ACTA SCIENTIAE

ISSN: 2178-7727
DOI: 10.17648/acta.scientiae.6369

SCALABILITY OF SPCE-BASED BIOSENSORS FOR GLOBAL CANCER SCREENING PROGRAMS

Abhishek Futane[1], Norhashimah Mohd Saad[2], Vigneswaran Narayanamurthy [3,4*], Kok Swee Leong[1]

[1]Advance Sensors and Embedded Systems (ASECs), Center for Telecommunication Research & Innovation (CeTRI), Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Jalan Hang Tuah Jaya, Durian Tunggal, Melaka 76100, Malaysia.
[2]Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka, Malaysia.
[3]Centre of Excellence in MEMS & Microfluidics, Rajalakshmi Engineering College, Chennai 602105, India
[4]Department of Biomedical Engineering, Rajalakshmi Engineering College, Chennai 602105
*Corresponding Author- Vigneswaran Narayanamurthy
Email: vigneswaran.narayanamurthy@rajalakshmi.edu.in

Abstract:

The global rise in cancer incidence underscores the need for scalable, cost-effective, and accessible diagnostic tools for early detection and monitoring. Electrochemical biosensors have come a long way thanks to screen-printed carbon electrodes (SPCEs), which are flexible, inexpensive, and have the potential for mass production. These attributes establish SPCE-based biosensors as a viable technology for global cancer screening initiatives, especially in resource-limited environments. Recent advancements involve the incorporation of nanomaterials, such as gold nanoparticles and carbon nanotubes, to improve sensitivity and specificity. It has been shown that SPCE-based systems can accurately find important cancer biomarkers like HER2, miRNA-21, and PSA. The integration of microfluidics and point-of-care devices highlights their potential for broad implementation. There are still big problems to solve, like making sure that SPCE fabrication is always the same, standardizing surface functionalization protocols, and raising the detection limits for finding biomarkers at very low concentrations. Scalability is further constrained by the necessity for strong multiplexing capabilities and the absence of real-time data integration with digital health platforms. There is a big research gap in how to make screen-printed carbon electrodes (SPCEs) work better for liquid biopsies, especially when it comes to circulating tumor DNA (ctDNA) or exosomes, which are very useful for cancer diagnosis with little harm. The regulatory landscape and the necessity for rigorous clinical validation pose significant challenges to global implementation. This review talks about the current state of SPCE-based biosensors in cancer screening, problems with scalability, and possible future directions. For example, AI could be used to analyze data, and sustainable fabrication techniques could be looked into for mass production that is beneficial for the environment. Addressing these gaps is essential for leveraging SPCE-based biosensors in transformative cancer diagnostics worldwide.

Keywords:

Screen-Printed Carbon Electrodes (SPCEs), Biosensors, Cancer Biomarker Detection, Point-of-Care Diagnostics

1.0 Introduction

The increasing global incidence of cancer requires the creation of diagnostic tools that are both effective and scalable, especially in resource-constrained environments. Conventional diagnostic techniques, including imaging and histopathology, frequently necessitate advanced infrastructure and skilled personnel, thereby constraining their broader implementation (Ahmad et al., 2021). Biosensors, particularly those utilizing screen-printed carbon electrodes (SPCEs), present a viable alternative owing to their cost-effectiveness, portability, and capacity for mass production(Paimard et al., 2023).

SPCEs have been thoroughly investigated for the detection of numerous cancer biomarkers, including proteins such as human mammaglobin (MG), which exhibits high specificity for breast cancer cells (Gajdosova et al., 2020). The incorporation of nanomaterials, including gold nanoparticles and carbon nanotubes, has improved the sensitivity and specificity of these biosensors, facilitating the detection of biomarkers at clinically relevant concentrations (Fritea et al., 2021). The incorporation of gold nanoparticles enhances the electrochemical response of screen-printed carbon electrodes (SPCEs), thereby facilitating the detection of biomarkers such as HER2 and miRNA-21, which are linked to breast cancer progression (Sadeghi et al., 2023). Despite these advancements, various challenges impede the scalability of SPCE-based biosensors for global cancer screening initiatives. Reproducibility in electrode fabrication and the standardization of surface functionalization protocols are essential for achieving consistent performance in large-scale production (Cong and Zhang, 2022). Furthermore, attaining the requisite sensitivity for the detection of biomarkers at ultra-low concentrations presents a considerable challenge. The proposal of integrated micro-total analysis systems (μ-TAS) that unify sample processing and detection on a single platform aims to tackle various challenges, providing a potential solution for point-of-care diagnostics (Tsai et al., 2023). This review presents an overview of recent advancements in SPCE-based biosensors for cancer diagnostics, identifies existing challenges, and discusses future directions to improve their scalability and clinical applicability. Addressing these issues may enable SPCE-based biosensors to serve as essential elements in global cancer screening efforts, especially in environments with limited access to conventional diagnostic resources.

