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Review Article

Properties of carbon nanotubes and its application in life science and health

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Abstract: Recent material technology has made remarkable progress in the field of construction of nano devices. Carbon nanotubes are synthetic one-dimensional carbon crystals exhibiting different diameters and chiralities. CNTs have been used as nano-carriers as they exhibited various fascinating properties such as functionalization of surface, large surface to volume ratio, better conductivity, biocompatibility with cellular system and improved porosity and can be easily incorporated with the therapeutic agents/pharmaceutical molecules. These properties have opened novel opportunities for researchers by exhibiting diverse potential applications in drug targeting, tissue engineering, detection of analyte, purification of water, detection of different kinds of pollutants and many more. These CNTs have been employed in the field of nanomedicines where they can be employed in diagnosis and treatment of several diseases, safety and conservation of food products and abatement of various environment pollutants to make eco-friendly surroundings. Hence, future efforts should be primarily focused on exploring the research based on carbon nanotubes which could provide solutions of challenges raised for commercialization of carbon-based applications for mankind with minimum toxicity. Present article describes the structure, properties of carbon nanotubes and their diverse medical applications which improve the health of human beings.

INTRODUCTION

Carbon nanotubes (CNTs) have created interest in the brains of researchers to make advancement starting from academic world to industrial level. These nanomaterials have offered many exceptional nanoscale properties which are helpful in the area of solid physics to chemistry. CNTs have offered various unique properties such as thermal stability upto 28000C in vaccume, electrical (about 1000 times higher current- carrying-capacity compared to copper wire), electronic and mechanical properties. Carbon nanotubes have played tremendous role in various therapeutic applications such as tissue engineering, thermal ablation and targeted drug delivery [1], [2]. They act as tissue scaffold materials as these CNTs can facilitate the growth of osteocytes [3], [4]), neuronal cells [5], [6], and cardiac cells [7]. They also support the stem cells to differentiate into specific cell or tissues, for example mesenchymal human stem cells targeted to differentiate into osteocytes [8],[9]. Moreover, the SWCNTs can absorb and convert electromagnetic radiation particularly radiation falls into near infrared (NIR) region into thermal or sound energy that can be used in either photothermal therapy (PTT) or photoacoustic therapy for the treatment of cancer [10],[11]. CNTs have been used as nanovectors in targeted drug delivery system, where these CNTs loaded with specific therapeutic agent and deliver the therapeutic molecules at the precise site which improve the therapeutic properties of pharmaceutical compounds, consequently reduce the side –effects of bioactive compounds. Undeniably CNTs have been used for the delivery of several pharmaceutics including antibiotics [12], antimicrobial compounds [13] and anti-inflammatory compounds [14], vaccines [15], antibodies [16], small interference ribonucleic acids (siRNA) [17] which reflects the efficiency as well as restricted side-effects of CNTs.

Why carbon nanotubes acting as nanocarriers?

Indeed, CNTs have exhibited various fascinating properties that make them remarkable nanocarriers for the delivery of various therapeutic compounds. Some of characteristics feature of CNTs as nanocarriers are given below:

(i) Beside other nanomaterials, CNTs have also showed the improved enhanced permeability and retention (EPR) effect as they can effectively accumulate at the tumor site than healthy tissues because they possess weak blood and lymphatic vessels for cancerous cells [18] and hence, can effectively transport targeted chemotherapeutic to the site of action [19].

(ii) CNTs have exhibited the needle like configuration which is compatible in intracellular transmembrane penetration [20]. They can also translocate the therapeutic agents intracellularly through endocytic pathways [21].

(iii) They also exhibit large surface area to volume ratio, unique capability of drug loading onto the surface or within the internal core of CNTs through covalent and non-covalent interactions [22].

(iv) The efficiency of CNT-based drug delivery system (DDS) for targeting pharmaceutics like folic acid (FA) [23], antibodies [24] and magnetic NP [25] can be conjugated with drug-loaded CNTs either covalently or non-covalently to deliver either active targeting through receptor-mediated endocytosis or local nanocarrier accumulation induced by external magnetic field.

