RESEARCH PAPER

Activated Nano-Carbon from Natural Sources for Water Treatment: A Comprehensive Review

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ABSTRACT

The growing worldwide need for pure water has spurred greater research into eco-friendly and effective water treatment approaches. Activated nano-carbon, valued for its numerous pores and large surface area, continues to be a key material in purification methods that use adsorption. Lately, focus has turned to synthesizing activated nano-carbon from natural materials, like farm waste, because they are inexpensive, readily available, and better for environment. This detailed review covers the basics of activated nano-carbon's characteristics, as its surface area, pore arrangement, and how it adsorbs substances. It also looks at how the choice of starting material and activation processes i.e., physical, chemical, and using microwaves affect its qualities. Natural sources like coconut shells, wood, corn cobs, and rice husks are given special attention, with an analysis of how well they work for removing specific pollutants. The review thoroughly examines how activated nano-carbon from natural sources is used in water treatment, including the adsorption of organic pollutants, heavy metals, disinfection byproducts, and compounds that cause unpleasant tastes and smells. The benefits, such as being renewable, cost-effective, and having a smaller environmental impact, are discussed alongside drawbacks like inconsistencies in the raw materials. The review also evaluates the environmental and economic consequences, suggesting the use of life cycle assessments to maximize sustainability.

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INTRODUCTION

In modern society, growing industrial progress led to polluting water sources due to presence of variety of contaminants in it. These water pollutants may include metals, dyes, pharmaceutical products and some other organic and inorganic pollutants. Main sources of these pollutants include waste coming from different

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industries as textile, food, pharmaceutical industries, agricultural waste and pesticide sector. When these kinds of pollutants get discharged to water system, without any proper treatment, it resulted in contaminating water sources. This resulted in overall affecting environment and health of humans and all life forms [1]. Although other conventional methods of water purification are crucial, however, they find limitations for removal of variety of pollutants [2-6]. In this view, studies revealed that adsorption process is one of the widely used method as it is an efficient process to remove variety of water pollutants to improve the quality of water [7-10]. Easy processing, simple working and effective use of adsorbents make this process as one of the promising methods among all other traditional processes used [11-14] for removal of all contaminants from water [15-17]. In adsorption, variety of materials have been employed till yet however, use of activated nano-carbon (AC) (having highly porous and vast surface) is increasing day by day and is gaining more importance in modern society [18-21]. However, more research needs to be carried out for exploring the use of novel adsorbent materials other than activated nano-carbon, as bio-based adsorbents and nanomaterials. AC works by removing contaminants by adsorption due to presence of numerous active sites on its surface [22-24]. It is available in variety of forms like granular activated nano-carbon (GAC) and powdered activated nano-carbon (PAC). Each type of AC is well-designed for precise uses for the purpose of treating polluted water [25-27]. As a result, recent research focusses on synthesis and application of AC derived from a wide variety of natural sources [27-29]. This increasing interest indicates a broader trend towards using renewable resources for water treatment (Fig. 1).

This study will investigate the diverse array of natural starting materials that can be employed, the various preparation techniques utilized, and how these aspects impact the characteristics of the produced activated nano-carbon. Moreover, this review will analyze the efficacy of naturally sourced activated nano-carbon in eliminating a wide range of waterborne contaminants, contrast its benefits and drawbacks with alternative water treatment methods, and discuss its economic viability and ecological consequences. Lastly, it will emphasize recent progress in field and explore potential future directions for use of activated nano-carbon from natural sources in water treatment.

FUNDAMENTALS OF ACTIVATED NANO-CARBON

Activated nano-carbon is a group of carbon-based materials defined by their large surface

