Carbon Based Material: A Step Towards Sustainable Development

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Abstract

The materials used in carbon-based structures are the most flexible renewable energy (i.e., production or storage) and environmental protection (like purification or remediation). However, there is a need and a desire to create traditional carbon resources in increasingly sustainable forms (such as activated carbons, carbon aerogels or carbon nanotubes and so on), especially when considering the entire life cycle i.e., from the "cradle" of the forerunner to "green" manufacture and the "grave" of the product. The use of natural, abundant, and more renewable precursors combined with simpler, lower energy synthetic processes that can help reduce the usage of harmful materials or the production of greenhouse gases might be seen as key factors in the development of new technologies in this regard and may even mimic some aspects of natural carbon cycles/production.

Keywords: sustainable, activated carbon, green method, carbon material.

1. Introduction

Due to its potential in biomedicine, carbon materials have been exploited extensively especially as the base for diagnostic nanodevices for in vitro diagnosis [1-4]. Applications for nanostructured carbon materials are also discussed. are gaining popularity, and they are becoming a hot topic in current materials research. However, due to the immense energy, resource, and CO_2 emissions generated throughout the manufacturing process, this rapid progress has produced serious environmental issues. For activated carbon, The average energy requirements were 97 MJ kg^{-1}, and the average greenhouse gas emissions were 6.6 kg CO_2 eq kg^{-1}, which is a common form of carbon in industry. These figures come from the life cycle assessment. While the average energy consumption for Graphene synthesis ranged from 1100 to 1640 MJ kg^{-1}, the ramifications of innovative carbon materials throughout preparation and uses are anticipated to be examined to ensure sustainable development. The more cost and also complexity of lengthy scale production of these futuristic carbon materials may be a barrier to their widespread use, highlighting the importance of sustainable precursors and a green path. Furthermore, future- proof carbon compounds are expected to have new or enhanced features over classic carbon materials like active carbon, graphene or carbon nanotubes (CNTs).

A few reviews have recently described the most recent developments for chemical and environmental uses of nanocarbon materials [5-9] , to the best of our knowledge;

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however, explicit reviews of important advancements have sustainable carbon materials been produced rarely.

Because current carbon materials are so important in catalysis and related sectors, there has been a lot of effort put into developing sustainable carbon materials [10-12]. As shown in Figure 2, We are concentrating on recent advances in the utilisation of biomass and its derivatives for the sustainable carbon precursor synthesis of porous carbon materials.

2. Sustainable precursors for carbon materials*:*

New applications in catalysis and biomedicine are being developed. For the use of sustainable and internationally available precursors, the process of novel functional and sustainable carbon materials is desirable. Biomass carbon atoms have the benefit of being both sustainable and scalable. It appears that synthesis of carbon compounds depends on plentiful carbon-rich biomass is appropriate in this regard. Biomass, for example, has a 104.9 gigatons annual net primary production in the world. [13], making it the wealthiest renewable resource on the planet. Agriculture and forestry, in particular, produce a huge volume of biomass waste each year. Furthermore, biomass heteroatoms can be used as a versatile designer platform for a variety of applications.

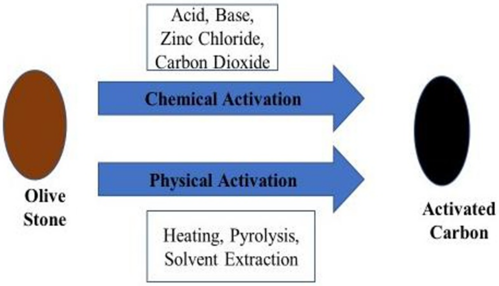

Figure 1. Production of activated carbons as adsorbents from olive stones.

By changing the surfacee and electrical properties of carbon, the mixing of heteroatoms made of carbon materials can considerably broaden its potential applications. Other elements in biomass (like O, N or S) may be employed as a group of catalytic active sites and precursors of heteroatom dopants to change the material's hydrophilicity [14-16]. Carbons that have been co-doped with one or more distinct heteroatoms, such as S and N or P and N have been generated from biomass. Additionally, single element heteroatom doping to achieve increased catalytic performance [17-18]. Furthermore, the co-doped carbon compounds' inherent photo oxidase activity (e.g., graphitic carbon nitride) contributes to their biosensing. Therefore, biomass heteroatoms can also be used for versatile designer platform with a variety of applications.

Furthermore, the catalytic performance of biomass is determined by its unique structure. The catalytic efficiency of the material is determined by the pore structure with variable size distribution, which affects substrate transport [19]. The use of micro-/mesopores in the pore structure improves mass-transfer efficiency during catalytic reactions. Micropores (2 nm) give a large surface area and a large number of intermediate adsorption sites in a hierarchical pore structure, for mass transfer substrates, mesopores (2–50 nm) offer a thicker channel [20–21]. Proteins, polysaccharides, nucleic acids or lipids are examples of the self-assembling polymers that nature is master at using to create a range of porous structures in biomass. In addition, holes can be created when high temperature carbonization causes materials to break down and release water and carbon dioxide [22]. Producing carbon compounds from natural biomass that have distinct hierarchical porous structures and clearly defined forms is even harder. Additionally, holes may be produced when materials undergo high temperature carbonization, which results in the release of water and carbon dioxide from the materials [22]. Therefore, it is highly valued to use sustainable techniques to use biomass as a precursor. For metal catalysts with carbon support in hydrogenation processes, functional groups have detrimental effects. When carbonaceous precursors are carbonised, a sizable amount of CO_2 moreover, emissions of volatile organic compounds (VOCs) into the atmosphere (such as biomass or organic materials).