(v) Furthermore, imaging tags such as radioactive nuclides [26] and fluorescence probes [24] have been combined with CNTs during their intracellular trafficking and distribution in vitro and in vivo smoothly and noninvasive.

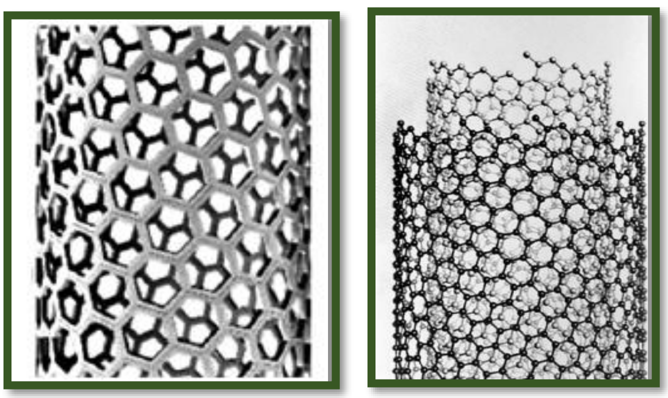

Fig. 1: Structure of SWCNT and MWCNT [28, 29]

STRUCTURE OF CARBON NANOTUBES

CNTs are graphene cylindrical nanostructures. When single graphene cylinder roll up seamlessly to form nanotubular structure called as single walled (SWCNT) and if few to few tens of concentric graphene cylinder roll up seamlessly to form nanotubular structures called as multiwalled (MWCNT). In CNTs carbon hexagons are arranged in a concentric manner along the tube length with tube ends capped by fullerene resembles to pentagon structures and form extended nanotubes. The carbon atoms used in CNTs are sp^2 hybridized to form graphite sheet structure which rolls to form tubules unlike diamond where all carbon atoms are sp^3 hybridized [27] [28]. Fig.1 shows the structural configuration of SWCNT and MWCNT. Properties of these CNTs are determined by length and diameter of nanotubes and arrangement of atoms of graphene sheets upon rolling [30]. Depending upon arrangement of atoms SWCNT are of three types: (i) arm chair (ii) zig-zag (iii) chiral or helical. These three atomic arrangements in single walled CNTs vary from each other in the direction of sheets in which they roll to form nanotubes. The atomic arrangement in carbon nanotubes has been shown in Fig. 2.

Material properties depend on the atomic configuration in the graphene sheets. These CNTs can be metallic and semi-conductor depending upon the atomic arrangement in a single tube [30]. Pairing between tubes in MWCNTs is week, thus causing comparable electronic properties of perfect MWCNTs and SWCNTs [31]. Recently categorized CNTs called as double walled carbon nanotubes (DWCNTs) and have been used for various novel applications. DWCNTs exhibits advantages of SWCNTs and MWCNTs that means at threshold voltage at which release of electrons is very low like SWCNTs and longer lifetime of DWCNTs is very unique which is similar to MWCNTs [32].

Table 1. Electrical, Mechanical and thermal properties of carbon nano materials

S.N.	Material	Band gap (eV)	Young's Modulus (Y) (TPa)	Thermal conductivity (W/m K)	References
1.	Diamond	-	~ 1	2000	[35]
2.	Graphite	~ 5	1	3000	[36]
3.	SWCNT	1.8 -0.18 (semiconducting)	0.32–1.47	200	[37], [38], [39]
5.	MWCNT	0.2-2.4	0.27–1.26	>3000	[27], [31], [39]

PROPERTIES OF CARBON NANOTUBES

Electrical properties

In electronic devices CNTs has created interest because they help in releasing and increasing the rate of electrons during electrical conductivity. These nanotubes are virtual wonderful 1D conductor and at low temperature diverse mesoscopic phenomena including single-electron charging, resonant tunneling through distinct energy intensities and proximity-induced superconductivity have been observed [33]. The structure of MWCNTs is highly complex because all carbon shells possess distinct electronic character, chirality and shell to shell interaction. Therefore, flow of electron generates electrical current which is preferentially due to outer shell conduction at low bias and temperatures and MWCNTs use metallic electrodes for their side-bondages. The electronic properties of ideal MWCNTs is comparable to that of ideal SWCNTs due to the weak cylindrical association in MWCNTs. Due to one-dimensional electronic structure, movement of electric current is ballistic [31].

