RESEARCH PAPER

Biosensors Enhanced with Nano-Silica in Cancer Detection

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Abstract:
Nano-silica is a versatile material, which is cost-efficient, non-toxic and abundant in nature. This material is effectively used for diagnosing cancer. Point-of-care devices are portable, user-friendly, highly accurate and capable of real-time detection. Point-of-care devices like biosensors incorporating silica nanoparticles demonstrate remarkable specificity and selectivity in cancer diagnosis. Types of cancer include blood cancer, ovarian cancer, cervical cancer, breast cancer, skin cancer, prostate cancer, etc. Detecting cancer in human cells and tissues is by the presence of appropriate cancer biomarkers. In this article, a systematic review is presented on the history and classification of silica nanoparticles. Special attention is given to their role in sensors and imaging, while silica nanoparticles contribute to enhanced sensitivity and reliability. This review further explores how silica nanoparticles are efficient in diagnosis of cancer. Additionally, it discusses diverse cancer biomarkers that aid in identifying cancer types, thereby contributing to improved early diagnosis and targeted treatment strategies.

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1. Introduction:

Cancer is one of the major causes of death worldwide, which is increasing sharply. Chemotherapy is the traditional method used in treating cancer, but it has certain limitations like it could affect normal healthy cells along with tumor cells, the radiation could cause subsequent complications including damage to the DNA, there are chances for the recurring of the disease and withstand therapy proving it less efficient. “Targeted drug delivery” is crucial to overcome limitations of conventional chemotherapy [1]. In addition to chemotherapy, tumor cells are removed surgically, or by radiation therapy or hormone-related therapy, each are successful towards cancer treatment at the same time less efficient in the view of specificity and selectivity [2].

Ligand-specific delivery systems are used to selectively bind to target site without causing any damage to surrounding sites. Lipid nanoparticle is also highly selective and specific to target tumor cells [3]. Cancer stem cells which are sub-groups of tumor cells are able to cause recurrent tumor. These cells are resistant to chemotherapeutic agents which cause the cells to rapidly multiply and withstand anti-cancer drugs [4]. Continuous growth of tumor lesions affects tissues and finally organs which are severe threats to human life. Cancer can affect any important part of the human body including lungs, liver, bones, blood and the brain [5]. Cancer cells are typically identified by the presence of biomarkers, which are specific to each type of cancer. These biomarkers help in early diagnosis of disease, thus improving the quality of life [6]. Cancer treatment is targeted towards inhibition of biomarkers which are biological molecules like genes, proteins or peptides used in identifying tumor cells [7]. To overcome the limitations of conventional cancer treatment methods, integration with nanomaterials could help. Due to the extremely small size of nanoparticles, they are capable of passing through tiny blood vessels and capillaries toselectively bind to cancerous cells and engulf them. Controlled drug release is possible for several weeks or months with ensured safety by using biocompatible materials in preparing nanomaterials. Different nanomaterials like carbon-based, metals and metal oxides, inorganic nanomaterials, polymeric and lipid nanoparticles are used in cancer diagnosis [8].

Silica nanoparticles is mainly used in diagnosing breast cancer due to its efficiency as a drug carrier [9]. Its inherent properties such as tunable particle size, less density, high drug loading efficiency have proved “core-shell” mesoporous silica as efficient candidates for “drug delivery” [10]. One dimensional form of silica is used in identifying “microRNA” which is a specific biomarker for breast cancer [11]. Silica is used in diagnosing prostate cancer, which is a common type of cancer in men [12]. An anti-cancer drug named “Docetaxel” is used in detecting prostate cancer cells [13]. Mesoporous silica was loaded with a drug called “Enzalutamide” along with folic acid, and used in prostate cancer diagnosis and treatment [14]. Core-shell mesoporous silica when coated with lipid and “Cabazitaxel” anti-cancer drug shows enhanced biocompatibility and cytotoxic effect against PC3 prostate cancer biomarker [15]. Mesoporous silica is also used in diagnosis and treatment of cervical and ovarian cancer using “5-Fluorouracil” anti-cancer drug [16]. Mesoporous silica with high porosity functionalized with folic acid is used in diagnosis of cervical cancer cells [17]. In addition, skin cancer “Melanoma” is diagnosed by mesoporous silica [18]. Enhanced cytotoxic effect to melanoma cells were found when silica is loaded with drugs like “Curcumin” and “Quercetin” [19].

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Table 1. Three major cancer types affecting men and women in the year 2022

Cancer caused in Men	**No. of cases**	**No. of deaths**	**Reference**
1. Prostate cancer	1,466,680	396,792	[20,21]
2. Lung cancer	1,571,868	1,233,109	
3. Liver cancer	600,243	521,433	
Cancers caused in Women	**No. of cases**	**No. of deaths**	**Reference**
1. Breast cancer	2,295,686	665,684	[20,21]
2. Cervical cancer	661,021	348,189	
3. Lung cancer	908,433	584,063	

Table 2. Top cancer prevailing countries and their statistics in 2020

Cancer incidence in Males:		**Cancer deaths in Males:**		**Reference**
No. of cases (per 100,000)	**Country**	**No. of cases (per 100,000)**	**Country**	[21]
494.2	Western Africa	165.6	Eastern Europe	
100.6	Australia/New Zealand	70.2	Central America	
Cancer incidence in Females:		**Cancer deaths in Females:**		**Reference**
No. of cases (per 100,000)	**Country**	**No. of cases (per 100,000)**	**Country**	[21]
405.2	Australia/New Zealand	118.3	Melanesia	
102.5	South Central Asia	63.1	Central America	

2. Silica nanoparticles:

Silica is prepared from “chemical” and “biogenic” methods. Figure 1 shows the production of silica from various agricultural sources [22].

