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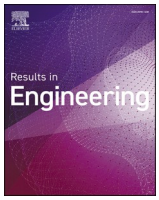

Review article

Sustainable carbon-rich materials from algae and biomass: Synthesis, characterisation, and applications

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ABSTRACT

The high demand for sustainable, high-performance materials has spotlighted carbon-rich materials derived from algae and other biomass sources. Algae-derived carbon compounds, including graphene and its derivatives, show promising applications across sectors like energy, environmental remediation, and catalysis. This review comprehensively discusses the synthesis, characterisation, and applications of these novel biomaterials, covering hydrothermal treatment, microwave irradiation, and pyrolysis- each offering unique benefits in structure, functionality, and yield. A detailed examination of key characterisation techniques, including Raman spectroscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD), provides insights into these materials' chemical and structural properties. Applications in supercapacitors, batteries, and other energy storage devices, as well as in environmental and catalytic contexts, are thoroughly explored. This review also highlights recent advancements in carbon biomaterial integration into cutting-edge technologies, focusing on scalability, sustainability, and novel applications that may drive future innovation. By presenting a holistic view of carbon biomaterials from algae and other biomass sources, this review aims to support the vast potential of sustainable carbon materials for next-generation manufacturing applications.

1. Introduction

The ultimate goal of carbon capture and storage, often known as CCS, is to either indefinitely store carbon dioxide in carbon sinks or transform it into consumer items. Carbon capture and storage (CCS) is and will continue to be a vital part of the portfolio of carbon mitigation remedies as long as fossil fuels dominate the world's economic system [1]. Since the 1950s, CO_2 emissions have risen sharply worldwide, with significant increases from both developed and developing nations [2]. Despite temporary declines during global events like the financial crisis and COVID-19, fossil CO_2 emissions remain high, as illustrated in Fig. 1 [3]. Tackling this issue requires collective efforts to reduce emissions as well as remove existing CO_2 from the atmosphere. In this context, converting captured carbon into value-added materials has emerged as a promising strategy. Among various carbon sources, biomass—particularly algae—has gained increasing attention due to its rapid growth, high carbon content, and ability to sequester CO_2 during cultivation. This positions algae as a unique feedstock that integrates carbon capture with sustainable material production.

Currently, the main precursors for carbon-based products are unsustainable derivatives of fossil fuels such as petroleum coke, ethylene, asphalt, methane, and polyacrylonitrile (PAN). Furthermore, the carbon molecules derived from these sources are also costly due to energy-intensive processes such as fractionation, cracking, and polymerization. Activated carbons (porous materials with a high surface area), carbon nanotubes (cylindrical nanostructures), and graphene nanosheets (single layers of carbon atoms) are novel carbon-based biomaterials. The search for alternatives to fossil fuels in carbon-based biomaterial production is driven by the fluctuating supply and demand of fossil resources and the urgent need to address the climate crisis. Biomass, including algae, an abundant and renewable carbon resource, has significant potential to replace fossil fuels in numerous applications due to its lower environmental impact. Algae-derived carbon materials, in particular, offer a sustainable and scalable route to producing high-performance carbon structures with diverse applications. Utilizing biomass for sustainable carbon biomaterials is a vital step toward reducing reliance on fossil fuels while opening pathways for a resilient bio-economy powered by biomanufacturing. With strategic investment and collaboration, biomanufacturing offers a transformative approach to producing renewable materials, sustainable fuels, and other

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critical goods through advanced biological processes [5]. This shift provides a unique opportunity for partners to co-create scalable solutions that address global environmental challenges and foster long-term economic resilience. Harnessing the full potential of biomass—whether algae, plants, or animal waste—promises a sustainable supply chain for biomanufacturing, replacing fossil-derived products and supporting the transition to more eco-conscious industrial production [6–9]. With advances in green chemistry and sustainable processing methods, biomass can be transformed into advanced carbon biomaterials with applications in diverse fields, including electronics, biomedicine, and energy storage. This review aims to provide a comprehensive overview of algae-derived carbon materials, focusing on their synthesis, structural properties, and emerging applications in energy storage, environmental remediation, and biomedicine. While several reviews have addressed biomass-based carbon materials in general, few have specifically examined algae as a distinct and promising feedstock. This review fills that gap by highlighting recent advances, identifying current challenges, and outlining future research directions in the field of algae-based carbon materials. This manuscript specifically focuses on algae-derived carbon materials, highlighting their synthesis, properties, and potential applications as a sustainable alternative to fossil-based carbon products. This shift represents a pivotal step in addressing the energy crisis and climate change by harnessing a renewable, abundant, and environmentally friendly resource.

2. Carbon biomaterials

Carbon materials will play an indispensable role in carbon capture and use (CCU) as composites, with elemental carbon materials serving as key components in processes that involve capturing carbon dioxide through adsorption (holding CO_2 on the surface) and transforming it through conversion processes into stable compounds or valuable products. Among the array of novel carbon materials is graphene (first synthesized in 2004), a planar sheet with a thickness of one atom formed by closely packed six-membered carbon atom rings (Fig. 2). It has undergone sp^2-hybridization via micromechanical exfoliation from graphite, a derivative of petroleum-based material [10]. Graphite may be chemically oxidized to make graphene oxide (GO), another graphene derivative, inexpensively. The new material, graphene oxide, has a high concentration of oxygen functional groups (epoxy, carboxyl, hydroxyl, and carbonyl) on its surface and edges (Fig. 3). Figs. 2 and 3 illustrate the structural contrast between graphene and graphene oxide: while

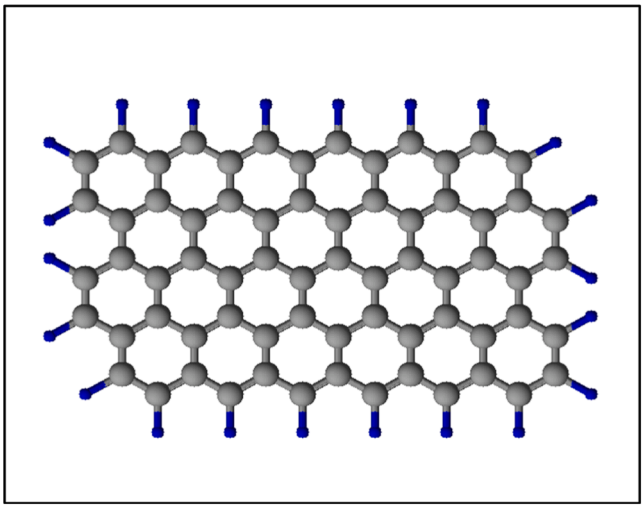

Fig. 2. Atomic structure of graphene (underpins graphene's exceptional electrical and mechanical properties) showing a single layer of carbon atoms arranged in a hexagonal lattice.

graphene exhibits a clean, uninterrupted hexagonal lattice conducive to high electrical conductivity, graphene oxide's disrupted lattice—due to oxygen functionalities—makes it more suitable for chemical modification and dispersion in aqueous media. This structural distinction underpins their divergent applications for environmental contamination management and remediation [11].

The most studied graphene synthesis processes include chemical vapor deposition(CVD), physical separation, epitaxial growth on silicon carbide(SiC), and the re-dox(reduction-oxidation process) [12]. Both top-down and bottom-up approaches can be used to synthesize graphene. Techniques used to fabricate graphene fall into the top-down category, including micromechanical exfoliation, electrochemical exfoliation, thermal exfoliation of graphite intercalation compounds, and the reduction of graphene oxide to reduced graphene oxide. Mechanical exfoliation is a widely used method for producing graphene by physically separating layers from bulk graphite. This process can involve different types of mechanical forces, such as tension, shear, or compression. For example, sonication applies ultrasonic energy to break apart layers, while ball milling or fluid-based methods use impact and

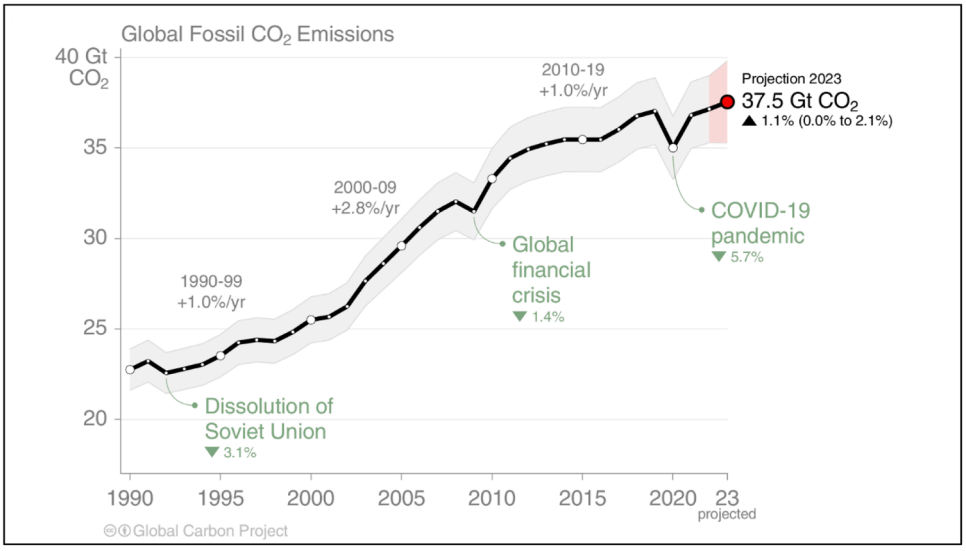

Fig. 1. Global fossil CO_2 emissions from 1990 to 2022, with a projected estimate for 2023. Data highlights key inflection points related to policy changes and global events (e.g., COVID-19, financial crises). Used with permission of the Global Carbon Project under the Creative Commons Attribution 4.0 International license [4].

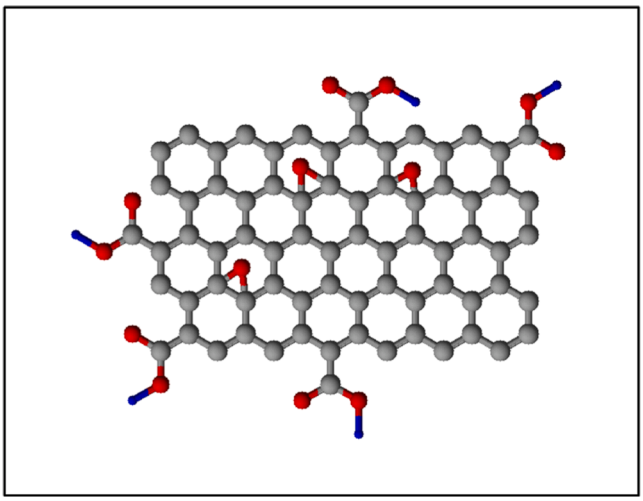

Fig. 3. Schematic of graphene oxide, illustrating oxygen-containing functional groups (e.g., hydroxyl, epoxy) on the basal plane and edges, which influences their solubility and reactivity. Atoms in grey colour are carbon, Red are oxygen, and Blue are hydrogen.

shear forces. A simple yet effective approach involves using adhesive tape to peel off thin graphene layers, a technique that highlights the material's unique layered structure and ease of separation. Nevertheless, these synthesis technologies are exclusively employed for research, because of their limited scalability and low productivity [13]. Graphene synthesis using a bottom-up approach is accomplished using epitaxial growth and chemical vapor deposition. Sublimation of Si atoms from the surface of SiC wafers allows for the growth (epitaxial growth) of graphene sheets, which are then graphitized by annealing at high temperatures (>1000 °C) in an ultrahigh vacuum. At elevated temperatures, Si atoms evaporate (arrows in bottom-up approaches in Fig. 4), leaving a carbon-rich surface that forms graphene sheets [14]. Chemical vapor deposition is a high-temperature furnace process that produces large-area graphene films by decomposing carbon-containing gas on a metal (eg, copper) substrate, offering greater thickness control. However, optimization and substrate selection in chemical vapor deposition are challenges [15]. Graphene and other 2D materials can be inexpensively produced via liquid-phase exfoliation (dispersing layered materials in a liquid and applying shear forces to separate them into sheets) [16], which has several variations aimed at specific industrial uses, such as shear mixing, ball milling, and micro-fluidization [17]. Graphene oxide can be safely and efficiently prepared using the Hummers method of chemical oxidation and exfoliation [18]. Fig. 4 displays the various ways that graphene can be synthesised. To make graphene oxide synthesis more suitable for industrial production, scientists are always looking for new and improved methods. Some of these include pre-oxidation treatment, changing oxidation intercalation agents, electrochemically assisted methods, ultrasonic waves or microwaves, and other techniques [19]. An improvement to the Hummers' approach incorporated significant temperature control with zero emission of toxic gases, resulting in a greater degree of formation of graphene oxide particles by increasing the concentration of potassium permanganate ($KMnO_4$) and replacing the catalyst, sodium nitrate with phosphonic acid, making it suitable for many potential applications [20].