Mechanical properties

In CNTs carbon-carbon atom is sp2 hybridized that possess rigidity and axial strength to these nanotubes. Young's modulus of MWCNT was found approximately 1.26 TPa. Nanotubes undergo buckling, plastic deformation or fracture due to large displacements, thus establishing their strength. For e.g. 1 mm long nanotubes were found to buckle elastically at large deflection angles of ~100. Distortion of nanotubes does not affect the small displacements. Level of toughness was measured by the stored elastic energy of material before failure. A 30 nm diameter nanotube had showed the stiffness approximately 100 keV which is about an order of magnitude larger than the strain energy stored in SiC nanorods [33].

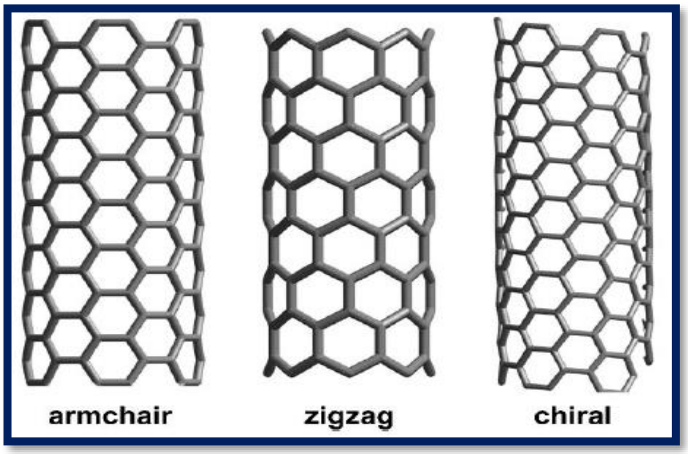

Fig. 2: Types of SWCNT: arm chair, zig-zag, helical SWCNT structures [31]

Thermal Properties

Carbon nanotubes can be heated up to 28000C in vacuum and exhibits thermal conductivity about twice as high as diamond [30]. Temperature dependent thermal conductivity has been shown in Fig. 3(Popov, 2004) [33]. CNTs have also enhanced the thermal properties of expanded perlite/paraffin in their composite form [34].

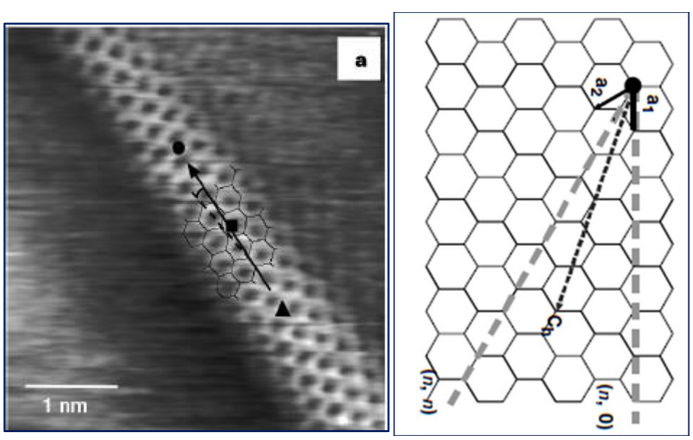

Fig. 3. Honeycomb-ring structure of SWCNT as revealed by STM (b) schematic of 2-D graphene sheet showing lattice vectors a1 and a2 and roll up vector ch = na1 + ma2 [42].

Optical properties

Carbon nanotubes are hollow tubes that are made up from carbon having diameters in the range of nanometres. These nanotubes are suitable for emitting light in the nano range and also exhibited optical significance particularly in the infrared wavelength region of interest. For instance, optical communication, CNTs have exhibited excitonic effects in semiconducting nanotubes. They have showed a sizeable shift of electronic energy levels as a function of axial strain [40]. This shift is called as optical transition which is sensitive to strain. Optically strained sensors exhibiting high mechanically tuneable sensitivity can be fabricated by CNT/micro-opto-electro-mechanical systems (MOEMS) [40].

