Eco-Innovative Waste-Derived Carbonaceous Nanocomposites: A Mini Review for Water Treatment

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Abstract: *Water pollution is a significant problem worldwide that requires creative treatment options from existing resources. This mini-review exposes the use of carbonaceous nanocomposites to remove water contaminants produced from waste materials. As for the use of pyrolysis, hydrothermal synthesis, co-precipitation, and ball milling techniques to produce high-performance adsorbents, nanoparticles are added to carbonaceous materials. This review highlights the need for a synthesis procedure that is easily scalable and economical and has an inconsequential environmental impact. In addition, further research should prioritize the improvement of material synthesis, investigate the diversity of nanocomposites, and guarantee the durability and ecological robustness of these materials.*

Keywords: Carbonaceous Nanocomposites, Waste-derived Materials, Water Treatment, Nanoparticle Incorporation

1. INTRODUCTION

Water is the basis of life on Earth, covering about 71% of the Earth's entire surface and about 60% of the human body [1]. Water plays a vital role in various biological and ecological processes, including hydration, digestion, and temperature regulation in humans. Health and overall body function can be affected without adequate water intake. Water is also essential in agriculture, industry, and energy production. Thus, clean and safe water access is essential to sustain health, support economic development, and conserve ecosystems [2], [3].

Although water is essential to daily life, water pollution cannot escape from a pervasive global issue that threatens the health and well-being of ecosystems. Rapid developing industrial activities, agriculture, and improper waste disposal contribute to the significant deterioration of water quality. In most developing countries, access to clean water is limited, leading to widespread waterborne diseases and high mortality rates. Conversely, developed countries face water pollution due to aging infrastructure and emerging contaminants. In surface water, hazardous substances such as pharmaceuticals [4]–[6], heavy metals [7], [8] and pesticides [9], [10], pose significant threats to human health and the environment. According to the World Health Organization (WHO), contaminated water is responsible for over 485,000 waterborne deaths annually, bringing to the urgent need for practical solutions to this crisis [11].

Considering the widespread occurrence of water pollution, there is an urgent need for sophisticated and effective water treatment methods. Chlorination and filtration, such conventional techniques often encounter challenges in effectively dealing with the intricate combination of contaminants, especially in current contemporary water sources [12]. Nevertheless, developing innovative solutions that can efficiently eliminate a diverse range of pollutants while being environmentally friendly and economically viable provides optimism for guaranteeing access to clean water [13], [14]. Advanced materials, namely nanocomposites, have become significant factors in improving the effectiveness of water treatment [15], [16]. By incorporating nanocomposites into conventional systems, the surface area's contact with contaminants may be significantly enhanced, leading to enhanced durability and lifespan of water treatment procedures [17], [18].

Researchers have played a pivotal role in advancing the understanding and development of novel carbonaceous nanocomposites in recent years. These carbon-based materials combine with other functional components to increase their performance in water treatment and owe their existence to the relentless efforts of these researchers. This material shows exceptional ability to adsorb contaminants since it has a large surface area and exhibits better catalytic properties, leading to excellent efficiency in eradicating various contaminants [19], [20]. Some examples of these kinds of materials include graphene-based composites, carbon nanotubes (CNTs), and activated carbon with metal nanoparticles [21]. There are also ongoing efforts to improve the synthesis of these nanocomposites in order to address the growing need for environmentally friendly water treatment solutions [22].

The development of eco-innovative materials, where the materials are produced from waste, is vital to minimize adverse effects on the environment and promote environmental sustainability. The use of waste-derived products helps efficient waste management and reduces dependence on non-renewable resources. These materials provide an environmentally friendly alternative to conventional water treatment techniques, promoting a more sustainable future. This strategy aligns with a circular economy, which involves turning waste materials into valuable outcomes for water treatment application while contributing to the environmental impact reduction [22], [23].

Based on the importance of innovating carbonaceous-based materials produced from the waste that has been stated, this mini-review paper briefly reviews relevant subjects in carbonaceous nanocomposites derived from waste materials to eliminate water contaminants. By examining the current state of research and identifying future directions, this paper sheds light on the potential applications and benefits of waste-derived carbonaceous nanocomposites and their effectiveness in removing various pollutants in water treatment. It highlights how waste materials can be transformed into valuable resources for sustainable water treatment solutions. Fig. *1* shows the schematic diagram of how the waste may be reused and transformed into beneficial output, particularly for water treatment applications.