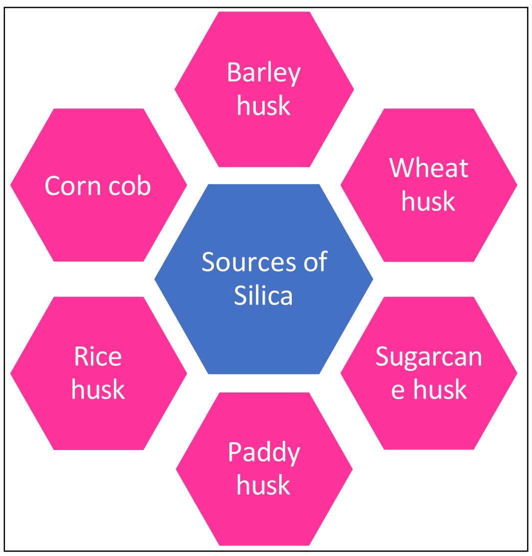


Figure 1. Agricultural Sources of Nano-Silica

The advantages of mesoporous silica nanoparticle is that its pore size, diameter of particles and its porosity can be tuned for specific applications. For
biomedical applications, one-dimensional nanoparticles with a size range of 10-300 nm are appropriate. Mesoporous silica comes in a variety of porous shapes. Figure 2 shows the porous shapes of mesoporous silica [23].

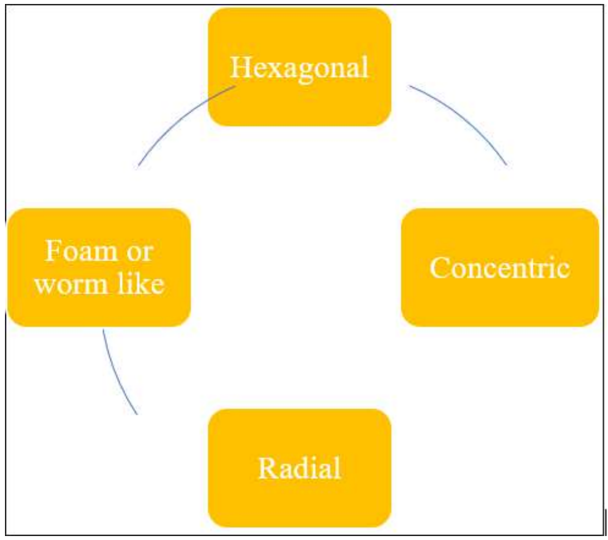


Figure 2. Porous shapes of Mesoporous silica

2.1 History and Development: (Only Silica) – who first invented Nano silica

A brief chronological order of the evolution of silica nanoparticles is shown in figure 3 [24–27].

