Journal of Environmental Chemical Engineering 4 (2016) 835–856

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

journal homepage: www.elsevier.com/locate/jece

Review

# Sustainable carbon nanomaterials: Recent advances and its applications in energy and environmental remediation

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ARTICLE INFO

*Article history:*
Received 29 July 2015
Received in revised form 5 November 2015
Accepted 17 November 2015
Available online 2 December 2015

*Keywords:*
Carbon nanomaterials
Graphene
Environmental remediation
Energy

ABSTRACT

Carbon nanomaterials represent one of the most diverse classes of materials with exceptional range of properties, which make them suitable for applications in widespread areas of research. There is an incisive need to look for new carbon nanostructures via sustainable and low-cost methods realizing their role in energy and environmental applications. Most of the conventional preparation strategies involve energy intensive conditions and hence high cost of production. In this regard, green synthesis of carbon nanomaterials via cost-effective strategies derives great relevance. Natural resources, particularly biomass; waste residues like industrial effluents and plastics can generate carbon nanomaterials. This review presents some of the recent advances in the synthesis of various carbon nanomaterials from sustainable resources and outlines their applications in energy storage, environmental remediation and purification.

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*Abbreviations:* 0D, zero dimensional; 1D, one dimensional; 2D, two dimensional; 3D, three dimensional; AFM, atomic force microscopy; BET, Brunauer–Emmett–Teller; CCS, carbon capture and storage; CD, carbon dots; CGs, carbonaceous gels; CNF, carbon nanofibers; CNM, carbon nanomaterials; CNS, carbon nanosheets; CNT, carbon nanotube; CV, cyclic voltammetry; CVD, chemical vapor deposition; EFB, empty fruit bunch; EELS, electron energy loss spectroscopy; FC, fuel cell; FFT, fast Fourier transform; GCN, graphitic carbon nanostructures; GO, graphene oxide; GNS, graphene nanosheets; GQD, graphene quantum dots; HPLC-FD, high-performance liquid chromatography coupled with fluorescence detection; HRTEM, high resolution transmission electron microscopy; HTC, hydrothermal carbonization; HTP-APN, hydrothermally carbonized activated pine needles; HTC-PN, hydrothermally carbonized pine needles; MB, methylene blue; MCA, magnetite carbon aerogels; MG, malachite green; NAC, *N*-acetyl-L-cysteine; NDFC, nitrogen doped fullerene-like carbon shell; N–S–C Dots, nitrogen–sulphur–coped carbon dots; OMMT, organically-modified montmorillonite; ORR, oxygen reduction reaction; PCNS, porous carbon nanosheet like structures; PE, poly ethylene; PET, poly ethylene terephthalate; PFLG, planar few layer graphene; PHC, porous heteroatom doped carbon; PL, photoluminescence; PP, polypropylene; PS, polystyrene; SAED, selected area diffraction pattern; SEM, scanning electron microscopy; SiC, silicon carborandum; SPP, spongy pomelo peels; SWCNTs, single-walled carbon nanotubes; TEM, transmission electron microscopy; TP, tea polyphenols; TPG, tea polyphenol reduced graphene; XPS, X-ray photoelectron spectroscopy.

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http://dx.doi.org/10.1016/j.jece.2015.11.026
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## 1. Introduction

"Carbon" is a unique element in the periodic which is known to mankind since ancient times. Carbon and its compounds form the basis of all known forms of life on earth. It is one of the abundant non-metal elements present in earth crust and its diverse properties makes it remarkable [1]. The diversity of various types of carbon bonding allows the formation of different allotropes such as amorphous carbon, graphite, diamond and fullerenes. Depending on the hybridization of carbon atoms, their physical and chemical properties vary. For example, diamond is one of the hardest materials existing in nature and graphite is one of the softest materials known. Moreover, diamond has $sp^3$ hybridized carbon atoms forming an extended 3D network, whereas graphite has $sp^2$ hybridized carbon atoms forming 2D planar sheets.

Carbon materials find extensive applications in the day to day aspects of life. These materials own a long history in terms of its synthesis and applications. For instance, activated carbon in filters for deodorization in refrigerators and water purification, graphite in lead for pencils, carbon fibers for the reinforcement of rackets and fishing rods, carbon black in inks, etc. [2]. Carbon black fabricated via partial combustion of oils was used in inks, pigments, tattoos, etc., which dates back to about 3000 years [3]. The history of synthetic graphite originated in 19th century when it was accidentally discovered by Acheson EG in an attempt to manufacture SiC in an electric furnace from silica and amorphous carbon [4]. This lead to the development of other graphite related carbon materials, glass like carbon, pyrolytic carbon, carbon fibres, etc., which found wide industrial applications [5].