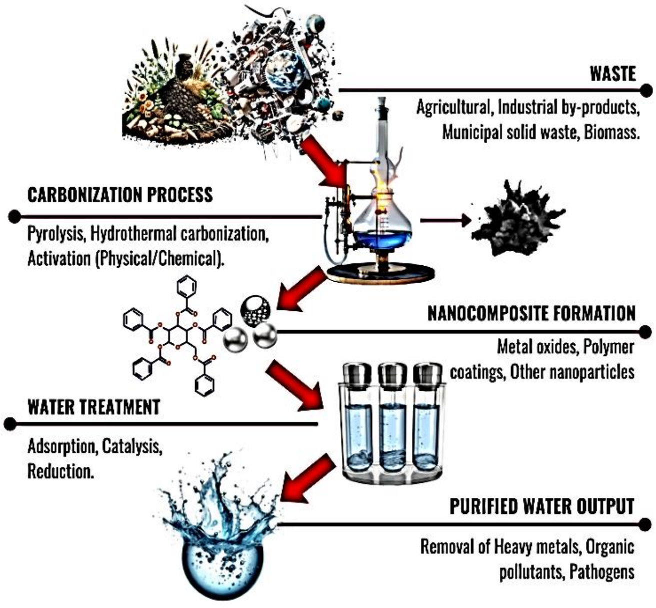

Fig. 1. Waste transforming into beneficial outcomes.

2. SOURCES OF WASTE-DERIVED MATERIALS USED AS CARBONACEOUS NANOCOMPOSITES PRECURSORS

2.1 Agricultural Waste

Agricultural residues, such as crop residues, vegetable residues, fruit peels, and husks, are a valuable raw material and substantial biomass resources for the development of carbonaceous nanocomposites. These abundant and renewable resources are often not fully utilized, making them potential for sustainable nanocomposite manufacturing. Agricultural waste such as rice husks, corn straws, coconut shells, and sugar cane have been extensively studied for their potential in producing activated carbon and graphene-based products. Carbonated materials obtained from waste can be modified with metal nanoparticles to create nanocomposites with a high capacity to adsorb pollutants and improve their antibacterial properties. The use of rice husk has been reported to produce activated carbon with a broader surface area, further increasing its ability to absorb materials [24], [25]. Activated carbon obtained from coconut shells has been shown to be very effective in removing pollutants from water [26], [27]. Additionally, research has shown that sugarcane bagasse is a very efficient source material for the production of carbon nanotubes (CNTs) and other nanomaterials [28]–[31].

Palm waste source also offers outstanding prospects in the manufacture of carbonaceous nanocomposites. Palm kernel shells and empty fruit bunches contain a large amount of *lignocellulosic* material, which makes them very suitable for conversion into carbon products with excellent performance. Research has proven that palm kernel shells can be efficiently used for the production of activated carbon and graphene oxide (GO), where both materials show remarkable properties for use in water treatment [32], [33].

2.2 Industrial By-products

Industrial wastes such as fly ash, slag, and spent catalysts can also be excellent precursors for carbonaceous nanocomposites. These by-products contain a large amount of carbon and can be easily converted into activated carbon or carbon nanotubes (CNT) using different series synthesis techniques. These materials are often considered useless waste in industrial operations and present difficulties for disposal. This waste reuse process for nanocomposite synthesis achieves efficient waste management while recovering valuable materials. It has been reported that the fly ash has been used to produce carbon nanotubes (CNTs) and graphene-based materials, leveraging the advantage of its high carbon content and diverse characteristics [34]. Spent catalysts, which often contain large amounts of carbon and metal elements, have been effectively converted into multifunctional nanocomposites with excellent adsorption and catalytic properties [35], [36]. The use of industrial by-products to create environmentally friendly water treatment solutions is in line with the concept of a circular economy, which aims to minimize environmental harm and optimize the use of resources [37].

