Organic and Inorganic Template Assisted Synthesis of Silica Nanotubes and Evaluation of Its Properties for Drug Targeting

Logesh Mahendran[1], Abimanyu Ravichandran[1], A.M. Ballamurugan[1*]

[1]Department of Nanoscience and Technology, Bharathiar University, Coimbatore-641 046, Tamilnadu, India

Email Address: balamurugan@buc.edu.in (Corresponding Author)

logeshchemistry@gmail.com (Logesh Mahendran)

abimanyanbu1998@gmail.com (Abimanyu Ravichandran)

Abstract

Mesoporous silica network nanotubes were fabricated using both organic and inorganic templates such as citric acid (CA), cetyltrimethylammonium bromide (CTAB), and sodium bicarbonate (SBC). The phase analysis of synthesized silica network was confirmed by X-ray diffractometer (XRD) analysis, and the present functional groups were revealed by Fourier Transformer Infrared Spectroscopy (FTIR) and the formation of tubular morphology was analyzed by Transmission Electron Microscopy (TEM). The mesoporous nature of each template sample was studied using Brunauer–Emmett–Teller (BET) instrument. The surface area and porous size were calculated successfully for fabricated silica network nanotubes.

Keywords: Sol-gel; Silica nanotube; Surface area; Porosity; Surfactant

1. Introduction

Last two decades, tubular two-dimensional unique structured silica nanotubes show a special interest in developing the drug delivery system, catalysis, and biomedical applications [1-4]. The important property of silica nanotube is biocompatibility, superior mechanical property, excellent hydrophilic in nature especially easy acceptability of surface functionalization on both inner and outer wall due to presence of silane group and adjustable pore size and large surface area [5,7]. Mostly the synthesis of metal inorganic single-wall nanotubes by several routes such as thermal evaporation, centrifugal jet spinning, and template-directed sol-gel [8-11]. Among them, the template-directed sol-gel pathway is a very favorable method to prepare the facilely adjusted silica nanotube using the suitable templates [12], especially the long-chain organic surfactants offer to get unique inorganic oxide nanotubes with uniform porosity [13]. In the drug delivery system, the pore size for drug carrier, drug stability, drug solubility, bioavailability, biocompatibility, drug-releasing rate, and dissolution rate are very important parameters. The inorganic materials those are having a rigid structure with a mesoporosity nature which is inhibiting the drug molecules aggregation; this is the major advantage for the stability of the drug into the career [6]. The controlled drug release is another important thing, which is based on the physical interaction between the career and the drug molecule. For that, the career should be easy to functionalize and aid in making hydrogen bonding to control the release of the drug on the target site [14]. The silica nanotubes are excellent promising materials for satisfying the above properties to the controlled delivery of the drug on the targeted location. The porosity is one of the very important vital roles in the drug delivery system. Both inorganic and organic templates modification pores are used

as specific applications. But the organic templates modified porous silicates can give the precise, controlled release of the drug on the suitable biological environment [15]. In this study, the silica nanotubes were fabricated using different types of organic and inorganic templates and analyzed their porosity nature for drug delivery application.

2. Experimental

The synthesis of silica nanotubes was carried out at room temperature. The double-distilled water, ethanol, TEOS, citric acid monohydrate, and ammonia were used as the starting materials, and all are in research grade. The mixture of 1.5 ml water and 60 ml of ethanol was taken under stirring conditions followed by the addition of 12 ml of TEOS, 28% aqueous solution of 24 ml ammonium hydroxide with 360 mg of citric acid monohydrate was added into ethanol. The ethanolic solution was added to the TEOS mixture under stirring conditions. The precursor mixture was stirred continuously until it reaches the homogeneous condition. The formed gel was centrifuged and washed with distilled water and dried in a hot air oven at 80˚C for about 24 h. Finally, the fabricated product was calcinated at 500˚C for about 2 h with the heating rate at 1˚C per minute. In order to obtain silica nanotubes with different pore sizes, CTAB and SBC were used as a sacrificial template.

3. Characterization

Transmission Electron Microscopy (TEM) images were taken with Tecnai G2 F30. The FTIR (Fourier Transfer Infrared Spectroscopy) were analyzed on BRUKER TENSOR 27 instrument with the frequency range from 400 to 4000 cm^{-1}. The XRD (X-ray Diffractometer) was used to phase analysis (Rigaku, Ultima-IV with Kα radiation (λ= 1.54187 Å) at 40 kV and 40 mV. The diffraction was implemented between 10˚ and 80˚ with 10˚ per minute scanning rate. The surface area and the porosity nature of the material have been analyzed by the BET instrument with the Belsorp program.

