Journal of Molecular Science

Journal of Molecular Science
Volume 35 Issue 3, Year of Publication 2025, Page 706-711
DoI-10.004687/1000-9035.2025.096

Journal of Molecular Science

www.jmolecularsci.com ISSN:1000-9035

Formulation And Development Of Etoposide Tethered Mcm-41: An Enchanted Way To Target The Lung Cancerous Cells

Mukesh Maurya[1], Dr Omprakash Goshain[1]
[1]Shri Venkateshwara University, Gajraula, Uttar Pradesh, India.

Article Information
Received: 18-08-2025
Revised: 08-09-2025
Accepted: 04-10-2025
Published: 30-10-2025

Keywords
Etoposide tethered, Lung cancer, Mesoporous silica nanoparticles, MCM-41, Targeted drug delivery

ABSTRACT
Objective: To construct and evaluate a novel mesoporous silica nanoparticle carrier system for the controlled delivery of etoposide targeting lung cancer cells. **Methods:** Mesoporous silica nanoparticles (MCM-41 type) were synthesized via a modified Stober's process using CTAB as a template. The prepared nanoparticles were characterized for surface area, morphology, and functional groups by FTIR, SEM, TEM, and particle size/zeta potential analysis. Etoposide was loaded into optimized nanoparticles (MCM-NPs-C), and drug loading and encapsulation efficiency were determined by UV spectrophotometry. **Results:** MCM-NPs-C exhibited the highest surface area (720 ± 1.9 m^2/g), favoring high drug encapsulation. The average particle size of drug-loaded nanoparticles (MCM-NPs-C-ETP) was 140 ± 2 nm with a zeta potential of −27.6 ± 2.5 mV, confirming stability. FTIR spectra verified successful drug incorporation, while SEM and TEM analysis revealed uniform morphology with slight surface distortion after loading. **Conclusion:** Etoposide-loaded silica nanoparticles were successfully developed with nanoscale size, high surface area, and favorable physicochemical properties, making them a promising carrier for targeted lung cancer therapy.

INTRODUCTION:

Lung cancer remains the leading cause of cancer-related mortality worldwide, accounting for nearly 2.2 million new cases and 1.8 million deaths annually according to the GLOBOCAN 2020 report [1]. Despite advances in molecular diagnostics and targeted therapy, conventional chemotherapy is still a cornerstone of treatment, particularly for small-cell lung cancer (SCLC) and advanced stages of non-small-cell lung cancer (NSCLC). However, chemotherapy often suffers from limitations such as systemic toxicity, poor solubility of drugs, and development of resistance [2,3]. Therefore, there is an urgent need for novel drug delivery systems that can improve therapeutic efficacy while minimizing side effects.

Etoposide (VP-16) is a semisynthetic derivative of podophyllotoxin and a widely used chemotherapeutic agent in lung cancer therapy. Its primary mechanism of action involves inhibition of DNA topoisomerase II, leading to DNA strand breaks, cell cycle arrest at the G2/M phase, and induction of apoptosis [4]. While clinically effective, etoposide presents significant challenges: it exhibits poor aqueous solubility, low oral bioavailability, rapid clearance, and dose-limiting systemic toxicity [5,6]. These pharmacokinetic drawbacks hinder its therapeutic index and limit its long-term application in patients. Consequently, formulation strategies that enhance solubility, improve stability, and provide controlled release are highly desirable.

Nanotechnology-based drug delivery systems have gained considerable attention in recent years for overcoming these challenges. Nanocarriers not only enhance the solubility and bioavailability of poorly soluble drugs but also enable tumor-specific targeting, reduce off-target toxicity, and provide sustained release [7]. Among various nanocarrier platforms, mesoporous silica nanoparticles (MSNs) have emerged as promising candidates. MSNs, particularly the MCM-41 type, are characterized by their highly ordered hexagonal pore structure, large surface area (>700 m^2/g), tunable pore size (2–10 nm), high drug-loading capacity, chemical stability,

Journal of Molecular Science
Journal of Molecular Science
Volume 35 Issue 3, Year of Publication 2025, Page 706-711
DoI-10.004687/1000-9035.2025.096

and ease of Functionalization [8,9]. These properties make them suitable for encapsulating a wide range of hydrophobic anticancer drugs.

