Review Article

Carbon Nanotubes in Biosensing Systems

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Abstract

In the rapidly developing world, it is very much necessary to make use of sensors and analytical devices for various applications. As nanotechnology is grabbing global attention, developing biosensors with the use of nanoparticles (Nps) is one of the trending topics among research communities. Owing to the properties such as high stability, sensitivity and selectivity carbon nano tubes (CNT) is found as one of the promising candidates for the fabrication of biosensors. From various research results, it is clear that both the single walled CNT and multi walled CNT are used as bio-sensing element. In this context, this short review consolidates the working principle, target analytes and other applications of CNT in a detailed manner.

Key words : Carbon nano tube, biosensor; target analytes, applications.

Overview

Nanotechnology and its products are gaining interests all over the world. Owing to the size depended properties of nanoparticles (Nps), they are utilized by various industries to manufacture commercial products of interest.[1] As Nps have higher sensitivity promoted through large active sites they receive high interest by research communities for the fabrication of diagnostic tools especially sensors.[2] Existing technologies and detecting devices are highly expensive and requires sophisticated environment.[3] So, there is a need to develop facile detecting devices to sense the target analytes with higher sensitivity and selectivity. A biosensor usually works by emitting signal when an analyte comes in contact with the sensing element. When an analyte comes into contact, the transducer converts the biological response into electrical signal.[4] Owing to the large surface area of Nps, a very small quantity of analyte is required to trigger the signal and therefore, the sensitivity of the biosensor is enhanced.[5] Further, nano biosensors require only a small quantity of sample for analysis which is a major advantage where the nanosensors out-performs bulk sensor types. Even though, there are many Nps such as magnetite Nps, palladium Nps, silver Nps, zinc oxide Nps, cobalt ferrite Nps, etc. that can be utilized for bio-sensing applications, the high electronic conductivity, high active surface area and mechanical durability of carbon nano tubes (CNT) make it an absolute candidate for the fabrication of bio-sensors.[6] Owing to large active surface area, CNT possess high surface to volume ratio which further enhances the sensitivity towards target analyte.[7] CNTs are one-dimensional manmade allotropes of carbon.[8] It is a tube-like structure with sp2 hybridized C-C bond resembling cylindrically folded graphene sheets.[9] Depending on the number of sheets on the outer wall, CNTs are categorised into single walled CNT (SWCNT) and multi walled CNT (MWCNT).[10] The SWCNT poses an uncomplicated surface chemistry with a single layer of sheet constitute the wall whereas for MWCNT they have two or more sheets present at the wall.

CNT as bio-sensing system

The CNTs grab the attention of researchers due to their interesting electronic properties i.e. it is a highly conductive material. Owing to the high electrical conductivity, a small change in its surrounding environment can drastically affect its conductivity.[11] Scientists make use of this phenomenon to detect the presence of target analyte. For selective sensing of target analyte, the CNTs are usually functionalized with complimentary anti-bodies.[12] There are many types of biosensors fabricated using CNT which are summarized in Table 1.

Based on the fabricated biosensor with the help of CNT, different bio-molecules can be detected which are discussed in detail.

Sl. No.	Type of biosensor	Role of CNT
1	Electrochemical biosensors[13]	CNT accelerates electron transfer
2	Optical biosensors[14]	MWCNT found to enhance the electron transfer
3	Colorimetric biosensor[15]	Enhanced the sensitivity
4	Electronic biosensor[16]	Improved sensitivity by promoting the electron transfer
5	Piezoelectric biosensor[17]	When CNT incorporated over the $Pb(ZrTi)O_3$ membrane, the sensitivity is found to be enhanced
6	Gravimetric biosensor[18]	The resonators using CNT as top electrode showed a higher frequency change
7	Pyroelectric biosensor[19]	The pyro voltage is found to enhanced with temperature by the addition of the MWCNTs

