

REVIEW ARTICLE

Advancements in Sensor Technologies for Forensic Toxicology: Enlightens the Way for Future Toxic Detection

Suman Sangwan¹, Jasbir Lather², Sitaram³, Jyoti Malik⁴,
Diksha Thakur⁵, Madhup Singh⁶, Rinku⁷, Ajay Kumar⁸

HOW TO CITE THIS ARTICLE:

Suman Sangwan, Jasbir Lather, Sitaram et. al, Advancements in Sensor Technologies for Forensic Toxicology: Enlightens the Way for Future Toxic Detection. J Forensic Chemistry Toxicol. 2025; 11(1): 50-56.

ABSTRACT

The evolution of sensor technologies has significantly impacted forensic toxicology, offers more efficient, sensitive, and precise means of detecting toxic substances in biological samples. This review critically examines the recent advancements in sensor techniques employed in forensic toxicology, focusing on their potential to improve the detection and identification of toxins, drugs, poisons, and other harmful substances in forensic investigations. From electrochemical sensors and biosensors to optical and mass spectrometric techniques, sensor-based technologies are enhancing the speed, accuracy, and accessibility of toxicological testing. This critical review paper explores the benefits, limitations, and future directions of these advanced sensor systems, highlighting their role in simplifying and accelerating toxicological analyses in both clinical and criminal investigations.

KEYWORDS:

• Forensic Toxicology • Sensors • Diagnosis

INTRODUCTION

Forensic toxicology plays an essential role in determining the cause of death, poisoning, and drug-related crimes. Traditional methods for detecting toxic substances, such

as chromatographic techniques and mass spectrometry, are effective but often require complex, time-consuming processes and expensive equipment. In contrast, sensor technologies offer an attractive alternative,

AUTHOR'S AFFILIATION:

¹ Senior Scientific officer, Toxicology Division, Regional Forensic Science Laboratory, Hisar 125001, Haryana, India.

² Scientific Assistant, Toxicology Division, Regional Forensic Science Laboratory, Hisar 125001, Haryana, India.

³ SSO, Toxicology Division, Haryana Forensic Science Laboratory, Madhuban 132037, Karnal, Haryana, India.

⁴ SSO, Toxicology Division, Haryana Forensic Science Laboratory, Madhuban 132037, Karnal, Haryana, India.

⁵ SSO, NDPS Division, Haryana Forensic Science Laboratory, Madhuban 132037, Karnal, Haryana, India.

⁶ Scientific Assistant, Toxicology Division, Regional Forensic Science Laboratory, Hisar 125001, Haryana, India.

⁷ Laboratory Assistant, Toxicology Division, Regional Forensic Science Laboratory, Hisar 125001, Haryana, India.

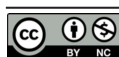
⁸ Deputy Director cum Incharge of Lab, Regional Forensic Science Laboratory, Hisar 125001, Haryana, India.

CORRESPONDING AUTHOR:

Suman Sangwan, Senior Scientific officer, Toxicology Division, Regional Forensic Science Laboratory, Hisar 125001, Haryana, India.

E-mail: drsumanhfsl@gmail.com

➤ Received: 09-05-2025 ➤ Accepted: 12-06-2025



Creative commons non-commercial CC BY-NC: This article is distributed under the terms of the creative commons attribution non-commercial 4.0 License (<http://www.creativecommons.org/licenses/by-nc/4.0/>) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the Red Flower Publication and Open Access pages (<https://rfppl.co.in>)

providing rapid, cost-effective, and non-invasive means of detecting and quantifying toxic substances in various biological samples.

With the increasing prevalence of biosensors, their practical utility and applications have expanded significantly. Given the growing threat of drug abuse to both human health and societal well-being, there is an urgent need for rapid, portable, and highly sensitive drug detection technologies capable of analyzing common biological samples. Despite advancements in the realistic assessment of drug classes and their constituents, the real-world implementation of these technologies faces several challenges. In forensic investigations and medical research, the demand for precise and accurate drug and toxicity analyses has become more critical, with drug poisoning fatalities serving as a pertinent example (Kumar *et al*; 2023 and Gao; 2024).