An environmentally friendly and effective method of producing Controllable microstructure and morphology in graphitized carbon and CO_2 at extremely low temperatures was investigated by Liang et al. This method offered a way to produce graphitized carbon from greenhouse gases. [32] In order to optimize the financial gains and sustainability of carbon materials obtained from biomass, Zhang et al. implemented a novel technique to enhance the preparation of useful carbon materials from biomass waste pyrolysis gases.

3. **Sustainable carbon material strategies*:***

The surface chemistry and porosity of sustainable carbon are significantly influenced by the synthetic process. However, because the porosity of these carbons from biomass is frequently influenced by the architectures of their antecedents, it is rather challenging to precisely regulate the porous structure [33-34]. As a result, producing porous carbon with manageable structural or also chemical properties is still difficult, mainly in an easy, affordable, sustainable manner.

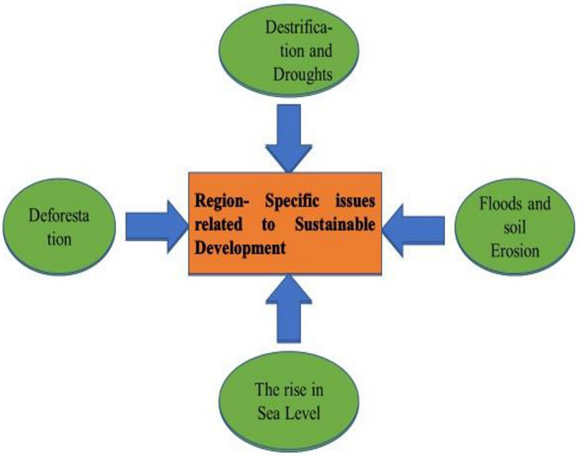

Figure 2. Global issues related to Sustainable Development.

4. ***Sustainability of Carbons created by hydrothermal carbonizing biomass:***

The main technique for creating carbon compounds is called hydrothermal carbonization (HTC), and it has numerous potential applications [35-36]. Natural plant matter, agricultural waste, and by-products from forests can all be used as carbon precursors. Hydrocarbons are converted into tiny molecules during the HTC process, such as both hydroxy methyl furfural and levulinic acid, which then undergo a number of intricate processes, to produce the conjugated hydrocarbons, processes like dehydration, decarboxylation, polymerization, and Diels-Alder reactions are used. The final shape, porosity and physicochemical characteristics can be properly measured to suit a variety of applications thanks to advancements in polymer and colloid research. It falls under the category of a "green" process since it doesn't need organic solvents, surfactants, or catalysts can be performed with minimum carbon dioxide emissions and mild temperatures [37].

Banana peels were used in a one-step hydrother to create highly fluorescent carbon dots with pronounced blue fluorescence [38] by Nguyen et al. The obtained carbon compounds are typically nonporous or microporous, despite the HTC step being a minimum cost approach to generate carbon directly from biomass. This indicates that it is challenging to manage the porosity of the carbon composites produced using the HTC process [29, 39]. Consequently, adding a secondary component that serves as a porosity-directing agent is beneficial. In order to control the porosity of carbon materials, it is therefore preferable to introduce a secondary component that serves as a directing porosity agent. the production of carbons with clearly defined structures that are sustainable and porosities is still quite difficult and this field needs more investigation. By using hydrothermal carbonization, xylose self-assembly, Liu et al. created an ordered mesoporous carbon with the block copolymer F127 a nano ellipsoid morphology [40].

Additionally, it has been claimed that using various hydrothermal conditions, including adding borax or creating hypersaline conditions, can produce carbons with a high specific surface area. For instance, the surface area of the carbon produced by the HTC of glucose in LiCl and $ZnCl_2$ was 673 m^2g^{-1} [34]. Furthermore, because the carbons produced by the HTC process often have low carbon contents (less than 60%), they might not be regarded as "genuine" carbon materials. In order to create a structure of graphite in the generated carbon material more carbonization is therefore required. Additionally, even if the HTC techniques are inexpensive, the energy consumption is high at high temperatures is anticipated to be substituted utilizing solar energy in order to create a sustainable method.