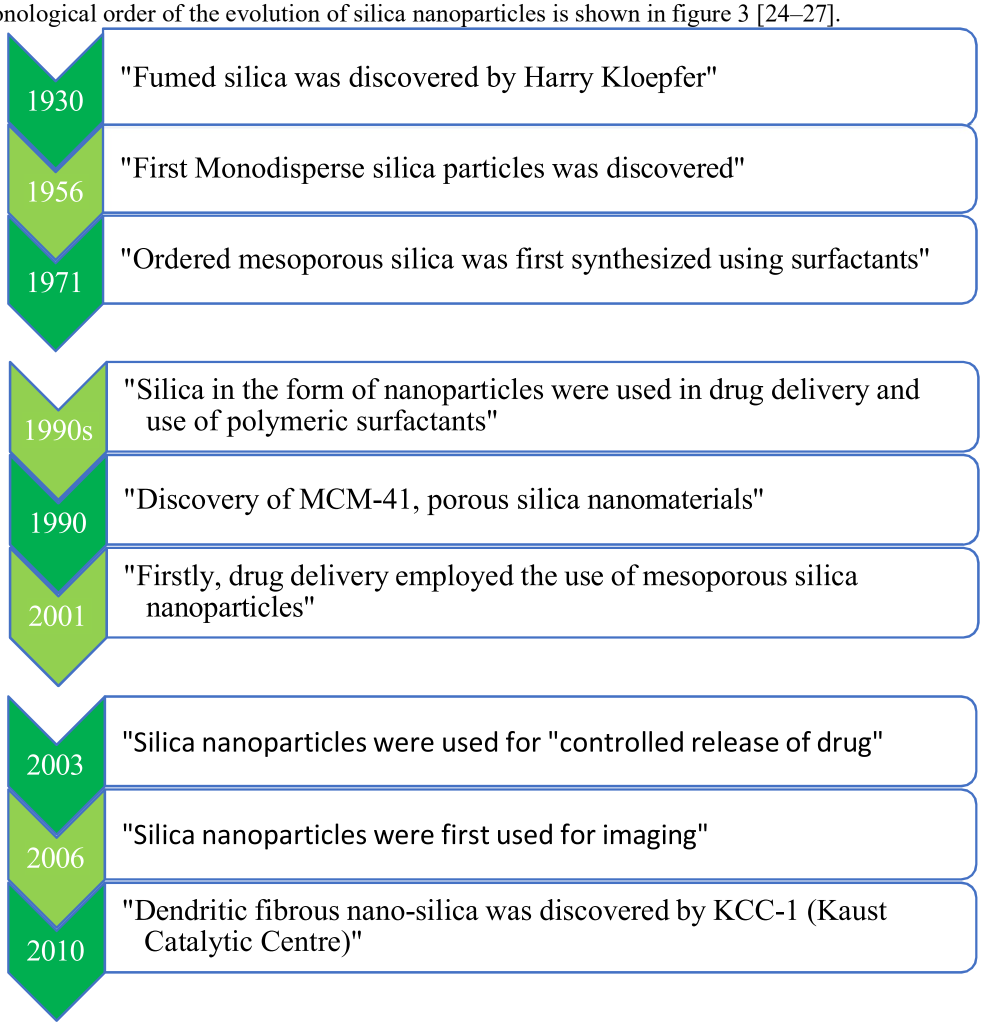


Figure 3. History of silica nanoparticles

2.2 Classification of silica based on phase or structure:

Silica nanoparticles are broadly classified into:

(i) Mesoporous silica nanoparticles
Has a porous structure with large pore volume
(ii) Solid silica nanoparticles
Has a non-porous structure and useful for biomedical applications [28].
Based on pore diameter, porous nanostructures are classified into three types.
(i) Microporous – less than 2 nm
(ii) Mesoporous – between 2 to 50 nm
(iii) Macroporous – more than 50 nm [28].
Silica exists in porous and non-porous forms:

POROUS SILICA	NON-POROUS SILICA	REFERENCE
• Has unique pore structure • Suitable for application in medical field • Specifically used in drug delivery, diagnosis and therapy.	• Has no unique pore structure • Biocompatible in nature • Due to its structure, not suitable for biomedical field	[29]

Table 3. Differences between porous and non-porous types of silica (SiO_2)

2.3 Quantum Confinement effect of nano-silica:
Due to quantum confinement effect, the size of nanocrystal decreases but there is an increase in band gap. Silicon quantum dots have pronounced effects in "biomedical tagging" [30]. The nanostructures that exhibit quantum confinement effect are nothing but "Quantum Dots". For quantum dots of size 1 nm, the strain and energy gap decreases, which is reverse for 2 nm size quantum dots [31]. Quantum dots, mesoporous silica nanoparticles are biocompatible in nature, so used in biomedical imaging, cancer diagnosis and treatment [32].

3. Mesoporous Silica Nanoparticles in POC devices: Silica nanoparticles are used in Electrochemical biosensors for detection Escherichia Coli bacteria, with a detection limit of 2×10^3 CFU/ml (colony forming unit/millilitre). Mesoporous silica is used in calorimetric and fluorescence biosensors for detecting Salmonella Typhimurium, typhoid-causing bacteria, with detection limit of 63 CFU/ml and 40 CFU/ml respectively [33]. Optical biosensors use porous silicon for detecting biological units like "DNA, enzymes, cells, bacteria and antigen". Optical biosensors fabricated using porous silicon is used in diagnosing cancer. For example, it can detect heat shock protein 70, to identify several types of cancer [34]. "Porous silicon biosensor was fabricated to detect Escherichia Coli bacteria with 10^1 to 10^2 CFU/ml limit. Mesoporous silica combined with other metal oxides or carbon nanomaterials are used in early identification of bacterial infections with high accuracy [35]. Porous silicon when coated with carbon used in designing Glucose Sensor which helps identify "Glucose dehydrogenase" and Glucose oxidase" [36]. Mesoporous silica is used in "Microfluidic devices" to detect presence of infections caused by Helicobacter pylori and Hepatitis A by scanning a blood drop and detects glucose and urea from sweat. Cotton threads which are cheap raw material is coated with silica to improve its efficiency in such point-of-care devices [37]. Mesoporous silica along with ruthenium is used in "Electrochemiluminescence", a point-of-care device to identify "Severe-Acute- Respiratory Syndrome", a ratory disease with a range of $1 - 10^4$ ng/ml with 52 ng/ml as detection limit [38]. CRP protein is detected by using silica coated with fluorescent materials. Silica with quantum dots increase its performance, thus mesoporous silica is used efficiently sensing devices which is advantageous due to its low cost and zero toxicity [39].

4. Metal oxides in Nano-silica POC devices:

4.1 Titanium dioxide:

Titanium dioxide (TiO_2) based nanocomposites have attracted a rising interest as functional materials for biosensor applications. Biosensors based on TiO_2 are used in electrochemical, optical, electrochemiluminescence biosensors [40].

4.2 Tin oxide:

Tin oxide along with mesoporous silica is used in sensing "volatile organic compounds" which detects diseases such as gingivitis, oral carcinoma, periodontal diseases and diabetes mellitus. [41].

4.3 Copper oxide:

Copper oxide nanoparticles possess significant intrinsic properties which are suitable for cancer diagnosis and treatment. Nanorods of copper oxide are used in detecting and destroying tumor cells causing breast cancer without any disruption to normal healthy cells [42].

4.4 Zinc oxide:

Silica prepared by green synthesis, when coated with zinc oxide, has increased efficiency to combat bacterial infections caused by Staphylococcus, Escherichia coli and Pseudomonas [43].