Table 1: Types of biosensors developed making use of CNT

Biosensor for the detection of bacteria

Staphylococcus enterotoxins are a major group of toxins which cause about many types of illness especially food-borne diseases which may contaminate eatables such as meats, diary, salad, bakery products etc., so, it is important to check and assure the quality of the eatables to prevent from infections caused by them. Bhardwaj et al[20] developed paper based electrochemical biosensors using SWCNT for the detection of *Staphylococcus aureus* (S. aureus) which is responsible for major types of food borne diseases. The SWCNTS are conjugated with antibodies by N-(3-dimethylaminopropyl) - N'- ethylcarbodiimide hydrochloride / N-hydroxysuccinimide. When a milk sample with *S. aureus* contamination is subjected to detection using this sensor by differential pulse voltammetry electrochemical characterisation, changes in the current peak is observed owing to the antigen-antibody interaction. The fabricated biosensor has a detection limit of 13 CFU mL^{-1}. Likewise, Yang et al.[21] fabricated an optical immunosensor for sensing Staphylococcal Enterotoxin B (SEB) in food. CNT is functionalized with anti-SEB antibodies by electrostatic adsorption; the complex is fixed over the polycarbonate film. The introduction of CNT improves the detection limit more than 6 times.

Biosensor for the detection of glucose

It is important to maintain the sugar level in the body in order to prevent the risks of diabetes and heart diseases. Therefore, it is very important to detect the sugar level in human body. Zhou et al.[22] wrapped SWCNT with chitosan molecules which can act as bio-electrochemical sensor for glucose detection. These sensors catalyse the glucose and detect their presence. The biocompatibility of chitosan molecules and the electric properties of the carbon nanotubes together contribute to the development of highly sensitive, highly selective and a reproducible glucose detector. Similarly, a highly stable MWCNT based electrochemical sensor was fabricated for glucose detection by Wang et al.[23] The sensitivity towards glucose was appreciable in different applied potentials (+0.65 V and +0.45 V). Their stability along with the storage also was durable. It was suggested that the high stability was due to the immobilized enzymes along with the carboxylic acid groups on nanotubes surface. This was due to the open ends of the nanotubes which allowed the enzymes inside the hollow cavity.

Biosensor for the detection of hydrogen peroxide

In the present situation, there is a need to develop a rapid detecting biosensor for H_2O_2 analysis. Too much exposure to hydrogen peroxide may cause tissue damage and gastrointestinal irritation with several adverse effects. An amperometric biosensor was fabricated by horseradish peroxidase in aormosil composite doped with ferrocene monocarboxylic acid-bovine serum albumin conjugate and MWCNT by Tripathi et al.[24] The fabricated biosensor displays excellent conductivity owing to the presence of MWCNT where the ferrocene was responsible for the electron transfer. The results proved that the sensor was capable of performing good biosensing activity.

Similarly, H_2O_2 detection was facilitated by incorporating CNT on a graphene paper and preparing an electrochemical biosensor by Yimin sun et al.[25] This improved the mechanical strength and surface roughness of the paper followed by decorating the paper with Pt nanoparticles. Their electrochemical sensing properties towards H_2O_2 were impressive and can be very well used for analysing H_2O_2 secreted by cells.

Biosensor for the detection of herbicide

Many research procedures are carried out to detect the presence of herbicides in the water sources. The DNA/MWCNTs–CHIT/PGE electrodes were fabricated by Ensafi et al.[26] to detect amitrole in water resource and soil. This electrode can be used to trace the amitrole concentration which contaminates the water sources. This voltammetric detection was found to be fast, simple, sensitive, selective and cost effective for tracing amitrole.

All plastic biosensor was developed using SWNT as an active element for detecting 2,4-dicholoro-phenoxy acetic acid (2,4-D) herbicides by Wijaya et al.[27] This was a simple, cost-effective and label free technique was developed that can detect 500 fM levels of herbicide in soil sample. Likewise, there are many biosensors fabricated using CNT for different applications which are provided as Table 2.

Other applications of CNT

Other than biosensing applications, the CNT is utilized in wide range of applications due to their unique physicochemical properties. It can be used in drug delivery, gene delivery, tissue engineering, osteoproductive material, etc. Some of the applications are tabulated in Table 3.

