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Review

Characterization of carbon nanotubes and analytical methods for their determination in environmental and biological samples: A review

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HIGHLIGHTS

- Analytical techniques for characterization of CNTs: classification, description and examples.
- Determination methods for CNTs in biological and environmental samples.
- Future trends and perspectives for characterization and determination of CNTs.

GRAPHICAL ABSTRACT

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ABSTRACT

In the present paper, a critical overview of the most commonly used techniques for the characterization and the determination of carbon nanotubes (CNTs) is given on the basis of 170 references (2000–2014). The analytical techniques used for CNT characterization (including microscopic and diffraction, spectroscopic, thermal and separation techniques) are classified, described, and illustrated with applied examples. Furthermore, the performance of sampling procedures as well as the available methods for the determination of CNTs in real biological and environmental samples are reviewed and discussed according to their analytical characteristics. In addition, future trends and perspectives in this field of work are critically presented.

Abbreviation: AD, arc discharge; AFM, atomic force microscopy; BAC, benzalkonium chloride; BC, black carbon; bmimBF_4, 1-butyl-3-methylimidazolium tetrafluoroborate; CB, cyanobacteria; CE, capillary electrophoresis; CFF, cross flow filtration; CNT, carbon nanotube; CPCl, cetylpyridinium chloride; c-SWCNT, carboxylic single-walled carbon nanotube; CTAB, cetyltrimethylammonium bromide; CTAC, hexadecyltrimethylammonium chloride; CTAT, hexadecyltrimethylammonium *p*-toluenesulfonate; CTO-375, chemothermal oxidation method; CVD, chemical vapor deposition; DDBS, dodecyl benzenesulfonate; DGU, density gradient ultracentrifugation; DIOCT, dioctyl sulfosuccinate; DOC, deoxycholate; DOS, electronic density of states; EDS, energy dispersive spectroscopy; EFM, electronic force microscopy; FFF, field flow fractionation; FS, fluorescence spectroscopy; FT-IR, Fourier transform infrared spectroscopy; HATD, hydrogen-assisted thermal degradations; HPLC, high performance liquid chromatography; HPMC, hydroxypropylmethylcellulose; HRB, total height of the band; ICP-MS, inductively coupled plasma mass spectrometry; IR, infrared spectroscopy; LA, laser ablation; LDOS, local electronic density of states; LOD, limit of detection; LOQ, limit of quantification; MIH, microwave-induced heating; MS, mass spectrometry; MWCNT, multi-walled carbon nanotubes; NAA, neutron activation analysis; NaDDBS, sodium dodecylbenzenesulfonate; ND, neutron diffraction; NIR, near infrared spectroscopy; NIRF, near infrared fluorescence spectroscopy; NMR, nuclear magnetic resonance; PAGE, polyacrylamide gel electrophoresis; PTA, programmed thermal analysis; RB, resonant band; RS, Raman spectroscopy; RSD, residual standard deviation; SC, sodium cholate; SDBS, sodium dodecyl benzenesulfonate; SDC, sodium deoxycholate; SDS, sodium dodecyl sulfate; SEC, size exclusion chromatography; SEM, scanning electron microscopy; SERS, surface enhanced Raman scattering; SPM, scanning probe microscopy; SS-GFAAS, solid-sample graphite furnace atomic absorption spectrometry; STM, scanning tunneling microscopy; SWCNT, single-walled carbon nanotubes; TERS, tip-enhanced Raman spectroscopy; TDOC, sodium taurodeoxy cholate; TEM, transmission electron microscopy; TGA, thermogravimetric analysis; THF, tetrahydrofuran; TPO, temperature programmed oxidation; UA, urban air; UC, ultracentrifugation; UV–vis, ultraviolet–visible spectroscopy; WRB, half-height of the band; XPS, X-ray photoelectron spectroscopy; XRD, X-ray diffraction.

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