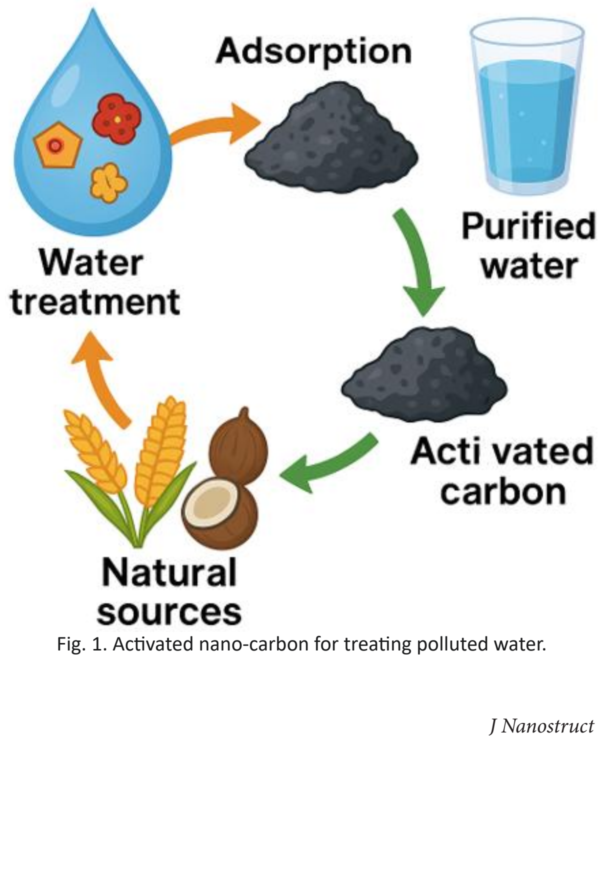

Fig. 1. Activated nano-carbon for treating polluted water.

area, pore size distribution, and potential to adsorb substances [30, 31]. A key feature of activated nano-carbon is its extensive network of interconnected pores, typically classified into micropores (diameter < 2 nm), mesopores (diameter 2-50 nm), and macropores (diameter > 50 nm). This tri-disperse pore structure is crucial as it allows for the adsorption of a wide spectrum of molecules with varying sizes. The fundamental structural unit of activated nano-carbon resembles that of graphite, with layers of carbon atoms arranged in a graphitic platelet structure[1]. However, the activation process disrupts the regular arrangement of carbon bonds on the surface of these crystallites, yielding highly reactive free valences. This imperfect arrangement creates the extensive internal surface area, which can exceed 500 m^2/g and in some cases reach up to 3000 m^2/g[1]. Several key properties of activated nano-carbon are particularly relevant to its application in water treatment. Surface area is directly proportional to the number of available adsorption sites and, consequently, the overall adsorption capacity of the material [32, 33]. Generally, a higher surface area translates to a greater ability to remove contaminants from water. The pore size distribution is another critical factor, as it dictates the type and size of molecules that can be effectively adsorbed within the pore network. Micropores are most effective for adsorbing small molecules, while mesopores and macropores play a vital role in the adsorption of larger molecules and in facilitating the transport of adsorbates to the micropores. Adsorption capacity refers to the amount of contaminant that can be retained per unit mass of activated nano-carbon [34]. This property is influenced by the surface area, pore structure, and the specific nature of the contaminant being removed. The particle size of the activated nano-carbon affects both the filtration rate and the availability of the surface area for adsorption. Finer particles generally offer a larger surface area but may result in slower filtration rates, while larger particles might exhibit reduced adsorption efficiency due to lower external surface area. Ash content, which represents the non-carbonaceous material present in the activated nano-carbon, is an important indicator of purity. Lower ash content is typically desired as it signifies a purer form of activated nano-carbon and can lead to improved adsorption performance. For water treatment applications, pH neutrality is a beneficial property, as it ensures that the activated nano-carbon does not significantly alter the pH of the treated water [34-36] (Fig. 2).

Contaminant removal by activated nano-carbon occurs via several adsorption mechanisms. Physisorption involves weak van der Waals forces or London forces between adsorbate and surface of activated nano-carbon. In contrast, chemisorption involves the formation of chemical bonds between the adsorbate and the activated nano-carbon surface [37-41]. Chemisorption can

