS

Activated C is used to immobilise heavy metals in solids, liquids, and gaseous environments due to its high degree of adsorption capabilities. Because they have a greater specific surface area and larger micropore volumes, activated C generated at higher temperatures has a higher degree of sorption property (Zhang *et al*., 2020). According to recent research, bamboo activated C can be utilised to remove heavy metals for environmental reasons (Thotagamuge *et al*., 2021). In a study, Huang and Wen (2014) used 4-5-year-old thorny bamboo as the raw material for synthesising activated C. The production of bamboo charcoal dropped and the pH value increased as the activation temperature was raised. According to the study, the thorny bamboo activated C made at 800°C for 1 hour had the highest iodine sorption value and Brunauer–Emmett–Teller (BET) surface area value. The findings indicated that prickly bamboo activated C produced at high temperatures for a short time had a high degree of adsorption capacity.

In another study by Ocreto *et al.* (2019), aqueous solutions were used from single-metal, bimetal and trimetal solutions, and the adsorption properties of modified activated C from bamboo were tested. The results showed that Cu, Cd, and Pb were 89, 87.4, and 99.5%, respectively, for single metal aqueous solution adsorption. The percentage adsorption of CuCd, CuPb, CdCu, CdPb, PbCu, and PbCd for the bimetal aqueous solution was 90.6, 98.9, 55.1, 80.7, 99.6, and 96.1%, respectively. On the other hand, the percentage of Cu, Cd, and Pb adsorption for trimetallic aqueous solution was 87.4, 73, and 98.4%, respectively. Taiwo and Chinyere (2016) investigated the use of Nigerian bamboo activated C on the several adsorption properties of six heavy metal ions commonly contained in refinery wastewaters. Adsorption isotherms in the study showed competition among various metals for adsorption sites on the Nigerian bamboo activated C. It can provide multiple and simultaneous metal-ions removing potentials, making it a better substitute for commercial activated C in applications.

BAMBOO ACTIVATED C IN REMOVAL OF PESTICIDE AND ORGANIC POLLUTANTS IN WATER

Chemical pesticides are widely employed in agriculture to ensure a decent crop (Aktar *et al.*, 2009; Hughes *et al.*, 2021). Chemical pesticides in the environment, on the other hand, have become a social issue as these toxins have been found in a variety of water, river, and soil sources in recent years. Depollution programmes for these water sources rely on broad policies centred on public understanding and water management. The new technologies that use activated C to extract contaminants that are doing havoc on the environment could be promising. A study by Santana *et al.* (2017) revealed that bamboo activated C was efficient for removing the three analysed pesticides, presenting high adsorption capacity for Furadan (868.98 mg g^{-1}), Metribuzin (756.47 mg g^{-1}), and 2,4-dichlorophenoxy acetic (274.70 mg g^{-1}). In another study by Chang *et al.* (2011), activated C tests produced excellent high adsorption capacities using methylene blue, iodine and phenol, namely 667, 1495, and 635 mg g^{-1}, respectively. These represent some of the highest activated C values ever recorded. For safranin dye, another extremely high capacity has been reported as 526 mg g^{-1}.

The enrichment of gaseous or liquid chemicals on the surface of a solid is referred to as adsorption. The binding forces between the individual atoms of the solid structure are not fully saturated in the active centres on their surface adsorbents. The adsorption of external molecules happens at these centres. Biochar is a porous substance with a large pore volume and a wide surface area. As a result, activated C as an adsorbent for removing pollutants from wastewater has attracted a lot of attention in recent years and has a lot of potential to solve the wastewater treatment problem (Yeo *et al.*, 2012). A study by Meng *et al.* (2013) investigating the effects of bamboo charcoal in improving the adsorption of organic pollutants in solution had concluded that Langmuir isotherm suits the equilibrium adsorption data better. The physical adsorption process of adsorption of organic materials from 2,4,6-Trinitrotoluene (TNT) red water has been further indicated by the Dubinin-Radushkevitch (D-R) isotherms. The adsorption kinetics have been found to obey a pseudo-second-order model, and intra-particle diffusion leads to the actual adsorption process. In another study by Suwanasing and Poonprasit (2014), bamboo waste activated C in wastewater treatment to remove acid dye revealed that when activated by NaCl and temperature, the bamboo activated C achieved equilibrium in 180 minutes and had a colour removal effectiveness of 77.36%.

Rhodamine-B (RhB) and acid fuchsin (AF) are commonly used organic dyes in spin printing, dyeing, and biomedical science. However, traditional biological treatment procedures are insufficient for total removal and degradation, poisonous to the environment and harmful to human health, due to the high effluent concentration and increased stability of these new synthetic colours. A study carried out by Yu *et al.* (2015) to investigate the removal of two basic organic dyes, namely Rhodamine B (RhB) and acid fuchsin (AF), by using nanostructure ZnO-bamboo charcoal composites found that bamboo charcoal with smaller particle sizes had a higher effect on removing colours. The removal rate of RhB was significantly higher in a strong acid state, although it was better for removing AF under a weak acid condition. Another study by Taiwo *et al.* (2010) revealed that organic concentration expressed as chemical oxygen demand (COD) decreased from an initial value of 378 mg L^{-1} for the first hour to 142 mg L^{-1} for the second hour, 152 mg L^{-1} for the third and fourth hours, and

156 mg L^{-1} for the final hour after using Nigerian bamboo activated C. The study's findings indicated that Nigerian bamboo could be turned into a high-capacity adsorbent that may be utilised to treat contaminated industrial waste fluids.