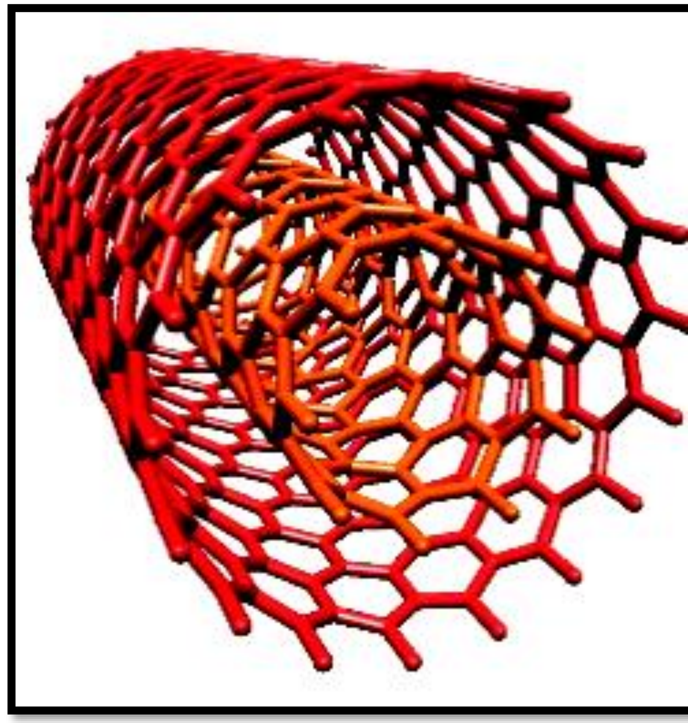

Fig 4. DWCNT explicitly showing a tube within a tube (Source: [47])

TYPES OF CNTs

Single walled CNTs

Single-walled carbon nanotube (SWCNT) is designed from a single graphite sheet that rolled up seamlessly to form a cylindrical tube [31]. Fig.3 shows the honeycomb ring structure of SWCNT and scheme of 2-D graphene sheet. Electronic properties of SWCNT are decided from their atomic configuration. They can be metallic or semi-conducting depending upon the rolling axis of graphene sheet to form nanotube. Due to 1D structure, direction of electric current in metallic SWCNTs occurs ballistically over long nanotube lengths, allowing them to carry high currents with basically no heating [31]. Semi-conducting nanotubes have bandgaps that are inversely proportional to its diameter, ranging from approximately 1.8 eV for very small diameter tubes to 0.18 eV for the widest possible stable SWCNT [41]. At every temperature thermal conductivity is dominated by phonons which propagate along the nanotube. At low temperature superconductivity has also been noticed [31].

Double Walled CNT (DWCNT)

Double-walled carbon nanotubes (DWCNTs) are made up of two coaxial single-walled carbon nanotubes (Fig. 4). Properties of DWCNTs are far better than from both SWCNT and MWCNT properties because of unique displaying flexibility of SWCNTs and the electrical and thermal stability of MWCNTs. The most interesting feature of DWCNTs is the possibility of functionalising the outer shell which allows associations with the external environment, while the mechanical and electronic properties of the inner tube are retained [43-46]. DWCNTs also possess exceptionally physical and field emission properties such as field-emission displays (FEDs), super rigid fibres and field-effect transistors. The most important application of DWCNTs is release of electron, because they have the merits of both SWCNT and MWCNT emitters, that is, low threshold voltage and high stability [47]. DWCNTs uniqueness was confirmed by electron diffraction. In every case, the current-voltage (IV) curves are linear between 0.5 V, giving us assertion that contacts are Ohmic [48].