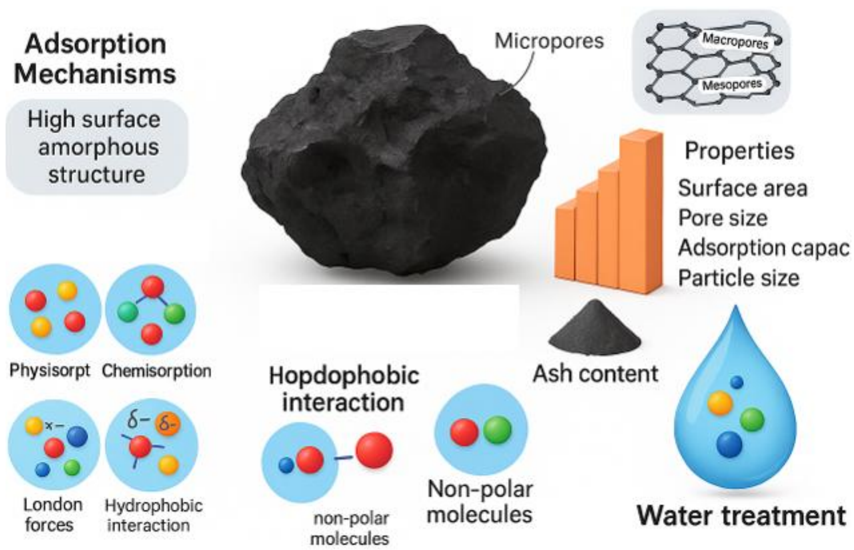

Fig. 2. Key features of activated nano-carbon.

be more selective than physisorption and may involve chemical reactions occurring on the surface of the activated nano-carbon. London forces, arising from temporary fluctuations in electron distribution around carbon atoms, lead to the formation of instantaneous dipoles that can induce dipoles in other molecules, resulting in attraction, particularly for non-polar molecules. Hydrophobic interactions also play a significant role, as the surface of activated nano-carbon often exhibits a preference for non-polar organic compounds in aqueous solutions, driving their adsorption. Electrostatic interactions can contribute to the adsorption of charged contaminants if the activated nano-carbon surface possesses oppositely charged sites, which can be particularly relevant for activated nano-carbons that have been modified. The dominant adsorption mechanism in a specific water treatment application depends on the characteristics of both the activated nano-carbon material and the specific pollutant being targeted for removal. While physisorption is a primary mechanism, activated nano-carbon does not readily bind to alcohols, diols, strong acids and bases, metals, and most inorganic compounds through this process alone. This limitation underscores the importance of considering the types of contaminants present in the water and potentially employing surface modifications or relying on chemisorption mechanisms for effective removal of these specific pollutants [42-45] (Table 1).

NATURAL SOURCES FOR ACTIVATED NANO-CARBON PRODUCTION

A diverse range of carbon-containing materials derived from renewable resources can be used as starting materials for making activated nano-carbon. Among these, coconut shells are often preferred due to their strong ability to adsorb substances, low amount of impurities, and high level of hardness. Their structure, which is mainly composed of very small pores, makes them particularly effective at removing tiny molecules found in drinking water. It's interesting to note that activated nano-carbon made from coconut shells was used in gas masks during World War I. Wood, including various types and sawdust, is another important natural source. Activated nano-carbon made from wood often has medium-sized and large pores, making it suitable for removing color from liquids and capturing bigger molecules. Pine wood is a commonly used type for this purpose. Agricultural waste offers a large and inexpensive supply of starting materials for activated nano-carbon production. This category includes a wide array of materials such as the shells of nuts (walnut, almond, pecan), the hard parts of fruits (olive, peach, cherry), corn plant material (leaves, stalks silk, kernels), rice husks, rice straw, soybean

Table 1. Key Properties and Characterization Parameters of Activated nano-Carbon [46-48].

Property/Parameter	Relevance to Water Treatment	Typical Measurement Units/Range
Surface Area	Directly related to adsorption capacity; higher surface area generally leads to better contaminant removal.	m²/g; 500 - 3000
Pore Size Distribution	Determines the size and type of molecules that can be adsorbed (micropores for small, mesopores/macropores for large).	Å or nm
Adsorption Capacity	Amount of contaminant that can be retained per unit mass of activated nano-carbon.	mg/g, g/g
Particle Size	Affects filtration rate and surface area availability.	mm, US mesh size
Ash Content	Indicator of purity; lower ash content generally desirable for better adsorption.	%
pH Neutrality	Important for water treatment to avoid altering the pH of the treated water.	pH units
Iodine Number	Indicates micropore content and activity level, often used as a measure of overall performance.	mg/g; 500 - 1200
Molasses Number	Measures mesopore content and adsorption of large molecules.	95 - 600
Tannin Adsorption	Indicates the ability to adsorb a mixture of large and medium-sized molecules.	ppm; 200 - 362
Methylene Blue Adsorption	Measures the adsorption of medium-sized molecules in mesopores.	g/100g; 11 - 28
Dechlorination Half-life Length	Measures the efficiency of chlorine removal.	Minutes
Apparent Density	Relates to volume activity and overall quality of the activated nano-carbon.	g/cc
Hardness/Abrasion Number	Indicates the resistance of the activated nano-carbon to physical attrition and breakdown.	%
Carbon Tetrachloride Activity	Measures the overall porosity of the activated nano-carbon.	%