4. Results and discussion

4.1. X-ray diffraction analysis

Figure 1 demonstrates that the XRD pattern for the as-prepared silica nanotubes such as SBC, CTAB, and CA. The amorphous silica frame formation has been broadly attributed at 23˚ with a slight alteration of intensity; this may be due to the nature of the template. We can conclude from the XRD pattern that the silica network is formed well using a different template without any other secondary phase.

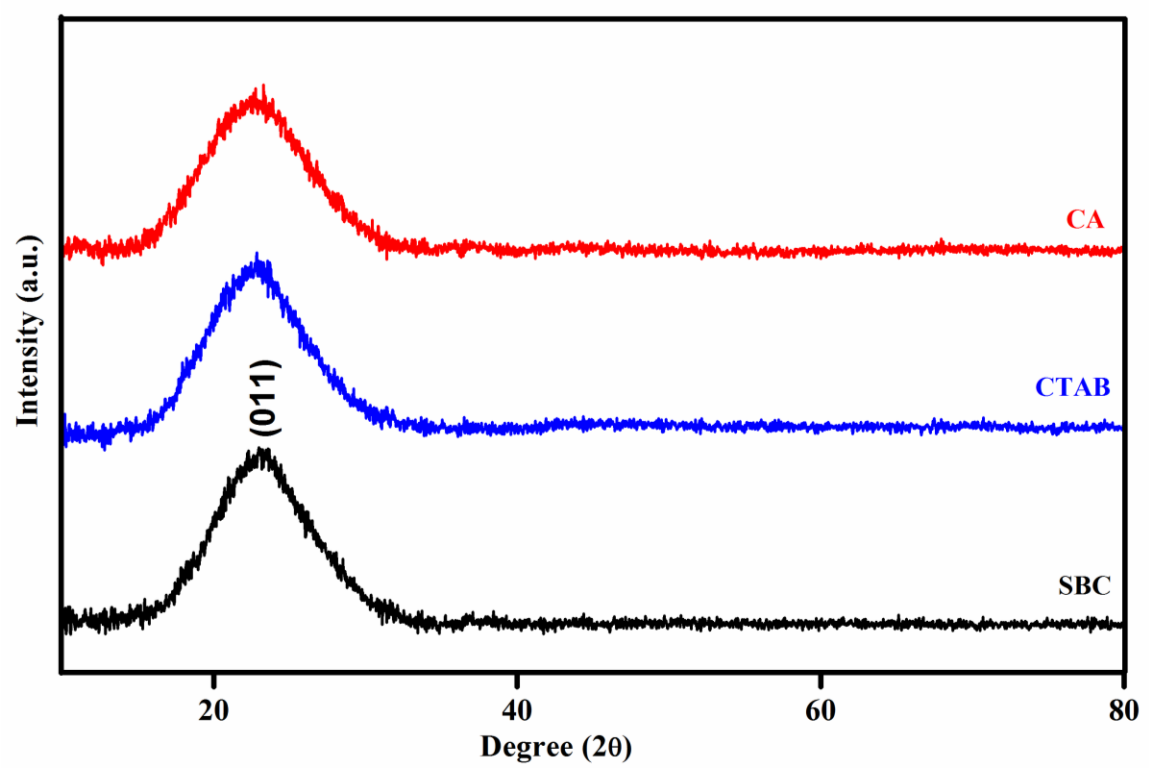

Fig. 1 XRD pattern for CA, CTAB, and SBC assisted silica nanotube

4.2. Functional group revelation

Figure 2 revealed that the FTIR spectra for all three different silica nanotube. The range between 750 cm^{-1} and 1350 cm^{-1} has clearly proved that the formation of silica layer, the symmetric stretching frequency for Si-O-Si group was the band at 806 cm^{-1} [16], the broadband at 1100 cm^{-1} is due to oxygen asymmetric frequency mode, which may be due to existence of siloxane strained links and the presence of surface silanol groups. It favors the formation of siloxane bonding with the templates. The wide peak at 3452 cm^{-1} is indicated that the presence of atmospheric OH molecules.