2.0 Advantages of SPCE-Based Biosensors

SPCE-based biosensors offer significant advantages in cancer detection and monitoring, enhancing early diagnosis and treatment outcomes. These biosensors leverage advanced materials and technologies, providing high sensitivity, selectivity, and rapid response times, which are crucial for effective cancer management. SPCE-based biosensors utilize materials like gold and carbon, which enhance their sensitivity to cancer biomarkers, enabling the detection of low-abundance targets such as microRNA-21 and prostate-specific antigen (Mohammadniaei et al., 2019). Biosensors based on SPCE have been successfully used to identify a number of diseases. One example is an electrochemical immunoassay for hypoxia-inducible factor-1α (HIF-1α), a marker linked to tumor growth and metastasis, that used magnetic beads with SPCEs to obtain a detection limit of 76 pg/mL (Deng et al., 2023). An innovative SPCE-based biosensor showed ultrasensitive lncRNA detection capabilities, with a detection limit as low as 0.33 fM. This demonstrates how SPCEs can be used to find nucleic acid biomarkers linked to cancer (Chen et al., 2012). Surface modifications with nanomaterials increase the active surface area, improving sensitivity. Advanced electrochemical techniques, such as cyclic voltammetry and differential

pulse voltammetry, enable precise detection of cancer biomarkers at low concentrations. These biosensors facilitate real-time monitoring of cancer biomarkers, allowing for timely adjustments in treatment strategies(Wasilewski et al., 2024). The ability to detect various cancer types, including breast and cervical cancers, underscores their versatility in clinical applications. SPCE-based biosensors provide swift analysis, often delivering results within minutes, which is advantageous over traditional methods like ELISA or PCR.
SPCE-based biosensors are generally cost-effective and require minimal sample preparation, making them accessible for widespread clinical use. Their compatibility with miniaturized devices enhances their practicality in point-of-care settings (Singh et al., 2023). SPCEs are fabricated using screen-printing technology, which is both economical and scalable, allowing for mass production of disposable sensors suitable for widespread use. The manufacturing process ensures consistent quality across large batches, facilitating the production of customized electrode designs tailored to specific diagnostic needs. SPCEs can be functionalized with a variety of biorecognition elements, including antibodies, aptamers, and enzymes, enabling the detection of diverse cancer biomarkers. The incorporation of nanomaterials, such as gold nanoparticles and carbon nanotubes, further enhances their electrochemical performance. Their compact and lightweight nature makes SPCEs ideal for integration into portable diagnostic devices, facilitating point-of-care testing and real-time data acquisition. The carbon surface of SPCEs allows for straightforward chemical modifications, facilitating the efficient immobilization of biomolecules essential for biosensing applications. The production of SPCEs involves minimal material waste, aligning with eco-friendly manufacturing practices. SPCE arrays can be engineered to detect multiple biomarkers simultaneously, enabling comprehensive cancer profiling in a single assay. Requiring only microliter-scale sample volumes, SPCE-based biosensors are suitable for applications where sample availability is limited. The flexibility and miniaturization of SPCEs support their integration into wearable or implantable biosensors for continuous monitoring of cancer biomarkers.

Table No 1. Advantages of SPCE Biosensor in Cancer

Advantage	**Description**
Cost-Effectiveness	Low-cost, disposable electrodes suitable for large-scale production and use.
Scalability	Consistent, high-volume manufacturing with customizable designs.
Versatility	Compatible with various biorecognition elements and nanomaterials.
Portability	Compact and lightweight, ideal for point-of-care devices.
High Sensitivity and Specificity	Enhanced by surface modification with nanomaterials and advanced electrochemical techniques.
Rapid Detection	Fast analysis with results in minutes.

Ease of Functionalization	Carbon surface allows efficient immobilization of biomolecules.
Environmental Compatibility	Eco-friendly production processes with minimal waste.
Multiplexing	Capable of detecting multiple biomarkers simultaneously.
Minimal Sample Volume	Requires only microliters of sample, ideal for limited availability.
Potential for Wearables	Flexible design supports integration into wearable or implantable devices.