Carbon-based materials such as carbon dots (CDs), graphene

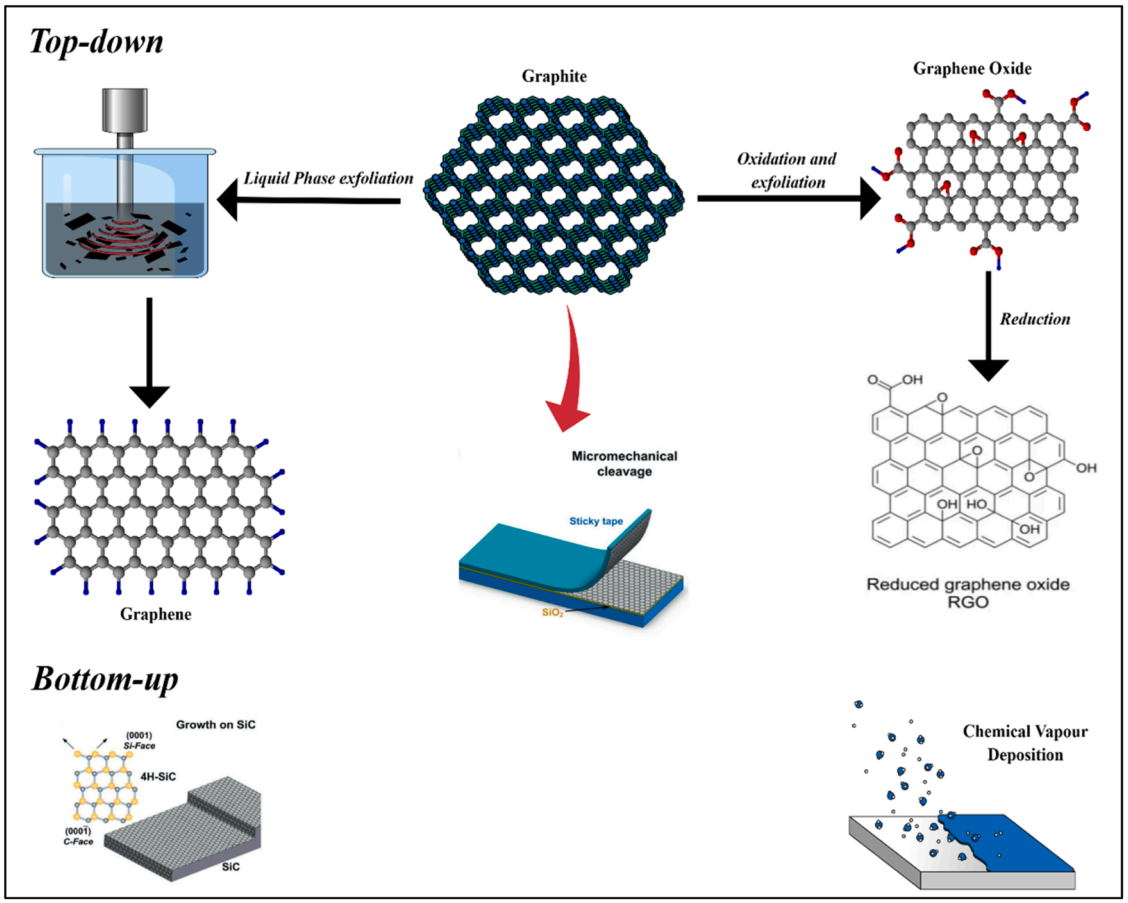

Fig. 4. Brief overview of the main methods to synthesize graphene. Gold and grey spheres represent silicon and carbon atoms, respectively. Reprinted and modified with permission from [21]. Copyright 2017 Elsevier Publishing.

nanoribbons, graphene oxide, and carbon nanotubes (CNTs), synthesized through conventional and green methods, are known for their catalytic efficiency, selective interactions, and structural stability. CDs are nanoscale particles known for their excellent photoluminescence and biocompatibility, making them ideal for sensing and imaging applications [22]. Graphene nanoribbons, with their narrow width and high aspect ratio, exhibit tunable electronic properties suitable for nanoelectronics [23]. CNTs, cylindrical nanostructures composed of rolled graphene sheets, are valued for their exceptional mechanical strength, electrical conductivity, and high surface area, making them highly effective in catalysis, energy storage, and environmental remediation. Zhang et al. provide a comprehensive listing of carbon nanotubes, zero-dimensional-C60 fullerenes, graphene sheets, carbon dots, and related compounds, underscoring the diversity of carbon nanostructures available for sustainable applications [24]. In comparison to CNT, carbon nanofiber (CNF), another carbon-rich material, is a one-dimensional nanofiller composed of a series of graphite planes stacked longitudinally along the fiber. CNTs have a smaller diameter (10 nm) than CNFs (50–200 nm), which increases CNF chemical reactivity by exposing active carbon atoms on the nanofibers' outer surfaces [25]. In parallel, a variety of carbon-rich materials—activated carbon, biochar, and hydrochar—are produced from organic sources through different thermal processes, each offering unique properties and environmental benefits. Activated carbon, created by high-temperature activation, exhibits a highly porous structure with exceptional adsorption capacity, making it valuable for energy storage, water purification, and air filtration [26,27]. Biochar is generated via pyrolysis, a process that thermally decomposes biomass in the absence of oxygen; it is widely used in agriculture for fertilizer retention, carbon sequestration, and enhancing soil fertility. Hydrochar, produced through hydrothermal carbonization using moderate temperatures in aqueous environments, retains a higher number of functional groups and is suited for soil conditioning, nutrient management, and waste remediation [28,29]. Collectively, these materials contribute to eco-friendly waste management by converting organic waste into useful carbonaceous products. Additionally, the high surface area, porosity, and chemical stability of these carbon materials make them ideal for applications in energy storage, such as in electrodes, batteries, and supercapacitors, where excellent thermal and electrical conductivity is essential. Graphene (both one-dimensional and two-dimensional), activated carbon, char (Hydro and biochars), and others, from a wide variety of substrates, offer great promise in the field of electronic applications [30,31], photonic device conductive coatings [32], long-term color painting preservation [33], the development of efficient and dependable perovskite solar cells [34], cancer drug delivery systems [35], and countless other areas of research.

The advantages of green-synthesized carbon materials—particularly in energy storage, catalysis, and environmental applications—demonstrate their superior properties compared to conventionally synthesized counterparts, aligning well with sustainable development goals and addressing critical industry needs [36]. As illustrated in Fig. 5, carbon compounds prepared using green chemistry principles can be more sustainable, efficient, and environmentally friendly. By applying these principles—such as minimizing harmful reagents, reducing energy use, and maximizing atom efficiency—biomass can be transformed into sustainable, regenerative materials. This eco-friendly approach aligns green chemistry with green nanotechnology, enabling innovative, ethical and solutions for the world's sustainability challenges.

The latest breakthroughs in the synthetic process and uses of algal and non-algal carbons are summarized in this article, emphasising precursors and processing techniques.

3. Carbon materials from biomass

3.1. Algal sources

Algae, members of a group of predominantly aquatic photosynthetic organisms, are among the most prolific at removing CO_2 from the atmosphere. Algae are broadly classified into three main groups: Chlorophytes (green algae), Phaeophytes (brown algae), and Rhodophytes

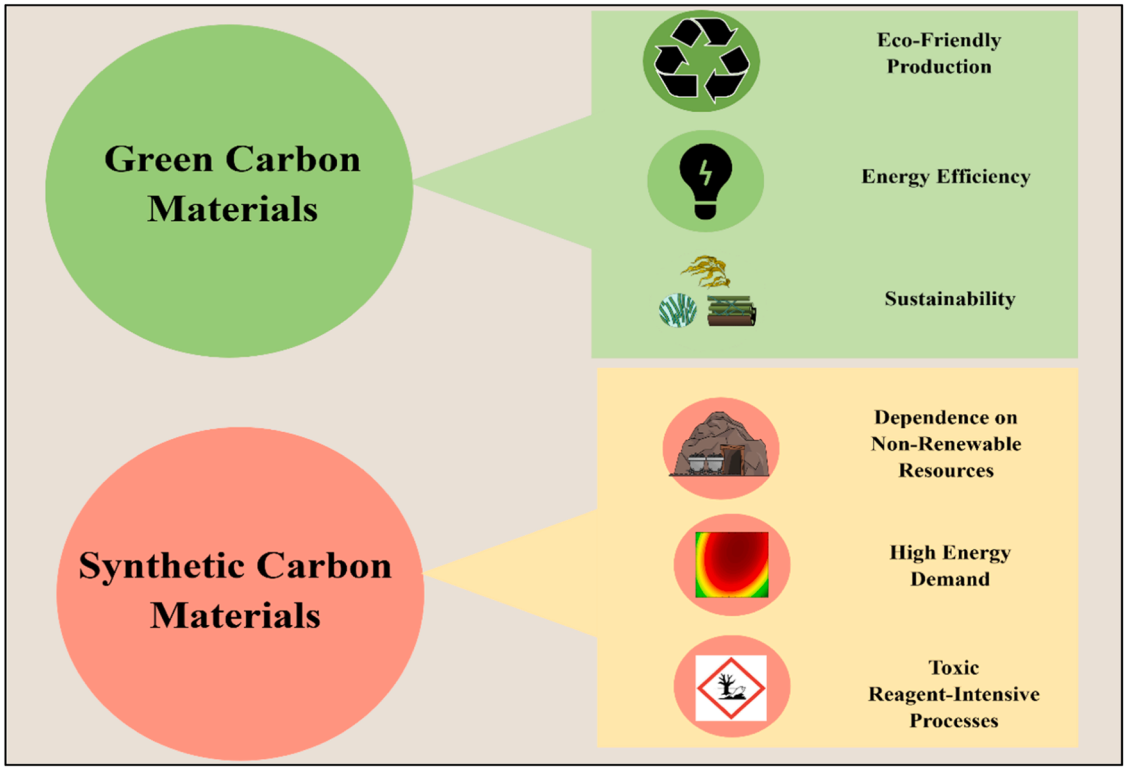

Fig. 5. The key features of green chemistry-made carbon compounds and other synthetic materials.