The importance and uniqueness of carbon have now been extended to nanomaterials due to its exciting structural, physical, chemical, mechanical and electrical properties [6]. A whole range of dimensionalities can be found in carbon nanomaterials ranging from zero, one, two and three dimensional structures such as fullerenes, CNTs, nanofibers, graphene and nanodiamond [7]. There also exists hierarchical structures like carbon fibre bundles, carbon polyhedral particles, carbon spherules and the discovery of all these established a world-wide research boom that is still growing [7,8]. In this context, the development of carbon nanomaterials their properties and applications opens up new areas of research.

A new epoch in carbon based nanomaterials started in the mid-1980s when the family of buckminsterfullerene ("buckyballs") were discovered followed by the discovery of fullerene nanotubes ("buckytubes") [9–11]. In due course, other members of the nanocarbon family also gained attention, the latest material of interest being graphene. The 2D form of carbon, graphene was first isolated from graphite by Geim AK and co-workers [12,13]. This discovery eventually won the Nobel Prize in Physics in 2010.

Graphene is a flat monolayer of carbon atoms tightly packed into a 2D honeycomb lattice, and forms the basic building block for all other graphitic materials which can be considered as the mother form of all the other carbon nanostructures. This can be wrapped up into 0D fullerenes, rolled into 1D tube or stacked into 3D graphite (Fig. 1). Fullerenes, nanotubes and graphite-based nanomaterials are inherently connected. Researchers who produced carbon filaments had been unknowingly growing nanotubes until in 1991; Iijima observed helical multiwall nanotubules of graphite with closed ends deposited on the negative electrode during the DC arcing of graphite [10]. The synthesis of aligned multiwall nanotube films in the presence of a catalyst by CVD was reported by Geim and Novoselov [14]. The popularity of carbon nanostructures arose with the discovery of fullerenes, nanotubes and graphene.

Most of these carbon nanostructures are prepared by laser ablation of graphite or coal [15–17], metal-catalyzed arc

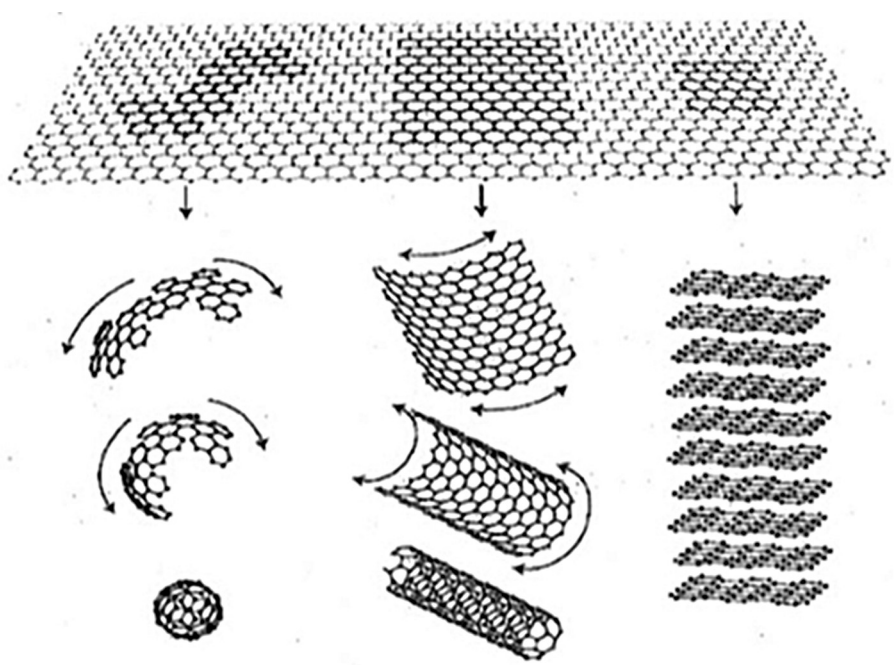

**Fig. 1.** Graphene as a 2D building material for carbon materials of all other dimensionalities: 0D fullerenes, 1D nanotubes or 3D graphite. Adapted from Ref. [13].

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