5. ***Green Activation Method Synthesized Sustainable Carbons:***

In particular catalytic applications, the characteristics of carbon materials are substantially determined by their porous structure. Therefore, the search for carbons with high surface areas, tunable hierarchical pores, and motivates ongoing efforts to create effective synthesis methods [41]. A cost-effective option to boost specificity is an activator-assisted activation approach. The less yield also high dosage of hazardous activator or cleaning agent limit chemical activation's ability to create carbon materials with hierarchical porous architectures or the high specific surface areas, despite the fact that it is a useful and frequently used technique. For instance KOH is a powerful alkalinity's violent activator, which is bad for the environment [42-44]. Additionally, the application of KOH during high temperature processing might alter the shape of the initial carbon material and significantly boost surface area [45-46]. More work is still needed to create a more straightforward procedure that is more practical in terms of cost effectiveness or environmental friendliness. The More work is still needed to create a less complicated method to produce big surface area carbon extracted from biomass in order for it to be more economically and environmentally advantageous.

Utilizing alternate, secure activation agents like $KHCO_3$, $NaHCO_3$, or alkali carbonates like K_2CO_3 and Rb_2CO_3 is one effective approach [47]. In order to create a porous biomass-derived carbon, ‘Wang et al. [42] utilized gas-producing chemicals reactions. This work was motivated by employment of gaseous reagents (such as baking soda or yeast) to create a porous-structured loaf of bread [48, 49]. By carbonizing inorganic biomass in one step or by pyrolyzing biomass without an activator, that is a potential technique for creating carbon with a wide surface area, the in situ self-activation could be accomplished. This simple technique demonstrates that it works with both biomass and biomass. Both biomass and its products can be processed using this simple procedure. Additionally, the pore structure and morphology of the carbon produced are influenced by the composition of the biomass (namely, cellulose, hemicellulose and lignin).

To investigate the impact of various ratios of each component on the sustainable carbons, Wang et al. used a ternary mixture of cellulose, hemicellulose, and lignin (Figure 3) [49]. During pyrolysis, cellulose and hemicellulose include a number of oxygen-containing groups disintegrated into H_2O, CO_2, and CO, leaving micropores behind. Lignin, on the other hand, included chemically inert and having numerous aromatic units, it was a nonporous carbon material. Both biomass and its products can be processed using this simple procedure. Additionally, the pore structure and morphology of the carbon produced are influenced by the composition of the biomass (namely, cellulose, hemicellulose, and lignin).

Wang et al. studied the effects of various ratios of each component using a ternary mixture of cellulose, hemicellulose, and lignin. Numerous hydroxyls are cellulose and hemicellulose dehydrated and condensed among different polymers after the addition of $KHCO_3$ to the pyrolysis process to produce macropore structure. While the lignin's -O-4 bands underwent pyrolysis, producing benzene-containing units that eventually led to the production of carbon nanosheets. By altering the raw material composition, Tan et al. produced a variety of porous carbon compounds with different specific surface areas [50]. In comparison to hemicellulose and lignin, cellulose tends to create carbon compounds with a greater surface area that have a microporous or mesoporous structure. Furthermore, when the lignin level was less than 50%, a blend of lignin, cellulose, and hemicellulose might display a 3D hierarchically porous structure.

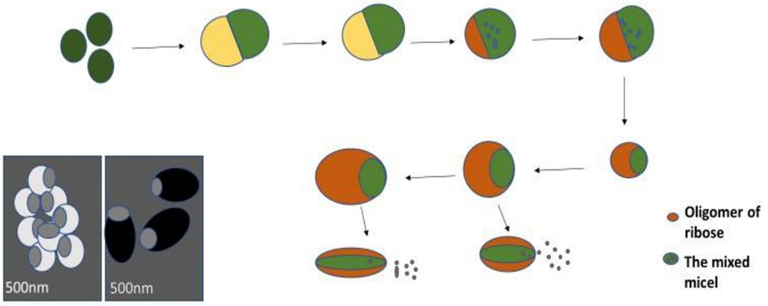

Figure 3. Green Templating Method.

5.1 Sustainable Carbons using the StōBer Method:

To produce the advantages of both spherical colloids and spherical materials are combined in spherical carbon materials, such as good liability, controllable particle sizes, and uniform geometry. Therefore, the novel materials provide considerable potential for a variety of applications, including as energy storage and conversion, adsorption, water or air purification, catalysis, or storage [51-53]. Over the past few decades, significant advancements have been made in the synthesis, characterization and also the use of porous carbon nanospheres [54-55]. In comparison to hemicellulose or lignin, cellulose tends to create carbon compounds with a greater surface area that have a microporous or mesoporous structure. Additionally, a compound made of lignin, cellulose, and hemic Aldehydes are used to create polymeric resins (such as formaldehyde/furfural) Aldehydes (like formaldehyde and furfural) can be converted into phenolic resins, and phenolic compounds (like phenol or resorcinol) are frequently utilized as precursors in the production of carbon spheres. There have been few studies for a long time on the monodisperse phenolic resin nanospheres that self-assemble into colloidal crystals, despite the fact that there have been several papers on the creation of carbon nanoparticles/micro-spheres from phenolic resin. The application of the Stöber method, which is frequently used to create silica spheres but has not previously been applied in the research of resorcinol-formaldehyde (RF) nanospheres with high nano dispersibility and changeable particle size—the development of nanoporous carbon spheres (NCS), as shown in (Figure 3) [56]. It was discovered that the phenolic polymer formed by the reaction of resorcinol or formaldehyde was comparable the solgel reaction of silicon sphere. Polymer microspheres carbonized with highly NCS yield or 150–900 nm range of variable particle size. With the help of the currently available soft-template-forming agents, this expanded Stöber approach demonstrates the ability to self-assemble sustainable carbons of the right size and chemistry. In the prior Stöber approach, only a few carbon precursors were used (e.g. phenols, aldehydes).