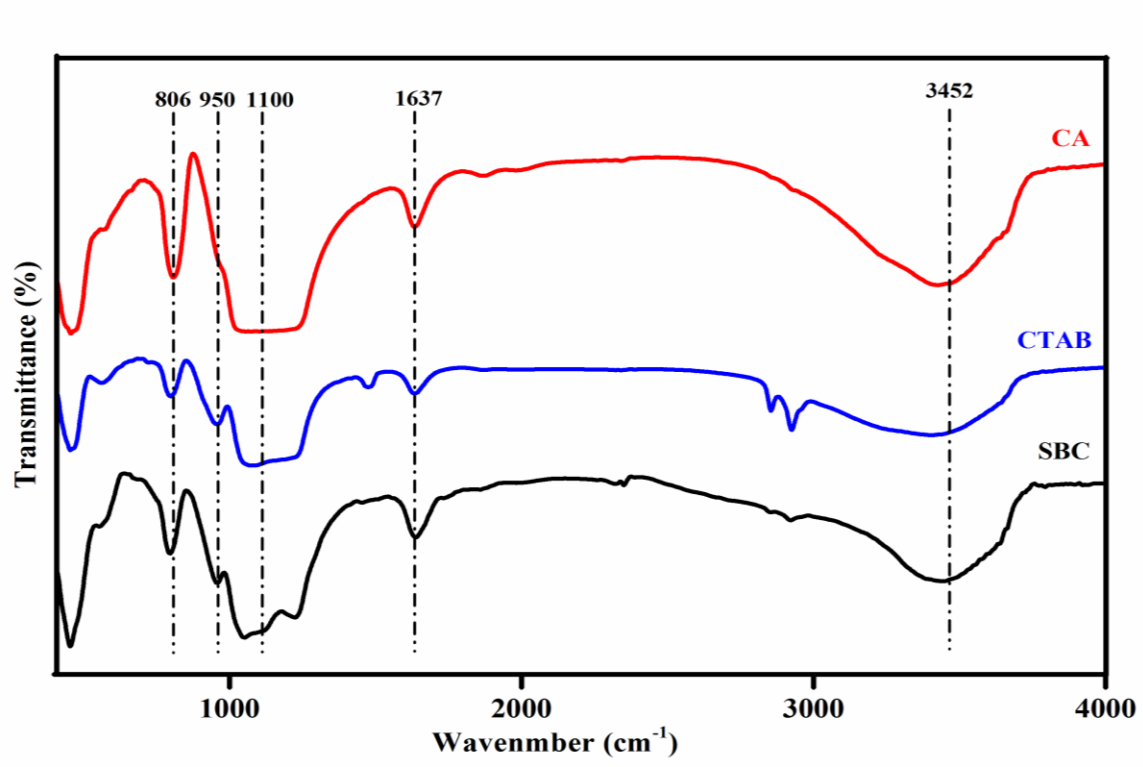

Fig. 2 FTIR analysis for CA, CTAB, and SBC template silica Nanotube

4.3. Transmission Electron Microscope (TEM) observation

Figure 3 demonstrates the TEM images for synthesized silica nanotubes. Figure 3a (CTAB) clearly shows that several short-length tubes are agglomerated and hoarded with each other. The average outer diameter of the tube is 6 nm, and its length is approximately 36 nm. At higher magnification, it shows well-defined structured nanotubes because of the typical nanotubes having light in the shade, but the edges show very dark in color. It may be due to the structural property of the template. In figure 3b (SB) shows that the lump of silica particles having improper tubular formation with an agglomerate appearance. Even though at high magnification the figure 3c (CA) shows the improper formation of the tubular structure, it's due to the binding nature of the citrate template. The TEM images for all the three different templates show the construction of hallow structure; the nanotubular structure of silica was an attempt in the CTAB assisted synthesis of silica nanotubes. This may be due to the different ionic arrangements on the template may affect the tubular structure.