Recent advancements in sensor technology have led to more sophisticated, sensitive, and portable detection systems, which hold promise for the future of forensic toxicology (Parra *et al*; 2020 and Dhawan *et al*; 2021). These advancements aim to reduce the reliance on traditional laboratory-based techniques, enabling faster and more accurate results, and facilitating the detection of a broader range of toxins, including emerging or unknown substances.

Toxins derived from both animal and plant sources, including snake venoms, spider toxins, plant cyanides, thioglucosides, as well as mycotoxins such as aflatoxins and fumonisins, alongside pesticides and veterinary pharmaceuticals, have become critical focal points in the medical and forensic sciences for the effective detection of these hazardous substances (Khan *et al*; 2024 and Britzi *et al*; 2013). The identification and quantification of such toxins hold paramount importance across legal, medical, and emergency response sectors. Over recent decades, chemical and instrumental analytical techniques have undergone significant advancements, establishing themselves as indispensable tools in forensic toxicology. These methodologies now serve as the cornerstone for the precise identification and quantification of drugs, their metabolites, and other toxic compounds in biological matrices.

Common instrumental analytical methods include presumptive tests, such as colorimetric

assays and thin-layer chromatography (TLC), as well as confirmatory tests like gas chromatography-mass spectrometry (GC-MS) and array biosensors. Presumptive tests are used for preliminary identification of toxins, while confirmatory tests like GC-MS provide definitive analysis to determine the specific poisons ingested by the victim. Array biosensors also play a crucial role in the rapid and efficient detection of toxic substances (Ligler *et al*; 2003).

In contrast, biosensors offer significant advantages over these traditional methods. They are portable, cost-effective, and capable of providing real-time results with high sensitivity and specificity. Biosensors can be designed to detect a wide range of toxic substances at low concentrations, making them ideal for point-of-care applications in forensic and medical settings. Moreover, they can be integrated into handheld devices, allowing for rapid detection without the need for extensive sample preparation or complex instrumentation. Recent advancements in biosensor technology have further enhanced their accuracy and reliability, positioning them as promising tools for the future of toxicological analysis (López *et al*., 2020; Kumar *et al*., 2019).

This review emphasizing the current state of sensor technologies in forensic toxicology, including electrochemical sensors, biosensors, optical sensors, strip based and mass spectrometry-based sensors, and also discuss their implications for future toxicological analysis. Fig. 1 below provides a visual insight into the key concepts explored in the following sections of this paper, offering a comprehensive overview of the advancements in forensic toxicology.

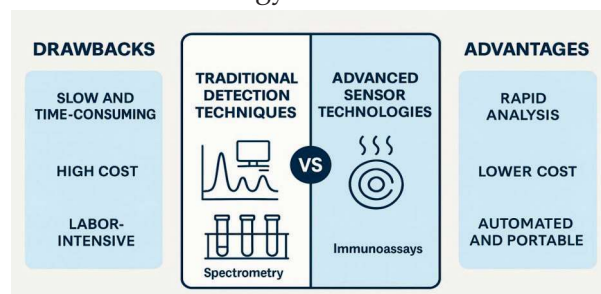


Fig. 1: Showing the evolution of Forensic Toxicology along with advancements and scientific challenges

ADVANCEMENT OF SENSORS IN FORENSIC TOXICOLOGY TO TOXIC MOITIES

Forensic toxicology relies on various sensor technologies to detect and quantify toxic substances in biological and environmental samples. These sensors function by converting chemical or biological interactions into measurable signals, ensuring accurate and rapid detection of poison analytes. The given

figure 2 summarizes the principal categories of sensors employed in forensic toxicology include electrochemical sensors, biosensors, optical sensors, and mass spectrometry-based sensors, each offering distinct advantages in terms of sensitivity, specificity, and applicability.