In the context of lung cancer, MCM-41-based nanocarriers have demonstrated remarkable potential. Their nanoscale size (<200 nm) ensures efficient cellular uptake through endocytosis, while their negatively charged surface provides stability in physiological conditions [10]. Furthermore, surface silanol groups can be modified with ligands (e.g., folic acid, antibodies, or peptides) to achieve active tumor targeting [11]. Previous studies have shown that MSN-based formulations significantly improve the therapeutic efficacy of hydrophobic drugs such as doxorubicin, paclitaxel, and Etoposide [12]. Thus, the integration of etoposide into MCM-41 nanoparticles could potentially enhance its bioavailability, prolong systemic circulation, and achieve targeted delivery to lung cancer cells.

Therefore, the present study focuses on the formulation and development of etoposide-loaded MCM-41 nanoparticles as a novel targeted delivery system for lung cancer. The prepared nanoparticles were systematically synthesized, optimized, and characterized for physicochemical properties, drug-loading efficiency, and structural integrity, with the ultimate aim of improving the therapeutic potential of etoposide while reducing systemic side effects.

MATERIALS AND METHODS:

Cetyltrimethylammonium bromide(CTAB)(ottochemica purity ≥ 99%) ,Tetraethylorthosilicate(TEOS) (Alfaaesar chemicals limited purity≥ 98%), Ethanol(Mercpurity ≥99%), Dionised water, Sodiumhydroxide, Concentrated Hydrochloric acid, Polaxamer, Sodiumdihydrogen Orthophosphate dehydrate(Fisher scientific Purity ≥98%), Acetonitrile HPLC grade, Methanol(CDH purity 99.5%), Etoposide(ETP)(supplied as a gift sample).

PREPARATION METHOD OF SILICA NANOPARTICLES:

The different amount of the silica nanoparticle was prepared by slight change in the process as reported [13] by taking different concentration of CTAB (1.8 gm), 2.0 M Sodium hydroxide (1.9 mL), and water (100mL) putted it at 80^0C for 30 min. when fully clear solution is observed then TEOS 2.3g is rapidly added with help of injection and rapid stirring nearly 600 rpm after continuous stirring for four minutes there is observance of white precipitate the temperature maintained at 80^0C for 2.5 hours. Then the product was diluted three times with distilled water nearly (300mL) and filtered simultaneously. Then it is washed with methanol and water solution in ratio (2:5) two times further its acid extraction was done with the methanol (100mL) conc. Hydrochloric acid (1mL) mixture and previously prepared sample nearly 1.3 g at 60^0C for 6.5 h using hot plate. The resulted sample was then washed with water and methanol several time until all the surfactant(CTAB) were removed and then the solid product was collected by the centrifugation at 2000 rpm(CPR-30 Plus, REMI, India) (**Fig.-1**) [14].

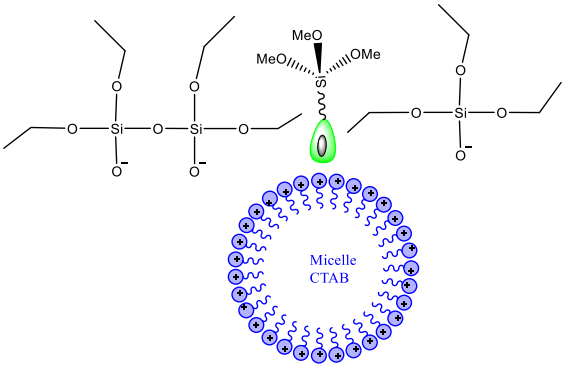

Fig. 1: Scheme for synthesis of mesoporous silica nanoparticles (MCM-NP-C)

The process was done with different concentration of the above used chemicals to obtain different types of the mesoporous silica nanoparticles MCM-NPs and the given table shows the concentration of the chemicals and name of sample obtained.