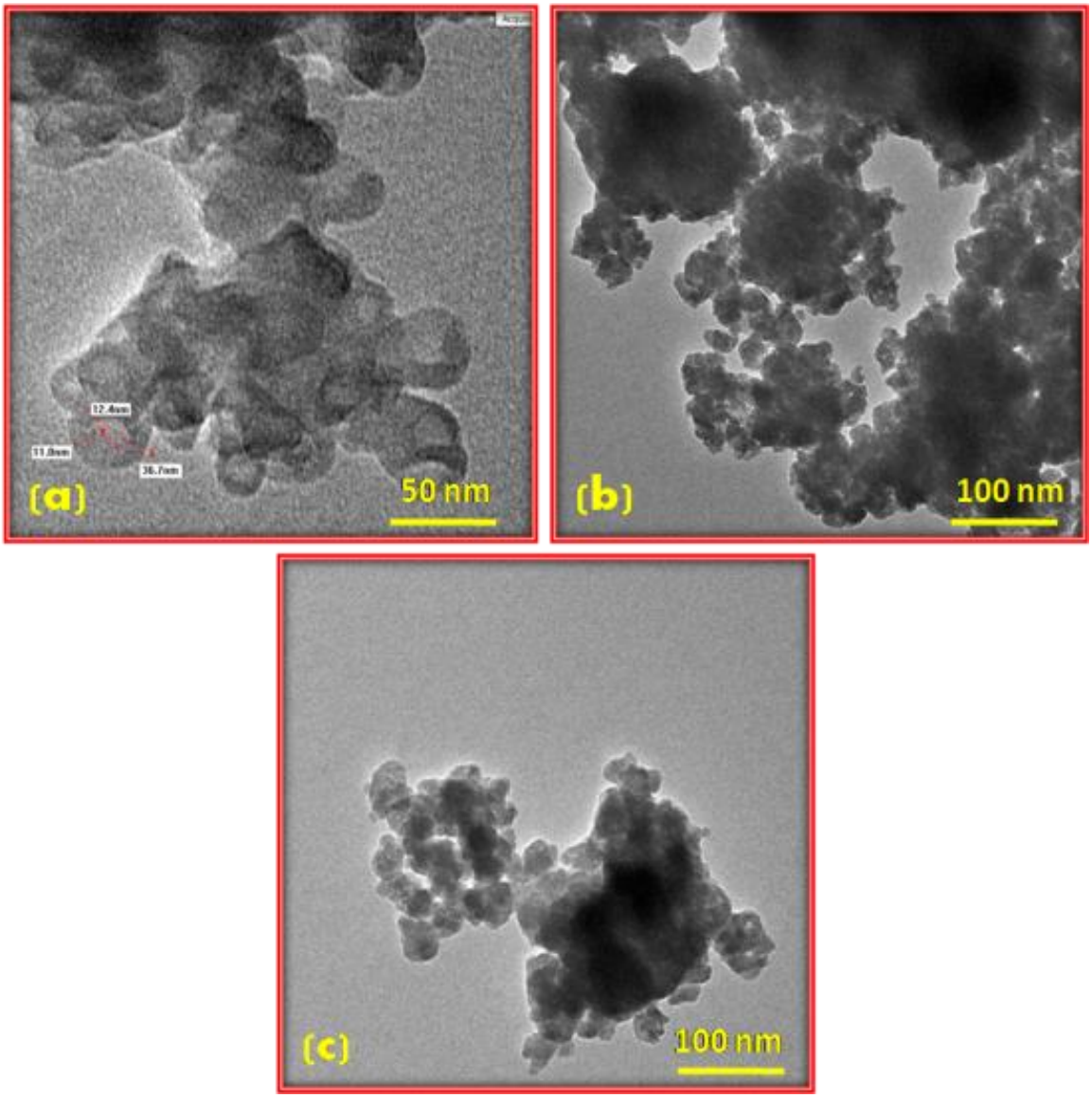

Fig. 3 Typical TEM images of **a** CTAB templated synthesized Si nanotube, **b** SB templated synthesized Si nanotube, **c** CA assisted synthesized Si nanotube.

4.4. The possible mechanism for the formation of silica nanotubes in the surfactant-assisted synthesis is given below.

In general, the quaternary cationic surfactant like CTAB [17, 18] is responsible for forming even surface tubular structures. The micelles predominantly build cylindrical hollow structures in aqueous conditions. The cationic species on the surfactant has arranged on the peripheral inorganic layer, which leads to organizing the

arrangement of the hexagonal siloxane package. The TEOS hydrolysis starts with the addition of ethanol and ammonia, which govern the accumulation of anionic charge density on the surfactant/inorganic interface. Then, the hydrolyzed product undergoes polycondensation, and the hydrated SiO_2 forms over the micelles. Upon calcination, the surfactants disappeared with the formation of a hollow tubular structure which illustration is shown in figure 4.