4.5 Iron oxide:

These metal oxides have improved magnetic properties, so proven to be used in bio-imaging of cancer cells. Ovarian cancer is identified and treated by targeted drug delivery using iron oxide nanoparticles [44]. Iron oxide is synthesized in environment friendly plant-based approaches which are effective in diagnosing and treating cancer cells in human body [45].

5. **Biosensors:A biosensor uses electrical, thermal and optical signals to detect diseases in tissues, cells, enzymes and immune system [46]. In 1960, the first biosensor was discovered by "Leland C. Clark Jr." to detect amount of glucose in diabetes patients [47]. Diseases like cancer are quickly diagnosed and treated using biosensors [48]. Modern technologies include biosensors that are wearable to enable people to assess health information any moment, at any location [49]. A biosensor uses electrical, thermal and optical signals to detect diseases in tissues, cells, enzymes and immune system [50].**

The advantages of biosensors include,

- Simplicity
- Flexibility
- Accuracy
- Specificity
- High speed and
- Cost effectiveness [47].

The broad classification of biosensors include:

- Electrochemical biosensors
- Optical biosensors
- Piezoelectric biosensors
- Fluorescent biosensors and
- Thermometric biosensors [51].Capillaries are a type of point-of-care devices that are used in biosensors for detecting proteins, carbohydrates, lipids and nucleic acids [52]**.** A typical biosensor consists of four stages

(i) **Biological recognition element:** - Interacts with blood and bodily fluids

(ii) **Transducer:** – Converts the interaction into signal

(iii) **Signal processor:** – Converts biological signal into electrical signal

(iv) **Reader:** – Displays the output [53].

Biosensor in the form of paper can be strips on which blood samples and other body fluids are tested, whereas chip-sized biosensors are made up of "Polydimethylsiloxane - PDMS", both are used in immediate and accurate detection of infectious diseases [54].

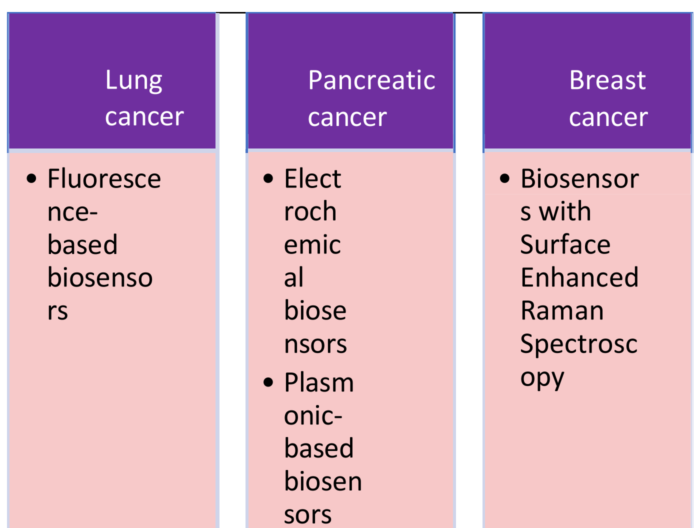
The four main types of Electrochemical biosensors used in detecting analytes in the human body are as follows:

- Conductometric
- Potentiometric
- Voltammetric

Amperometric
[48]

Figure 4 lists the biosensors used in three different types of cancer identification [55].

Figure 4. Biosensors used to detect three main types of CancerWith the increasing risk of cancer which originates in a cell or tissue and



multiplies affecting other cells and organs of

the body and pose a severe threat, nanomaterials play a significant role in early diagnosis and treatment of cancer due to its advanced properties [56].

5.1 Nano-silica in Biosensors:

The stability of biosensors is due to factors like, temperature, pH and conditions for storage. Nanomaterials like mesoporous silica can better enhance thermal and chemical stability which are efficient than polymeric and organic materials that are used in conventional biosensors. Further when quantum dots are used in biosensors, it is used to detect cardiac biomarkers [57]. The main advantage of using silica is its flexible mechanical, optical, thermal and physical properties, adjustable pore size, biocompatibility and biodegradability which are used effectively forbiomedical applications such as drug delivery, imaging and sensors [58]. Biosensors play a vital role in identifying cancer by detecting specific biomarkers, glucose levels, and several diseases. Inorganic nanomaterials, carbon-based nanomaterials and organic nanomaterials lesser than 500 nm is used in enhancing the efficiency of biosensors [59]. Nanoscale materials in the form of tubes, rods, wires and particles at size 1-100 nm is used in biosensors for precise detection of biomolecules (Narware et al. 2025).

Combination of different nanomaterials like polymers, metal nanoparticles and carbon-based materials are proved to improve the stability, accuracy and sensitivity of biosensors. Biosensors provide digital output by analyzing different biomolecules. Due to its advantages, it is ideal for point-of-care diagnostics [60]. Biosensors are divided into number of groups according to the physical principles and processing technique employed Optical biosensors are highly efficient than

electrochemical biosensors due to its advantages such as rapid response, sensitivity, accuracy and stability. These compact devices are used point-of-care diagnostics [61].

Biomarkers – its types for cancer cells:

The classification of biomarkers that are used in detecting cancer

(i) Diagnostic biomarkers:

Identifies disorders when they occur

(ii) Prognostic biomarkers:

Offer information about a patient’s total intended clinical progress

(iii) Predictive biomarkers:

Determine the general intended clinical result [62,63].