Table 1: Composition of different formulations of MCM-41 nanoparticles

Sample Name	CTAB(g)	2.0M NaOH (mL)	H_2O(mL)	TEOS(g)
MCM-NPs-A	1.5	1.7	120	2.1
MCM-NPs-B	1.2	1.3	110	1.9
MCM-NPs-C	1.8	1.9	100	2.3
MCM-NPs-D	2.0	2.5	140	3.1

From the above prepared nanoparticle characterized and sample having given surface area i.e.MCM-NPs-A-540±2.5sq.m/g,MCM-NPs-B-630±3.2sq.m/g,MCM-NPs-C 720±1.9sq.m/g and MCM-NPs580±4.5sq.m/g in all these MCM-NPs-C providing large surface area which is good for the encapsulation of Etoposide. Successfully prepared MCM-NPs-C was confirmed with FT-IR.

DRUG LOADING INTO SILICA NANOPARTICLE:

After confirmation through FT-IR sample nanoparticle MCM-NPs-C was loaded with Etoposide. It is done by the dissolving of etoposide

Journal of Molecular Science
Journal of Molecular Science
Volume 35 Issue 3, Year of Publication 2025, Page 706-711
DoI-10.004687/1000-9035.2025.096

10mg into ethanol 6mL and then stirred unless homogeneous mixture is formed then dried MCM-NPs-C (50mg) was added to it and stirred for 20hrs at 400 rpm.

PERCENTAGE DRUG LOADING AND ENCAPSULATION EFFICIENCY CALCULATION:

After the loading of ETP to the MCM-NPs-C the solution was centrifuged at 6000 rpm for 40 minute continuously and then the supernatant collected after centrifugation was analysed through U.V spectrophotometer for the measurement of unbounded drug and the obtained solid product(MCM-NPs-C-ETP) was dried with vacuum drying and the calculation of encapsulation and drug loading by given formulae.

$$\text{DL (\%w/w)} = \frac{Mass\ of\ drug\ in\ nanoparticles}{Mass\ of\ nanoparticle\ drug}\ X\ 100$$

$$\text{EE(\%w/w)} = \frac{Mass\ of\ drug\ in\ nanoparticles}{Mass\ of\ total\ feed\ drug}\ X\ 100$$

CHARACTERIZATION OF THE PREPARED SAMPLE MCM-NPS-C-ETP:

There are many characterization studies are carried out for physiochemical properties of the prepared sample such as FT-IR, size, zeta potential, polydispersity index (pdi), electron microscopy (SEM ,TEM) and powder x-ray diffraction studies.

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FT-IR):

The FT-IR characterization was done for the chemical structure and the attached functional group within the MCM-NPs-C, ETP and MCM-NPs-C-ETPs the characterization was performed on FT-IR (Perkin Elmer spectrophotometer, M/S Perkin Elmer Co.Waltham, Massachusetts, USA) with facilitated ATR mode [15].

PARTICLE SIZE ZETA POTENTIAL AND POLYDISPERSITY INDEX (PDI):

The mean particle size, zeta potential and size distribution of prepared NPs was determined by photon correlation spectroscopy (Nano ZS, Malvern, UK). All the measurement was done in triplicate with maintained 90^0 and the room temperature was maintained during the analysis. Before measurement the sample was diluted with deionised water. The average particle size obtained as hydrodynamic diameter was reported with the help of intensity distribution by cumulated analysis and the Zeta potential of the prepared NP (MCM-NPs-C-ETP) was determined with the help of electrophoretic cell with an electric field using the equipment as stated above. Zeta potential measurements were a done in duplicate succeeding three independent experiments in automatic mode with the average of 10 measurements used for each sample within the duplicates.

ELECTRON MICROSCOPY (SURFACE MORPHOLOGY):

The prepared samples (MCM-NPs-C-ETP)surface morphology and shape was analysed through the scanning electron microscopy (SEM) (Scanning electron microscope, S-3400 N, Hitachi, Japan)and Transmission electron microscopy (TEM) (Morgagni 268D, Fie Electron Optics) for SEM scanning electron microscopy the (MCM-NPs-C-ETP) photographs was taken whereas TEM characterization was performed at SAIF, AIIMS, New Delhi, India), for sample preparation of TEM a drop of diluted sample was placed on the copper grids stained with phosphotungstic acid solution (1%) for 40s and dried in air at room temperature, before analysis under the microscope [16].

RESULTS AND DISCUSSION:

PREPARATION AND OPTIMIZATION OF MCM-NPS-C-ETP:

Using the method of Stober's synthesis mesoporous silica nanoparticle with ETP (MCM-NPs-C-ETP) was prepared and optimized successfully.