Conclusion

From the various research outcomes, it has been understood that the stability, electrical conductivity and high surface area of CNTs make them suitable for successful bio-detection of various analytes such as pathogens, bio molecules etc. Also, it is clear that for selectivity and sensitivity CNTs are functionalized with suitable molecules which are contrary to the target analytes. Further, the surface modified CNTs can be used for many other applications especially for drug delivery and gene delivery. Although there are too many advantages in using

Sl. No.	Biosensor	Target analyte
1	Maltose biosensor based on α-glucosidase and pyranose oxidase immobilised CNT[28]	Maltose
2	Titanium dioxide nanotube arrays[29]	Hydrogen peroxide
3	Iron -phthalocyanine functionalised MWNT based biosensor[30]	Hydrogen peroxide
4	CNT-Polyethylene amine functionalised ionic liquid thin films[31]	Glucose
5	Poly cyclodextrin and CNT composite electrochemical biosensor[32]	Glucose
6	Magnetic nanoparticles based MWCNT biosensor[33]	Catechol
7	Specific biosensor using CNT functionalised with gold nanoparticles[34]	Antigen-antibody binding event
8	MWCNTs/ graphene oxide/ pyrogallol biosensor35	Omeprazole
9	ZnO-MWCNT hybrid nanocomposite[36]	Urea
10	Titanium dioxide/CNT nanocomposite based electrode[37]	Cancer cells
11	Hyaluronic acid dispersed CNT[38]	NADH
12	Poly brilliant cresyl blue-CNT modified electrode[39]	NADH
13	ds DNA decorated Fe_2O_3/SnO_2-chitosan modified MWCNT[40]	Doxorubicin
14	Platinum electrode modified MWCNT[41]	Doxorubicin, anthracycline
15	Magnetite nanoparticles based MWCNT[42]	Nucleotide
16	Electrochemical CNT sensor[43]	DNA
17	Nitrogen doped MWCNT[44]	Paracetamol
18	Conductive polymer MWCNT based sensor[45]	Paracetamol
19	Chitosan modified CNT sensor[46]	Glutamate
20	poly amidoamine dendrimer-encapsulated platinum nanoparticles modified MWCNT[47]	Glutamate

Table 2: Carbon nanotubes-based biosensors and their target analytes

Sl. No.	Biosensor	Application	Significance
1	SWCNT modified with chitosan[48]	Delivering doxorubicin for liver cancer	The treatment was highly efficient than using free doxorubicin
2	CNT conjugated with chitooligosaccharide[49]	Delivering gliotoxin for cervical cancer	More effective due to controlled drug release
3	CNT-liposome conjugate[50]	For delivering anticancer drugs	Improved therapeutic index with high drug loading capacity and less toxicity.
4	Magnetic MWCNT[51]	For delivering chemotherapeutic drugs for cancer	High drug loading capacity and highly selective.
5	Multifunctional polymer coated CNT[52]	Drug delivery	Decrease the toxicity and increase therapeutic efficacy.
6	Polyamidoamine based MWCNT[53]	Gene delivery	Stability (upto six months)
7	Phospholipid based CNT[54]	Gene delivery	Ability to effectively condense plasmid DNA.
8	MWNT-polycaprolactone composite scaffold[55]	Tissue engineering	MWNTs improved the mechanical property.
9	Chitosan-MWNT composite/ hydroxy apatite nanocomposite[56]	Bone tissue engineering	Good mechanical strength was observed.
10	Polyurethane based scaffolds incorporated with MWNTs and zinc oxide nanoparticles[57]	Bone tissue engineering	Promote osteogenic differentiation of pre-osteoblast cells.

Table 3: Other applications of carbon nanotubes

CNTs, there are some limitations that push them back. However, many researches are being performed to overcome the current limitations and challenges faced with the CNTs for the betterment of futuristic demand.

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References

1. Yoon J, Lee T, Jo J, Oh BK, Choi JW. Electro-chemical H2O2 biosensor composed of myoglobin on MoS2 nanoparticle-graphene oxide hybrid structure. Biosensors and Bioelectronics. 2017; 93:14-20.

2. Naik KK, Rout CS. Electrodeposition of ZnCo2O4 nanoparticles for biosensing applications. RSC Advances. 2015; 5:79397-404.

3. Liu X, Zhu Y, Nomani MW, Wen X, Hsia TY, Koley G. A highly sensitive pressure sensor using a Au-patterned polydimethylsiloxane membrane for biosensing applications. Journal of Micromechanics and Microengineering. 2013; 23(2):025022.

4. Young P, Lu Y, Terrill R, Li J. High-sensitivity NO2 detection with carbon nanotube–gold nanoparticle composite films. Journal of nanoscience and nanotechnology. 2005; 5(9): 1509-13.

5. Tang L, Zhu Y, Yang X, Li C. An enhanced biosensor for glutamate based on self-assembled carbon nanotubes and dendrimer-encapsulated platinum nano bio composites-doped polypyrrole film. Anal Chim Acta. 2007; 597(1):145-50.