2.3 Other Waste Sources

In addition to agricultural and industrial waste, some other categories of waste materials can be used as precursors for these carbonaceous nanocomposites, such as municipal solids, electronic waste (e-waste), and specific categories of plastic waste. Plastics that have been discarded could be pyrolyzed, turning them into carbon nanostructures. This process has the advantage of reducing waste and recovering valuable resources. Research has proven that polyethylene terephthalate (PET) bottles could be transformed into graphene-like materials that provide remarkable adsorption and catalytic properties [38], [39]. On the other hand, e-waste, which has a combination of organic and inorganic elements, may undergo recovery processing to recover necessary carbon materials [40]. This strategy addresses the growing issue of electronic waste and adds to the progress of high-performance nanocomposites for environmental purposes [41].

3. SYNTHESIS OF WASTE-DERIVED CARBONACEOUS NANOCOMPOSITES

3.1 Pyrolysis and Calcination Strategies

Pyrolysis and calcination are widely used thermal decomposition processes to convert waste materials into beneficial carbon compounds. Pyrolysis applies heat to organic waste in the absence of oxygen, causing the decomposition of complex organic compounds into more superficial carbon-rich structures. This technique is highly efficient for treating agricultural and municipal waste, producing activated carbon and carbon black materials with a large surface area and porosity. The pyrolysis process has been used to convert rice husks and coconut shells into activated carbon, which has been shown to have an excellent ability to absorb pollutants [22], [42], [43]. Moreover, in the manufacturing process, biochar also uses pyrolysis, and this material has attracted interest due to its capacity to function as a carbon absorber and, at the same time, act as a precursor for advanced carbon compounds [44]. Carbon nanoparticles for environmental applications have been effectively produced using biochar from agricultural residues such as corn stover and wheat straw [45]–[47].

In contrast, calcination refers to subjecting inorganic waste materials, such as industrial by-products, to high temperatures in the presence of oxygen. This procedure facilitates the formation of pure carbon structures by eliminating volatile constituents, which can then be used to produce nanocomposites. Fly ash and slag are commonly used waste materials that undergo calcination to produce carbon compounds [48], [49]. These processed materials can then be functionalized to improve their surface characteristics and used in various applications, including water purification [50].

3.2 Hydrothermal synthesis

Hydrothermal synthesis is one of the versatile methods that uses high-pressure water and medium temperature to create waste-derived carbonaceous nanocomposites. Hydrothermal carbonization (HTC) is a strategy that facilitates the conversion of biomass and other organic wastes into carbon-rich nanomaterials. During this process, organic precursors undergo dehydration and polymerization, forming carbonaceous structures that have beneficial properties for water treatment [51], [52]. Hydrothermal synthesis efficiently converts agricultural waste, such as sugarcane bagasse and palm oil waste, into carbon nanomaterials with a large surface area [53]. This method also allows the inclusion of further functional elements, such as metal nanoparticles, to improve the performance of the resulting nanocomposite further [54], [55].

3.3 Co-precipitation

Co-precipitation is a chemical synthesis technique in which several components are precipitated simultaneously from an aqueous solution, creating a composite material. This method is handy and beneficial to integrate metal nanoparticles into waste-derived carbonaceous structures. Co-precipitation has been used to produce iron oxide-carbon composites using agricultural waste. This composite has exceptional adsorption and catalytic properties for water treatment, as reported in references [56] and [57]. The properties of the resulting nanocomposites can be precisely controlled by manipulating co-precipitation conditions, such as pH and temperature [58]. This approach offers a simple and effective way to produce versatile nanocomposites for water treatment applications.

3.4 Ball Milling

The ball-milling method is a mechanical procedure that requires mechanical grinding and mixing of waste materials to produce a fine powder, which can then be used in the synthesis of carbonaceous nanocomposites. This technology is advantageous because its simplicity and scalability suit large-scale manufacturing well. Ball-milling applies mechanical pressure to the waste material, causing chemical reactions and structural changes, thus producing carbon nanomaterials with enhanced surface characteristics [59]. Ball-milling has been used to transform waste graphite and biochar into graphene nanoplatelets and carbon nanostructures [60]. In addition, Ball-milling is very useful because it can be integrated with other synthesis methods, such as pyrolysis and hydrothermal procedures, further to improve the characteristics of nanocomposites [61].