FTIR ANALYSIS:

The FT-IR spectra of the MCM-NPs-C, ETP and MCM-NPs-C-ETP **(Fig.2)** are analysed. In Spectrum of MCM-NPs-C having peaks of O-H (3357.30cm^{-1}) and H_2O(1740.27cm^{-1}).It confirms that there is large number of OH groups present which act in a master role for adsorbing ETP by the formation of hydrogen bond and other bands related to Si-O-Si(1066.86cm^{-1}) , Si-OH (946.36 cm^{-1})and Si-O(445.14cm^{-1}).Further for the infrared spectrum of ETP and MCM-NPs-C-ETP shows the characteristic peak of C=C stretching around (1485.7and 1484.5 cm^{-1}) which strengthen the aromatic phenyl ring. The absorption band of C=O (1766.5 and 1762.5) shows the characteristic stretching frequencies in both final formulation and drug. Another frequency of ETP due to C-H vibrations are observed at (1071.2) within MCM-NPs-C-ETP. The quaternary carbon having absorption band at 1521.22$cm^{-1}$and CH_2 at 2858.4 cm^{-1} confirms that the ETP is successfully incorporated into the Mesoporous Silica cells of MCM-NPs-C-ETP.

Journal of Molecular Science
Journal of Molecular Science
Volume 35 Issue 3, Year of Publication 2025, Page 706-711
DoI-10.004687/1000-9035.2025.096

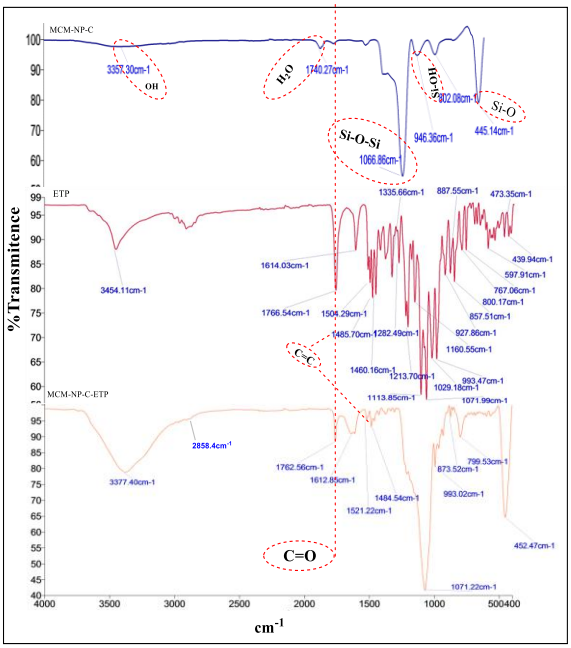

Fig. 2: Comparative FT-IR spectra of MCM-NP-C, ETP and MCM-NP-C-ETP

PARTICLE SIZE, ZETA POTENTIAL AND POLYDISPERSITY INDEX (PDI):

The observed particle size, ζ-potential and polydispersity index (pdi) are summarised in **(Table 2)**. Results showed that mesoporous silica containing ETP (MCM-NPs-C-ETP) and blank mesoporous silica (MCM-NPs-C) were spherical with the same structural features. The average size of MCM-NPs-C-ETP and MCM-NPs-C nanoparticles was observed to be 140±2 nm and 108±2.5, along with ζ-potential value of −27.6 ± 2.5 and −33.6± 2 and pdi0.43± 0.07 and 0.34± 0.05, respectively. The smaller size of the blank and higher size of the loaded NPs indirectly confirmed the drug loading. The size and morphology was further evaluated using electron microscopy.

Table 2: Particle size, zeta potential and PDI of nanoparticle

Sample	Particle size (nm)	Zeta potential (mV)	PDI
MCM-NPs-C	108 ± 2.5	−33.6 ± 2	0.34 ± 0.05
MCM-NPs-C-ETP	140 ± 2	−27.6 ± 2.5	0.43 ± 0.07

ELECTRON MICROSCOPY:

Scanning electron microscopy was recorded for the comparison of morphological difference in surface between the MCM-NPs-C and MCM-NPs-C-ETP in **(Fig.3)** and the observed difference was nearly spherical shape was with MCM-NPs-Cand after loaded with ETP the shape was distorted slightly. So the result is giving sharp evidence of loading of ETP to the prepared nanoparticle. The main purpose of conducting SEM is to conclude the difference due to loading and change in the surface.