6. Ye JS, Wen Y, De Zhang W, Cui HF, Xu GQ, Sheu FS. Electrochemical biosensing platforms using phthalocyanine-functionalized carbon nanotube electrode. Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis. 2005; 17:89-96.

7. Dai Tran L, Nguyen DT, Nguyen BH, Do QP, Le Nguyen H. Development of interdigitated arrays coated with functional polyaniline/MWCNT for electrochemical bio detection: Application for human papilloma virus. Talanta. 2011; 85(3):1560-5.

8. Zheng M, Jagota A, Semke ED, Diner BA, McLean RS, Lustig SR et al. DNA-assisted dispersion and separation of carbon nanotubes. Nature materials. 2003; 2: 338-42.

9. Meng L, Zhang X, Lu Q, Fei Z, Dyson PJ. Single walled carbon nanotubes as drug delivery vehicles: targeting doxorubicin to tumors. Biomaterials. 2012; 33(6): 1689-98.

10. Boero C, Carrara S, Vecchio G, Calzà L, Micheli G. Highly sensitive carbon nanotube-based sensing for lactate and glucose monitoring in cell culture. IEEE transactions on nano bioscience. 2011; 10(1): 59-67.

11. Luo X, Killard AJ, Morrin A, Smyth MR. Enhancement of a conducting polymer-based biosensor using carbon nanotube-doped polyaniline. Anal Chim Acta. 2006; 575(1): 39-44.

12. Mao S, Lu G, Yu K, Chen J. Specific biosensing using carbon nanotubes functionalized with gold nanoparticle–antibody conjugates. Carbon. 2010; 48: 479-86.

13. Choi BG, Park H, Park TJ, Kim DH, Lee SY, Hong WH. Development of the electrochemical biosensor for organophosphate chemicals using CNT/ionic liquid bucky gel electrode. Electrochemistry communications. 2009; 11:672-5.

14. Zhang Y, Arugula MA, Wales M, Wild J, Simonian AL. A novel layer-by-layer assembled multi-enzyme/CNT biosensor for discriminative detection between organophosphorus and non-organophosphrus pesticides. Biosensors and Bioelectronics. 2015; 67:287-95.

15. Hayat A, Haider W, Raza Y, Marty JL. Colorimetric cholesterol sensor based on peroxidase like activity of zinc oxide nanoparticles incorporated carbon nanotubes. Talanta. 2015; 143:157-61.

16. Timur S, Anik U, Odaci D, Gorton L. Development of a microbial biosensor based on carbon nanotube (CNT) modified electrodes. Electrochemistry Communications. 2007; 9:1810-5.

17. Xu T, Wang Z, Miao J. Fabrication of carbon-nanotube enhanced piezoelectric membrane-based biosensor. In: 2008 2nd IEEE International Nanoelectronics Conference. IEEE; 2008. pp. 555-558.

18. García-Gancedo L, Zhu Z, Iborra E, Clement M, Olivares J, Flewitt AJ, Milne WI, Ashley GM, Luo JK, Zhao XB, Lu JR. AlN-based BAW resonators with CNT electrodes for gravimetric biosensing. Sensors and Actuators B: Chemical. 2011; 160:1386-93.

19. Edwards ME, Batra AK, Chilvery AK, Guggilla P, Curley M, Aggarwal MD. Pyroelectric properties of PVDF: MWCNT nanocomposite film for uncooled infrared detectors. Materials Sciences and Applications. 2012; (4): 25407.

20. Bhardwaj J, Devarakonda S, Kumar S, Jang J. Development of a paper-based electrochemical immunosensor using an antibody-single walled carbon nanotubes bio-conjugate modified electrode for label-free detection of foodborne pathogens. Sensors and Actuators B: Chemical. 2017; 253:115-23.

21. Yang M, Kostov Y, Rasooly A. Carbon nanotubes based optical immunodetection of Staphylococcal Enterotoxin B (SEB) in food. International journal of food microbiology. 2008; 127(1-2):78-83.

22. Zhou Y, Yang H, Chen HY. Direct electrochemistry and reagentless biosensing of glucose oxidase immobilized on chitosan wrapped single-walled carbon nanotubes. Talanta. 2008; 76(2):419-23.