3.0 Scalability Considerations

To guarantee reliable performance, affordability, and broad accessibility, a number of crucial issues must be resolved before expanding the use of screen-printed carbon electrode (SPCE)-based biosensors for cancer screening worldwide. Because differences in the quality of the electrode material and printing accuracy might affect sensitivity and specificity, manufacturing consistency is still a significant concern. To solve this problem, sophisticated methods like automated quality control systems and roll-to-roll printing are crucial (Hosseine et al., 2024). Furthermore, even though SPCEs are naturally inexpensive, production costs may increase if nanomaterials like gold nanoparticles and functionalization procedures for certain biomarkers are included. These financial obstacles can be lessened by investigating substitute materials and scalable production techniques, such as hydrogel-based biosensors (Sun and Chen, 2024). Another challenge is functionalization scalability, since standardizing procedures for various cancer indicators is still difficult. A potential remedy is the creation of universal or flexible surface modification techniques, like bead-based biosensors (Cheng et al., 2024). Additionally, for real-time data monitoring and worldwide healthcare networking, SPCE-based biosensor integration with digital health systems is essential. This integration can be made easier by integrating wireless communication technologies and making sure they work with digital systems(Iannazzo et al., 2021, p. 0). Scalability is also significantly impacted by regulatory issues because several international frameworks require thorough clinical validations. Clinical efficacy can be demonstrated and the approval process streamlined through early involvement with regulatory agencies and multicenter trials (Hosseine et al., 2024). Lastly, multiplexing capabilities are crucial for thorough cancer screening; yet, it is still difficult to create sensors that can detect many biomarkers with precision. This need can be met by developments in multiplexing methods, such as multi-electrode arrays (MDPI, 2023). Leveraging SPCE-based biosensors for scalable, affordable, and accessible worldwide cancer screening programs requires addressing these factors through technological innovation, strategic partnerships, and sustainable practices (Ozer and Henry, 2021).

4.0 Future Prospects

The future potential of SPCE-based biosensors in worldwide cancer screening is optimistic, propelled by ongoing technological developments and integration with developing disciplines. Using both artificial intelligence (AI) and machine learning (ML) together for real-time data analysis and pattern recognition is a trend that stands out. This makes it easier to quickly and accurately interpret biomarker signals. This can improve early cancer identification and surveillance, especially in resource-limited environments. Furthermore, progress in nanomaterial engineering, such as the use of quantum dots and different types of graphene, is expected to make SPCE-based biosensors more sensitive and specific, allowing them to find biomarkers even at very low concentrations. The development of SPCE-based biosensors that are flexible and wearable opens the door to non-invasive and continuous monitoring of cancer, which improves personalized healthcare. Adding microfluidics and point-of-care systems will make it easier to manage samples and make the devices smaller, which makes these biosensors perfect for home diagnostics. Implementing sustainable manufacturing methods, including the utilization of biodegradable materials, will mitigate environmental issues while facilitating mass production. Using blockchain and cloud technology can also make sure that health data is exchanged securely, interoperable, and in real time across global digital health networks, which encourages widespread use. Nonetheless, overcoming obstacles like regulatory permissions, clinical validation, and multiplexing capabilities is essential for their deployment. Through ongoing research and collaborations between different fields, SPCE-based biosensors will revolutionize the way cancer is diagnosed around the world by providing scalable, cost-effective, and easy-to-use options for early detection and monitoring.

5.0 Conclusion

SPCE-based biosensors have the potential to completely change the way cancer is screened around the world by making early detection and monitoring options that are scalable, affordable, and easy to get to. Due to their inherent benefits, such as being cost-effective, flexible, and compatible with large-scale production, they are ideal for use in places with limited resources. Nanomaterials, microfluidics, and digital health technologies have recently made big steps forward in how sensitive, specific, and useful they are. This makes it easier to use them in point-of-care devices and personalized healthcare. Nonetheless, obstacles such as attaining uniform fabrication, standardizing functionalization procedures, and enhancing multiplexing capabilities must be resolved to facilitate wider use. Moreover, surmounting legislative obstacles and establishing clinical reliability are essential for worldwide deployment. Future projects should focus on using AI to analyze data, looking into sustainable and scalable ways to make things, and encouraging people from different fields to work together to fix current research gaps. By fixing these issues and using new developments, SPCE-based biosensors could become a revolutionary tool for finding cancer, making screening programs around the world more fair and effective.

6.0 Acknowledgement

The Author would like to thank and acknowledge the financial support from **Universiti Teknikal Malaysia Melaka (UTeM) Zamalah Scheme.**

7.0 Conflict of interest

The Authors have no conflicts of interest in this manuscript.

8.0 Data availability statement

There is no data for this review.

9.0 Ethics statement

None.

10.0 Informed consent

None.