(red algae). Each group has distinct pigment compositions and environmental adaptations that impact their growth, carbon storage potential, and structural properties, making them promising candidates for sustainable material synthesis in various applications [37,38]. Macroalgae, in particular, offer distinct advantages over terrestrial plants for producing advanced carbon compounds like graphene due to their rapid growth, shorter life cycles, and higher overall yield. Unlike microalgae, macroalgae generally grow in aquatic environments and possess a unique, porous channel network within their cell walls [39,40]. This network of micro- and nano-scale channels, enables efficient nutrient uptake and rapid internal fluid transport, making macroalgae ideal for producing nanotextured carbon materials [41]. Macroalgae are highly effective at absorbing essential nutrients such as nitrogen, phosphorus, and various minerals from their environment. This nutrient-rich composition contributes to their potential as a sustainable resource for generating novel carbon biomaterials [42,43].

Algae biomass can be a raw precursor for carbons that have been self-doped with heteroatoms, which improves the carbons' performance. The introduction/doping of heteroatoms (eg: nitrogen) into materials containing carbon structures enhances its properties like conductivity, reactivity, surface area with porous architecture (porous carbons), and absorption capability [44]. Lu et al. successfully produced nitrogen-doped carbon materials from *Enteromorpha* macroalgae using a novel, easy-to-use method that accomplished carbonization, activation, and nitrogen doping, while keeping the temperature reasonably low. Incorporating cobalt ferrite ($CoFe_2O_4$) into nitrogen-doped carbon materials from *Enteromorpha* macroalgae improves its oxygen reduction reaction (ORR) efficiency and lithium storage characteristics [45]. A study by Gupta et al. shows that graphene, which is obtained from macroalgae *(Ulva fasciata)* by a simple synthesis method, has a synergistic impact when combined with other materials. This combination increases electrical conductivity and a high charge storage capacity, making it ideal for energy storage applications [46]. Xu et al. reported the synthesis of three-dimensional porous graphene from algal precursors utilizing a mix of chemical activation and high-temperature metallic catalysis [47]. Graphene-like biochar from *Enteromorpha* was used as a persulfate activator for sulfamethoxazole (SMX) degradation. It exhibited superior adsorption energy and enhanced SMX degradation, with reduced toxicity [48]. Without modifying the biomass material, algae may adsorb metal ion catalysts uniformly since they are a solid carbon source and have adsorption qualities for metal ions [49]. Biochar made *from Capsosiphon fulvescens* (green macroalgae) biomass has heteroatoms and trace metals and degrades the pollutants in groundwater remediation [50]. An efficient method for removing fluoride from naturally occurring drinking water has been developed by Sharma et al. It involves synthesizing metal oxide functionalized graphene nanosheets directly from the pyrolysis of macroalgae *Sargassum tenerrimum* and deep eutectic solvents [51].

A low-cost *Enteromorpha prolifera*-activated carbon-MnO_2(Manganese dioxide) composite electrode material was successfully developed by Liu et al., and applied for high-performance dual-mode capacitive deionization, exhibiting superior capacitive performance and dual-mode sodium storage behaviour, offering a feasible strategy for processing marine bio-waste and addressing ecological challenges [52]. A novel approach to the production of hierarchical porous carbons from biomass precursors has been developed by Yu et al. for applications in advanced supercapacitors and lithium-ion batteries. The process involves impregnating macroalgae biomass from *Enteromorpha* with KOH solution and carbonization/activation at 800 °C. These carbons have a high surface area, abundant *meso*/micro-porosity, sponge-like interconnected structure, and rich heteroatom doping [53]. Wang et al. synthesized a novel nitrogen-doped *Chlorella vulgaris(microalgae)* biomass-based carbon material, which exhibits superior oxygen reduction reaction performance, electrode stability, and higher power density in microbial fuel cells compared to microalgae carbon [54]. While cyanobacteria can damage natural water, preparing magnetic nitrogen-doped microalgae-derived carbon from *Spirulina platensis* as a renewable carbon feedstock to deal with antibiotics is possible. The composite showed superior efficiency and stability under various conditions, with peroxymonosulfate acting as both an acceptor and a donor for efficient activation [55]. The study by Yang et al. examined the effects of pyrolysis temperature on nitrogen transformation and structural properties of nitrogen-doped carbon materials from *Chlorella vulgaris* residue [56].

Graphene quantum dots (GQDs) are the largest among carbon nanomaterials (<100 nm), and show unique photoluminescence properties; on the other hand, carbon quantum dots (CQDs) are smaller in size and only about 10 nm wide. Graphene nanofragments can be transformed into GQDs by adding functional groups in only a few atomic layers. Highly luminous graphene quantum dots were created from macroalgae, sourced from the Beibu Gulf in Guangxi, China, using a new environmentally friendly solvothermal approach [57]. The method involved using ethanol as a solvent and doping with chlorine atoms. They have been used in bioimaging at long-wavelength excitation because of their high-intensity white fluorescence. For their study on the effects of mineral nutrients on suspension colloids and biomass selection for sustainable carbon dot production and mass production, J. Zhang et al. utilized three different kinds of algae: *Spirulina* (Cyanophyta), red algae (Rhodophyta), and green algae (Chlorophyta). In addition, the photoluminescence (PL) emissions from the algae-derived quantum dots were comparable, indicating that they may be employed directly for H_2O_2 sensing [58]. Compared to other carbon sources like polyethylene glycol (PEG) and polystyrene, biomass carbon sources are environmentally safe natural resources with several benefits for making biomass-based carbon dots (BCDs), such as low cost, abundant, and green. Biomass-prepared CDs have been used in various fields such as biological imaging, sensors, and drug delivery [59].

Fang et al. describe a process using algae *(Spirulina or Chlorella)* biomass powder, a condensation accelerator, and magnesium pre-templates to create nitrogen-containing porous carbons suitable for energy storage applications, with the type of magnesium template affecting the reaction solution pH [60]. As a result of the ability to tune the optical and electronic characteristics as well as the chemical reactivities of the resulting CDs. Heteroatom doping of CDs has grown in popularity and effectiveness over the past few years [61,62]. Examples of heteroatoms in carbon frameworks include nitrogen, oxygen, and sulfur. Godavarthi et al. used waste macroalgae (*Sargassum fluitans*) as a carbon source precursor for creating nitrogen-doped carbon dots using hydrothermal methods. The nitrogen-doped carbon dots demonstrate exceptional fluorescent properties, serving as fluorophores for detecting deoxyribonucleic acid (DNA), single-stranded DNA, and ribonucleic acid (RNA) [63]. The massive amounts of pelagic *Sargassum* (brown macroalgae) that wash up on Caribbean coasts could give rise to new technical approaches in nanoscience, such as the large-scale production of carbon quantum dots(CQDs) utilizing simple, cheap technologies [64]. Carbon biomaterials reported from sources of algae described above are summarized in Table 1*:*

Overall, harnessing macroalgae as a sustainable carbon source can create high-value carbon biomaterials, with applications extending from energy storage to environmental remediation, and opens pathways for sustainable carbon materials from diverse algal species [41,65,66].

3.2. Non-algal sources

Biomass derived from plants and other non-marine sources can be converted into high-value carbon materials with properties, such as high surface area and mechanical strength, making them suitable for a wide range of applications [67]. We provide a short overview of products derived from non-algal biosources to provide a reference for the algae-based carbon biomaterials covered in this review. Making graphene originally began with carbonising populus wood biomass using nitrogen in an inert environment. The carbon from Populus wood biomass was chemically activated with KOH and the graphene has

Table 1
Summary of the reported carbon materials from algal sources through different synthesis methods.

Source/Algae species	Synthesis/ Thermal Methods	Biomass-Derived Products
Algal precursors	Chemical activation and metallic catalysis	Three-dimensional porous graphene
Capsosiphon fulvescens	Pyrolysis	Biochar with heteroatoms
Chlorella vulgaris	Activation/Pyrolysis	Nitrogen-doped carbon material
Chlorella vulgaris	Pyrolysis	Nitrogen-doped carbon materials
Enteromorpha	Persulfate activation	Graphene-like biochar
Enteromorpha	Carbonization/ Activation	Nitrogen-doped carbon materials
Enteromorpha macroalgae	Carbonization/Activation	Hierarchical porous carbons
Enteromorpha prolifera	Hydrothermal/Pyrolysis	Activated carbon-MnO2 Composite
Macroalgae from Beibu Gulf	Solvothermal approach and Doping	Graphene quantum dots
Rhodophyta, Chlorophyta, Cyanophyta	Hydrothermal	Carbon dots
Sargassum fluitans	Hydrothermal	Nitrogen-doped carbon dots
Sargassum tenerrimum	Pyrolysis	functionalized graphene nanosheets
Spirulina or Chlorella	Hydrothermal/Pyrolysis	Nitrogen-containing porous carbons
Spirulina platensis	Pyrolysis	Magnetic Nitrogen-doped carbon
Ulva fasciata	Chemical Activation and Pyrolysis	Graphene

Table 2
Summary of the reported carbon materials from non-algal sources through hydrothermal/pyrolysis treatment.

Sources	Synthesis/ Thermal Methods	Biomass Derived Products	References
Bengal gram bean	Pyrolysis Graphitization	Graphene	[73]
Brunch	Pyrolysis Graphitization	Graphene	[69]
Camphor leaves	Pyrolysis	Graphene	[74]
Empty Fruit	Pyrolysis	Graphene Oxide	[75]
Husk	Pyrolysis Graphitization	Graphene	[73]
Lignin biomass	Pyrolysis	Graphene	[76]
Lignin biomass	Pyrolysis	Graphene Oxide	[77]
Lignin biomass	Hydrothermal	Graphene	[78]
Lignin biomass	Hydrothermal	Graphene	[79]
Macadamia nut shell	Hydrothermal Pyrolysis	Graphene	[80]
Mango peel	Pyrolysis	Graphene	[81]
Oil Palm Leaves	Pyrolysis	Graphene Oxide	[75]
Palm Kernel Shell	Pyrolysis	Graphene Oxide	[75]
Peanut shell	Pyrolysis	Graphene	[82]
Populus wood	Pyrolysis	Graphene	[68]
Rice Husks	Pyrolysis	Graphene	[83]
Rice Husks	Pyrolysis	Graphene Quantum Dots	[84]
Rice Husks	Pyrolysis	Graphene	[85]
Rice Husks	Pyrolysis Chemical activation	Graphene	[86]
Soybeans	Pyrolysis	Graphene	[87]
Spruce bark	Hydrothermal Pyrolysis	Graphene	[88]
Sugarcane bagasse	Pyrolysis	Graphene	[89]
Sugarcane bagasse	Hydrothermal Pyrolysis	Graphene Quantum Dots	[90]
Wheat straw	Hydrothermal Pyrolysis	Graphene	[91]

several desirable properties, such as a microporosity of up to 94%, a total pore volume of 0.604 m^3/g, an average micropore diameter size of 1.84 nm, a Brunauer–Emmett–Teller (BET) surface area of 1317.1 m^2/g. At 293 K and 1 bar pressure, the sample exhibited a significant absorption capacity of 7.2 mmol/g [68]. Similarly, biomass-derived materials are being explored for graphene production; for example, using a two-stage pyrolysis method on empty oil palm fruit bunches yielded an increase in graphene production, with the highest yield—approximately 70% higher than that of a single heating stage—achieved at 350 °C [69]. Papaya biomass-derived carbon dots and reduced graphene oxide composites were developed using a simple hydrothermal method for visible-light degradation of Methylene Blue dye and antibacterial applications [70]. Briscoe et al. showed carbon dots can be synthesized from waste materials like chitin, chitosan, and glucose [71]. Nitrogen and sulfur co-doped carbon dots (CDs) from garlic exhibit good water dispersibility, strong blue fluorescence emission, and excellent photo and pH stabilities. They resist metal ions, biomolecules, and high ionic strength environments, making them ideal for cellular multicolor imaging and radical scavenging [72]. Carbon biomaterials reported from sources other than algae are summarized in Table 2.