Significant effort has recently been made to promote the production of sustainable carbon materials by focusing on greener carbon precursors like dopamine and also tannins [57-59].

5.2 *Sustainable carbons (green templating method):*

Materials have been given a certain porosity structure using templates [60]. Hard, soft, or dual templates can all be used to accomplish this. Hard templating is typically risky, difficult, and expensive since it uses a sacrificial template (such silica) that must be post-treated by etchants. However, either by utilizing the reactants themselves as templates or by deleting the template without the use of harsh chemicals, it can be made "greener." For instance, gelatin and crystals of boric acid were used to create B/N co-doped carbon nanosheets. The hard template and the B precursor were both the boric acid [61].

The biomass precursor used as the model for another illustration. In this case, collagen served as the N and C precursor, while nano minerals served as the hard template, to create the N-doped mesoporous carbon materials from shrimp skin. These materials could then be removed by acid etching [62]. It's interesting to note that a simple dual-templating technique was used to create hierarchical carbon materials from a variety of biomass precursors including carrot stems, Chinese yam leaves, ginkgo, tung blossoms or long beans. The hard templates used were $Mg_5 (OH)_2(CO_3)_4$ and $ZnCl_2$. Additionally, the synthesis of single-atom metal phosphorus/Nitrogen/carbon/sulfur (M-N/P/S-C) catalysts has attracted significant interest due to the hard template technique. The preparation of porous carbon materials using a soft template is more effective and environmentally friendly. To create mesoporous structure in a liquid environment using self-assemble micelles, it uses surfactants and polymers. The subsequent heat treatment can then be used to remove the soft template, producing a variety of porous carbon compounds. For instance, by combining micelles of P123, sodium oleate or ribose, intriguing porous hollow open carbon nanoflasks (PHOCFs) were created using hydrothermal technique (Figure 3).

The soft template approach [63] has substantially accelerated the production of porous carbon materials, but crucial phenolic crosslinking reaction requires the condensation of many solvents with the aid of an acid or base [64-66].

5.3 Mechanochemical method:

Some carbon precursors have limited solubilities in typical solvents, making them unsuitable for use in solutions-based synthesis. In this sense, solid-state reactions are an increasingly common method of creating novel materials [65]. Grinding in solid states is a quick or efficient way to create different porosity nanomaterials, and it should be simple to scale up [67-68]. By ball milling polyphenols coordinated composites made of metal and segmented poly (ethylene oxide)-propylene oxide-poly (ethylene oxide) copolymers, A multifunctional mechanochemical self-assembly strategy was created by Zhang et al., and generated OMCs after further carbonization [65]. Additionally, OMC materials showed greater potential for real-world techniques due to the accessible, plentiful, and biogenic tannin precursor. Alternately, tannin derivatives and low-molecular-weight lignin can be employed as precursors for the creation of OMC. Additionally, by pyrolyzing the enlarged polysaccharides, Clark et al. created a simple and environmentally friendly approach to produce mesoporous carbon compounds, which they refer to as Starbons [69]. Mesoporous carbon materials were easy to fabricate and could be used as a catalyst or catalyst support manufacturing technique in the future [70].

5.4 Fabrication of monolithic carbon materials:

The most common form in which carbon nanomaterials are given is as powder. The particles would cause a drop in pressure along the catalyst bed, impede product movement, and lengthen the time product and reactants are in contact. Carbon nanomaterials must be manufactured in a certain shape for engineering applications in order to provide effective contact of the multiphase interface, lower pressure drops, remove catalyst bed inhomogeneity, and enhance reactant and product mass transfer [71-72]. As a result, having the appropriate mechanical strength is a basic prerequisite for shaping carbon. The binder participates in the moulding of carbon materials and can be used to modify the material's mechanical strength. Additionally, the interconnected microporous open structure of freestanding monolithic carbon nanomaterials has demonstrated tremendous potential in catalytic systems [73-74]. Citric acid and d-glucose were employed by Ba et al3D.'s Open-cell foams that can stand alone and take on various shapes have the potential to serve as inexpensive, secure natural predecessors [75]. A 3D-carbon-monolith (3DCM) supported Ag-Co_3O_4 catalyst with outstanding Joule-heating property was created by Wang et al. and might be used as a supporting material for catalysts as well as heating element. Because starch is cohesive and flexible, a cylinder-shaped extrudate of N-doped mesoporous carbon was utilizing wheat flour as precursors [76]. This is important to remember the carbonizing organic binder’s procedure that is comparable to preparing carbon compounds. Therefore, future studies should focus more on the function and role of organic binders in the product engineering of carbon materials. As was previously mentioned, significant effect had been made to lower the energy consumption, hazardous emissions, and cost associated with the production of carbon compounds. To accomplish the sustainability of carbon materials but it's also important to consider how carefully energy and element balance are used while creating carbon compounds. For instance, the pyrolyzing carbon precursor during the manufacture of carbon compounds will release and squander a significant amount of energy.