BAMBOO ACTIVATED C IN GAS ABSORPTION

Despite its ability to absorb heavy metals and remove organic contaminants from water, several studies have found bamboo an effective gas absorbent material. This coincides with Takashi *et al.* (2002), who investigated the adsorption effect of bamboo activated C when used as an adsorbent and deodorant at different carbonising temperatures. A study by Takashi *et al.* (2002) was to identify concrete countermeasures against "Sick Building Syndrome," also known as "Sick House Syndrome," by utilising the removal ability of charcoal, particularly bamboo charcoal, to reduce the problem of harmful indoor air pollution caused by the chemical. Takashi *et al.* (2002) found that the bamboo activated C exhibited a good removal effect for odorants, whereas the effect for ammonia is the best on bamboo activated C carbonised at 500°C. The merit of bamboo activated C is further consolidated by Chien *et al.* (2011), who affirmed the excellent adsorptive efficiency of the Taiwan native bamboo activated C for treating I-contaminated air in the laboratory.

In another study by Wei *et al.* (2012), granular bamboo-derived activated C is introduced as a convenient and frugal precursor for high CO_2 adsorption. Wei *et al.* (2012) also accentuated in their research that the adsorption-desorption process by the bamboo activated C is highly reversible. Instead of considering the granular bamboo, Huang *et al*. (2014) unfold the current knowledge on the CO_2 adsorption performance of Moso -bamboo activated C based on several carbonisation parameters. Fundamental characteristics of Moso-bamboo porous activated C consisting of pH value, iodine value, BET surface area, ash content, powder size, and pore volume were thoroughly analysed and it was reported that the optimum CO_2 adsorption occurs when the bamboo porous activated C is carbonised at 1,000°C for 2 hours with a mesh size of 170. In this work, the CO_2 concentration, as a function of time on the adsorption for Moso-bamboo with carbonisation temperatures of 600°C to 1,000°C was assessed for 120 hours. It was shown that the 170 mesh size Moso-bamboo activated C outshined all the criteria and parameters considered by substantially diminishing the CO_2 concentration, from 1.854% to 0.836%. Bamboo activated C has become a prominent adsorbent material for absorbing natural gas in the life sciences sector due to its cost-effective and renewable superlative qualities. Negara *et al.* (2016) gave a thorough overview of the research and application of bamboo activated C and its efficacy in treating natural gas. Sudibandriyo and Oratmangun (2018), on the other hand, demonstrated the use of a Betung bamboo activated C to recover hydrogen from a hydrogen-methane gas combination. They concluded that their experimental data were valid. The data fit the Langmuir isotherm model, implying that the Betung bamboo activated C is an excellent adsorbent for the separation of hydrogen-methane gas.

Rengga *et al.* (2017) suggested bamboo activated C as a functional material for eliminating volatile organic chemicals, specifically formaldehyde, that can cause indoor and outdoor air pollution. They found that bamboo activated C linked to silver nanoparticles outperformed solo bamboo activated C in terms of mass formaldehyde elimination in an adsorption experiment. They additionally validated that their experimental data from column tests agreed with Thomas and Yoon's model prediction with absolute variances below 5%. Sudibandriyo and Jamil (2018), on the other hand, suggested a gas mask filter prepared from the bamboo-based activated using H_3PO_4 and K_2CO_3. Tetraethyl orthosilicate (TEOS) compound was used to perform the dip-coating for the antipollution mask. The proposed mask can filter harmful gases with 0.103 mmol CO/gram AC adsorption capacity and 4.806 mmol CO_2/ gram AC (Sudibandriyo and Jamil, 2018).

Food preservation is regarded as critical to ensuring food security. Astuti *et al.* (2021) recently extended bamboo-activated C to aid food preservation. They used ori bamboo activated C and red ginger obtained from the Precet DAU Malang, Indonesia, as natural components to create an air purifier for the food cabinet that efficiently prevents bacteria growth that causes deterioration and sickness. According to their research, the best filter result is obtained by combining a 100% charcoal maturity level with a combination of activated C and ginger extract. Their study is regarded as a recent breakthrough in the use of bamboo activated C for commercial applications of unique or unconventional food preservation technologies that reduce degradation of the fresh flavour, texture, and nutritional content of food.

Conclusion

The bamboo activated C has good surface features and porosity properties, allowing it to be used to adsorb heavy metals, remove organic pollutants and chemicals such as pesticides in the agricultural sector, and for gas adsorption. Due to its versatile applications, bamboo activated C is securing its area of relevance in today's period. There is widespread use of bamboo activated carbon in industry, agricultural, and natural-environment operations. The important one is the use of bamboo activated C for the adsorption of heavy metals and removal of pollutants in both water and gas. The present overview of bamboo as an activated carbon would help to make it useful for its multipurpose applications.

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Conflict of interest
The authors declare that they have no conflict of interest.

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