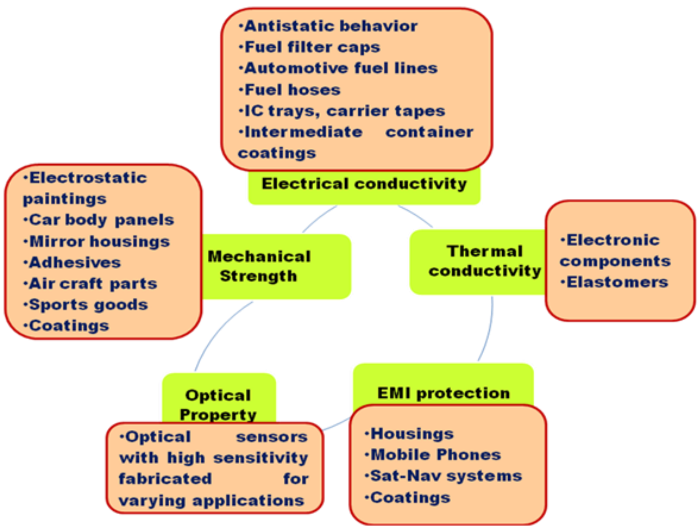

Fig.5. Properties of MWCNTs leading to number of applications (Source: [49])

Multi Walled CNT (MWCNT)

Iijima firstly discovered MWCNTs, in 1991, that are consisting of a few to a few tens of concentric cylinders placed around a common central hollow, with the interlayer spacing close to that of graphite (0.34 nm) [29]. The diameter varies from 0.4 - few nm and their outer diameter ranges from 2 - 30 nm [27]. The surface of MWCNTs can be modified by diverse ways of functionalization which offers plethora of applications. The electrical conductivity (as conductive as copper), mechanical properties (15-20 times stronger and 5 times lighter than steel), and thermal conductivity (same as that of diamond; > 5 times that of copper) makes these nanomaterials particularly interesting for industrial application purposes. Various properties along with their applications of MWCNTs have been depicted in Fig.5.

APPLICATION OF CNTs IN LIFE SCIENCES AND HEALTH

Nanotubes have more benefits as compared to nanoparticles in some applications. These nanotubes are internally filled with various chemicals and biomolecules with size ranging from small molecules to large proteins. Distinct inner and outer surfaces of certain types of nanotubes can be differentially functionalised with specific drugs internally and to evade immunogenic response externally. Further, drug loading has been made simple due to the open-mouthed structure of nanotubes [50]. Fig. 6 shows the carious properties of CNTs which have been used in diverse medical applications such as stem cell differentiation, cell adhesion, in designing organic as well as inorganic composites, cell compatibility and scaffolding element. Conjugated CNT with polymers have showed better extensions as well as directional outgrowth and proliferation over fibers without giving electrical stimulation using electrospun PLA/MWNT nanofibers [51]. Aligned CNT also involved in tissue regeneration as they can alone improve cell elongation, proliferation and electrical stimulation.These properties of nanotubes offer many biomedical applications which are discussed here in detail.

Table 2. Applications of carbon nanotubes in different fields

S.N.	Nanomaterial/ Composite	Application	References
1	CNT-fluoroscein isothiocyanate	Drug delivery	[59]
2	CNT-Streptavidin	Drug delivery	[59]
3	SWCNTs	Cancer treatment	[39]
4	Methotrexate	Cancer treatment	[52]
5	AmphotericinB-CNTs	Fungal diseases treatment	[52]
6	Phospholipid-PEG-SWCNT-DNA	Gene delivery	[60]
7	CNTs	Food packaging and refrigeration	[58]
8	CNTs	Nanoherbicides	[61]

Applications of CNTs in medicine

Targeted drug delivery

As a result of sustain innovations in the novel drug delivery vehicles have been successfully improved to get better therapeutic results. Conventional drug transport systems include viral vectors, liposomes, cationic lipids, polymers, and nanoparticles. However, some safety issues have been associated with the use of viral vectors, whereas non-viral systems suffer from reduced penetration of some therapeutic agents into target cells. Cancer and other deadly diseases can be treated by using CNTs as they deliver drugs at specific site. The capability of carbon nanotubes to carry multiple therapeutic moieties or other functional molecules helps in probing, imaging and targeting at precise sites. Thus, multimodal alternatives can be accessed for the treatment of such diseases using CNTs or functionalised CNTs [52].