Of the three main components of plant cell walls- hemicellulose, lignin, and cellulose- the largest component, cellulose, has received much attention from researchers because of its potential to produce carbon materials for various applications [92]. In a planar arrangement, hydrogen bonds bind (1/4)-β-D-glucan chains in a model chemical cellulose structure, which is a 2D crystal [93]. The surface area available for interaction with microbes and enzymes is increased by transforming bundled cellulose crystals into a planar 2D form, making cellulose more accessible for chemical transformations.

The efficient utilization of cellulose for producing chemicals and materials from sustainable resources holds promise using eco-friendly synthesis approaches. Long et al. demonstrated the fabrication of 2D graphene crystals from cellulose by carbonization and graphitization, utilizing an eco-friendly hydrolysis method [93]. In this context, agricultural waste has become a valuable precursor for producing low-cost and environmentally friendly graphene, contributing to a pollution-free synthesis process. Recently, significant attention has been directed toward sugarcane biomass, extracts, and bagasse as promising sources for synthesizing graphene derivatives through various heat treatment methods. Table 3 highlights graphene's synthesis techniques, products, applications and its derivatives from agricultural waste (specifically sugarcane).

Recently, researchers have studied green graphene (graphene from biomass) nanoparticles, which are environmentally friendly nanomaterials and are characterised by their sustainable and eco-friendly synthesis, production, and applications. Yadav et al. utilized rice charcoal to create green graphene with a size ranging from 3 to 10 nm and a sheet dimension of 4 mm. The glassy carbon electrode, which included graphene oxide from rice charcoal, demonstrated a specific capacitance

Table 3
Graphene and its agricultural-waste (sugarcane) derivatives: production processes, end products, and uses (mostly including heat treatment).

Sources	Synthesis Methods	Final derived products	Applications	References
Sugarcane Bagasse	Chemical exfoliation	Reduced graphene oxide with wrinkles of graphene layers	Removal of dye	[94]
Sugarcane Bagasse	Chemical and heat treatment	Highly fluorescent graphene quantum dots	–	[95]
Sugarcane Bagasse	Pyrolysis	Graphene microcrystal	–	[90]
Sugarcane Biomass	Carbonization	Graphene-like material	Adsorption of organic pollutants	[89]
Sugarcane Molasses	Chemical and heat treatment	Graphene-like carbon composite	Batteries	[96]

of 158 Fg^{-1} and maintained a retention rate of 93% after undergoing 2000 galvanostatic charge-discharge operations [97]. Graphene compounds were previously synthesized from woody biomass, food or agricultural waste, insects, and sewage sludges, and studies found few-layer graphene structures, despite high temperatures (>2000 °C) [98]. Bio-graphite (graphite from biomass), is distinguished because it receives its feedstock only from forestry by-products supplied locally and at a reasonable cost [99]. This not only lessens the reliance on the unpredictable pricing of petroleum coke or graphite flakes mined from the ground, but it also significantly reduces energy expenses. It is possible to circumvent the weeks-long manufacturing cycles of synthetic graphite by using a production process that operates at far lower temperatures (less than 1500 °C as opposed to 3000 °C for synthetic graphite) and takes a significantly shorter time. Through the facilitation of local manufacturing, bio-graphite can avoid the import charges, taxes, and high transportation expenses involved with producing the material [99].

Various complicated chemical reactions are used to pretreat biomass to extract useful carbon-based structures from organic matter. If the end carbon material is to have its characteristics modified to suit a particular use, these upstream procedures are crucial. According to He et al., the steps needed to create carbon materials from biomass include breaking down the biomass, polymerizing it, aromatizing it, carbonizing it, and graphitizing it [100].

4. Biomass conversion technologies

Biomass conversion to carbon materials involves transforming organic biomass into carbon-rich products through various methods. Common techniques for creating biomass-derived carbon materials include chemical oxidation and pyrolysis, hydrothermal carbonization, microwave carbonization, and combined energy sources using microwave-hydrothermal treatment. Hydrothermal treatment (carbonization) is the most widely applied approach [101]. Although there is a wide range of techniques for preparing biomass-derived carbon materials, research is ongoing on producing high-quality biomass-derived carbon materials using simple, economical, and size-controlled methods. This review also examines three widely utilized processes—microwave, pyrolysis, and hydrothermal treatments—used to create bio-based carbon compounds.

4.1. Hydrothermal treatment

The two primary categories of traditional and contemporary methods for transforming biomass into products with added value are biochemical degradation, which involves using enzymes as a biocatalyst, and thermochemical degradation, which utilises heat and chemical catalysts [102]. Gasification, carbonization, and liquefaction are all parts of the efficient hydrothermal process. By subjecting solid biopolymers to a high-pressure water environment for an extended period of time, hydrothermal liquefaction transforms biomass into liquid fuels [103]. Standard hydrothermal gasification is based on the nature of biomass and is a type of supercritical water gasification. Hydrothermal gasification achieves high carbon efficiency by reducing the amount of organic carbon in the water, an advantage over hydrothermal liquefaction [104].

Hydrothermal carbonization (HTC) is a low-temperature, autogenous-pressure biomass conversion process that converts biomass into hydrochar, a carbon-rich solid biomaterial with higher oxygen content and a more porous structure than normal biochar. It improves transport, storage, and handling characteristics with reduced preparation and treatment time, making it economically attractive [105]. Hydrothermal carbonization has been extensively used to produce carbonaceous compounds from biomass with high moisture content, including lignin, hemicellulose, and cellulose. Many see it as a potential solution for recycling biomass into valuable carbon compounds [105], as it converts biomass into carbonaceous solids without energy-intensive drying. The hydrothermal carbonization phase degrades harmful chemical compounds and residual micropollutants [106]. The efficiency of hydrothermal carbonization is influenced by reaction temperature, pressure, and duration, while the type of biomass employed impacts the products produced.

Recent advancements in hydrothermal carbonization have highlighted its versatility in converting a wide range of biomass sources into functional carbon nanomaterials, with promising applications in environmental remediation and energy storage. Amir Faiz et al. demonstrated the synthesis of reduced graphene oxide from tea waste, which was further combined with TiO_2 via hydrothermal treatment to form nanocomposites exhibiting enhanced photocatalytic activity [107]. In a similar vein, Zhao et al. developed a one-step hydrothermal process to convert bean dregs and coffee grounds into graphene quantum dots (GQDs), which displayed excellent fluorescence and high metal ion detection sensitivity [108]. Poorna et al. provided a comprehensive review of hydrothermal carbonization's potential for producing porous, heteroatom-doped graphene materials from agricultural residues like rice husk and wheat straw—materials well-suited for supercapacitors and lithium-ion batteries [109]. Moreover, hydrothermal carbonization was successfully applied to synthesize magnetic iron-carbon (Fe/C) composites from avocado seeds, yielding magnetite-based materials with significant potential for dye adsorption and catalytic hydroalkoxylation reactions [110].

Expanding the scope of hydrothermal carbonization applications, a recent study employed microwave-assisted hydrothermal carbonization to synthesize carbon nanomaterials from red algae species *Chondrus crispus* and *Palmaria palmata*. These carbon materials showed high efficiency in removing ciprofloxacin and malachite green from contaminated water. The adsorption process was both exothermic and entropically favorable, and the carbon material maintained high removal efficiency over at least three regeneration cycles [111]. These findings underscore the viability of algae biomass as a renewable feedstock in hydrothermal carbonization processes, offering an environmentally friendly pathway to develop reusable sorbents for water purification and reinforcing the role of hydrothermal carbonization in advancing green nanomaterials.

Applications of hydrothermal carbonization on marine biomass have proved successful for some macroalgae and microalgae. Hydrothermal carbonization of microalgae yields unique, bituminous coal-like char products with energy content in the coal range, with mild process conditions [112]. Hydrochars from *Sargassum horneri* (brown macroalgae), prepared through hydrothermal carbonization at 180–210 °C, were characterised for their potential as a valuable feedstock for carbon-based material synthesis, with carbon contents of 36.8–50.55% and higher heating values [113]. Nitrogen-doped microporous carbons were successfully fabricated from nitrogen-rich microalgae using low-cost hydrothermal carbonization and KOH activation processes, resulting in Brunauer–Emmett–Teller (BET) surface areas of approximately 1800–2200 $m^2\ g^{-1}$ [114].

Table 4 shows that hydrothermal carbonization is applied to treat

Table 4
Published works of the hydrothermal carbonization process on micro and macro algae.

Algae Species	Hydrothermal carbonization Process conditions	Products	References
Gelidium sesquipedale	Temperature: 200 °C and 230 °C, Time: 2 and 6 h	Hydrochar	[116]
Laminaria digitata *Laminaria hyperborean* *Alaria esculenta*	Temperature: 200 °C and 250 °C	Hydrochar	[117]
Sargassum horneri	Temperature: 180–210 °C, Time: 2–16 h	Biochar	[113]

defatted microalgal residuals and lower-value macroalgae, highlighting its role in converting diverse algae types into carbon biomaterials [115].

Briscoe et al. synthesised carbon quantum dots using biomass derived from waste products, which included chitin, chitosan, and glucose, which underwent hydrothermal carbonization treatment at 200 °C for 6 h. New hybrid materials made from zinc oxide nanorods sensitized with three carbon quantum dots (CQDs) from biomass (waste products of chitin, chitosan, and glucose) through hydrothermal carbonization, were used to construct solid-state nanostructured solar cells, with the performance of the CQDs influenced by their functional groups [71]. Hydrothermal treatment of willow leaves yielded nitrogen-doped carbon dots with an outstanding electrocatalytic activity; this environmentally friendly process was developed by Gao et al. [118].

Xie et al. showed that plant biomass materials heated to high temperatures can be utilized to generate mesoporous carbon (highly ordered porous structure with pore sizes in the range of 2 to 50 nm) and carbon nanotubes, which eliminates carbohydrates and generates a highly durable carbon-rich material with turbostratic (disordered regions of graphitic carbon) crystallites with large graphene layers [119]. To tailor surface properties like porosity, surface area, and other desirable properties, the pyrolysis process, which involves heating biomass without oxygen, is often employed in the next downstream processing phase to control carbon structure and enhance graphitization [120].

4.2. Pyrolysis treatment

Pyrolysis is the high-temperature thermochemical process of breaking down biomass into smaller, simpler gas, liquid, and charcoal molecules, without(or limited) oxidizing agents [121]. The basic chemical reaction is multi-step and complicated. Biomass pyrolysis produces biochar, bio-oil, and gases, primarily carbon dioxide, carbon monoxide, methane, and hydrogen. Organic materials in the biomass substrate decompose at 350–550 °C and 700–800 °C without air/oxygen.

The biochars used by Liu et al. were from six different types of macroalgae, including three Phaeophytes (*Sargassum fusiforme, Sargassum thunbergii, and Sargassum vachellianum*), one Chlorophyte (*Ulva pertusa*), and two Rhodophytes (*Grateloupia turuturu and Chondria crassicaulis*). This pyrolysis process occured at temperatures ranging from 200 to 500 °C and fluorescence excitation-emission matrix spectroscopy with parallel factor (PARAFAC) analysis study was performed to know the impact of pyrolysis temperature and extraction solution pH (measure of hydrogen ion concentration in a solution) on the properties of macroalgal biochar-derived dissolved organic matter which contains carbon [122]. Pre-treatment methods such as salt-based activation, chemical blowing, a template-based approach, and hydrothermal carbonization followed by pyrolysis were reported by Kong et al. as ways to produce two-dimensional graphene. Due to their scalability, effectiveness in achieving graphitization, and ease of implementation, salt-based activation procedures(which include physical activation (e.g., steam, CO_2), chemical activation using various chemicals) and pyrolysis combined with hydrothermal treatment methods are commonly used to produce graphene-like materials from biomass [123].