4. INCORPORATION OF NANOMATERIALS INTO WASTE-DERIVED CARBONACEOUS COMPOSITES FOR WATER TREATMENT APPLICATIONS

Integrating nanoparticles with waste-derived carbonaceous material to form carbonaceous nanocomposites can provide noteworthy advantages, especially for water treatment. These nanocomposites exhibited increased adsorption capacity, increased surface area, and better catalytic properties compared to their components, making them highly efficient in removing various contaminants. Nanomaterials, including metal nanoparticles, metal oxide nanoparticles, graphene, and CNTs, have unique characteristics that can improve the overall performance of carbon-based materials. This strategy, in turn, provides a more effective and environmentally friendly solution for water purification [62].

Metallic nanoparticles such as gold (Au), silver (Ag), and iron (Fe) are often used to enhance the properties of carbonaceous materials. These nanoparticles increase the ability to attract and react with materials, making them suitable for water treatment applications [55]. Ramasundaram et al. [63] have proven the effectiveness of Ag nanoparticles combined with activated carbon produced from cashew nut shells in eliminating Escherichia coli (E. coli) and *Staphylococcus aureus (S. aureus)* from water in their study, indirectly revealing better antibacterial properties of the composite material. Strategies used to incorporate metal nanoparticles into carbon matrices include chemical reduction, impregnation, and in-situ growth procedures. This approach ensures that the nanoparticles are evenly distributed in the matrix [64].

Moreover, water treatment performance with waste-derived carbonaceous materials can be improved by including metal oxide nanoparticles, such as titanium dioxide (TiO_2), zinc oxide (ZnO), and magnetite (Fe_3O_4). These nanoparticles have photocatalytic and magnetic capabilities to remove organic pollutants and heavy metals from water. A study by Wen et al. [65] implemented Fe_3O_4 nanoparticle incorporation into biochar made from tea leaf waste where a co-precipitation approach was used to achieve a uniform dispersion of Fe_3O_4 nanoparticles in the carbon matrix. The combination resulted in the creation of a nanocomposite material that has improved adsorption capacity for the removal of Cu(II) and Zn(II). This study shows that including metal oxide nanoparticles in carbonaceous materials can improve nanocomposites' performance in water treatment applications.

Furthermore, graphene and its derivatives, such as GO, are incorporated into waste-derived carbonaceous materials in order to utilize the superior surface area and potential to function better. This objective often uses chemical vapor deposition, solution-based mixing, and in-situ reduction. Graphene-based nanocomposites have superior adsorption capacity and good mechanical properties, making them highly efficient in pollutant removal. Huang et al. [66] combined graphene oxide (GO) with biochar made from corn-derived sawdust, resulting in a nanocomposite material with a remarkable ability to remove sulfamethazine (a type of antibiotic) from water. The better performance is also closely related to the enlarged surface area and functional groups offered by GO [60].

Additionally, CNTs are incorporated into waste-derived carbonaceous materials to increase mechanical strength and the ability to adsorb contaminants. Before pyrolysis or post-synthesis functionalization, CNTs are combined with precursor materials to incorporate them into the carbon matrix. For instance, integrating CNTs into biochar produced from sugarcane bagasse biomass showed an increased ability to adsorb methylene blue (a type of organic dye) from wastewater [67]. These results show that carbon nanotubes (CNTs) have the ability to improve the effectiveness of carbon-based materials obtained from waste in applications related to water treatment.

In a nutshell, most studies incorporate waste-derived carbonaceous material with other nanoparticles to enhance the material's effectiveness in removing specific contaminants. Each composite component will have a synergistic effect and contribute to each other's advantages in contaminant removal. Table 1 displays the performance of waste-derived carbonaceous functional nanoparticles for eliminating contaminants in water.

Table 1. Contaminant removal capacity by waste-derived carbonaceous functional nanoparticles.