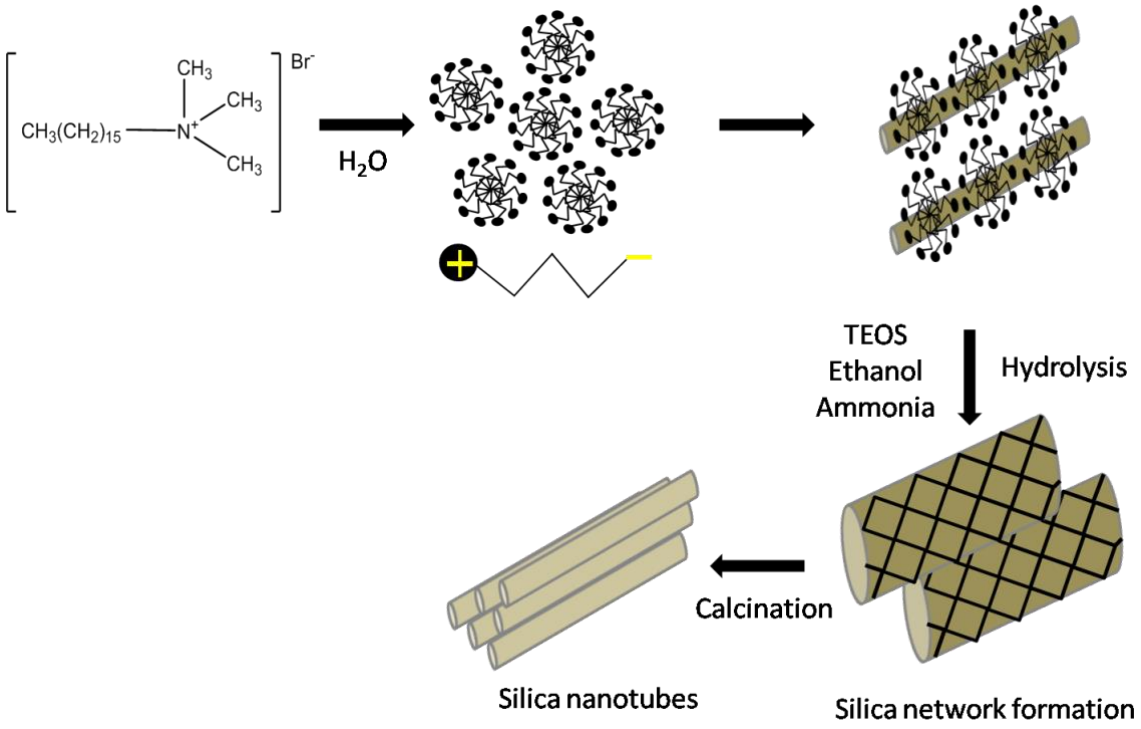

Fig. 4 Illustration of silica nanotube formation mechanism using CTAB template

4.5. Surface analysis

The adsorption, desorption isotherm and pore size, surface area measurement details are provided in figure 5 and figure 6. The obtained adsorption and desorption isotherm for the synthesized materials are in agreement with type II isotherm. Figure 5 exhibits that the adsorption and desorption were occurred in the first adsorption monolayer, for citric acid assisted silica nanotube has 40.85 m^2/g surface area, and the surface area for sodium bicarbonate assisted silica nanotube is 44.46 m^2/g. Many fold increment in the surface area (643 m^2/g) of the silica nanotubes was observed for the cationic surfactant (CTAB) assisted synthesis it also shows the formation of

monolayer adsorption. The vital parameters for the formation of hollow nanotubes are given in table 1, and its chart graph is shown in figure 6. Silica nanotubes with a large pore size (13 nm) were calculated for the sodium bicarbonate-assisted synthesis. In contrast, CTAB templated silica nanotubes show pore size considerably less in size (4.0 nm). The pore size difference for different surfactants solely depends on the ionic nature of the surfactants.

Table 1 The vital parameters for the formation of hollow silica nanotubes

Sample Code	Surface Area (m^2/g)	Pore size (nm)
SBC	4.45E+01	13
CA	40.855	8.3749
CTAB	643.03	4.0028