coverings, sugarcane residue, groundnut shells, the fibrous residue after processing sugarcane, jute stalks, coffee waste, pineapple waste, outer layer of *camellia oleifera* seeds, bamboo, used tea leaves, paulownia flowers, strawberry seeds, and pistachio shells. Using these agricultural leftovers not only provides a sustainable alternative to traditional sources but can also result in unique surface properties depending on specific material used. Other natural sources that can be used to produce activated nano-carbon include peat, lignite coal, bituminous coal, and animal bones [49-55] (Fig. 3).

The choice of a specific natural source significantly affects the pore structure and how well the resulting activated nano-carbon can adsorb substances. This highlights the importance of carefully selecting the source based on how the activated nano-carbon will be used. When comparing different natural sources, several factors are important. The amount of carbon in the raw material varies, which directly affects how much activated nano-carbon can be produced [28, 56, 57]. Generally, plant-based sources tend to have less carbon compared to fossil fuels. How easily available and how cheap the source is are also major considerations, and agricultural waste and other plentiful plant-based sources offer significant advantages in this regard. How well a source can be used to create specific pore sizes is also crucial; for example, coconut shells are well-suited for making activated nano-carbon with very small pores, while wood is often better for medium-sized and large pores. The amount of ash and other impurities present can differ depending on the source, which might require different pre-treatment steps to ensure the final product is of good quality. Furthermore, the environmental impact of obtaining the raw material, considering factors like whether it can be regrown, is an increasingly important factor. Plant-based sources are generally considered more environmentally friendly than non-renewable sources like coal [58]. A thorough assessment of natural sources (Table 2) should therefore consider not only their carbon content but also their environmental impact and their potential for turning waste into valuable materials. This comprehensive approach is essential because the move towards using natural sources is largely driven by concerns about

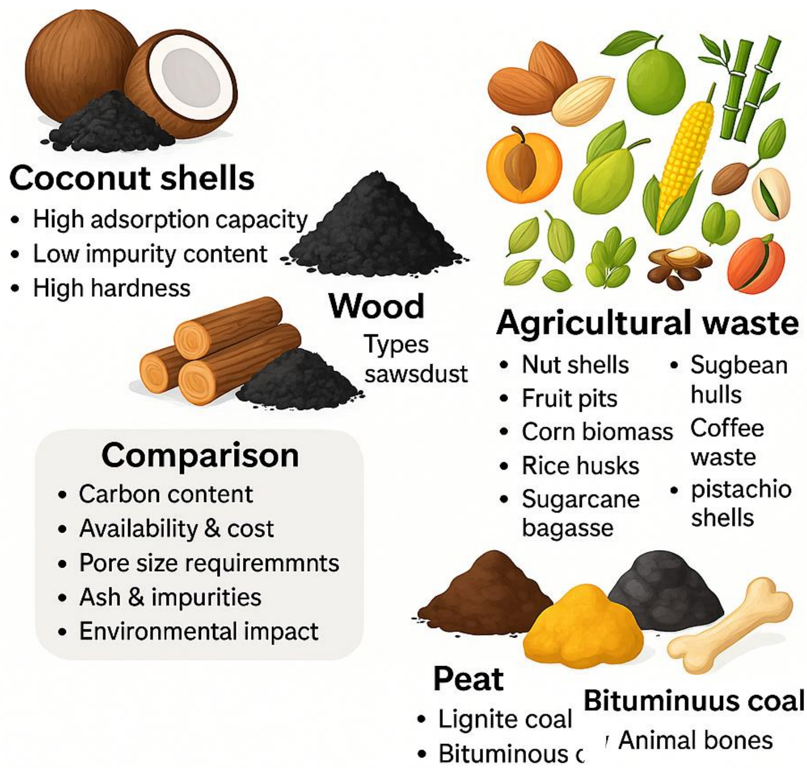

Fig. 3. Natural sources of activated nano-carbon.

sustainability (Table 2).