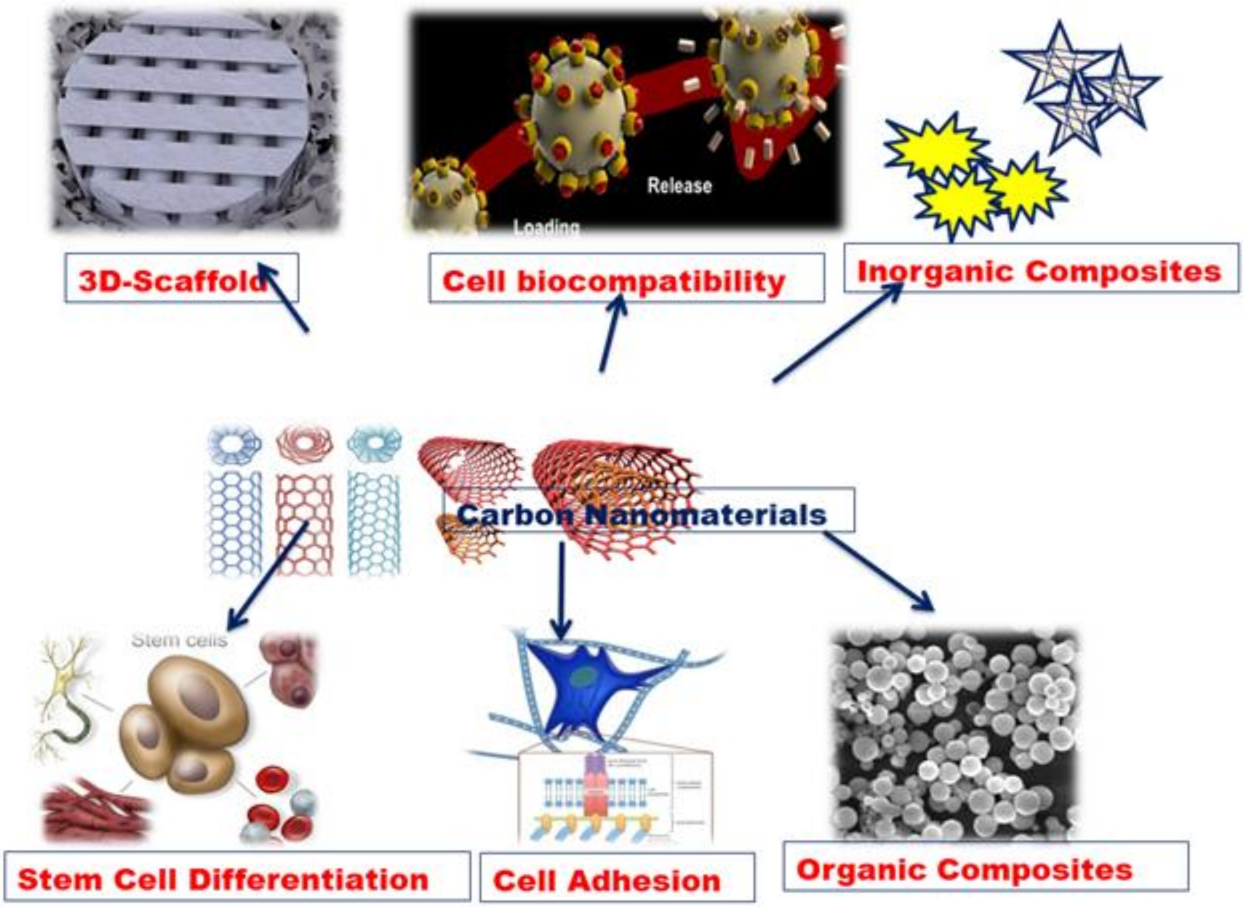

Fig. 6. Applications of carbon nanomaterials in different areas of pharmaceutical science