Table 4. Different biomarkers used in identifying types of cancer

TYPES OF CANCER	TYPES OF BIO-MARKERS	REFERENCE
1. Breast cancer	ER, PR, HER2 and Ki-67	[64]
2. Lung cancer	EGFR, ALK, ROS1, MET, HER2	[65,66]
3. Prostate cancer	PSA, PCA3, Prolaris, ProMark, PHI	[67]
4. Ovarian cancer	CA-125, HE4, BRCA1/2, FGF	[68]
5. Gastric cancer	CEA, CA72-4, CA19-9, CA125	
6. Endometrial cancer	PTEN, TPS, HE4, E-cadherin	
7. Pancreatic cancer	CA19-9, CEA, CA125, CA50	[69]
8. Cervical cancer	CCR7, CD3D, ITGB2, TP53	[70]
9. Liver cancer	AFU, DCP, AFP, GP73	[71]
10. Colorectal cancer	CEA, EGFR, KRAS, MSI	[72]

6. Conclusion:

Nano-silica emerges as a highly promising material in the biomedical field, particularly in the development of advanced biosensors and cancer diagnostic tools. Its inherent features such as biocompatibility, low toxicity, cost-effectiveness and structural versatility, make it an ideal candidate for integration into point-of-care technologies. When combined with other functional materials, silica nanoparticles significantly enhance the sensitivity,
specificity and reliability of biosensors, enabling the rapid detection of a wide range of biomarkers. Such improvements hold particular value in early cancer detection, where accuracy and timeliness are crucial. Beyond diagnosis, the adaptability of nano-silica paves the way for personalized medical applications and next-generation healthcare systems. With ongoing advancements in nanotechnology, the use of silica nanoparticles is expected to revolutionize biosensing platforms and transform point-of-care testing, thus this material is excellent choice for biomedical applications.\

References:

[1] Gu Y, Yang R, Zhang Y, Guo M, Takehiro K, Zhan M, et al. Molecular mechanisms and therapeutic strategies in overcoming chemotherapy resistancein cancer. Molecular Biomedicine 2025;6. https://doi.org/10.1186/s43556-024-00239-2.

[2] Zafar A, Khatoon S, Khan MJ, Abu J, Naeem A. Advancements and limitations in traditional anti-cancer therapies: a comprehensive review of surgery, chemotherapy, radiation therapy, and hormonal therapy. Discover Oncology 2025;16. https://doi.org/10.1007/s12672-025-02198-8.

[3] Miao H, Fang Y, Pan C, Yang H, Wang Z, Qi Y, et al. Transforming the landscape of cancer treatment with seven promising novel therapies: evolution and future perspectives. Medicine Plus 2025;2. https://doi.org/10.1016/j.medp.2025.100087.

[4] Tan Y, Qin S, Zhang Z, Liu Y, Zhou L, Li B, et al. Unraveling the underlying mechanisms of cancer stem cells in therapeutic resistance for optimizing treatment strategies. MedComm - Oncology 2025;4. https://doi.org/10.1002/mog2.70009.

[5] Li Y, Liu F, Cai Q, Deng L, Ouyang Q, Zhang XHF, et al. Invasion and metastasis in cancer: molecular insights and therapeutic targets. Signal Transduct Target Ther 2025;10. https://doi.org/10.1038/s41392-025-02148-4.

[6] Qoronfleh MW, Al-Dewik N. Cancer Biomarkers: Reflection on Recent Progress, Emerging Innovations, and the Clinical Horizon. Cancers(Basel) 2025;17. https://doi.org/10.3390/cancers17182981.

[7] DaCosta Byfield S, Bapat B, Becker L, Reyes C, Chatzitheofilou I, Schroeder BE, et al. Biomarker Testing Approaches, Treatment Selection, and Cost of Care Among Adults With Advanced Cancer. JAMA Netw Open 2025;8:e2519963. https://doi.org/10.1001/jamanetworkopen.2025.19963.

[8] Ciftci F, Özarslan AC, Kantarci İC, Yelkenci A, Tavukcuoglu O, Ghorbanpour M. Advances in