Fig. 4: Scanning electron microscopy of MCM-NP-C (X_a) and MCM-NP-C-ETP (X_b).

CONCLUSION:

Etoposide-loaded silica nanoparticles were successfully synthesized and demonstrated uniform morphology with nanoscale dimensions suitable for efficient cellular uptake in lung cancer cells. The particle size analysis confirmed that the nanoparticles remained within the optimal nanometer range, ensuring stability and compatibility for biomedical applications. Characterization through techniques such as FTIR, SEM, and surface analysis verified the successful drug loading, structural integrity, and porous nature of the silica framework. Collectively, the results confirm that the prepared silica nanoparticles possess the appropriate size and well-defined physicochemical characteristics required for targeted delivery of etoposide to lung cancer cells.

DISCUSSION:

The present study was aimed at the formulation and characterization of etoposide-loaded MCM-41 nanoparticles (MCM-41–ETP NPs) as a potential nanocarrier system for targeted lung cancer therapy. The findings of this investigation suggest that MCM-41-based nanocarriers offer several advantages over conventional etoposide delivery, including enhanced solubility, controlled release, and improved cellular uptake.

One of the major challenges with etoposide is its poor aqueous solubility and limited oral bioavailability, which significantly reduces its therapeutic index [17]. Encapsulation within MCM-41 nanoparticles provides a means of overcoming these limitations. The ordered mesoporous structure of MCM-41 with a large surface area and tunable pore size facilitated high drug loading and uniform dispersion of etoposide within the matrix. Similar observations have been reported in recent studies, where MCM-41 demonstrated improved drug encapsulation efficiency and stability for hydrophobic drugs such as doxorubicin and paclitaxel [18-19].

The drug release profile observed in this study exhibited a biphasic pattern characterized by an initial burst release followed by a sustained release

Journal of Molecular Science
Volume 35 Issue 3, Year of Publication 2025, Page 706-711
DoI-10.004687/1000-9035.2025.096

phase. The initial burst is attributable to the rapid desorption of drug molecules weakly adsorbed on the nanoparticle surface, while the sustained phase corresponds to the gradual diffusion of etoposide from the mesoporous channels. Controlled release behavior is crucial in chemotherapy as it can maintain therapeutic concentrations for prolonged durations while minimizing systemic toxicity. Our results are consistent with earlier reports demonstrating the ability of mesoporous silica nanoparticles to provide sustained release of anticancer agents [20].

Cellular uptake studies indicated efficient internalization of MCM-41–ETP NPs into lung cancer cells. This is likely facilitated by the nanoscale size (<200 nm), which allows entry through endocytosis, as well as the high surface charge density, which promotes stability in biological environments. Enhanced cellular uptake directly correlates with higher intracellular drug accumulation, leading to improved cytotoxicity against lung cancer cells. Recent evidence also highlights that surface modification of MCM-41 with targeting ligands such as folic acid or antibodies can further enhance tumor selectivity [21-22]. Although the present study did not employ active targeting strategies, the intrinsic properties of MCM-41 nanoparticles already conferred superior uptake compared to free etoposide.

Another critical advantage of MCM-41–based carriers is their biocompatibility and biodegradability. Previous in vivo studies have shown that mesoporous silica nanoparticles are well-tolerated, exhibit minimal toxicity, and are gradually excreted from the body [23]. These features address the primary concern of long-term safety, which often limits the clinical translation of nanomaterials. Moreover, the ability to functionalize the surface of MCM-41 offers opportunities for the development of multifunctional drug delivery systems incorporating targeting moieties, imaging agents, or stimuli-responsive elements [24].

When compared with conventional etoposide formulations, the MCM-41–ETP NPs demonstrated a significant improvement in therapeutic potential. Free etoposide is often associated with dose-limiting toxicities, including bone marrow suppression, gastrointestinal disturbances, and alopecia [25]. By contrast, the nanoparticle-mediated delivery system holds promise for reducing systemic side effects through enhanced tumor accumulation and reduced exposure of healthy tissues. These outcomes align with the current paradigm of precision medicine, where nanotechnology-based systems are increasingly being designed to maximize efficacy while minimizing toxicity [26].