The energy required for the preparation of carbon material can be decreased with a favorable balance of energy during carbonization techniques. Additionally, during low-temperature carbonization process, some low-molecular-weight organic molecules may volatilize. These VOCs can serve as building blocks for the production of high value-added chemicals. The sustainability of carbon materials can be significantly increased by combining the creation of carbon materials with other beneficial industrial processes, such as biorefining. High value-added biomass chemicals and high efficiency nanostructured carbon materials are produced together in a single operation. Utilization of the biorefining waste leftover may also result in a cylinder-shaped extrudate and precursors made of wheat flour, we were able to produce sustainable N-doped mesoporous carbon. Worth noticing is the similarity between the carbonization of organic binders and the preparation of carbon compounds.

6. The use of renewably sourced carbon materials in catalysis:

6.1 Sustainable catalysis using metal-free catalysts:

An emerging green catalytic material is carbon-based metal-free catalyst. Because industrial catalysis is more efficient, cost-effective, and environmentally beneficial, they have recently caused a lot of anxiety. Notably, chemical groups on the surface and also structural flaws can serve as lively reaction sites for the carbon material to operate the catalyst [77]. For the purpose of creating catalytic applications, the carbon compounds produced from Surface chemistry can quickly functionalize biomass.

Solid acid catalysts were the first successful application of functional carbons produced from biomass for catalysis. The acidity could be raised by refluxing strong sulfuric acid graft sulfonic acid groups. The Starbons were functionalized with SO_3H groups, for instance, by Clark et al. This might be used in acid-catalyzed [78-79]. Compared to other solid acids of a similar nature, it showed higher acylation and alkylation activity for aromatic compounds [78]. Through the direct sulfonation of discarded banana peels, pineapple peel, and empty fruit bunches, Wong et al. created sulfonated carbon-based solid acid catalysts. These solid acid catalysts based on sulfonated carbon demonstrated good catalytic activity for the synthesis of biodiesel without glycerol [80].

Heteroatom incorporation was used to produce the second substantial catalytic application of functional carbons obtained from biomass. The use of wheat has created a novel method for making inexpensive biomass materials into metal-free acetylene hydrochlorination catalysts.

Additionally, ethylene oxychlorination and dehydrochlorination were combined using a bifunctional catalyst made of N-doped carbon and $CuCl_2/Al_2O_3$ to create vinyl chloride [81].

It is advised to combine the metal-free catalysts with other catalysts in the future. Additionally, the added nitrogen species are also thought to encourage the oxidation and dissociation of H_2S and organic pollutants [82-84]. Biochar made from rice straw that has been doped with N and S was created by Ding et al. [85-87]. to catalyse the oxidation of peroxymonosulfate to degrade metolachlor. Xu et al. [88] showed how biomass-derived waste airlaid paper could be converted into N-doped porous carbon used as a catalyst without metals for the process to selectively oxidise H_2S. Due to their superior electrical and mass transfer properties, among the most alluring oxygen reduction reactions electrocatalyst is carbon material [89-90]. The usage of green carbon materials in practical applications is on the rise when they are made from renewable resources [91]. When Liu et al. used spinach as a precursor to create heteroatom-doped porous carbon sheets, they discovered that these sheets' ORR activity in acidic environments was comparable to that of commercial Pt catalysts. A micro/mesoporous nitrogen-doped carbon with outstanding resistance to the methanol crossover effect and ORR activity that was comparable to Pt/C was made by Xu et al. using polyamide and cellulose as precursors [92]. (Onset potential, 0.98 V compared to RHE) a porous carbon tube with a hierarchically honeycomb-like structure was made by Tang and colleagues via pyrolysis [93].

6.2 Biomass-derived carbon as metal catalyst supports for sustainable catalysis:

Considering their great chemical resistance, affordability, and substantial surface area porous carbon materials have been used widely in heterogeneous catalysts as metal catalyst help for sustainable catalysis utilizing carbon produced from biomass.