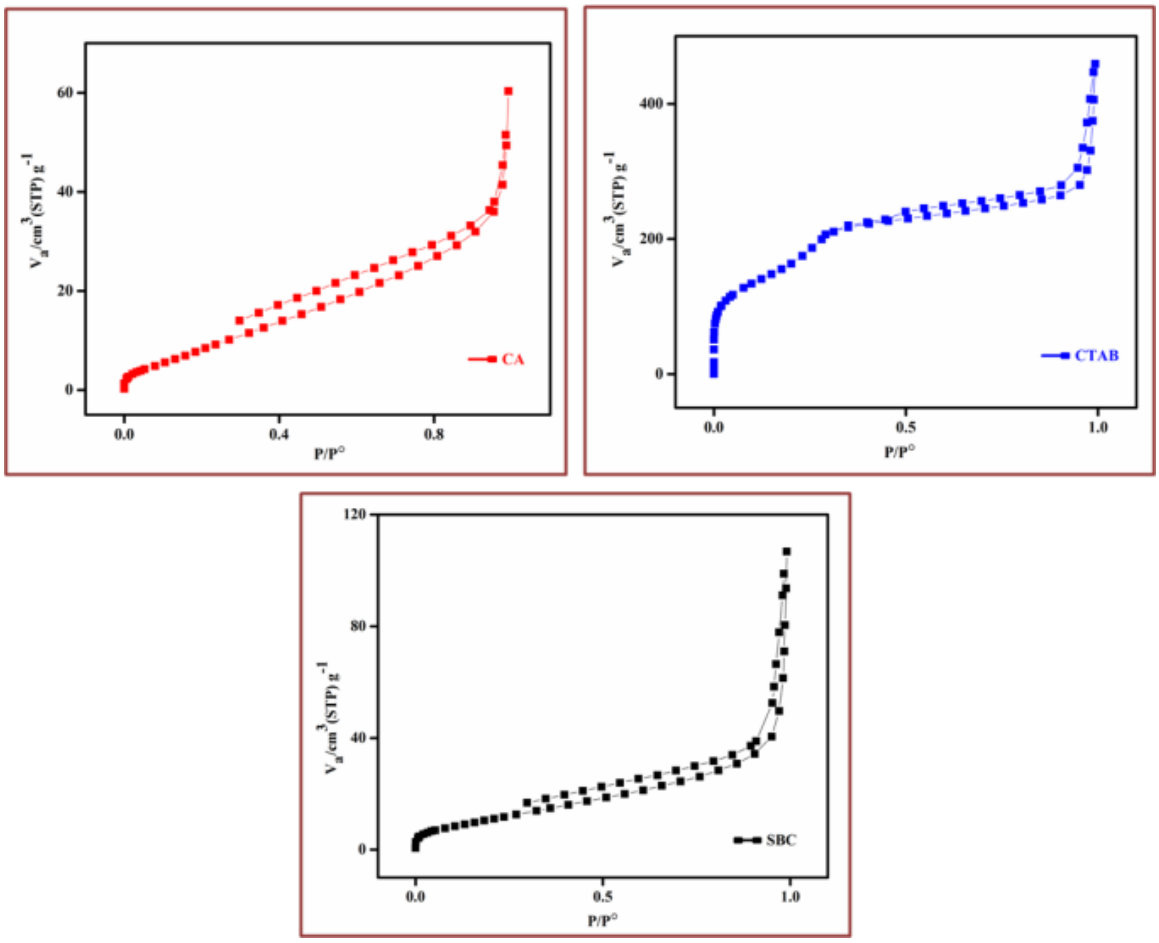

Fig. 5 The adsorption and desorption curve for CA, CTAB, and SBC assisted silica nanotubes.