11.0 References

Ahmad, Z., Rahim, S., Zubair, M., Abdul-Ghafar, J., 2021. Artificial intelligence (AI) in medicine, current applications and future role with special emphasis on its potential and promise in pathology: present and future impact, obstacles including costs and acceptance among pathologists, practical and philosophical considerations. A comprehensive review. Diagn Pathol 16, 24. https://doi.org/10.1186/s13000-021-01085-4

Chen, C., Zhao, J., Jiang, J., Yu, R., 2012. A novel exonuclease III-aided amplification assay for lysozyme based on graphene oxide platform. Talanta 101, 357–361. https://doi.org/10.1016/j.talanta.2012.09.041

Cheng, H.-P., Yang, T.-H., Wang, J.-C., Chuang, H.-S., 2024. Recent Trends and Innovations in Bead-Based Biosensors for Cancer Detection. Sensors 24, 2904. https://doi.org/10.3390/s24092904

Cong, H., Zhang, N., 2022. Perspectives in translating microfluidic devices from laboratory prototyping into scale-up production. Biomicrofluidics 16, 021301. https://doi.org/10.1063/5.0079045

Deng, Y., Zhang, Y., Zhou, M., Wu, B., Zhou, J., 2023. Application of Biosensors in Detecting Breast Cancer Metastasis. Sensors 23, 8813. https://doi.org/10.3390/s23218813

Fritea, L., Banica, F., Costea, T., Moldovan, L., Dobjanschi, L., Muresan, M., Cavalu, S., 2021. Metal Nanoparticles and Carbon-Based Nanomaterials for Improved Performances of Electrochemical (Bio)Sensors with Biomedical Applications. Materials 14, 6319. https://doi.org/10.3390/ma14216319

Gajdosova, V., Lorencova, L., Kasak, P., Tkac, J., 2020. Electrochemical Nanobiosensors for Detection of Breast Cancer Biomarkers. Sensors 20, 4022. https://doi.org/10.3390/s20144022

Hosseine, M., Naghib, S.M., Khodadadi, A., 2024. Label-free electrochemical biosensor based on green-synthesized reduced graphene oxide/Fe3O4/nafion/polyaniline for ultrasensitive detection of SKBR3 cell line of HER2 breast cancer biomarker. Sci Rep 14, 11928. https://doi.org/10.1038/s41598-024-62231-8

Iannazzo, D., Espro, C., Celesti, C., Ferlazzo, A., Neri, G., 2021. Smart Biosensors for Cancer Diagnosis Based on Graphene Quantum Dots. Cancers (Basel) 13, 3194. https://doi.org/10.3390/cancers13133194

Mohammadniaei, M., Nguyen, H.V., Tieu, M.V., Lee, M.-H., 2019. 2D Materials in Development of Electrochemical Point-of-Care Cancer Screening Devices. Micromachines 10, 662. https://doi.org/10.3390/mi10100662

Ozer, T., Henry, C.S., 2021. Review—Recent Advances in Sensor Arrays for the Simultaneous Electrochemical Detection of Multiple Analytes. J. Electrochem. Soc. 168, 057507. https://doi.org/10.1149/1945-7111/abfc9f

Paimard, G., Ghasali, E., Baeza, M., 2023. Screen-Printed Electrodes: Fabrication, Modification, and Biosensing Applications. Chemosensors 11, 113. https://doi.org/10.3390/chemosensors11020113

Sadeghi, M., Sadeghi, S., Naghib, S.M., Garshasbi, H.R., 2023. A Comprehensive Review on Electrochemical Nano Biosensors for Precise Detection of Blood-Based Oncomarkers in Breast Cancer. Biosensors 13, 481. https://doi.org/10.3390/bios13040481

Singh, S., Podder, P.S., Russo, M., Henry, C., Cinti, S., 2023. Tailored point-of-care biosensors for liquid biopsy in the field of oncology. Lab Chip 23, 44–61. https://doi.org/10.1039/D2LC00666A

Sun, S., Chen, J., 2024. Recent Advances in Hydrogel-Based Biosensors for Cancer Detection. ACS Appl Mater Interfaces 16, 46988–47002. https://doi.org/10.1021/acsami.4c02317

Tsai, H.-F., Podder, S., Chen, P.-Y., 2023. Microsystem Advances through Integration with Artificial Intelligence. Micromachines 14, 826. https://doi.org/10.3390/mi14040826

Wasilewski, T., Kamysz, W., Gębicki, J., 2024. AI-Assisted Detection of Biomarkers by Sensors and Biosensors for Early Diagnosis and Monitoring. Biosensors 14, 356. https://doi.org/10.3390/bios14070356