METHODS FOR PREPARING ACTIVATED NANO-CARBON FROM NATURAL SOURCES

The production of activated nano-carbon from natural sources typically involves an activation process, which can be broadly categorized into physical activation and chemical activation [31]. Emerging techniques also include microwave-assisted activation. Physical activation is generally a two-step process involving carbonization followed by activation/oxidation. The first step, carbonization (also known as pyrolysis), involves heating the natural source material at high temperatures, typically ranging from 600 to 900 °C, in an inert atmosphere such as nitrogen or argon. This process removes volatile organic compounds and moisture, leading to an increase in the fixed carbon content and the production of charcoal [31]. The second step, activation/oxidation, involves exposing the carbonized material to an oxidizing atmosphere, such as steam, carbon dioxide (CO2), air, or oxygen, at high temperatures, usually between 600 and 1200 °C, although lower temperatures (above 250 °C) can be used with air. Hot gases are employed to develop the porous structure of the activated nano-carbon. Physical activation relies on controlled oxidation reactions that selectively remove carbon atoms, thereby creating and enlarging pores within the material. The choice of the activating agent and the temperature at which the activation is carried out significantly influence the resulting pore structure of the activated nano-carbon. Carbonization is a critical preparatory step as it increases the fixed carbon content of the material, making it more amenable to effective activation in the subsequent stage [64-66].

In chemical activation, carbonization and activation occur in a single step. This method involves the impregnation of the natural carbon material with chemical activating agents. Common agents include acids like phosphoric acid, sulfuric acid, and acetic acid; strong bases like potassium hydroxide, sodium hydroxide, and potassium carbonate; or salts like zinc chloride and calcium chloride. The impregnation ratio, which is the ratio of the activating agent to the precursor material, is an important parameter that affects the properties of the final activated nano-carbon [67]. Following impregnation, the material is subjected to relatively lower high temperatures, typically ranging from 250 to 600 °C (although some processes may go up to 800-900 °C), to induce activation and the development of microscopic pores. A crucial step in chemical activation is the subsequent washing of the activated nano-carbon to remove any residual chemicals used in the process. Chemical activation generally offers advantages such as higher carbon yields, better consistency in quality, and shorter activation times compared to physical activation [68].

Microwave-assisted activation (Fig. 4) is an emerging technique that utilizes microwave energy to provide rapid, selective, and volumetric heating for the activation process. This method can be combined with either chemical or physical activation [69]. Microwave-assisted activation

Table 2. Comparison of Common Natural Sources for Activated nano-carbon Production [59-63].

Natural Source	Typical Carbon Content	Predominant Pore Size	Availability and Cost	Suitability for Water Treatment Applications
Coconut Shell	High	Micropores	Abundant, Moderate	Excellent for drinking water purification, removal of small organic molecules, taste and odor control.
Wood (Pine/Hardwood)	Moderate to High	Meso- and Macropores	Abundant, Low to Moderate	Good for decolorization of liquids, removal of larger organic molecules, taste and odor control.
Corn Cobs	Moderate	Variable	Abundant, Low	Potential for removal of heavy metals and organic pollutants; properties depend on activation method.
Rice Husks	Moderate	Micropores	Abundant, Very Low	Shows promise for removal of various pollutants; often requires chemical activation for high surface area.
Sugarcane Bagasse	Moderate	Variable	Abundant, Very Low	Potential for removal of dyes and heavy metals; activation method significantly affects properties.
Fruit Pits (Olive, Peach, Cherry)	Moderate to High	Variable	Abundant, Low	Can be effective for removing heavy metals and organic pollutants; properties depend on the type of pit and activation method.