Applications of CNTs in environment monitoring

As CNTs exhibits unique characteristics such as small pore size, structural uniformity, antimicrobial nature, high thermal conductivities, and excellent mechanical properties which have been exploited in diverse applications including environmental applications. Environment science CNTs have been used as: (i) sorbents (ii) high-flux membranes (iii) depth filters (iv) antimicrobial agents (v) environmental sensors (vi) renewable energy technologies (vii) pollution prevention strategies [53]. Chemical, biological, thermal, optical, stress, strain, pressure, and flow sensors possess unique electrical conductivity, chemical stability, increased surface area, mechanical rigidity, and possibility of functionalisation of CNTs is to increase conventional carbon electrode sensor platforms. Biosensor research also helps in monitoring environmental microbial ecology and detecting microbial pathogens [53]. Different types of CNTs have reinforced the solid-phase microextraction technique and their application in the environmental analysis [54].

Role of CNTs in pollution prevention
The application of CNTs in computer reduces the environmental pollution by minimsing toxic heavy metals which would result in drastic reduction in material and energy requirements, without compromising the expected enhanced performance for consumer requirements. Recently, display technology uses CNTs in the field emission displays (FEDs) which are now commercially available [55]. Chen et al. have reported that CNTs, graphene and their derivatives played an important role in pollution control [56].

Application of CNTs in food sector

Carbon nano tubes have created interest among the scientific community in the food sector. Efforts are going on this area to incorporate the carbon nano tubes into polymer structure (liquids, solutions, melts, gels, amorphous and crystalline matrices) which increase their mechanical properties such as tensile strength and elasticity and resistant to moisture [57]. Fig. 7 illustrates the applications of nanotechnology in food sector.

Role of CNTs in food packaging
After food manufacturing, it is necessary that food must be packed to protect from dirt/dust, oxygen, light, pathogenic microorganisms, moisture, and other destructive or harmful substances when food is not consumed instantly after its manufacture. Moreover, the packaging of food must also be: (i) safe not toxic (ii) inert/no reaction (iii) cost effective (iv) lightweight (v) easily disposable/reusable (vi) stability/ able to withstand harsh condition during processing or filling (vii) impermeable to a host of environmental storage and transport conditions (viii) Resistant to physical abuse.

CNTs based food sensors

Consumers avoid the use of spoiled or inedible food products which can be easily recognized by specific odours, colours or other sensory characteristics. Hence, there is need to detect the presence of gasses, aromas, chemical contaminants and pathogens, or response to changes in environmental conditions. Such issues can be solved by chemical and electro-optical properties of nanoscale particles which will improve the quality, augment food safety and reduces the incidences of food-borne diseases. Consequently, consumers will be able to get fresh and flavour some food products. Electrochemical nano-sensors help in detection of food. These nanosensors work by attaching specific antibodies to a conductive carbon nanotube followed by monitoring changes in conductivity of the nanomaterial as soon as the analyte binds to the antibodies. For example, when Microcystin-LR (MCLR) (a toxin produced by cyanobacteria), binds to the surface of anti-MCLR-coated single-walled carbon nanotubes, conductivity changes that occur due to this specific binding that lowers MCLR concentrations by the approximately, 0.6 nM in drinking water, which is within the limits set by the World Health Organization (WHO) [58]. Table 2. Summarizes the various applications of CNTs in diverse fields.