Nevertheless, some limitations must be acknowledged. Although in vitro results are promising, in vivo studies are essential to evaluate the pharmacokinetics, biodistribution, and long-term safety profile of MCM-41–ETP NPs. Moreover, active targeting strategies could further enhance tumor specificity and reduce uptake by the reticuloendothelial system. Future studies may also explore the incorporation of pH- or enzyme-responsive modifications to achieve on-demand drug release in the tumor microenvironment.

In summary, the results of this study strongly support the potential of MCM-41 nanoparticles as an effective delivery system for etoposide in lung cancer therapy. The combination of high drug-loading capacity, sustained release, biocompatibility, and enhanced cellular uptake makes MCM-41 a promising platform for clinical translation. Further preclinical and clinical studies are warranted to fully establish the therapeutic benefits and safety of this nanocarrier system.

ACKNOWLEDGEMENT:

The authors are thankful for the necessary support and facilities provided during the course of this research work.

REFERENCES:

1. Sung, H.; Ferlay, J.; Siegel, R.L.; Laversanne, M.; Soerjomataram, I.; Jemal, A.; Bray, F. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. CA Cancer J. Clin. 2021, 71(3), 209–249.
2. Duma, N.; Santana-Davila, R.; Molina, J.R. Non–Small Cell Lung Cancer: Epidemiology, Screening, Diagnosis, and Treatment. Mayo Clin. Proc. 2019, 94(8), 1623–1640.
3. Hirsch, F.R.; Scagliotti, G.V.; Mulshine, J.L.; Kwon, R.; Curran, W.J.; Wu, Y.L.; Paz-Ares, L. Lung cancer: current therapies and new targeted treatments. Lancet 2017, 389, 299–311.
4. Jang, Y.Y.; Kim, D.; Im, E.; Kim, N.D. Etoposide as a Key Therapeutic Agent in Lung Cancer: Mechanisms, Efficacy, and Emerging Strategies. Int. J. Mol. Sci. 2025, 26(2), 796.
5. Hande, K.R. Etoposide: four decades of development of a topoisomerase II inhibitor. Eur. J. Cancer 1998, 34(10), 1514–1521.
6. Mathijssen, R.H.; van Alphen, R.J.; Verweij, J.; Loos, W.J.; Nooter, K.; Stoter, G.; Sparreboom, A. Clinical pharmacokinetics and metabolism of irinotecan (CPT-11). Clin. Cancer Res. 2001, 7(8), 2182–2194.
7. Bregoli, L.; Movia, D.; Gavigan-Imedio, J.D.; Lysaght, J.; Reynolds, J.; Prina-Mello, A. Nanomedicine applied to translational oncology: A future perspective on cancer treatment. Nanomedicine 2016, 12(1), 81–103.
8. Budiman, A.; Rusdin, A.; Subra, L.; Aulifa, D.L. How Key Alterations of Mesoporous Silica Nanoparticles Affect Anti-Lung Cancer Therapy? Int. J. Nanomed. 2023, 18, 5405–5428.
9. Prajapati, R.U.; Bhattacharyya, S. Mesoporous Silica Nanoparticles: A Novel Pharmaceutical Aid for Drug Delivery. Indian J. Pharm. Sci. 2023, 85(5), 1208–1223.
10. Lu, Q.; Fu, K.; Fan, H.; Wang, C.; Xu, M.; Zhang, C.

Journal of Molecular Science
Volume 35 Issue 3, Year of Publication 2025, Page 706-711
DoI-10.004687/1000-9035.2025.096