Table 5 provides an overview of non-algal sources, graphene products produced from each biomass source, along with the particular temperatures used to conduct the pyrolysis:

Table 5
Summary of the Reported Carbon Materials from Non-algal sources through pyrolysis.

Sources	Synthesis/ Thermal Methods	Temperature	Biomass-Derived Products	References
Bengal gram bean	Pyrolysis Graphitization	400 °C & 850 °C	Graphene	[73]
Brunch	Pyrolysis Graphitization	350 °C & 900 °C	Graphene	[69]
Camphor leaves	Pyrolysis	1200 °C	Graphene	[74]
Empty Fruit	Pyrolysis	700 °C	Graphene Oxide	[75]
Husk	Pyrolysis Graphitization	400 °C & 900 °C	Graphene	[73]
Lignin biomass	Pyrolysis	1000 °C	Graphene	[76]
Lignin biomass	Pyrolysis	1100 °C	Graphene Oxide	[77]
Mango peel	Pyrolysis	750 °C	Graphene	[81]
Oil Palm Leaves	Pyrolysis	700 °C	Graphene Oxide	[75]
Palm Kernal Shell	Pyrolysis	700 °C	Graphene Oxide	[75]
Peanut shell	Pyrolysis	800 °C	Graphene	[82]
Populus wood	Pyrolysis	950 °C	Graphene	[68]
Rice Husks	Pyrolysis	550 °C	Graphene	[83]
Rice Husks	Pyrolysis	700 °C	Graphene Quantum Dots	[84]
Rice Husks	Pyrolysis	1300 °C	Graphene	[85]
Rice Husks	Pyrolysis Chemical activation	300 °C & 850 °C	Graphene	[86]
Soybeans	Pyrolysis	800 °C	Graphene	[87]
Sugarcane bagasse	Pyrolysis	900 °C	Graphene	[89]

4.3. Microwave treatment

Microwave radiation, covering frequencies from 30 GHz to 300 MHz, is widely used in communications and food heating but has also gained traction as an effective tool for material synthesis and activation. Unlike conventional heating, which heats from the outside in, microwave heating produces uniform, rapid heating by energizing water molecules from the inside out, allowing for greater control and efficiency [124, 125]. These unique characteristics have positioned microwave techniques as a powerful method in carbon material synthesis, offering benefits over traditional heating methods.

Gedye et al. show that using a microwave oven technique("microwave-assisted") can significantly reduce the time for laboratory organic syntheses, especially those involving low-boiling solvents or reagents, by providing rapid and affordable access to high temperatures and pressures, unlike alternatives that require elaborate apparatus and long heating times [126]. Microwave-assisted pyrolysis can be tailored by manipulating parameters such as temperature rate, microwave absorber addition, and gas residence time, which determine product type and yield [127]. For instance, lower temperatures and shorter residence times favor liquid products, while higher temperatures yield more gaseous products. Combining microwaves with flash pyrolysis also enhances efficiency, offering an alternative to conventional pyrolysis [128].

Microwave-assisted pyrolysis has shown distinct advantages in the synthesis of carbon biomaterials. For instance, T. Li et al. prepared porous graphene nanosheets from black sesame seeds using microwave-assisted pyrolysis, achieving a larger specific surface area, optimized micropore diameter, and a higher degree of graphitization than conventional methods [129]. Similarly, *X.* Li et al. employed microwave pyrolysis with *Artemisia selengensis*(a perennial herbaceous plant) to create biochar, demonstrating that dye adsorption capacity increased, though yield decreased, as the pyrolysis temperature rose [130]. This demonstrates how microwave methods can be fine-tuned to enhance specific properties of carbon biomaterials.

Microwave-assisted techniques also prove valuable in catalytic applications. Ahmad Farid et al. reported a microwave-assisted transesterification method that synthesized a graphene catalyst from ground bamboo, showing enhanced catalytic efficiency for transesterification

when using refined palm oil [131]. Additionally, Ao et al. comprehensively reviewed microwave irradiation's role in biomass activation, detailing its heating properties, optimization parameters, progress, and economic viability in the field [132].

Beyond biochar and catalysts, microwave radiation has facilitated the creation of functional carbon-based nanomaterials. Ramanan et al. developed the first green microwave thermal oxidation technique, transforming eutrophic algal blooms into fluorescent carbon dots. This method produces carbon dots with biocompatible imaging potential due to their strong luminescence, water solubility, stability, and resistance to photobleaching [133]. Similarly, Olmos-Moya et al. produced co-functionalized carbon quantum dots from orange peel powder, enhancing their optical properties [134], while Si et al. devised a one-pot method to create nitrogen-doped carbon nanodots from rice straw with vibrant photoluminescence properties [135]. Together, these examples illustrate microwave techniques' diverse, sustainable applications in carbon nanomaterial synthesis.

Thermochemical treatment and activation of carbons can be achieved through microwave treatment, which offers great promise because of its distinctive features—namely, its small, low-volume pores. In their review, Ao et al. detail the use of microwave treatment to produce activated carbon from a variety of biomass materials, including agricultural byproducts, woody biomass, and sewage sludge. Along with that, it describes the properties of activated carbons produced by microwave and conventional activation methods. In comparison to more traditional methods, microwave irradiation of biomass produces activated carbons with comparable maximum Brunauer-Emmett-Teller (BET) surface areas, methylene blue adsorption capacities, iodine numbers (a measure of the micropore content of activated carbon), and yield ranges [132]. However, microwave-assisted preparation of activated carbons is still far from maturity, and more research and process development are needed.

Microwave techniques have also been utilised for the preparation of specialized carbon materials (Table 6). Kaewtrakulchai et al. used oil palm male flowers in microwave-assisted pyrolysis with potassium hydroxide to produce nanoporous carbons [136]. Similarly, Villota et al. optimized the microwave carbonization of cocoa pod husks, finding that H_3PO_4 activation led to higher yields and improved texture over KOH [137].

Innovative methods, such as the chemical vapor deposition technique developed by Ruan et al., use unconventional carbon sources like cookies, plastic, and even dog feces to grow graphene on copper foil at high temperatures [138].

Table 6
Summary of the Reported Carbon Materials from algae and other biomass sources through microwave treatment.

Sources	Synthesis/ Thermal Methods	Biomass-Derived Products
Black sesame seeds	Microwave-assisted pyrolysis	Porous graphene nanosheets
Artemisia selengensis	Microwave pyrolysis	Biochar
Ground bamboo	Microwave-assisted transesterification	Graphene catalyst
Eutrophic algal blooms	Microwave thermal oxidation	Fluorescent carbon dots
Orange peel powder	Microwave-assisted synthesis	Cobalt-functionalized carbon quantum dots
Rice straw	Microwave-assisted synthesis	Nitrogen-doped carbon nanodots
Agricultural by-products, woody biomass, and sewage sludge	Microwave treatment	Activated carbon
Oil palm male flowers	Microwave-assisted pyrolysis	Nano porous carbons
Cocoa pod husks	Microwave carbonization with activation	Activated carbon

5. Characterisation techniques for carbon materials

5.1. Scanning electron microscopy (SEM)

SEM allows for observing and characterising organic and inorganic heterogeneous materials on a scale ranging from nanometers to micrometers. A region or microvolume to be examined or analyzed is illuminated with a focused electron beam in a scanning electron microscope (SEM). This beam can either be raster movement across the specimen's surface to create images or fixed at one point to provide a single analysis. Various photons of different energies, including secondary electrons, backscattered electrons, x-rays, and others, are generated when the electron beam in the SEM interacts with the sample. These signals can be used to examine various sample characteristics (surface topography, crystallography, composition) obtained from specific emission volumes inside the sample [139]. This microscopic technique has become useful for understanding two-dimensional materials' structure, surface shape, irregularities, and optical features like graphene, sulfides, and nitrides. All these features are examples of layered elements [140].

The effects of carbonization and activation on the surface deformation, size, and shape of carbon-based supercapacitor electrode material produced from *Chlorella zofingiensis* algae were confirmed using SEM [141]. Cobalt-doped porous carbon derived from the macroalgae *Enteromorpha sp.* is an effective catalyst for the oxygen reduction reaction. Its high catalytic performance is attributed to its porous structure, which provides ample surface area and allows reactants to access active sites, as confirmed (Fig. 6: a–d) by SEM analysis [142]. Rectangular-aligned anisotropic (physical or mechanical properties vary in different directions) -large channels, closely packed, and loosely arranged structures were observed in SEM (Fig. 6: e–g) for the graphitic materials synthesized, respectively, from wood, filter paper, and cotton through microwave-assisted pyrolysis [143].

5.2. X-ray diffraction or X-ray powder diffractometry (XRD)

The graphite family of carbon materials, including highly ordered and disordered carbons, all share the fundamental structural unit of "crystallites," consisting of parallel stacking of carbon hexagonal net layers. One non-destructive method for studying these material structures, especially at the molecular or atomic level, is X-ray diffraction (XRD). It is used to examine non-crystalline and crystalline or partially crystalline materials (those with periodic structural order). X-ray powder diffractometry uses monochromatic light, where the output chart of the XRD measurement is not a "spectrum" but rather a "diffraction pattern". The diffraction pattern is the product of diffraction intensity and goniometer angle 2θ. Because carbon(graphitic) structures are quite anisotropic, their diffraction lines fall into one of three categories: the (00l), (hk0), or (hkl) index [144,145]. The creation of graphite structures is shown by the reflection of specific lines from different planes: (00l) lines from the crystallographic basal planes (crystal lattice parallel to one of the primary axes of the crystal structure), (hk0) lines from perpendicular planes, and (hkl) lines from three-dimensional structures [146].

Biochar containing graphene was synthesized using bamboo biomass as the precursor and K_2CO_3 as an activating agent, where the crystal structure was examined using X-ray diffraction (XRD) using Cu Kα radiation. The XRD patterns (Fig. 7a) show typical amorphous carbon in carbonized biochar, while biochar containing graphene exhibited typical graphene or graphene-like carbon materials. The sharp peaks of biochar containing graphene also indicated a high graphitization degree and crystallinity [147]. Pyrolysis of iron-impregnated cellulose at three distinct temperatures (1000, 1400, and 1800 °C) resulted in the production of highly graphitic biochar, confirmed by the XRD data acquired (Fig. 7b), showing that as the pyrolysis temperature increases, the (0 0 2) carbon XRD peak becomes more pronounced [148]. An XRD peak comparison was conducted by Li et al. between traditional

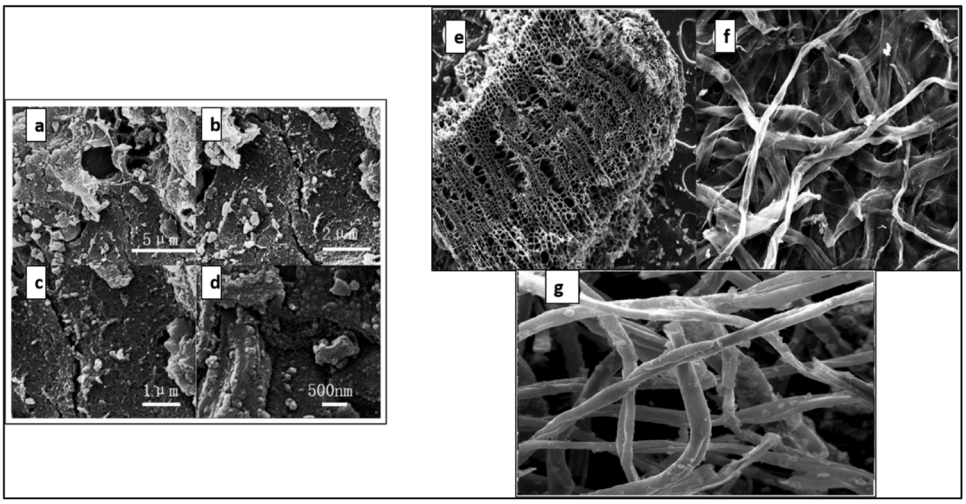

Fig. 6. a–d) SEM images of Cobalt-doped porous carbon from the macroalgae Enteromorpha algae with different magnifications. Reprinted and edited with permission from [142]. e–g) SEM images of graphitic carbon materials using wood, filter paper, and cotton. Reprinted and edited with permission from [143]. Copyright 2008 ACS Publishing.