Lack of active sites for tethering metal nanoparticles (NPs) on carbon supports with intact graphitic structures is a common problem, causing NPs to congregate and leach from the carbon surface. The carbon support's dispersion, sintering resistance, and catalytic effectiveness are significantly influenced by its surface qualities [94-95]. It has been shown that adding oxygen groups to a surface reduces the carbon's hydrophobicity increasing the metal precursor's surface accessibility in the aqueous solution [96, 97]. The abundance of oxygen-containing groups in carbon compounds obtained from biomass makes them a great support for metal catalysts. In order to effectively hydrogenate platform molecules in moderate and watery environments, Ru NPs must be loaded onto the biomass-derived Starbon Clark et al. demonstrated a methodology. This Ru-based catalyst displayed exceptional activity and also selectivity because of the tiny and homogeneous particle size or the extensive benefits of the outstanding water resistance of the Starbon substrate [98]. The cellulose fibre surface of cotton, a widely grown crop with cheap labour and plentiful raw resources are rich in -OH groups and can be used to absorb metal ions. Yang et al. synthesised carbon fibre using commercial cotton or they loaded Ru-Co as a metal catalyst [99]. Ammonia borane could be effectively hydrolyzed by this Ru@Co/CCF catalyst. A unique nickel catalyst supported by carbon-silica from rice husk was created and used to upgrade furfural and levulinic acid generated from biomass. Functional groups that include nitrogen can be used to anchor metal nanoparticles and act as the primary coordination sites for stabilising tiny metal nanoparticles [100]. N-doped carbon derived from biomass carefully investigated in order to create high-performance metal catalysts [101]. N-doped mesoporous carbon substance was made from wheat flour by Liu et al. and utilised to support Au NPs in their catalyzation of the acetylene hydrochlorination [102]. Li et al. also described a practical method for producing nitrogen-doped porous carbon with a 9weight percent nitrogen content that was adequate for attaching tiny Ru Nps. When aromatic compounds were hydrogenated in the liquid phase, The porous carbon supported Ru catalyst that had been nitrogen-doped was more efficient than it had been before (like benzoic acid or toluene). The study previously described demonstrated how nitrogen doping increased different hydrogenation processes' catalytic activity [103].

Other techniques are combining the precursors of carbon, nitrogen and metal through the pyrolysis process in addition to depositing of metal on pre-synthesised N-doped carbon structures. Beller et al. used cobalt or Fe-metal cores contained in nitrogen doped graphene shells to create a range of nanostructures and heterogeneous catalysts [104]. Metal complexes impregnated on suitable supports are pyrolyzed, these materials were created. During the high-temperature carbonization process, the chemical anchoring between ligands and metal atoms—for example, sucrose and 1,10-phenanthroline—is crucial for stabilising metal atoms and producing high active sites [105]. To stop metal NPs from accumulating, ligands were transformed into carbon shells during the pyrolysis process. Despite the fact that these catalysts were made from commonly accessible and affordable metal precursors the intricacy of the ligands may be a negative. Beller et al. created a biomass-derived heterogeneous catalyst by annealing a combination of $Co(OAc)_2$ and biowaste-derived chitosan [106]. The catalyst had strong functional group tolerance, good selectivity, and the ability to hydrogenate nitroaromatics with a variety of functional groups (including potential therapeutic candidates). By pyrolyzing a rhodium compound with chitin, Cao et al. disclosed a straightforward method to create an N-doped carbon supported Rh catalyst (Rh/N-C), when used to hydrogenate benzoic acid it displays strong catalytic activity [101]. A further benefit of one-pot pyrolysis was that it considerably reduced the migration or leaching of Rh NPs from carbon surface, resulting better stability of the product. In large-scale applications, this synthesis technique has shown the ability to generate environmentally benign Rh/N-C catalyst.

The single-atom or single-site catalysts, particularly the single atom carbon-based catalysts produced from biomass have been a popular study focus [107-109]. The carbon-based composites could offer extremely high specified surface area with sufficient reaction stability to anchor metal atoms. For instance, the maximum atomic surface area porous single-site (M-N-C) catalysts typically display remarkable catalytic performance. For instance, porous single-site (M-N-C) catalysts frequently display remarkable catalytic activity with the catalysis's highest possible atomic utilization [110]. The oxidation of ethyl benzene was carried out using Compared to Co nanoparticles, a single-atom Co catalyst on an N-doped porous carbon nanobelt (Co-ISA/CNB) demonstrated much greater conversion rates (up to 98%) and selectivity (99%). Using glucose [111], Han et al. created Zn single atoms (SAs) distributed over N-doped carbon. This carbon material consisting of glucose has a high CH_4 FE of 85% at 1.8 V against SCE. demonstrated outstanding stability during the electrochemical reduction of CO2 to CH4 [112-114]. In the future, more effective and environmentally friendly processes for using biomaterials to build highly distributed single-atom/single-site catalysts will be developed.

6.3 Enzyme mimicry for biocatalysis:

Biocatalysts, like enzymes, which precisely catalyse a variety of processes under benign conditions, have continued to advance quickly.

By resolving the inherent constraints of natural enzymes, the nanomaterials imitated enzyme, also known as nanozyme, has been extensively investigated for bio catalysis (such as low stability and high cost) [115].

Fe_3O_4 has a wide range of biomedical uses as a result of its discovery to imitate peroxidase in 2007 [116-117]. Nanozymes made of transition metals and noble metals, such as Co, Zr, V, and Pt, have increased biomedical applications as well as biocatalytic performance as peroxidase, superoxide dismutase (SOD), and hydrolase mimics [118–124] are all made possible by the successful development of Fe_3O_4 [125]. Particularly, it has been shown that carbon materials with Fe/N doped carbon and carbon dots have high catalytic performance as peroxidase mimics. By employing glucose, -cyclodextrin (CD), -cyclodextrin (CD), and -cyclodextrin (CD) as precursors, Yang et al. created four different variety of carbon dots and examined how well they worked as peroxidases [126]. They discovered that the glucose@C-dots demonstrated exceptional affinity for TMS substrates like horseradish peroxidase in addition to retaining the catalytic activity in a complex serum system.