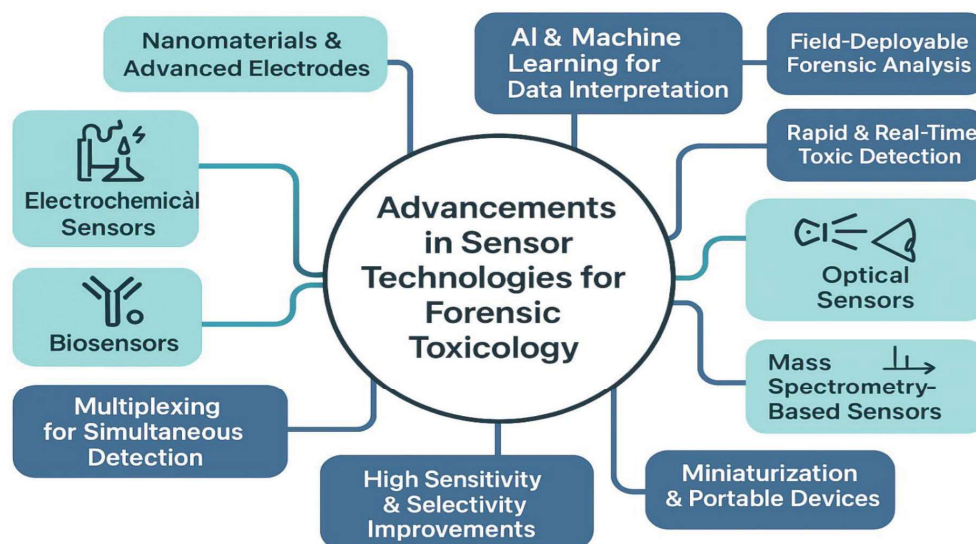


Fig. 2: summarizes the advancement of the sensor techniques in the rapid detection in the forensic toxicology

Electrochemical sensors have gained prominence in forensic toxicology due to their high sensitivity, rapid response time, portability, and cost-effectiveness. These sensors operate by detecting variations in electrical properties, such as current or potential, upon interaction with toxic substances. Their primary applications include the detection of alcohol, drugs of abuse (e.g., cocaine, opiates), and poisons such as cyanide in biological samples like blood, urine, and saliva. However, challenges such as limited selectivity and potential interference from complex biological matrices necessitate ongoing advancements. The integration of nanomaterials and carbon based electrodes has significantly enhanced their performance and specificity (Wang, 2005; Arduini *et al.*, 2017). Various methodologies for transducing the resulting biological events are evaluated, with a critical discussion of their applications in forensic toxicological analysis classified based on the nature of the target analytes as well as in the detection of chemical and biological warfare agents (Yanez-sedeno *et al.* 2014).

Biosensors, employing biological recognition elements such as enzymes, antibodies, and genetically engineered molecules, offer high specificity in toxin detection. These sensors have been widely utilized for identifying drugs, poisons, and their metabolites in forensic toxicology. Enzyme-based biosensors are particularly effective in detecting organophosphate pesticides, while antibody-based biosensors facilitate the detection of substances like amphetamines and cocaine. Despite their specificity, challenges such as the stability of biological elements and their limited detection range pose significant concerns. However, advancements in biosensor technology continue to improve their stability and multiplexing capabilities, enabling simultaneous detection of multiple analytes (Turner, 2013; Bahadir & Sezgintürk, 2015).

Optical sensors utilize changes in optical properties, such as fluorescence, absorption, and scattering, to detect toxic substances. Techniques such as surface plasmon resonance (SPR), fluorescence spectroscopy, and fiber-

optic sensors have been instrumental in forensic investigations. These sensors provide non-destructive, highly sensitive, and field-deployable solutions for toxin detection. Their applications include the identification of drug metabolites, pesticides, and environmental toxins. However, their susceptibility to environmental conditions, such as light intensity and temperature variations, as well as the complexity of data interpretation, remains key challenges (Fan *et al.*, 2008; Xu *et al.*, 2019).