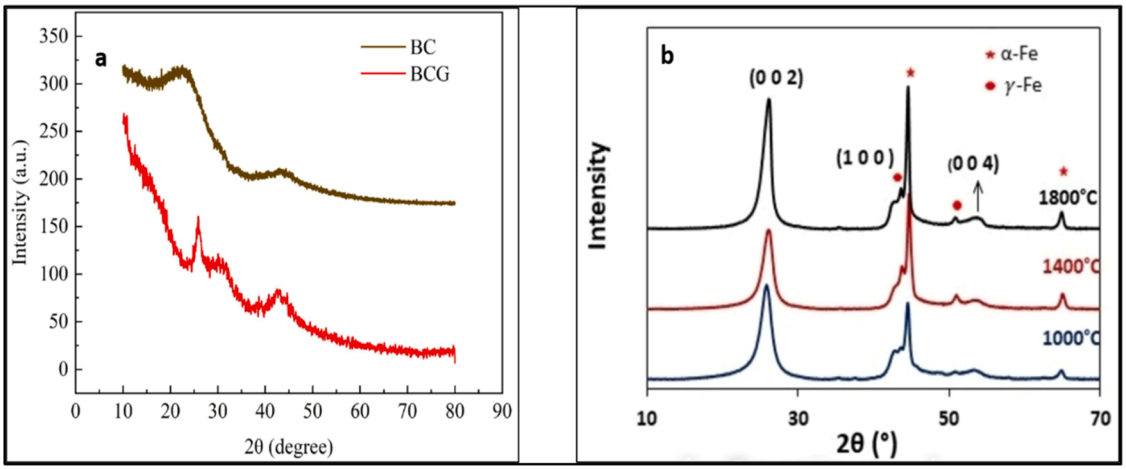

Fig. 7. a) XRD patterns of biochar (BC) and biochar-derived graphene (BCG). Reprinted and edited with permission from [147]. Copyright 2021 Elsevier Publishing b) XRD pattern of graphitic biochar that was pyrolyzed at temperatures of 1000, 1400, and 1800 °C: Based on the graphite crystal structure, the carbon peaks have indices (0 0 2), (1 0 0), and (0 0 4), α-Fe and γ-Fe are associated with ferrite and austenite, respectively. Reprinted and edited with permission from [148]. Copyright 2022 John Wiley & Sons Publishing.

carbonization and microwave production of porous graphene nanosheets (PGNS-4) generated from black sesame seeds. According to Li et al., the presence of dense micropores is confirmed by the (001) interlayer distance, which indicates amorphous graphitic carbon as seen by the faint peak at the center of ~43 degrees and the (002) plane and graphitic carbon were suggested by a diffraction peak that developed at around 26 degrees [129].

5.3. Raman spectroscopy

Raman spectroscopy is one of the powerful methods for studying carbon materials because it is both non-invasive and highly sensitive to molecular geometry and bonding [149,150]. The method is also well-suited to studying structural changes in graphitic carbon atoms because they are light and have strong sp^2 σ-bond interactions. The G-band, D-band, and 2D-band are the three primary components of the Raman spectra used with carbon-based materials. The G-band, which is positioned at ~1582 cm^{-1} and represents the in-plane sp^2 vibrational mode, gives the profile of the graphitic structures and crystallinity in carbon materials. The D-band, at ~1350cm^{-1}, also known as the disorder or defect band, is a ring breathing mode from sp^2 carbon rings, with its intensity directly proportional to the sample's defects [151–155]. There is a statistically significant peak-to-distribution ratio between the G-band and the D-band, and the disorder of the material is directly related to the G-band's dispersion [146]. Indicative of the sample's layer count is the 2D-band, which is also called the G'-band. A lateral vibrational process involving two phonons enhanced by double resonance is the source of the 2D band [156].

Ai et al. obtained the Raman spectrums of graphene samples synthesized from *Sargassum horneri* to study the degree of graphitization and the changes in the degree of disorder with increasing activation temperature in between 700 and 850 °C. A distinct 2D-band peak at 2642 cm^{-1} was observed in samples synthesized from *Sargassum horneri*, at an activation temperature of 850 °C (in Fig. 8), which was reduced compared to single-layer graphene [39,157,158]. This suggests that this study's sample at 850 °C is a multilayered graphene with defects, and KOH activation is crucial for its formation. By pyrolyzing used car tyres and using the microwave's heating characteristics, Wu et al. created highly valuable graphene. Experiments were performed using the holding temperature (°C)-holding duration (h) relationship.

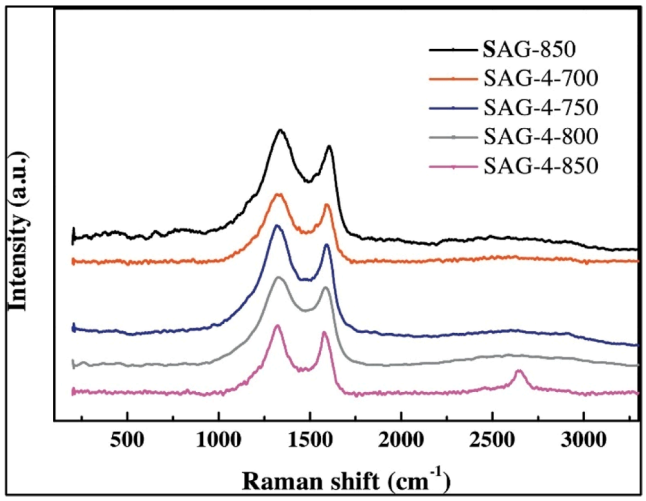

Fig. 8. Raman spectra of graphene samples synthesized from Sargassum horneri. Reprinted and edited with permission from [39]. Copyright 2021 Elsevier Publishing.

Experiments conducted at 800 °C showed the low graphene production with the highest I_D/I_G and the lowest I_{2D}/I_G values. In the other three sets of experiments, graphitization was strong and the defect density decreased as the holding duration increased which raised the I_{2D}/I_G values, it concluded that these values impact graphene conversion, and heat insulation during the production which helps to separate oxygen atoms in tyres [159]. Raman spectroscopy further confirmed the graphitic structure of the products obtained from wood, filter paper, and cotton using microwave-assisted pyrolysis [143]. The Raman spectra of the carbon by-products of the aforementioned materials treated with microwaves reveal a faint peak at around 1370 cm^{-1}, which can be attributed to the disorder-induced line (D band) of a carbon structure that is disordered. Notably, the spectra were dominated by a strong peak at 1590 cm^{-1}. In hexagonal graphite, the vibration of sp^2-hybridized carbon atoms in the graphite layer is associated with the E_{2g} mode, which is a doubly degenerate Raman active optical vibration, as shown by the G band in graphite [143,160].

Raman spectroscopy is an invaluable tool for characterising carbon-based materials' structural integrity, graphitization level, and defect density. By analysing the key bands (D, G, and 2D), researchers can assess the carbon structure's order, disorder, and layer count, enabling precise insights into the effects of synthesis conditions, activation methods, and precursor types on carbon material properties. This sensitivity to molecular geometry and bonding variations makes Raman spectroscopy indispensable for optimizing carbon materials across diverse applications.

6. Application of bio-based carbon materials

Bio-sourced carbon materials have garnered significant attention for their potential to enhance efficiency and reduce environmental impact across various applications, particularly in the field of bio-manufacturing. These materials are valued for their sustainability and versatility, making them suitable for diverse industries. In particular, they have shown great promise in energy storage, environmental remediation, electronics, catalysis, pharmaceuticals, and materials science. Each of these sectors benefits from the unique properties of bio-derived carbon, such as high surface area, conductivity, and adsorption capacity, positioning them as key contributors to advancing sustainable technologies and driving biomanufacturing in the new bioeconomy [9,161,162].

6.1. Water purification and environmental remediation

In water purification and environmental remediation, studies demonstrate the efficacy of algae-derived porous carbon and biochar. Lin et al., Qin et al., and Ke Wang et al. investigated high-performance adsorption of pharmaceuticals such as sulfamethoxazole and sulfathiazole using algae-derived carbon materials produced through pyrolysis. For instance, Spirulina biochar activated at different mass ratios (e.g., 0.5:1, 1:1) showed significant improvements in sulfathiazole removal from aquatics compared to non-activated biochar [163]. Multielement-doped biochar from Enteromorpha prolifera(macroalgae), treated at 800 °C, was found to enhance sulfamethoxazole adsorption and reusability [164]. This material achieved an impressive 95.05% removal efficiency for sulfamethoxazole, illustrating its suitability for water purification applications [165].

6.2. Carbon capture and dye adsorption

A study demonstrated the use of Sargassum horneri, a subtropical macroalgae, as a sustainable biomass precursor for synthesizing porous graphene through KOH activation. The resulting material exhibited a high specific surface area (~1411 m^2/g), well-developed micro- and mesoporous structures, and a strong CO_2 adsorption capacity of 2.78 mmol/g at 30 °C and 1 bar. The adsorption behavior followed the intraparticle diffusion model, suggesting that both the pore architecture and nitrogen-containing surface functionalities played critical roles in CO_2 capture performance [39]. Similarly, high-salinity Spirulina algae-derived biochar has shown strong potential for removing ionized dyes from aqueous environments. Its rich content of sodium and calcium minerals, along with tunable surface properties, enhances dye adsorption through electron donor–acceptor interactions and metal-bridging mechanisms [166]. These findings collectively highlight the versatility of algae-derived carbon materials in addressing both atmospheric and waterborne pollutants, offering sustainable solutions for environmental remediation and carbon management.

Liu et al. developed a graphene-like fuel cell with a high surface area (1510 m^2/g) derived from Nori algae, demonstrating excellent oxygen reduction reaction (ORR) performance(Fig. 9*d–f*) [167], and Siipola et al. explored biochar from the bark of scots pine as a water filtration adsorbent, extending its utility to environmental remediation [168].

6.3. Energy storage: supercapacitors and batteries

Applying bio-based carbon materials in high-performance supercapacitors and batteries highlights their role in energy storage. Carbon-based electrodes are particularly desirable due to their low cost, abundance, and ease of modification, which allows for tailoring conductivity and surface area to enhance performance. Purkait et al. created a binder-free supercapacitor using a few layers of graphene nanosheets from peanut shells with tremendous pore capacity, facilitating the electrode to accomplish 58.125 W h Kg^{-1} energy density and 37.5 W Kg^{-1} power density [82]. A new one-step approach was used to prepare nitrogen-doped carbon from *Enteromorpha* algae at a low temperature of 600 °C for 3 h. Further anchoring of cobalt ferrite on these carbon is performed and the storage capacity (Fig. 9*a–c*)in lithium-ion batteries [45], making it a promising candidate for fuel cells and lithium-ion batteries.