offers several potential benefits, including shorter activation times, lower energy consumption, and high yields of activated nano-carbon [70, 71]. It is generally considered more environmentally friendly due to the use of inert gases and the absence of harsh chemicals, although it typically requires higher operating temperatures. While chemical activation is characterized by less energy costs and less activation temperatures but with high efficiency, high quality consistency and less times [72, 73]. However, chemical activation can potentially introduce mineral impurities into the activated nano-carbon if the washing step is not performed adequately [74]. The choice between these two methods depends on the desired characteristics of the activated nano-carbon, the type of precursor material being used, and various economic and environmental considerations. Each method presents its own set of advantages and disadvantages that need to be carefully evaluated for a specific application [75].

Both physical and chemical activation processes may involve pre-treatment and post-treatment steps. Pre-treatment of the natural source material can include washing, drying, crushing, and sieving to remove initial impurities and achieve the desired particle size for subsequent processing [28]. In some cases, specific pre-treatments like heat and acid treatments can be employed to enhance the surface area of spent activated nano-carbon before regeneration [76]. For certain precursors like pine sawdust, a period of storage might be beneficial to allow for the natural volatilization of rosin components [77]. Post-treatment of AC involves cooling as well as washing to remove residual chemicals, followed by drying as well as quality control tests to investigate its characteristics. Regeneration of used AC is important for sustainability, and impregnation with specific chemicals improve its pollutant removal capabilities [78].

APPLICATIONS OF NATURALLY SOURCED ACTIVATED NANO-CARBON IN WATER TREATMENT

Activated nano-carbon derived from natural

Fig. 4. Synthesis of activated nano-carbon.

sources has exhibited notable efficacy across a diverse range of water treatment applications, primarily attributable to its superior adsorption capabilities. A particularly significant application lies in the elimination of organic contaminants from water. This encompasses the adsorption of volatile organic compounds (VOCs), pesticides, herbicides, pharmaceuticals, endocrine disrupting compounds, solvents, fuel oil, polychlorinated biphenyls (PCBs), dioxins, and disinfection byproducts (DBPs) [79, 80]. Coconut shell activated nano-carbon, recognized for its finely porous structure, proves especially effective in capturing small organic molecules [81]. Conversely, wood-based activated nano-carbon, characterized by its larger meso- and macropores, is well-suited for the removal of larger molecular structures such as 2-Methylisoborneol (MIB) and Geosmin [82], which are common sources of undesirable taste and odor in water [83]. Moreover, activated nano-carbons originating from agricultural waste have demonstrated promising outcomes in the sequestration of various organic dyes, including methylene blue, methyl orange, and Orange G [84]. The broad-spectrum effectiveness of naturally sourced activated nano-carbon against a wide variety of organic pollutants underscores its significance in addressing water quality challenges. Furthermore, naturally sourced activated nano-carbon can be employed for the sequestration of inorganic pollutants, including specific heavy metals and arsenic (Fig. 5) [69].

While naturally sourced activated nano-carbon can be effective for certain heavy metals, modifications may be necessary to achieve high removal efficiencies for a broader array of inorganic contaminants. This highlights the ongoing research efforts to tailor activated nano-carbon properties for specific inorganic pollutant removal. In the context of drinking water treatment, activated nano-carbon assumes a pivotal role in disinfection byproduct (DBP) control. Granular activated nano-carbon is commonly implemented in drinking water treatment facilities for this precise purpose [85]. The ability of naturally sourced activated nano-carbon to enhance the aesthetic quality of water by eliminating unpleasant tastes and smells represents a significant benefit for consumer satisfaction and overall water quality. Beyond these primary applications, naturally sourced activated nano-carbon finds extensive utilization in the treatment of industrial wastewater streams [31]. Additionally, activated nano-carbon can be utilized to remove toxic and even radioactive substances from industrial wastewater streams [86]. This versatility renders it a cost-effective and

Fig. 5. Applications of activated charcoal.

environmentally conscious solution for treating a wide spectrum of industrial discharges, aiding in regulatory compliance and environmental protection. Extending beyond these major uses, naturally sourced activated nano-carbon is also integrated into small-scale and point-of-use (POU) water filters commonly found in residential settings. It finds application within the bottled water and beverage industry to ensure the consistent quality of their products, and in the filtration systems of swimming pools and spas to remove chloramines and other undesirable contaminants [87]. Furthermore, activated nano-carbon has established medical applications, including detoxification procedures and as an antidote for specific types of poisoning [88].