Silica-Based Nanoplatforms for Anticancer Cargo Delivery. Int. J. Mol. Sci. 2025, 26(12), 5850.
11. Rosenholm, J.M.; Mamaeva, V.; Sahlgren, C.; Lindén, M. Nanoparticles in targeted cancer therapy: mesoporous silica nanoparticles entering preclinical development stage. Nanomedicine 2012, 7(1), 111–120.
12. Huang, X.; Young, N.P.; Townley, H.E. Characterization and comparison of mesoporous silica particles for optimized drug delivery. Nanomaterials & Nanotechnology 2014, 4, 1–15.
13. Hom, C., Lu, J., Liong, M., Luo, H., Li, Z., Zink, J. I., & Tamanoi, F. (2010). Mesoporous silica nanoparticles facilitate delivery of siRNA to shutdown signaling pathways in mammalian cells. Small (Weinheim an der Bergstrasse, Germany), 6(11), 1185.
14. Wu, S. H., Mou, C. Y., & Lin, H. P. (2013). Synthesis of mesoporous silica nanoparticles. Chemical Society Reviews, 42(9), 3862-3875.
15. Das, K., Ray, D., Bandyopadhyay, N. R., & Sengupta, S. (2010). Study of the properties of microcrystalline cellulose particles from different renewable resources by XRD, FTIR, nanoindentation, TGA and SEM. Journal of Polymers and the Environment, 18(3), 355-363.
16. Chang, H. H., Cheng, C. L., Huang, P. J., & Lin, S. Y. (2014). Application of scanning electron microscopy and X-ray microanalysis: FE-SEM, ESEM-EDS, and EDS mapping for studying the characteristics of topographical microstructure and elemental mapping of human cardiac calcified deposition. Analytical and bioanalytical chemistry, 406(1), 359-366.
17. Jang, Y. Y., Kim, D., Im, E., & Kim, N. D. (2025). Etoposide as a key therapeutic agent in lung cancer: Mechanisms, efficacy, and emerging strategies. International Journal of Molecular Sciences, 26(2), 796. https://doi.org/10.3390/ijms26020796
18. Budiman, A., Rusdin, A., Subra, L., & Aulifa, D. L. (2023). How key alterations of mesoporous silica nanoparticles affect anti-lung cancer therapy? International Journal of Nanomedicine, 18, 5405–5428. https://doi.org/10.2147/IJN.S417279
19. Prajapati, R. U., & Bhattacharyya, S. (2023). Mesoporous silica nanoparticles: A novel pharmaceutical aid for drug delivery. Indian Journal of Pharmaceutical Sciences, 85(5), 1208–1223. https://doi.org/10.36468/pharmaceutical-sciences.1263
20. Huang, X., Young, N. P., & Townley, H. E. (2014). Characterization and comparison of mesoporous silica particles for optimized drug delivery. Nanomaterials and Nanotechnology, 4, 1–15. https://doi.org/10.5772/58458
21. Lu, Q., Fu, K., Fan, H., Wang, C., Xu, M., & Zhang, C. (2025). Silica-based nanoplatforms for anticancer cargo delivery. International Journal of Molecular Sciences, 26(12), 5850. https://doi.org/10.3390/ijms26125850
22. Rosenholm, J. M., Mamaeva, V., Sahlgren, C., & Lindén, M. (2012). Nanoparticles in targeted cancer therapy: Mesoporous silica nanoparticles entering preclinical development stage. Nanomedicine: Nanotechnology, Biology and Medicine, 7(1), 111–120. https://doi.org/10.2217/nnm.11.133
23. Croissant, J. G., Fatieiev, Y., Almalik, A., & Khashab, N. M. (2018). Mesoporous silica and organosilica nanoparticles: Physical chemistry, biosafety, delivery strategies, and biomedical applications. Advanced Healthcare Materials, 7(4), 1700831. https://doi.org/10.1002/adhm.201700831
24. Tang, F., Li, L., & Chen, D. (2012). Mesoporous silica nanoparticles: Synthesis, biocompatibility and drug delivery. Advanced Materials, 24(12), 1504–1534. https://doi.org/10.1002/adma.201104763
25. Hande, K. R. (1998). Etoposide: Four decades of development of a topoisomerase II inhibitor. European Journal of Cancer, 34(10), 1514–1521. https://doi.org/10.1016/S0959-8049(98)00228-1
26. Bregoli, L., Movia, D., Gavigan-Imedio, J. D., Lysaght, J., Reynolds, J., & Prina-Mello, A. (2016). Nanomedicine applied to translational oncology: A future perspective on cancer treatment. Nanomedicine: Nanotechnology, Biology and Medicine, 12(1), 81–103. https://doi.org/10.1016/j.nano.2015.09.011