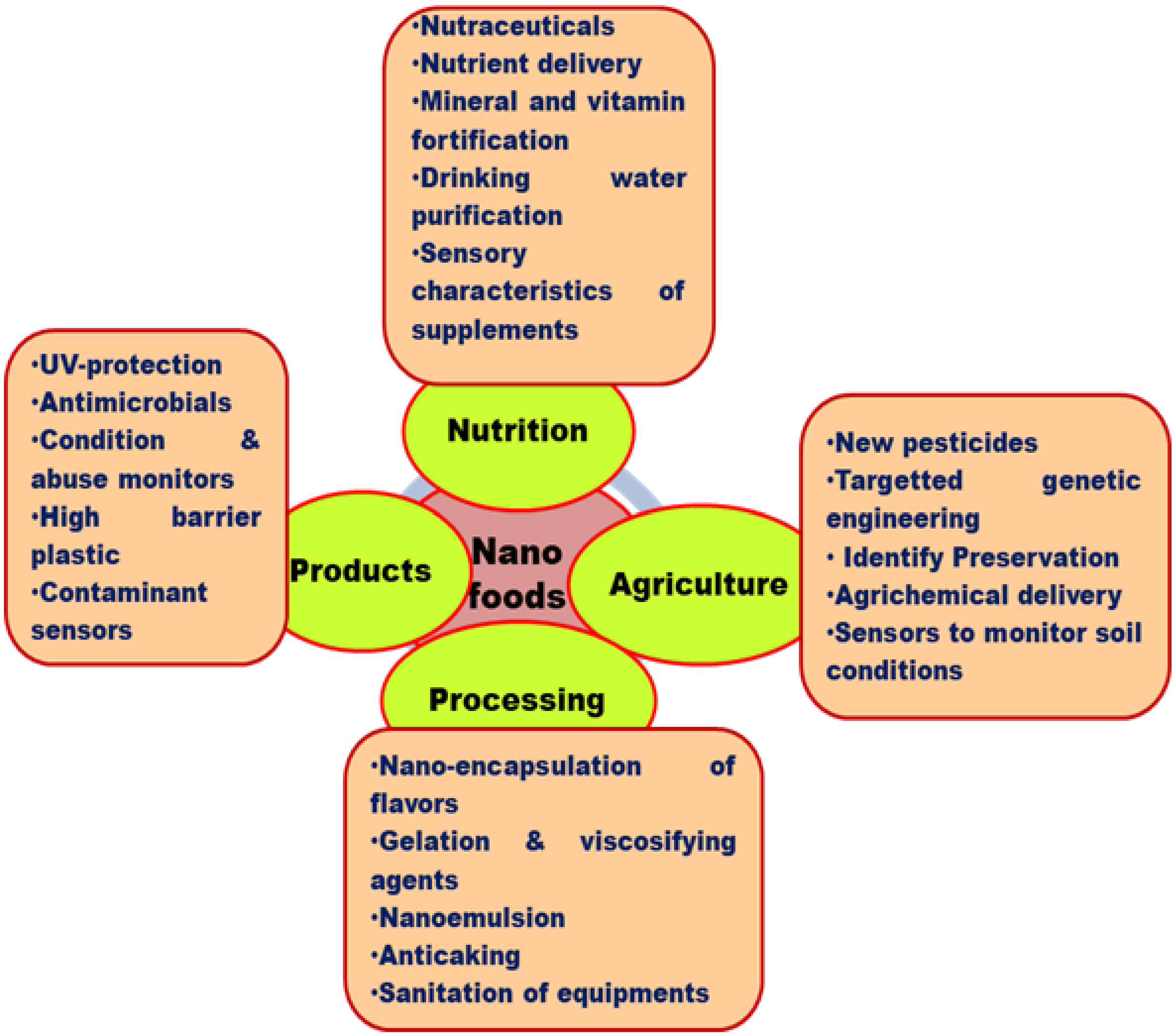

Fig. 7: Various applications of nano foods in different sectors [58]

CONCLUSION AND FUTURE PERSPECTIVE

The properties and characteristics of CNTs have offered promising and huge potential in the fabrication of futuristic devices. These tubular structures have exhibits marvellous properties, has been proven as safe vehicles and quite economic efficient alternatives for drug delivery approaches. Hence, future research should be focussed on to construct such nano devices based on carbon nanotubes which can solve serious challenges associated with better health of mankind by proper diagnosing life threatened diseases such as cancer, several neurological disorders, Acquired immune deficiency syndrome (AIDS) gene therapy, and then followed by their rapid and cost effective treatment. Besides this there is need to develop such technologies based on CNTs which could be used in multi-sectors for overall development of a country; which, must be more eco-friendly, rapid, sensitive, specific and economic over existing technologies.

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CONFLICT OF INTEREST
Authors of this paper declare no conflict of interest.

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