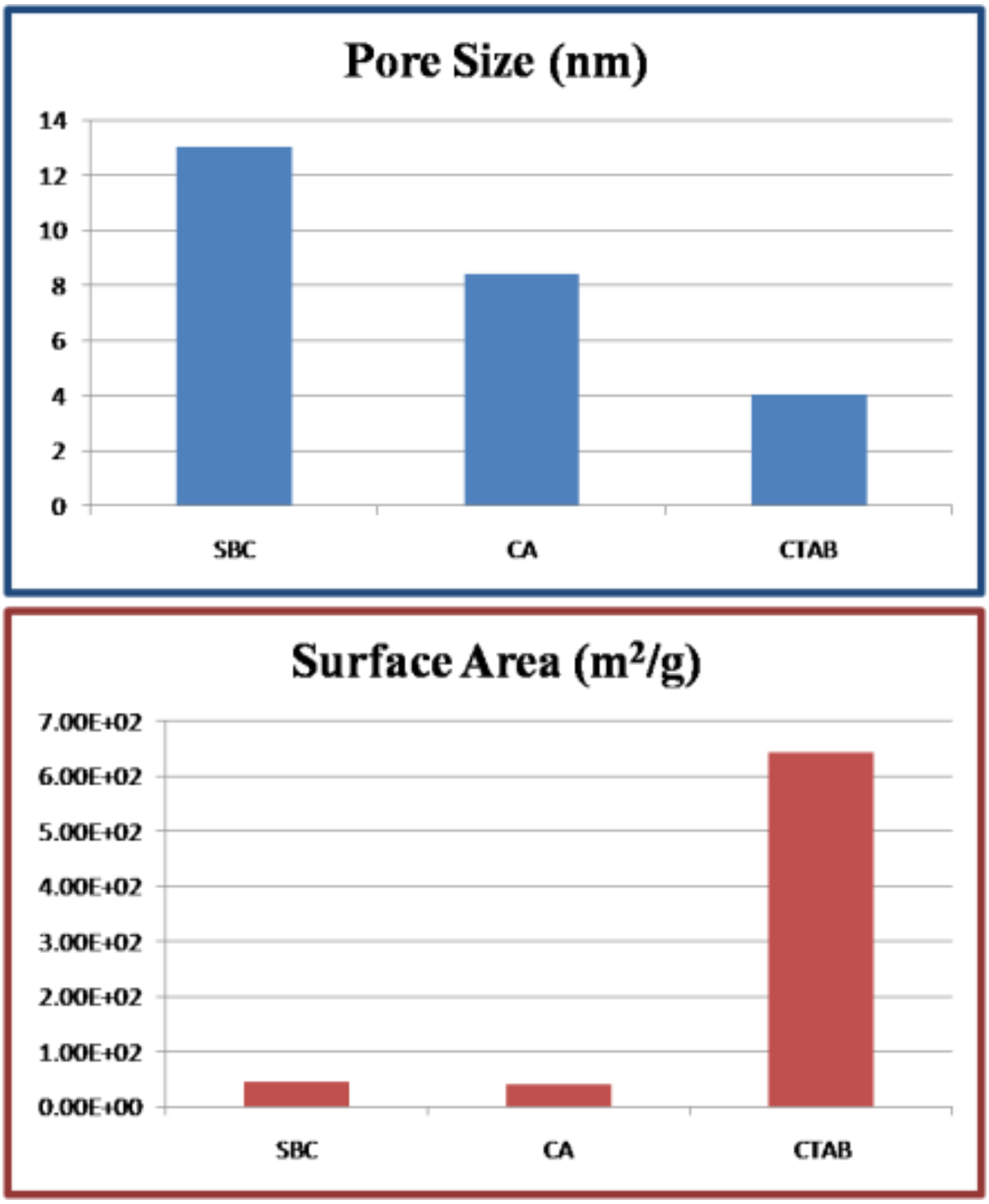

Fig. 6 Pore size and surface area analysis of synthesized silica nanotubes

5. Conclusion

The organic and inorganic surfactants were used as templates for the development of silica nanotubes; among the surfactants, CTAB assisted synthesis provided perfectly shape silica hallows tubes. The fabricated tubes

were characterized by various analytical tools such as XRD, FTIR, and TEM. The phase analysis was confirmed by XRD analysis, and functional groups were confirmed by FTIR revelation, and the tubular morphology was recorded by TEM. The fabricated tube's porosity and surface area was calculated by BET analysis. The organic template of CTAB shows the high surface area and perfect tubular shape. Here we conclude that the CTAB template silica nanotube is a promising material for the drug delivery process.

Declarations

Acknowledgment

The authors gratefully acknowledge the Indian Council of Medical Research (ICMR) for financial support in the form of Senior Research Fellow (SRF) [Grant no. 45/22/2019-Nan/BMS].

Authors' contributions

Logesh Mahendran: The author helps to characterization and analysis of application part and article written.

Abimanyu Ravichandran: The author worked on the synthesis part.

A.M. Ballamurugan: The author has given guidance to the overall work on this manuscript.

Compliance with Ethical Standards

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: All authors consented to the publication of this work. Authors all confirm the permission of publication for this study.

Competing Interests: The authors declare that they have no competing interests.

Reference

1. Wang, J. X., Wen, L. X., Wang, Z. H., Wang, M., Shao, L., & Chen, J. F. (2004). Facile synthesis of hallow silica nanotubes and their applications as supports for immobilization of silver nanoparticles. Scriptamat, 50, 1035-1039.
2. Chen, X., Klingeler, R., Kath, M., El Gendy, A. A., Cendrowski, K., Kalenczuk, R. J., & Palen, E. B. (2012). Magnetic Silica Nanotubes: Synthesis, Drug Release, and Feasibility for Magnetic Hyperthermia. Appl. Mater. Interfaces. 4, 2303-2309.