23. Wang SG, Zhang Q, Wang R, Yoon SF. A novel multi-walled carbon nanotube-based biosensor for glucose detection. Biochemical and biophysical research communications. 2003; 311(3):572-6.

24. Tripathi VS, Kandimalla VB, Ju H. Amperometric biosensor for hydrogen peroxide based on ferrocene-bovine serum albumin and multiwall carbon nanotube modified ormosil composite. Biosensors and Bioelectronics. 2006; 21(8):1529-35.

25. Sun Y, He K, Zhang Z, Zhou A, Duan H. Real-time electrochemical detection of hydrogen peroxide secretion in live cells by Pt nanoparticles decorated graphene–carbon nanotube hybrid paper electrode. Biosensors and Bioelectronics. 2015; 68:358-64.

26. Ensafi AA, Amini M, Rezaei B. Biosensor based on ds-DNA decorated chitosan modified multiwall carbon nanotubes for voltammetric biodetection of herbicide amitrole. Colloids Surf B Biointerfaces.. 2013; 109:45-51.

27. Wijaya IP, Nie TJ, Gandhi S, Boro R, Palaniappan A, Hau GW, Rodriguez I, Suri CR, Mhaisalkar SG. Femtomolar detection of 2, 4-dichlorophenoxyacetic acid herbicides via competitive immunoassays using microfluidic based carbon nanotube liquid gated transistor. Lab on a Chip. 2010; 10:634-8.

28. Odaci D, Telefoncu A, Timur S. Maltose biosensing based on co-immobilization of α-glucosidase and pyranose oxidase. Bioelectrochemistry. 2010; 79(1):108-13.

29. Xiao P, Garcia BB, Guo Q, Liu D, Cao G. TiO2 nanotube arrays fabricated by anodization in different electrolytes for biosensing. Electrochemistry communications. 2007; 9:2441-7.

30. Ye JS, Wen Y, De Zhang W, Cui HF, Xu GQ, Sheu FS. Electrochemical biosensing platforms using phthalocyanine-functionalized carbon nanotube electrode. Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis. 2005; 17:89-96.

31. Jia F, Shan C, Li F, Niu L. Carbon nanotube/ gold nanoparticles/ polyethylenimine functionalized ionic liquid thin film composites for glucose biosensing. Biosensors and Bioelectronics. 2008; 24(4):945-50.

32. Yang H, Zhu Y, Chen D, Li C, Chen S, Ge Z. Electrochemical biosensing platforms using poly-cyclodextrin and carbon nanotube composite. Biosensors and Bioelectronics. 2010; 26(1):295-8.

33. Pérez-López B, Merkoçi A. Magnetic nanoparticles modified with carbon nanotubes for electrocatalytic magnetoswitchable biosensing applications. Advanced Functional Materials. 2011; 21:255-60.

34. Mao S, Lu G, Yu K, Chen J. Specific biosensing using carbon nanotubes functionalized with gold nanoparticle–antibody conjugates. Carbon. 2010; 48:479-86.

35. Mohamed MA, Yehia AM, Banks CE, Allam NK. Novel MWCNTs/graphene oxide/pyrogallol composite with enhanced sensitivity for biosensing applications. Biosensors and Bioelectronics. 2017;89(pt 2):1034-41.

36. Tak M, Gupta V, Tomar M. Zinc oxide–multiwalled carbon nanotubes hybrid nanocomposite based urea biosensor. Journal of Materials Chemistry B. 2013; 1:6392-401.

37. Shen Q, You SK, Park SG, Jiang H, Guo D, Chen B, Wang X. Electrochemical biosensing for cancer cells based on TiO2/CNT nanocomposites modified electrodes. Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis. 2008; 20:2526-30.

38. Filip J, Šefčovičová J, Tomčík P, Gemeiner P, Tkac J. A hyaluronic acid dispersed carbon nanotube electrode used for a mediatorless NADH sensing and biosensing. Talanta. 2011; 84(2):355-61.

39. Yang DW, Liu HH. Poly (brilliant cresyl blue)-carbon nanotube modified electrodes for determination of NADH and fabrication of ethanol dehydrogenase-based biosensor. Biosensors and Bioelectronics. 2009; 25(4):733-8.