Drug Targeting, Drug Delivery, and Nanotechnology Applications: Therapeutic Significance in Cancer Treatment. Pharmaceutics 2025;17. https://doi.org/10.3390/pharmaceutics17010121.
[9] 1. 2023 - Unlocking the potential of MSN in Breast cancer treatment n.d.
[10] Rani R, Malik P, Dhania S, Mukherjee TK. Recent Advances in Mesoporous Silica Nanoparticle-Mediated Drug Delivery for Breast Cancer Treatment. Pharmaceutics 2023;15. https://doi.org/10.3390/pharmaceutics15010227.
[11] Gao A, Wang F, Fan Z, Chen S, Wu K. Reliable breast cancer miRNAs detection with enhanced silicon nanowire biosensor by PNA probe and optical calibration. Sens Actuators B Chem 2024;401. https://doi.org/10.1016/j.snb.2023.135011.
[12] Mohanan S, Sathish CI, Ramadass K, Liang M, Vinu A. Design and Synthesis of Cabazitaxel Loaded Core-Shell Mesoporous Silica Nanoparticles with Different Morphologies for Prostate Cancer Therapy. Small 2024;20. https://doi.org/10.1002/smll.202303269.
[13] Rivero-Buceta E, Bernal-Gómez A, Vidaurre-Agut C, Lopez Moncholi E, María Benlloch J, Moreno Manzano V, et al. Prostate cancer chemotherapy by intratumoral administration of Docetaxel-Mesoporous silica nanomedicines. Int J Pharm 2024;664. https://doi.org/10.1016/j.ijpharm.2024.124623.
[14] Parmar K, Bhatt S. Enzalutamide Loaded Folic Acid Decorated Mesoporous Silica Nanoparticles for Targeted Drug Delivery for Prostate Cancer Management. J Inorg Organomet Polym Mater 2025;35:154–65. https://doi.org/10.1007/s10904-024-03292-0.
[15] Mohanan S, Sathish CI, Adams TJ, Kan S, Liang M, Vinu A. A Dual Protective Drug Delivery System Based on Lipid Coated Core-Shell Mesoporous Silica for Efficient Delivery of Cabazitaxel to Prostate Cancer Cells. Bull Chem Soc Jpn 2023;96:1188–95. https://doi.org/10.1246/bcsj.20230167.
[16] 12025-~1 n.d.
[17] Zeng Z, Zhao Y, Yang L, Xi F, Su D. Vertically ordered mesoporous silica film-assisted electrochemical cytosensor for the sensitive detection of HeLa cells. Front Chem 2023;11. https://doi.org/10.3389/fchem.2023.1222067.Liang X, Zhang J, Zhang C, Zhai H, Yang P, Chen M. Mesoporous silica coated spicules for photodynamic therapy of metastatic melanoma. J Nanobiotechnology 2024;22 . https://doi.org/10.1186/s12951-024-02471-y.
[18] 12025-~1 n.d.
[19] Bray F, Laversanne M, Sung H, Ferlay J, Siegel RL, Soerjomataram I, et al. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA Cancer J Clin 2024;74:229–63. https://doi.org/10.3322/caac.21834.
[20] Obafemi FA. A Review of Global Cancer Prevalence and Therapy. Journal of Cancer Research, Treatment & Prevention 2023. https://doi.org/10.37191/Mapsci-JCRTP-1(3)-011.
[21] Nayl AA, Abd-Elhamid AI, Aly AA, Bräse S. Recent progress in the applications of silica-based nanoparticles. RSC Adv 2022;12:13706–26. https://doi.org/10.1039/d2ra01587k.
[22] Manzano M, Vallet-Regí M, Manzano M, Vallet-Regí M. Progress Report on Mesoporous Silica Nanoparticles for Drug Delivery. n.d.
[23] Vallet-Regí M, Schüth F, Lozano D, Colilla M, Manzano M. Engineering mesoporous silica nanoparticles for drug delivery: where are we after two decades? Chem Soc Rev 2022;51:5365–451. https://doi.org/10.1039/d1cs00659b.
[24] Singh B, Na J, Konarova M, Wakihara T, Yamauchi Y, Salomon C, et al. Functional mesoporous silica nanomaterials for catalysis and environmental applications. Bull Chem Soc Jpn 2020;93:1459–96. https://doi.org/10.1246/BCSJ.20200136.
[25] Isa EDM, Ahmad H, Rahman MBA, Gill MR. Progress in mesoporous silica nanoparticles as drug delivery agents for cancer treatment. Pharmaceutics 2021;13:1–33. https://doi.org/10.3390/pharmaceutics13020152.
[26] Janjua TI, Cao Y, Kleitz F, Linden M, Yu C, Popat A. Silica nanoparticles: A review of their safety and current strategies to overcome biological barriers. Adv Drug Deliv Rev 2023;203. https://doi.org/10.1016/j.addr.2023.115115.
[27] Chang H, Kim J, Rho WY, Pham XH, Lee JH, Lee SH, et al. Silica Nanoparticles. Adv Exp Med Biol, vol. 1309, Springer; 2021, p. 41–65. https://doi.org/10.1007/978-981-33-6158-4_3.
[28] Chen J, Xu Z, Zhang M, Ju Z, Niu Z, Ma Y, et al. Mesoporous silica nanoparticles: A Synthesis Guide and Research Progress in the Biomedical Field. Mater Today Chem 2024;42. https://doi.org/10.1016/j.mtchem.2024.102426.
[29] Murase N, Li C. Silane-Coupled Silica Nanoparticles Encapsulating Emitting Quantum Dots: Advancing Robust Phosphors for Displays and Beyond. Molecules 2025;30. https://doi.org/10.3390/molecules30163369.
[30] Ghosh S, Eisenbach M. Strain engineering of doped hydrogen passivated silicon quantum dots. Sci Rep 2025;15. https://doi.org/10.1038/s41598-025-04532-0.Fatima R, Katiyar P, Kushwaha K. Recent advances in mesoporous silica nanoparticle: synthesis, drug loading, release mechanisms, and diverse applications. Frontiers in Nanotechnology 2025;7. https://doi.org/10.3389/fnano.2025.1564188.
[31] Karaman DŞ, Pamukçu A, Karakaplan MB, Kocaoglu O, Rosenholm JM. Recent advances in the use of mesoporous silica nanoparticles for the