3. Guo, L., Shen, L., Chen, S., Wei, A., Huang, D., Osaka, A., & Chen, W. (2019). Naturally derived silk fibroin/gelatin composites as novel sacrificial template for synthesis of silica nanotubes with controllable size and their in vitro biocompatibility. Materials Letters. 251, 89–93.
4. Xu, S., Wang, Y., Qi, W., Su, R., & He, Z. (2018). Design of Silica Nanostructures with Tunable Architectures Templated by Ferrocene Peptides. ChemistrySelect. 3, 4939 – 4943.
5. Calzo´n, J. A. G., & Garcı´a, M. E. D. (2012). Synthesis and analytical potential of silica nanotubes. Trends Analyt Chem. 35, 27-38.
6. Li, J., Wang, Y., Zheng, X., Zhang, Y., Sun, C., Gao, Y., Jiang, T., & Wang, S. (2015). The synthesis and application involving regulation of the drug release from mesoporous silica nanotubes. Appl. Surf. Sci. 330, 374-382.
7. Tran, H. Q., Bhave. M., & Yu, A. (2020). Current Advances of Hollow Capsules as Controlled Drug Delivery Systems. ChemistrySelect. 5, 5537 –555.
8. Hu, J. Q., Meng, X. M., Jiang, Y., Lee, C. S., & Lee, S. T. (2003). Fabrication of Germanium-Filled Silica Nanotubes and Aligned Silica Nanofibers. Adv. Mater. 15, 70-73.
9. Ren, L., Simmons, T. J., Lu, F., Rahmi, O., & Kotha. S. P. (2014). Template Free and Large-Scale Fabrication of Silica Nanotubes with Centrifugal Jet Spinning. Chem. Eng. J. 254, 39-45.
10. Chen, S., Zhang, Q., Jia, L., Du, X., & Hanagata, N. (2015). A facilely controlled length, cytotoxicity, lengthdependent and cell type-dependent cellular uptake of silica nanotubes and their applications in the delivery of immunostimulatory CpG Oligodeoxynucleotides. J. Mater. Chem B. DOI: 10.1039/c5tb01270h.
11. Matsuura, Y., Hirano, T., & Sakai, K., (2014). Friction torque reduction by ultrasonic vibration and its application to electromagnetically spinning viscometer. Jpn. J. Appl. Phys. 53, 07KC12-1 to 07KC12-4.
12. Chen, S., Osaka, A., & Hanagata, N. (2011). Collagen-templated sol–gel fabrication, microstructure, in vitro apatite deposition, and osteoblastic cell MC3T3-E1 compatibility of novel silica nanotube compacts. J. Mater. Chem. 21, 4332-4338.
13. Muhr, H. J., Krumeich, F., Schönholzer, U. P., Bieri, F., Niederberger, M., Gauckler, L. J., & Reinhard Nesper, R. (2000). Vanadium Oxide NanotubesÐA New Flexible Vanadate Nanophase. Adv. Mater. 12 (3), 231-234.

14. Sun, L., Wang, Y., Jiang, T., Zheng, X., Zhang, J., Sun, J., Sun, C., & Wang, S. (2013). Novel Chitosan-Functionalized Spherical Nanosilica Matrix As an Oral Sustained Drug Delivery System for Poorly Water-Soluble Drug Carvedilol. Appl. Mater. Interfaces. 5, 103-113.
15. Wang, S. (2009). Ordered mesoporous materials for drug delivery. Microporous. Mesoporous. Mater. 117, 1–9.
16. Vona, D., Cicco, S. R., Ragni, R., Leone, G., Presti, M. L., & Farinola. G. M. (2018). Biosilica/polydopamine/silver nanoparticles composites: new hybrid multifunctional heterostructures obtained by chemical modification of Thalassiosira weissflogii silica shells. MRS Commun. doi:10.1557/mrc.2018.103
17. Rahmani, S., Akrout, A., Budimir, J., Aggad, D., Daurat, M., Godefroy, A., Nguyen, C., Largot, H., Bobo, M. G., Raehm, L., Durand, J. O., & Charnay, C. (2018). Hollow Organosilica Nanoparticles for Drug Delivery. ChemistrySelect. 3, 10439– 10442.
18. Wu, Z., Li, Y., Li, J., Wang, M., & Wang, Z. (2020). Interaction and Properties of the Synthesized Anionic Surfactant with CTAB: An Experimental and Theoretical Investigation. ChemistrySelect. 5, 1663 –1670.