40. Taei M, Salavati H, Hasanpour F, Shafiei A. Biosensor based on ds-DNA-decorated Fe 2 O 3/SnO 2-chitosan modified multiwalled carbon nanotubes for biodetection of doxorubicin. IEEE Sensors Journal. 2015; 16:24-31.

41. Hajian R, Tayebi Z, Shams N. Fabrication of an electrochemical sensor for determination of doxorubicin in human plasma and its interaction with DNA. Journal of pharmaceutical analysis. 2017; 7(1):27-33.

42. Cheng G, Zhao J, Tu Y, He P, Fang Y. A sensitive DNA electrochemical biosensor based on magnetite with a glassy carbon electrode modified by muti-walled carbon nanotubes in polypyrrole. Anal Chim Acta. 2005; 533(1):11-6.

43. Abdullin TI, Rizvanov AA, Nikitina II. Carbon nanotube-based biosensors for DNA structure characterization. Applied biochemistry and microbiology. 2009; 45(2):229-32.

44. Tsierkezos NG, Othman SH, Ritter U. Nitrogen-doped multi-walled carbon nanotubes for paracetamol sensing. Ionics. 2013; 19:1897-905.

45. Bayram E, Akyilmaz E. Development of a new microbial biosensor based on conductive polymer/multiwalled carbon nanotube and its application to paracetamol determination. Sensors and Actuators B: Chemical. 2016; 233:409-18.

46. Chakraborty S, Raj CR. Amperometric biosensing of glutamate using carbon nanotube based electrode. Electrochemistry communications. 2007; 9:1323-30.

47. Tang L, Zhu Y, Yang X, Li C. An enhanced biosensor for glutamate based on self-assembled carbon nanotubes and dendrimer-encapsulated platinum nanobiocomposites-doped polypyrrole film. Anal Chim Acta. 2007; 597(1):145-50.

48. Ji Z, Lin G, Lu Q, Meng L, Shen X, Dong L, Fu C, Zhang X. Targeted therapy of SMMC-7721 liver cancer in vitro and in vivo with carbon nanotubes based drug delivery system. J Colloid Interface Sci. 2012; 365(1):143-9.

49. Bhatnagar I, Venkatesan J, Kim SK. Polymer functionalized single walled carbon nanotubes mediated drug delivery of gliotoxin in cancer cells. Journal of biomedical nanotechnology. 2014; 10:120-30.

50. Karchemski F, Zucker D, Barenholz Y, Regev O. Carbon nanotubes-liposomes conjugate as a platform for drug delivery into cells. J control release. 2012; 160(2):339-45.

51. Yang F, Jin C, Yang D, Jiang Y, Li J, Di Y et al. Magnetic functionalised carbon nanotubes as drug vehicles for cancer lymph node metastasis treatment. European journal of cancer. 2011; 47:1873-82.

52. Moore TL, Pitzer JE, Podila R, Wang X, Lewis RL, Grimes SW et al. Multifunctional Polymer-Coated Carbon Nanotubes for Safe Drug Delivery. Particle & Particle Systems Characterization. 2013; 30(4):365-73.

53. Liu M, Chen B, Xue Y, Huang J, Zhang L, Huang S et al. Polyamidoamine-grafted multiwalled carbon nanotubes for gene delivery: synthesis, transfection and intracellular trafficking. Bioconjugate chem. 2011; 22(11):2237-43.

54. Behnam B, Shier WT, Nia AH, Abnous K, Ramezani M. Non-covalent functionalization of single-walled carbon nanotubes with modified polyethyleneimines for efficient gene delivery. Inter J Pharm. 2013; 454(1):204-15.

55. Pan L, Pei X, He R, Wan Q, Wang J. Multiwall carbon nanotubes/polycaprolactone composites for bone tissue engineering application. Colloids Surf B Biointerfaces.. 2012; 93:226-34.

56. Chen L, Hu J, Shen X, Tong H. Synthesis and characterization of chitosan–multiwalled carbon nanotubes/hydroxyapatite nanocomposites for bone tissue engineering. J Mater Sci Mater Med. 2013; 24(8):1843-51.

57. Shrestha BK, Shrestha S, Tiwari AP, Kim JI, Ko SW, Kim HJ, Park CH, Kim CS. Bio-inspired hybrid scaffold of zinc oxide-functionalized multi-wall carbon nanotubes reinforced polyurethane nanofibers for bone tissue engineering. Materials & Design. 2017; 133:69-81.