diagnosis of bacterial infections. Int J Nanomedicine 2021;16:6575–91. https://doi.org/10.2147/IJN.S273062.
[32] Moretta R, De Stefano L, Terracciano M, Rea I. Porous silicon optical devices: Recent advances in biosensing applications. Sensors (Switzerland) 2021;21:1–26. https://doi.org/10.3390/s21041336.
[33] Singh S, Numan A, Cinti S. Point-of-Care for Evaluating Antimicrobial Resistance through the Adoption of Functional Materials. Anal Chem 2022;94:26–40. https://doi.org/10.1021/acs.analchem.1c03856.
[34] Fujii S, Yoshida A, Chuong TT, Minegishi Y, Pirabul K, Pan Z-Z, et al. Development of Microdrip Enzyme Device Using Carbon-Coated Porous Silica Spheres. ACS Applied Engineering Materials 2023;1:1426–35. https://doi.org/10.1021/acsaenm.3c00103.
[35] Mikolei JJ, Stanzel M, Pardehkorram R, Lehn R, Ceolin M, Andrieu-Brunsen A. Fluid Flow Control in Cotton Threads with Mesoporous Silica Coatings. Adv Mater Interfaces 2023;10. https://doi.org/10.1002/admi.202300211.
[36] Fu W, Wang X, Ying X, Sun T, Wang Y, Wang J, et al. Electrochemiluminescence Lateral Flow Immunoassay Using Ruthenium(II) Complex-Loaded Dendritic Mesoporous Silica Nanospheres for Highly Sensitive and Quantitative Detection of SARS-CoV-2 Nucleocapsid Protein. Adv Funct Mater 2024;34. https://doi.org/10.1002/adfm.202409632.
[37] Hou F, Sun S, Abdullah SW, Tang Y, Li X, Guo H. The application of nanoparticles in point-of-care testing (POCT) immunoassays. Analytical Methods 2023;15:2154–80. https://doi.org/10.1039/d3ay00182b.
[38] Sanattalab E, Kanarya D, Ebrahimi A, Didarian R, Doğan Güzel F, Yıldırım Tirgil N. Cutting-Edge Applications of Titanium Dioxide in Biosensors. Electroanalysis 2025;37. https://doi.org/10.1002/elan.70049.
[39] Sung M, Oh MJ, Wang T, Ahn J, Oh JH, Stebe KJ, et al. Metal-Oxide-Decorated Mesoporous Silica Chemiresistors for Exhaled Biomarker Detection. ACS Omega 2025;10:15629–36. https://doi.org/10.1021/acsomega.5c00912.
[40] Lôbo GCNB, Silva ALG, Barros-Cordeiro KB, Almeida R das N, Silva IGM da, Sales MP, et al. Copper Oxide Nanorods: Potential Agents against Breast Cancer. ACS Appl Bio Mater 2025;8:4621–32. https://doi.org/10.1021/acsabm.4c01700.Ali A, Ali SR, Hussain R, Anjum R, Liu Q, Elshikh MS, et al. Comparative study of silica and silica-decorated ZnO and ag nanocomposites for antimicrobial and photocatalytic applications. Sci Rep 2025;15. https://doi.org/10.1038/s41598-025-89812-5.
[41] Poonia N, Kumar V, Subudhi RN, Dalabehera M, Setia A, Bora KS, et al. Iron oxide nanoparticles: a versatile nanoplatform for the treatment and diagnosis of ovarian cancer. Ther Deliv 2025;16:379–92. https://doi.org/10.1080/20415990.2024.2442301.
[42] Soomro R, Abdelmonem M, Meli AD, Panhwar M, Che Abdullah CA. A novel plant-based approach for synthesis of iron oxide nanoparticles and cancer therapy. Discover Chemistry 2025;2. https://doi.org/10.1007/s44371-025-00091-5.
[43] Chu H, Liu C, Liu J, Yang J, Li Y, Zhang X. Recent advances and challenges of biosensing in point-of-care molecular diagnosis. Sens Actuators B Chem 2021;348. https://doi.org/10.1016/j.snb.2021.130708.
[44] Bhatia D, Paul S, Acharjee T, Ramachairy SS. Biosensors and their widespread impact on human health. Sensors International 2024;5. https://doi.org/10.1016/j.sintl.2023.100257.
[45] Karami E, Kazemi-Lomedasht F. Biosensors: Types, features, and application in biomedicine. Asian Pac J Trop Biomed 2022;12:367–73. https://doi.org/10.4103/2221-1691.354427.
[46] Wachholz Junior D, Deroco PB, Hryniewicz BM, Tatsuo Kubota L. Strategies for Electrochemical Point-of-Care Biosensors. Annual Review of Analytical Chemistry 2025;24. https://doi.org/10.1146/annurev-anchem-071124.
[47] Song J, Luo Y, Hao Z, Qu M, Huang C, Wang Z, et al. Graphene-based wearable biosensors for point-of-care diagnostics: From surface functionalization to biomarker detection. Mater Today Bio 2025;32. https://doi.org/10.1016/j.mtbio.2025.101667.
[48] Liu D, Wang J, Wu L, Huang Y, Zhang Y, Zhu M, et al. Trends in miniaturized biosensors for point-of-care testing. TrAC - Trends in Analytical Chemistry 2020;122. https://doi.org/10.1016/j.trac.2019.115701.
[49] Wang S, Cui X, Zhong Z, Zhang J. Photoactivatable Aptamer-Based Biosensors for Point-of-Care Testing: Advances and Applications. Biosensors (Basel) 2025;15. https://doi.org/10.3390/bios15060336.
[50] Lakhera P, Chaudhary V, Bhardwaj B, Kumar P, Kumar S. Development and recent advancement in microfluidics for point of care biosensor applications: A review. Biosens Bioelectron X 2022;11. https://doi.org/10.1016/j.biosx.2022.100218.
[51] Parihar M, Niharika WN, Sahana, Biswas R, Dehury B, Mazumder N. Point-of-care biosensors for infectious disease diagnosis: recent updates and prospects. RSC Adv 2025;15:29267–83. https://doi.org/10.1039/d5ra03897a.
[52] Inshyna NM, Chorna I V., Primova LO, Hrebenyk LI, Khyzhnia Y V. Biosensors: Design, classification and application. Journal of Nano- and Electronic Physics 2020;12.

https://doi.org/10.21272/jnep.12(3).03033.