A support-sacrificed method was developed by Chen et al. to disperse a single iron site nanozyme over porous N-doped carbon [127]. This nanozyme demonstrated strong peroxidase-like activity due to its well-defined structure and high density of active sites, and was subsequently used in colorimetric glucose detection. Nanozymes made of carbon have also been discovered. [J.G. Liu et al. 2020] As peroxidase, superoxide dismutase (SOD), and hydrolase mimics, well-designed carbon nanomaterials have demonstrated enhanced biocatalytic performance and are regarded as good candidates for nanozymes. [S. W. Lee et al. 2016] Particularly, it has been shown that carbon materials with Fe/Ndoped carbon and carbon dots have high catalytic performance as peroxidase mimics. ‘‘Yang et al.’’ produced distinct kinds of four carbon dots and assessed their efficiency as peroxidases utilizing glucose, -cyclodextrin, -cyclodextrin, or -cyclodextrin as precursors. 2019 [Y. Lv et al.] The glucose@C-dots were discovered to exhibit exceptional affinity for TMS substrates like horseradish peroxidase as well as maintaining their catalytic activity in a complex serum system.

This nozyme has a highly concentrated set of active sites and a strongly defined structural makeup. displayed robust peroxidase-like activity and was subsequently employed in colorimetric glucose detection. Additionally, because hydrolases are essential in biosystems due to their destructive effect on big molecules, carbon-based nanozymes have been studied as hydrolase mimics.

It was looked into how Ce-doped carbon dots (CeCDs), made by Du et al. using a one-step hydrothermal carbonization technique, mimicked phosphatase activity for phosphate ester hydrolysis cleavage. [J. Du et al. 2020] CeCdS showed good catalytic activity for speeding up the hydrolysis of bis(4-nitrophenyl) phosphate (BNPP), and it might mimic phosphatase, according to the Inner Filter Effect (IFE).The nanozyme exhibits outstanding biocatalytic activity and has a wide range of applications, but further research is required to enhance its catalytic activity and substrate selectivity.

6.4 Carbon-based nanoreactor for therapeutic and diagnostic uses:

The accelerated development of the biomedical field has been facilitated by advanced nanotechnology [128-129]. Due to their exceptional biosensing abilities, carbon materials play a crucial role in the diagnosis and treatment of diseases [130-131]. Due to their plasmonic resonance, the detection platform now relies heavily on noble metal-based nanomaterials such as Au, Ag, Pt, and Pd [132-135]. Carbon nanomaterials exhibit benefits for biosensing over noble metals because of the three factors listed below: 1) The cost of carbon nanomaterials is less than that of noble metals (carbon is $0.03 per gramme, Au is $60 per gramme, Ag is $25 per gramme, and Pt is $34 per gramme) [136-137]. 3) Noble metals with predictable composition and architectures have proved more challenging to create than the homogeneous and structurally diverse carbon nanomaterials. In particular, the traditional carbon materials have a high thermal/electrical conductivity and a large amount of derivatization potential, facilitating the detection of molecules (such as peptides) and cells [138-139]. For diagnostic and therapeutic purposes, the carbon hybrid materials, which are carbon compounds that have been doped with other elements, exhibit good biocompatibility, a wealth of catalytic sites, and high thermal/chemical stability. Numerous nanomaterials have been used in diagnostic applications. For instance, the FeOOH@ZIF-8 MOF composites showed improved ionization efficiency and, due to their size exclusion effect, interacted only with tiny molecules, making them useful for serum sample detection with quick analysis [140]. Biocarbon compounds may be crucial to the success of biosample sensing. A dopamine-based nanoreactor was created by Shu et al. to aid in the therapeutic evaluation of cervical cancer and be used for the detection of blood sample [141]. Due to their steady fluorescence and great resistance to photobleaching, carbon dots generated from biomass stood out for their abilities in cell imaging and bioimaging. Li et al. [142] stacked the Cy3-labeled ssDNA on the surface of oxidised mesoporous carbon nanospheres to create a fluorescent "turn-on" aptasensor (OMCN). This OMCN-based aptasensor had good cancer cell selectivity and could image cells for various cancer diagnosis. A variety of nanomaterials have been created for therapeutic use, including those that function as ion-interference therapy, theranostic nanoplatforms, nanodrugs, and theranostic nanoplatforms for gene therapy [143–146]. Because of their superior selectivity and strong load impact biomass carbon materials stand out among the materials and are regarded as the best prospects for therapeutic effects that are satisfied in real-world applications. Because of their superior selectivity and strong load impact, biomass carbon materials stand out among the materials and are regarded as the best prospects for therapeutic effects that are satisfied in real-world applications. Porphyrins, perylenequinone, and curcumin are examples of natural carbon compounds that have been used in photodynamic therapy (PDT) and sonodynamic therapy (SDT). A tiny molecule called gallic acid polyphenol (GA) can help with imaging-guided cancer therapy when combined with iron ions. A few carbon molecules from functionalized biomass may also be utilized for simultaneous in vivo near-infrared fluorescence imaging and tumour treatment as a fluorescence nanoprobe and photosensitizer. A carbon nanocomposite of CBQDCu made from spinach by Zhao et al. showed promise for use in near-infrared fluorescence imaging and provided improved PDT performance. When copper ions were added, Zhao et alcarbon.'s nanocomposite of CBQDCu derived from spinach increased PDT performance and potential for imaging with near-infrared fluorescence. Additionally, the peptide functionalized carbon compounds have the ability to perform both therapeutic and diagnostic tasks [147-150]. In order to properly promote the performance and explore the potential of carbon obtained from biomass, significant effort will be made into the design approach tailored for biosensing in the future.