Various bio-materials, including multistage carbon nanostructures and nanotubes, have proven effective when used as electrode materials in these devices [169]. Algae-derived carbons, particularly from *Lessonia nigrescens* (brown macroalgae) and *Chlorella vulgaris* (green microalgae), have shown strong potential in energy storage and environmental remediation. Pyrolysis of *Lessonia nigrescens* under nitrogen at 600–900 °C produced oxygen-rich or micro/mesoporous carbons, depending on conditions, with surface areas up to 1300 m^2/g. These materials demonstrated excellent performance as supercapacitor electrodes in

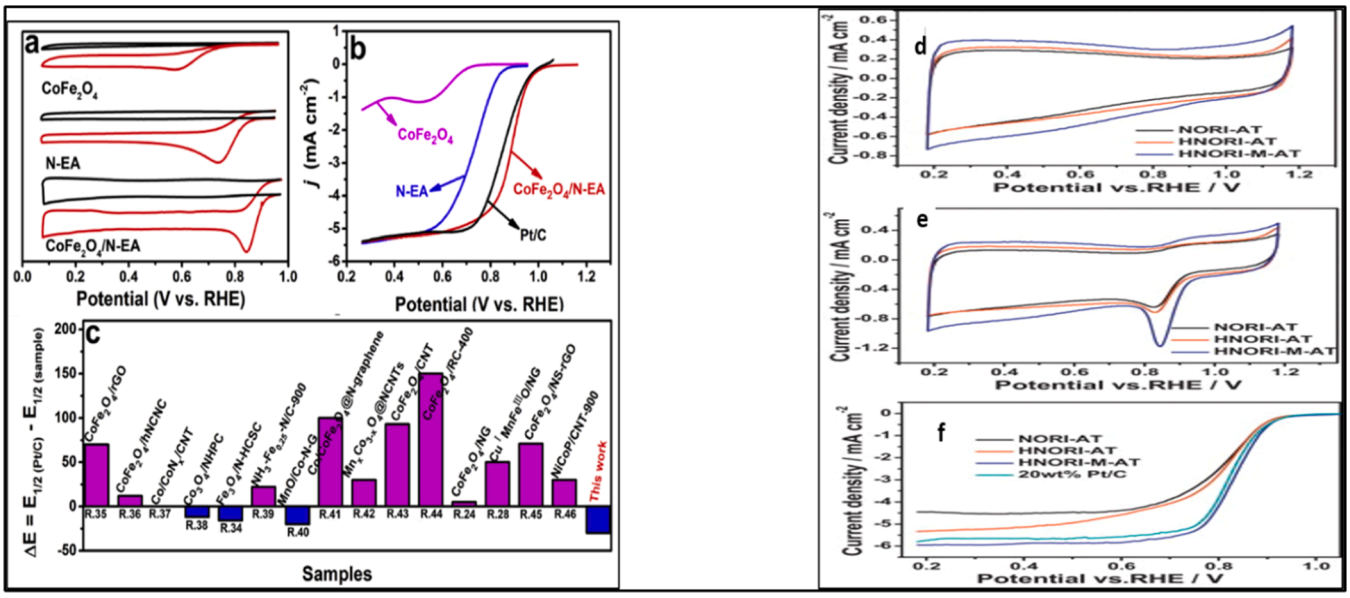

Fig. 9. a–c) Cyclic Voltammetry (CV) curves of pure $CoFe_2O_4$, nitrogen-doped carbon derived from Enteromorpha algae(N-EA), and $CoFe_2O_4$/N-EA in N_2-saturated (black) and O_2-saturated (red) 0.1 M KOH with a scanning rate of 10 mV s^{-1}. (b) Linear sweep voltammetry curves of each sample and commercial Pt/C in O_2-saturated 0.1 M KOH at a scan rate of 10 mV s^{-1}. (c) The comparison of ORR activities with recently reported catalysts in alkaline media. Reprinted and edited with permission from [45]. Copyright 2021 Elsevier Publishing d–f) CV curves of as-prepared catalysts (HNORI-AT and NORI-AT were synthesized using similar precursors (Nori Algae) and procedures without melamine, with NORI-AT additionally prepared without the hydrothermal carbonization process, while HNORI-M-AT was synthesized with melamine and subsequently acid-treated) from 1.2 to 0.2 V vs. RHE (reversible hydrogen electrode) in (d) N_2 or (e) O_2, and (f) ORR polarization plots, compared with 20wt% Pt/C. Reprinted and edited with permission from [167].Copyright 2014 Elsevier Publishing.

both aqueous and organic media, offering high volumetric capacitance suitable for compact energy storage devices [170]. Additionally, their simple, eco-friendly synthesis makes them promising for water and air purification. Another study investigated algae-graphene composites, where *Chlorella vulgaris*-based carbon combined with graphene achieved a high specific capacitance of 192 F/g after 10,000 cycles in K_2SO_4 electrolyte [171]. This underscores the potential of algae-based materials as efficient, durable electrodes for next-generation supercapacitors. Table 7 below highlights the electrochemical capacitances of carbon materials derived from natural compounds through pyrolysis treatment, underscoring the versatility of bio-based carbons in sustainable energy applications:

Table 7
Electrochemical capacitances of carbon materials derived from natural compounds.

Sources of Electrode Material	Electrode Material	Specific Capacitance, C_s (F/g)	References
Bovine bone	Carbon monoliths (3D porous carbons)	134	[172]
Tea waste	Activated carbon	167	[173]
Orange peel	Nitrogen-doped activated carbon	168	[174]
Areca Catechu Husk	Carbon nanofibers	182	[175]
Polycarbonate waste	Activated carbon	182.1	[176]
Lessonia Nigrescens (brown macro algae)	Nano-porous carbons	203	[170]
Wheat Straw Husk	Nitrogen-doped porous carbon	223.9	[177]
Lignin	Activated carbon	233	[178]
Chlorella vulgaris (green microalgae)	Graphene-algae composite	241	[171]
Kraft lignin	Tri-doped porous carbon	244.5	[179]
Pistachio nutshells waste	2D microporous carbon	261	[180]

The capacitance values in Table 7 highlight how different bio-waste sources contribute to high-performing, eco-friendly electrodes. These findings support bio-sourced carbons' potential for advancing energy storage technologies and their role in developing sustainable solutions across various applications.

6.4. Solar energy applications

Additionally, biomass-derived carbon dots have shown utility in solar cell applications. These photoluminescent properties can increase the efficiency of ZnO nanorods in visible light absorption, improving the performance of solid-state solar cells [71]. Zhang et al. discovered a fluorescence quenching technique that greatly increased carbon nanodots (derived from *Ophiopogon japonicus*(Monkey Grass)) sensitized aqueous solar cell conversion efficiency and proposed a theory that could improve solar cell performance using different fluorescent quantum dots/nanodots sensitizers [181]. Marinovich et al. investigated biomass-derived carbon dots for Titanium dioxide(TiO_2) - based nanostructured solar cells, highlighting the importance of functionalization in solar cell performance [182].

6.5. Biomedical applications

Bio-sourced carbon materials also show potential in medical applications. Xue et al. developed a near-infrared (NIR) fluorescence imaging nanoprobe using biobased carbon dots for image-guided photodynamic therapy, demonstrating their potential in cancer diagnostics and treatment [183].

Through these applications, bio-based carbon materials from algae and non-algae sources are emerging as vital contributors to sustainable and efficient solutions across industries, affirming their relevance in future technological advancements.

7. Recent developments in the field of carbon materials

In recent years, the development of advanced construction materials

has gained significant attention due to the growing demand for stronger, more durable, and environmentally sustainable infrastructure. Among these materials, composites made of cement containing varying amounts of carbon dots have been studied for their workability, mechanical characteristics, and microstructure. Research by Qu et al. highlights that the combined effects of nano-size and surface functional groups in carbon dots contribute significantly to the high mechanical strength of cement-based composites, as evidenced by specific experimental properties [184].

Table 8 outlines recent advancements in carbon materials, specifically focusing on algae derived carbon materials. These developments, spanning from 2021 to 2025, demonstrate carbon material's transformative potential in industries such as construction, automotive, and energy storage. Innovations in graphene-enhanced cement, advanced battery technologies, and CO_2 adsorption materials illustrate how these materials can pave the way for more sustainable and efficient solutions. This year-wise compilation emphasizes carbon materials ability to enhance the mechanical, electrical, and environmental properties, contributing to significant reductions in carbon emissions and improved overall performance.

As global greenhouse gas levels continue to rise, innovative solutions for carbon capture and environmental remediation are becoming increasingly critical. The highest levels of greenhouse gases have been recorded in the last decade, with carbon dioxide (CO_2) being the most concerning due to its long-lasting presence in the atmosphere. Among the latest developments in carbon materials, graphene oxide foams have emerged as a promising tool for CO_2 adsorption. Parks, public squares, trains, planes, airports, and cities with high CO_2 concentrations are just a few places where the Graphene Oxide-Foam-CO_2 prototype can be utilized for CO_2 capture, purification, and monitoring.

Possible applications of Graphene Oxide-Foam-CO_2 are illustrated in Fig. 10.

Carbon nanotubes (CNTs) exhibit potential for advanced technologies, provided their structure remains consistent. Their growth happens at elevated temperatures along a tube-catalyst interface, where defects may modify their characteristics. An understanding of these mechanisms at the atomic level remains insufficient. A recent study utilizing molecular dynamics simulations demonstrated that DeepCNT-22, a machine learning force field (MLFF), indicates the tube-catalyst interface is significantly dynamic during growth, exhibiting substantial fluctuations in the chiral structure of the CNT-edge [201].

Moreover, researchers suggest that further theoretical and experimental investigations into osmium decoration on single-walled carbon nanotubes (SWCNTs) are essential to confirm their superiority over other hydrogen storage materials [202]. Nitrogen doping in graphene with a three-dimensional porous structure offers potential for developing metal-air batteries for electric and electronic devices. These ongoing advancements underscore the critical role of carbon materials, particularly graphene and its derivatives, in addressing environmental challenges and enhancing the performance of emerging technologies across various industries.

8. Conclusion and future perspectives

The review presented demonstrates fascinating possibilities and a cost-effective approach to creating carbon products from inexpensive natural resources. These biomaterials have many potential applications, including gas storage adsorbents, organic and heavy metal removers, battery and supercapacitor electrode materials, and catalysts for chemical reactions involving organic radicals. Factors such as surface area, ash content, metallic impurities, and structural components like heteroatoms all influence the performance of these carbons. Especially, algae-derived carbon materials offer significant environmental advantages over fossil-based graphite, including low-cost, renewable production, waste valorisation, and net CO_2 reduction. In contrast, graphite extraction is energy-intensive and environmentally damaging, though it

Table 8
Recent advancements in the field of carbon materials.