[53] Cetinkaya A, Kaya SI, Ozkan SA. A review of point-of-care (POC) and lab-on-chip (LOC) approaches in molecularly imprinted polymer-based electrochemical sensors for biomedical applications. Anal Chim Acta 2025;1357. https://doi.org/10.1016/j.aca.2025.344080.

[54] Chaturvedi A, Tripathi D, Ranjan R. Nano-enabled biosensors in early detection of plant diseases. Frontiers in Nanotechnology 2025;7. https://doi.org/10.3389/fnano.2025.1545792.

[55] Hemdan M, Abuelhaded K, Shaker AAS, Ashour MM, Abdelaziz MM, Dahab MI, et al. Recent advances in nano-enhanced biosensors: Innovations in design, applications in healthcare, environmental monitoring, and food safety, and emerging research challenges. Sens Biosensing Res 2025;48. https://doi.org/10.1016/j.sbsr.2025.100783.

[56] Eswar K, Yadav DN, Rengan AK. Silica-based nanoparticles in biosensors. Materials and Components of Biosensors in Healthcare: Volume 2, vol. 2, Elsevier; 2025, p. 311–38. https://doi.org/10.1016/B978-0-443-21676-3.00025-X.

[57] Malode SJ, Akhdar H, Alodhayb AN, Shetti NP. Bio-based nanomaterials for smart and sustainable nano-biosensing and therapeutics. Ind Crops Prod 2025;234. https://doi.org/10.1016/j.indcrop.2025.121603.

[58] Gulati S, Yadav R, Kumari V, Nair S, Gupta C, Aishwari M. Nanosensors in healthcare: transforming real-time monitoring and disease management with cutting-edge nanotechnology. RSC Pharmaceutics 2025. https://doi.org/10.1039/d5pm00125k.

[59] Loi S, Michiels S, Adams S, Loibl S, Budczies J, Denkert C, et al. The journey of tumor-infiltrating lymphocytes as a biomarker in breast cancer: clinical utility in an era of checkpoint inhibition. Annals of Oncology 2021;32:1236–44. https://doi.org/10.1016/j.annonc.2021.07.007.

[60] Ogunwobi OO, Mahmood F, Akingboye A. Biomarkers in colorectal cancer: Current research and future prospects. Int J Mol Sci 2020;21:1–20. https://doi.org/10.3390/ijms21155311.

[61] Lopez-Gonzalez L, Sanchez Cendra A, Sanchez Cendra C, Roberts Cervantes ED, Espinosa JC, Pekarek T, et al. Exploring Biomarkers in Breast Cancer: Hallmarks of Diagnosis, Treatment, and Follow-Up in Clinical Practice. Medicina (Lithuania) 2024;60. https://doi.org/10.3390/medicina60010168.

[62] Batra U, Nathany S. Biomarker testing in lung cancer: from bench to bedside. Oncol Rev 2024;18. https://doi.org/10.3389/or.2024.1445826.

[63] Sears CR, Mazzone PJ. Biomarkers in Lung Cancer. Clin Chest Med 2020;41:115–27. https://doi.org/10.1016/j.ccm.2019.10.004.

[64] Das S, Ganguly SC, Bera S, Kundu M. Advance in prostate cancer biomarker discovery: bridging detection, prognosis and therapeutics. Discover Oncology 2025;16. https://doi.org/10.1007/s12672-025-02763-1.

[65] Zhou Y, Tao L, Qiu J, Xu J, Yang X, Zhang Y, et al. Tumor biomarkers for diagnosis, prognosis and targeted therapy. Signal Transduct Target Ther 2024;9. https://doi.org/10.1038/s41392-024-01823-2.

[66] Khomiak A, Brunner M, Kordes M, Lindblad S, Miksch RC, Öhlund D, et al. Recent discoveries of diagnostic, prognostic and predictive biomarkers for pancreatic cancer. Cancers (Basel) 2020;12:1–20. https://doi.org/10.3390/cancers12113234.

[67] Arip M, Tan LF, Jayaraj R, Abdullah M, Rajagopal M, Selvaraja M. Exploration of biomarkers for the diagnosis, treatment and prognosis of cervical cancer: a review. Discover Oncology 2022;13. https://doi.org/10.1007/s12672-022-00551-9.

[68] Mansouri V, Razzaghi M, Nikzamir A, Ahmadzadeh A, Iranshahi M, Haghazali M, et al. Gastroenterology and Hepatology From Bed to Bench. Assessment of liver cancer biomarkers. n.d.

[69] Das S, Dey MK, Devireddy R, Gartia MR. Biomarkers in Cancer Detection, Diagnosis, and Prognosis. Sensors 2024;24. https://doi.org/10.3390/s24010037