6.5 Antibacterial and antiviral applications of carbon-based nanomaterials:

By creating infections and illnesses linked to pathogens, bacteria and viruses have always posed a threat to the general public's health. Numerous experiments have been done to create nanomaterials with antiviral activity [151-152] and antibacterial activity to fight diseases caused by pathogens. The coronavirus-19 (COVID-19) outbreak has drawn a lot of attention to the creation of cutting-edge techniques for its quick diagnosis and suppression [153-155]. Notably, carbon materials have demonstrated positive outcomes in the field of antivirus, as their unique structures enable a number of tactics such singlet oxygen emission and the ability to block viral enzymes. Due to their superior optical qualities, carbon dots smaller than 10 nm in size have demonstrated specialised antiviral activities and broad-spectrum response. By using a hydrothermal process, Tong et al. were able to create the extremely biocompatible CDs (Gly-CDs) from the active ingredient (a Chinese herb remedy called glycyrrhizic acid) [156]. They showed that the Gly-CDs may activate innate immune responses that were antiviral and prevent the invasion and replication of the PRRSV (porcine reproductive and respiratory syndrome virus) encourage the innate immune system's antiviral defences and prevent the PRRSV infection's buildup of intracellular reactive oxygen species (ROS). Seven distinct carbon quantum dots (CQDs) were created by Locaechin et al. using the hydrothermal carbonization of ethylenediamine and citric acid and were then modified with boronic acid ligands [157]. The functional groups of CQDs may interact with HCoV-229E entry receptors to elicit their antiviral effects when utilised to treat human coronavirus HCoV-229E infections. Moreover, given that some metal oxide nanoparticles have been shown to have antibacterial activity, it is urgently necessary to manage bacterial infections with the aid of modern nanotechnology. Similar to noble metal-based nanomaterials, carbon nanoparticles have shown considerable promise for the treatment of infectious diseases (such as Ag). Their antibacterial activity can be produced by a number of methods, including oxidative stress, physical/mechanical damage, photothermal/photocatalytic effect, etc. ‘‘Xi et al.’’ discovered the anti-bacterial activities of carbon or copper nanozymes along with variable copper states. In addition, the released Cu2+ for the carbon nanozymes and Cuco modified copper may damage the membranes of Gram-negative bacteria, lead to lipid peroxidation, and weaken their DNA. The cytotoxicity and deteriorating effectiveness of carbon compounds, which have potential antibacterial and antiviral activities, must be addressed in future research more dependable than biomass, too. The attributes of carbon materials are influenced by the composition complexity and batch stability of the carbon source, which is important for the practical application of sustainable carbon materials. Therefore, the creation of sustainable carbon from industrial byproducts needs specific consideration. The handling of used sustainable carbon materials must be taken into consideration in addition to the environmental effects of the production of carbon materials. That sums up the carbon compounds' life cycle analysis. The cost of preparing carbon material, environmental pollution, and reliance on natural resources can all be significantly decreased by recycling the used carbon material. According to the life cycle analysis, recycling the industrial wastes could save money. According to the life cycle analysis, recycling those industrial wastes could have a positive impact on sustainability.

In order to measure the effect of sustainable carbon and compare it to current benchmarks for the production of activated carbon, life-cycle analysis should be employed.

Utilizing these highly efficient sustainable carbon compounds in practical applications is the ultimate goal. Emerging sustainable carbon materials must go from the experimental stage to an actual industrial level of manufacturing. In order to obtain affordable and environmentally favorable carbon materials, further research and the development of simpler manufacturing processes are urgently needed. These discrepancies in material synthesis need to be adjusted in order to give advice on how to design sustainable carbon materials for all of their potential applications.

Conclusion

Carbon-based nanomaterials represent a versatile and rapidly advancing class of materials owing to their unique structural, electronic, mechanical, and chemical properties. Materials such as graphene, carbon nanotubes, fullerenes, and carbon dots have demonstrated exceptional potential across diverse fields including energy storage, catalysis, environmental remediation, electronics, sensing, and biomedicine. Their high surface area, tunable functionality, excellent conductivity, and remarkable strength enable performance enhancements that are difficult to achieve with conventional materials. Despite these advantages, challenges related to large-scale synthesis, cost, uniformity, toxicity, and environmental impact remain and require systematic investigation. Continued interdisciplinary research focused on sustainable synthesis, surface modification, and safe application strategies will be crucial for translating carbon-based nanomaterials from laboratory studies to practical, real-world technologies. Overall, carbon-based nanomaterials are poised to play a pivotal role in the development of next-generation advanced materials and sustainable solutions.

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