Waste-Derived Carbonaceous	Nanoparticle	Contaminants	Maximum removal capacity (mg/g)	Ref.
Corn stalk-derived biochar	Nano-zero valent iron (nZVI)	Pb^{2+}	95.1,	[45]
Corn stalk-derived biochar	nZVI	Cu^{2+}	161.9	[45]
Corn stalk-derived biochar	nZVI	Zn^{2+}	109.7	[45]
Bamboo sawdust-derived biochar	GO	Sulfamethazine	101.61	[66]
Rice husk-derived Biochar	nZVI	Nonylphenol	19.31	[68]
Rape straw-derived Biochar	Manganese Oxide (MnO)	Cd(II)	81.1	[69]
Sugarcane leaves-derived Biochar	Magnesium Hydroxide (MgOH) /Aluminium hydroxide, $Al(OH)_3$	Phosphate	81.83	[70]
Corn plant straw-derived Biochar	Sulfur/nZVI	Tetracycline	505.68	[71]
Municipal wasted sludge-derived activated biochar	Sulfur/ nZVI	Tetracycline	174.06	[72]
Coconut Shells-derived Activated Carbon	Fe_2O_3	Pb	11.9	[26]
Coconut Shells-derived Activated Carbon	Fe_2O_3	Cr	22.1	[26]
Corn Cob-derived Activated Carbon	ZnO	Arsenic	25.9	[73]
Corn Cob-derived Activated Carbon	ZnO	Pb	25.8	[73]
Pomegranate-extracted Activated Carbon	nZVI	Furfural	222.22	[74]

5. FUTURE PERSPECTIVES

5.1 Emerging Trends in the Development of Eco-Innovative Carbonaceous Nanocomposites

In recent years, significant progress has been made in developing environmentally friendly carbon-based nanocomposites. The emerging conception aims to improve the properties and efficiency of these materials by integrating advanced synthesis methods with state-of-the-art nanoparticles. A noticeable trend is the use of green synthesis approaches. These methods often use plant extracts, microorganisms, and other bio-based components as reducing agents to produce environmentally friendly nanocomposites. Using this method to build advanced nanocomposites can effectively reduce the negative impact on the environment.

5.2 Potential Areas for Further Research and Innovation

There are still several areas where further research and innovation are required. An area that might be explored is the optimization of synthesis procedures to improve these materials' scalability and cost-effectiveness. It is essential to devise effective and sustainable techniques for producing water treatment systems on a large scale.

In addition, there is a growing interest in exploring the potential of eco-innovative carbonaceous nanocomposites derived from agricultural waste for the purpose of eliminating medicinal substances. These pharmaceutical by-products are classified as emerging pollutants that significantly harm human health and the environment. Research has shown that carbonaceous nanocomposites have the ability to effectively adsorb and degrade various pharmacological substances, including antibiotics, analgesics, and hormones [75]. Additional research is necessary to improve the effectiveness of these substances in removing a more comprehensive range of pharmaceuticals from surface water and to understand more comprehensively the basic mechanisms involved in their adsorption and degradation.

Furthermore, exploring multifunctional nanocomposites that can eradicate various pollutants is an exciting research area. Combining many nanomaterials with complementary properties enables the production of hybrid composites that can effectively target various pollutants. These efforts could lead to more efficient and adaptable water treatment technologies to address complex pollution issues.

Understanding the long-term stability and environmental consequences of these nanocomposites is essential. Future studies should emphasize the durability and reusability of these materials in natural water treatment systems to ensure the safe and durable use of eco-innovative carbon nanocomposites in water treatment applications.

6. CONCLUSION

In conclusion, raw materials from agricultural waste, industrial by-products, and other waste can be functionalized into carbonaceous materials, which are helpful in treating polluted water. The innovation of this material shows excellent adsorption capacity. Pyrolysis, hydrothermal synthesis, co-precipitation, and ball milling are techniques that are widely used in the production of waste-derived carbonaceous material. Incorporation of nanoparticles such as metals, metal oxides, graphene, and carbon nanotubes can improve pollutant removal performance. Even so, obstructions still need to be overcome to improve the synthesis process's scalability, cost-effectiveness, and sustainability. Based on the review, many research gaps still need to be closed. Further research is encouraged to explore environmentally friendly synthesis methods, enhance the elimination of pharmaceutical and emerging contaminants, and guarantee the usability of this material in natural water. This study found that functionalizing waste-derived carbonaceous material with nanoparticles offers a viable approach to achieving sustainable and efficient clean water solutions.

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