ADVANTAGES AND DISADVANTAGES OF NATURALLY SOURCED ACTIVATED NANO-CARBON

The application of activated nano-carbon derived from renewable origins presents a compelling and increasingly appealing strategy for purifying water. Notably, the wide availability of natural precursors, particularly agricultural byproducts, offers considerable economic advantages. These materials, frequently regarded as waste, can substantially decrease the production expenses associated with activated nano-carbon when contrasted with conventional sources such as coal, as emphasized in several investigations [89]. Beyond financial savings, the inherent sustainability of biomass and agricultural waste guarantees a renewable and dependable supply of raw materials for long-term utilization [90]. The sheer quantity of agricultural and forestry residues generated globally furnishes a substantial and easily accessible feedstock for activated nano-carbon manufacturing. Furthermore, activated nano-carbon originating from biomass generally exhibits a diminished ecological footprint compared to its fossil fuel-derived counterparts, such as coal [91]. Crucially, the characteristics of the resulting activated nano-carbon can be precisely tailored to fulfill the requirements of specific water treatment applications through careful selection of natural source and optimization of the activation process. This adaptability, coupled with the aforementioned ecological and economic benefits, positions naturally sourced activated nano-carbon as an increasingly favored substitute for traditional materials. Nevertheless, it is important to acknowledge certain limitations linked to natural precursors. The intrinsic variability in their chemical and physical attributes, influenced by factors such as origin, species, and harvesting methods, can result in inconsistencies in the final

Fig. 6. Advantages and disadvantages of activated charcoal.

product's quality and performance. Consequently, meticulous optimization of activation procedures, encompassing parameters like temperature, duration, and the concentration of the activating agent, becomes essential for each specific natural source to attain the desired characteristics and performance attributes. Certain biomass sources may possess a lower carbon content compared to fossil fuels, potentially leading to diminished yields of activated nano-carbon [92] (Fig. 6). Moreover, some natural sources may have a higher ash content, which can negatively affect the adsorption efficiency of the activated nano-carbon and may necessitate supplementary pre-treatment steps to minimize ash content. Addressing the inherent variability in raw materials and refining production processes are critical steps toward ensuring the consistent quality and dependable performance of naturally sourced activated nano-carbon for water treatment applications [93].

COST-EFFECTIVENESS AND ENVIRONMENTAL IMPACT ASSESSMENT

The adoption of activated nano-carbon from natural sources strongly supports the principles of economic efficiency in water treatment. The diminished cost of raw materials, such as agricultural waste and abundant biomass, can substantially lower overall production expenditures in comparison to activated nano-carbon derived from coal [94]. Furthermore, the feasibility of local production, particularly in regions with readily available agricultural waste, can lead to reduced transportation costs, further bolstering its economic viability. The capacity for granular activated nano-carbon produced from natural sources to be reactivated and reused multiple times offers considerable long-term cost savings. This economic advantage renders naturally sourced activated nano-carbon a particularly suitable solution for water treatment, especially in developing nations and rural areas where affordability is a key consideration [79]. From an ecological perspective, biomass-based activated nano-carbon generally demonstrates a reduced environmental impact throughout its life cycle compared to coal-based activated nano-carbon [58]. However, it's crucial to recognize that the specific environmental impact of producing activated nano-carbon from natural sources can fluctuate depending on the specific precursor used, the activation method employed, and the energy sources utilized during the process [95]. Conversely, physical activation methods are often considered more environmentally sound. Techniques as microwave-assisted activation offer the potential to reduce energy consumption in the production process [70]. Therefore, a comprehensive life cycle assessment (LCA) is essential for a thorough evaluation of the environmental sustainability of different production pathways for naturally sourced activated nano-carbon. Such assessments are vital for identifying the most environmentally responsible methods for producing these materials. The utilization of agricultural and forestry waste as precursors for activated nano-carbon aligns strongly with the principles of waste valorization and the circular economy [96]. This approach lessens our dependence on non-renewable fossil fuel resources and supports sustainable development goals related to clean water and sanitation, as well as responsible consumption and production. Even specific sources like coconut shells, often a byproduct of coconut industry, represent a sustainable and readily available feedstock. Overall, naturally sourced activated nano-carbon contributes to a more sustainable and resource-efficient approach to water treatment [28].