Application	Product/ Development	Results/Benefits	Industry/ References
Supercapacitors	Carbon electrode materials from algae	Enhanced electrochemical performance through carbon activation and doping	[185]
Automotive, aerospace, and sporting	Algae derived carbon-epoxy matrix composites	Improved mechanical properties -sustainable alternative to traditional reinforcing agents	[186]
Renewable energy	Hydrogen producing electrode from algal biochar	Enhanced efficiency and sustainability of hydrogen production processes	[187]
Energy storage	Lithium-ion battery's anode composites via algal-derived biomass gel carbon	Improved battery performance with enhanced charge/ discharge rates and cycle stability	[188]
Energy storage	Algae-derived hard carbon	Hard carbon anodes for sodium-ion batteries and comparable electrochemical performance to commercial synthetic hard carbon	[189]
Sensors	Graphene algae hydrogel	Enhanced sensitivity and flexibility	[190]
Electric vehicle (Aion V)	Graphene battery	1000 km range, 80% recharge in 8 min, lasts up to 1000,000 km without damage.	GAC Motor Co. Ltd [191]
3D printed construction using graphene-enhanced cement	Graphene-enhanced cement	Significant improvement in mechanical properties, reduction of CO_2 emissions by 20% by 2030.	Versarien -Graphene Flagship [192]
Automotive foams	Flash graphene from waste plastic	Increased tensile strength by 34%, improved noise absorption by 25%.	[193]
Cement industry	PureGRAPH® 50 (graphene platelets)	Enables cement manufacturers to meet the 20% CO_2 reduction target while enhancing cement's strength.	First Graphene Ltd [194]
Energy storage for consumer electronics	Graphene aluminum-ion batteries	Potential energy density up to 1050 Wh/kg, longer battery life, faster charging than conventional batteries.	Graphene Manufacturing Group Ltd (GMG) [195]
Energy storage for various applications	OrganoLyte™ (non-flammable graphene-based Li-ion battery)	Energy density of 162.5 Wh/kg, nearly 1400 cycles, increased safety.	Nanotech Energy [196]
Electric vehicles	Lithium-sulfur graphene battery	Three times energy density compared to traditional lithium-ion batteries.	Lyten [197]

(continued on next page)

Table 8 (*continued*)

Application	Product/ Development	Results/Benefits	Industry/ References
Li-CO_2 batteries	Ruthenium nanoparticles on graphene networks	Enhanced electrocatalytic activity, efficient decomposition of Li_2CO_3(lithium carbonate), promising for CO_2 capture and conversion.	[198]
CO_2 adsorption	Graphene oxide foams with varying oxidation percentages	CO_2 adsorption efficiency between 86.28% and 92.20%, yield between 60.10% and 99.50%.	[199]
Hybrid battery technology	Graphene-aluminum battery	Energy density of 150–160 Wh/kg, over 2000 cycles, enhanced safety and recyclability.	University of Queensland [200]

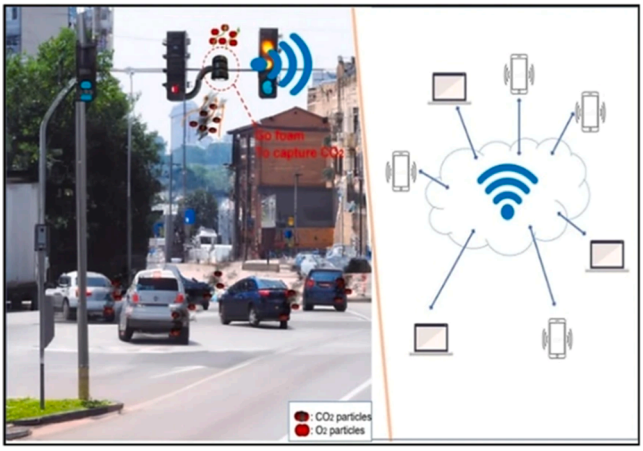

Fig. 10. Possible application of Graphene oxide–Foam–CO_2 for carbon removal in a traffic light. Reprinted with permission from [199]. Copyright 2017 Springer Nature Publishing.

provides high purity and consistent performance.

Despite the promising applications, the downstream processing of algal carbons faces challenges, including high costs, low carbon yields, and energy-cost imbalances. Achieving homogeneous structures and uniform diameters remains challenging with low-cost technologies. Future exploration should focus on improving pore architecture, enhancing functional groups, optimizing surface areas, and incorporating metals, oxides, or ions. While efforts have been made to find affordable methods for large-scale production of carbon biomaterials, more research is needed to assess the sustainability of using organic, naturally occurring materials. Algal carbons should perform comparably to more in properties such as surface area, porosity, conductivity, and stability, which are critical for applications in energy storage, environmental remediation, and catalysis to conventional carbon materials, such as coal, pitch, or polymers. If we build our understanding of their surface chemistry, algal carbons could be valuable in the energy and environmental sectors, particularly as composite materials for the construction industry and as electrode materials for batteries and supercapacitors.

Existing methods for tracking transformation phases and reaction sequences in biomass-derived carbons during pyrolysis—primarily based on analysing gaseous byproducts and mass loss—are insufficient for capturing the full complexity of these processes. *In-situ* characterisations are essential to gain a comprehensive understanding of the creation and chemical activation processes. Researchers are concentrating on improving the design of carbon materials, advancing nanotechnology, and developing integrated storage systems to enhance their efficiency as catalysts for hydrogen production and storage materials.

Fig. 11 below briefly overviews the problems and potential solutions discussed in this review. Green nanotechnology offers a flexible, cost-effective, and environmentally friendly approach to addressing global sustainability challenges by integrating sustainability into the synthesis of green carbon materials from natural sources. Given its high annual production, biomass waste should be reused as a precursor for biomass-derived carbons. However, there is limited literature on biomass precursors, especially algal sources, and biomass-derived carbons from the same precursor can vary significantly due to their composition.

Understanding the mechanisms of carbonization and activation is crucial for optimizing the properties of resulting carbon biomaterials. However, the transition from biomass to advanced carbon materials—such as graphene—at an industrial scale presents both opportunities and significant challenges. One major issue is the variability in feedstock properties, particularly with algae-derived materials, where porosity, elemental composition, and surface area can vary widely depending on species, cultivation conditions, and conversion methods like pyrolysis or hydrothermal carbonization. This inconsistency complicates standardization and hinders commercial scalability. Additionally, while algae-based biochar and hydrochar are often promoted for their environmental benefits, concerns remain about the potential leaching of heavy metals or organic contaminants into soil and water systems, raising questions about their long-term environmental stability. Economically, the cultivation, harvesting, and processing of algae at scale remain cost-prohibitive, limiting viability without substantial technological innovation or financial support [203–206]. Moreover, thermochemical conversion processes can emit volatile organic compounds if not properly managed, posing health and environmental risks. These challenges underscore the importance of emphasizing environmentally friendly production methods and cost-effective manufacturing strategies.

Recent advances in scalable synthesis techniques—such as flash Joule heating, microwave-assisted pyrolysis, and catalytic graphitization—offer promising pathways, but further research is needed to standardize processes and evaluate long-term economic and environmental impacts. Future efforts should focus on integrating green chemistry principles, developing robust supply chains for biomass feedstocks, and fostering interdisciplinary collaborations to accelerate the commercialization of biomass-derived carbon materials. Utilizing waste biomass not only minimizes environmental impact but also enhances sustainability and supports the circular bioeconomy. Additionally, characterising biomass is essential for improving the quality and functionality of the end products. The potential applications of these bio-based carbon materials are vast, particularly in hydrogen production, sustainable energy storage, and 3D printing. Among biomass sources, algae offer unique advantages due to their rapid growth, ability to thrive on non-arable land, and carbon sequestration potential. However, scalability remains a challenge due to high cultivation, harvesting, and processing costs, as well as variability in biomass composition. Economic feasibility can be improved through the co-production of high-value byproducts, integration with wastewater treatment and carbon capture systems, and the adoption of automation and smart monitoring technologies. Standardizing algae-based processes and implementing supportive policies will be crucial to unlocking their potential as a sustainable source of advanced carbon materials. In conclusion, by continuing to innovate and optimize the production and application of bio-based carbon materials, we can significantly contribute to a more sustainable future, addressing environmental challenges and meeting the growing demand for advanced materials.

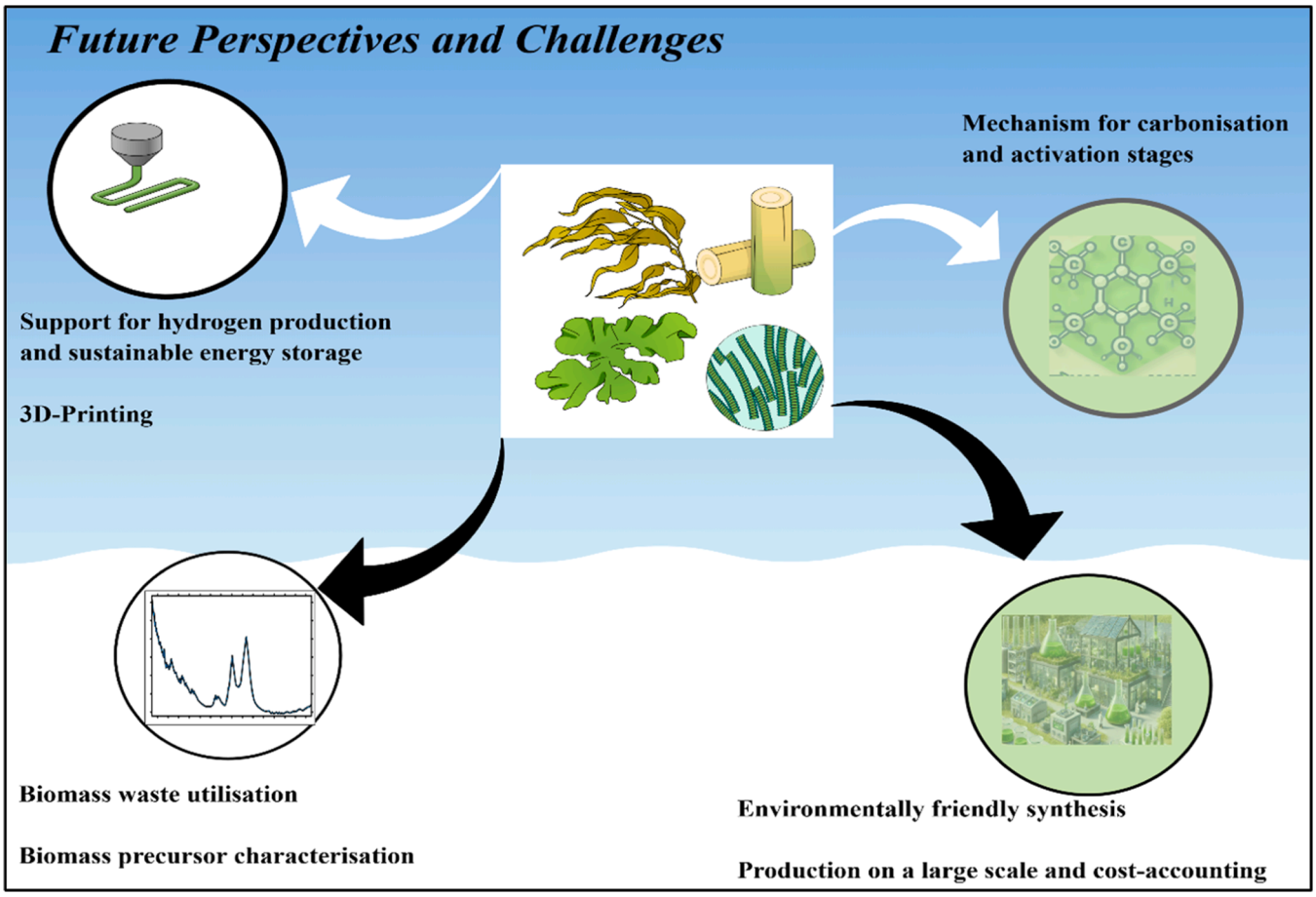

Fig. 11. A summary of challenges and future perspectives about the mechanism study, synthesis methods, biomass precursors, and the applications of carbon biomaterials.

CRediT authorship contribution statement

Shintu Varghese: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Data curation, Conceptualization. **Peter Ralph:** Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Unnikrishnan Kuzhiumparambil:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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