RECENT RESEARCH AND FUTURE TRENDS

Recent research in the field of activated nano-carbon derived from natural sources for water treatment has focused on several key areas. There has been a continuous exploration of novel natural sources, including a wide variety of agricultural wastes such as coffee waste, pineapple waste, and other unconventional biomass materials [28]. Researchers are also actively working on optimizing activation techniques, with a particular emphasis on microwave-assisted methods, to achieve enhanced surface area, porosity, and ultimately, improved adsorption capacity [69]. Another significant trend is the development of modified activated nano-carbons from natural sources. These modifications, often achieved through impregnation or surface functionalization, aim to enhance the selectivity of the activated nano-carbon for specific pollutants, such as heavy metals or pharmaceuticals. Furthermore, there is ongoing research into the use of more sustainable activating agents, such as acidic pyrolysis liquids like bio-oil and wood vinegar [97]. Studies on the regeneration of spent activated nano-carbon derived from natural sources are also crucial, with researchers exploring various methods to improve the efficiency and reduce the costs associated with regeneration. These recent advancements highlight a dynamic and continuously evolving field focused on expanding the range of usable natural precursors, improving the efficiency of production methods, and tailoring the properties of activated nano-carbon for increasingly specific water treatment challenges [98].

Looking towards the future, several potential research directions are emerging. There is a need for the development of highly porous activated nano-carbons from abundant yet underutilized natural resources. Further optimization of microwave-assisted activation techniques for a wider range of biomass precursors holds significant promise. The design and synthesis of hierarchical porous activated nano-carbons, with precisely controlled pore size distributions, could lead to enhanced adsorption kinetics and overall capacity. Investigating novel activating agents that are not only effective but also environmentally benign is another crucial area of research. Developing cost-effective and sustainable methods for the regeneration and eventual disposal of spent activated nano-carbon from natural sources remains a key challenge. The integration of naturally sourced activated nano-carbon with other water treatment technologies, such as membrane filtration or biological treatment, to create hybrid systems with synergistic effects warrants further exploration. The development of predictive models that can accurately correlate the properties of natural precursors and activation conditions with the final properties and performance of the resulting activated nano-carbon would be invaluable. Scale-up studies and pilot-scale demonstrations of promising production and application technologies are necessary to translate laboratory findings into real-world solutions. Comprehensive life cycle assessment studies comparing the environmental and economic sustainability of different natural sources and activation methods will be essential for guiding future development. Finally, exploring the catalytic properties of activated nano-carbon derived from natural sources in water treatment processes could open up new and innovative applications. Future research efforts should focus on addressing the current limitations and further enhancing the performance and sustainability of naturally sourced activated nano-carbon to fully realize its potential in water treatment technologies [99].

CONCLUSION

This paper has thoroughly examined the present understanding of employing activated nano-carbon originating from natural materials for purifying water. It delved into the definition and basic characteristics of activated nano-carbon, the wide array of natural starting materials that can be used, and the various methods utilized for its creation, encompassing physical, chemical, and innovative microwave-assisted activation approaches. The numerous uses of naturally derived activated nano-carbon in eliminating a broad spectrum of contaminants, ranging from organic substances and heavy metals to precursors of disinfection by-products and substances causing unpleasant taste and smell, have been discussed. Moreover, the benefits of utilizing activated nano-carbon from natural sources, such as its affordability, renewability, plentifulness, capacity for converting waste into valuable products, and generally reduced ecological footprint compared to traditional sources, have been emphasized alongside its drawbacks, including inconsistencies in the composition of raw materials and the necessity for refining production methods. Lastly, recent progress in research and encouraging future directions in the field have been outlined. The evidence presented strongly indicates that activated nano-carbon obtained from natural sources shows considerable potential as an economical, renewable, and environmentally sound substitute for conventional activated nano-carbon in a multitude of water treatment applications.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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