Mass spectrometry (MS)-based sensors represent a gold standard in forensic toxicology due to their unparalleled sensitivity and specificity. These sensors detect and quantify toxic substances by analyzing their mass-

to-charge ratios. The advent of portable and miniaturized MS-based sensors has expanded their utility for on-site forensic analysis (Zu *et al.*; 2021 and Ryan & Smith 2018). They have been extensively used to identify drugs of abuse, poisons, alcohol, and environmental contaminants, particularly in post-mortem toxicological investigations. However, their high cost, complexity, and the requirement for skilled personnel limit their widespread field applications (Smith, 2004; Figueiredo *et al.*, 2016). Table 1, given below summarizes the applications of the discussed sensors and unveiling the ideal role of sensor technology in the scientific inventions.

Table 1: Advanced Applications of Sensors in Forensic Toxicology

Sensor Type	Application in Forensic Toxicology	Advantages	Reference
Electrochemical Sensors	Detection of drugs of abuse (e.g., cocaine, opiates) in biological fluids	High sensitivity, portable, cost-effective	[Wang; 2005]
Biosensors	Identification of organophosphate pesticides and illicit drugs and viscera	High specificity, real-time analysis, multiplexing	[Bahadir & Sezgentürk, 2015]
Optical Sensors	Fluorescence-based detection of toxins in blood and urine	Non-invasive, high sensitivity, miniaturization	[Xu <i>et al.</i> , 2019]
Mass Spectrometry-Based Sensors	Identification of emerging drugs and poisons in post-mortem analysis	High specificity, trace-level detection, high throughput	[Figueiredo <i>et al.</i> , 2016]
Nanomaterials-Based Sensors	Rapid field detection of heavy metals and toxins in forensic samples	Enhanced sensitivity, selectivity, and stability	[Ullah <i>et al.</i> ; 2024]
AI-Integrated Sensors	Smart forensic toxicology tools for automated data interpretation	Improved accuracy, pattern recognition, rapid analysis	[Borkowska, & Kowalska, 2022]

Despite the challenges associated with each sensor type, continuous advancements in material science, nanotechnology, and analytical methodologies are driving the development of more robust, selective, and portable forensic toxicology sensors. The integration of novel materials and hybrid sensing technologies holds great promise for enhancing forensic investigations, enabling real-time and on-site toxicological assessments with improved accuracy and reliability.

ADVANTAGES OF SENSOR TECHNOLOGIES IN FORENSIC TOXICOLOGY

Sensor technologies in forensic toxicology provide significant advantages, particularly in terms of speed, portability, cost-effectiveness,

and multiplexing capabilities. These attributes have made them indispensable tools for forensic investigations, enabling rapid and accurate toxicological assessments in various scenarios. One of the primary advantages of sensors is their ability to deliver real-time results, reducing the time required for analysis and allowing forensic experts to make timely decisions. Unlike conventional laboratory-based techniques such as chromatography and spectrophotometry, which often require extensive sample preparation and prolonged processing times, sensor-based detection offers immediate and actionable insights. This rapid detection capability is particularly crucial in forensic cases involving drug abuse, poisoning, and post-mortem toxicology, where time-sensitive evidence can be critical (Wang, 2005; Arduini *et al.*, 2017).

The portability of sensor technologies further enhances their utility in forensic applications, allowing toxicological analyses to be conducted directly at crime scenes, accident sites, or emergency settings. Portable biosensors, electrochemical sensors, and miniaturized mass spectrometry devices provide on-site testing capabilities, reducing the dependency on centralized laboratories and expediting forensic workflows. This portability is particularly beneficial in remote or resource-limited areas, where access to sophisticated laboratory facilities may be restricted. Moreover, the ability to conduct field-based toxicological testing can support law enforcement agencies in roadside drug testing, workplace substance monitoring, and emergency medical interventions (Turner, 2013; Bahadir & Sezgintürk, 2015).

Cost-effectiveness is another notable advantage of sensor technologies in forensic toxicology. Traditional analytical techniques, while highly accurate, often require expensive instrumentation, trained personnel, and time-intensive procedures. In contrast, sensors offer a more economical alternative, minimizing operational costs while maintaining high analytical performance. The lower cost of sensor-based detection enables broader adoption across forensic and medical institutions, facilitating routine toxicological screening and large-scale substance monitoring programs. This affordability also makes sensor technologies accessible in developing regions, where forensic infrastructure may be limited (Fan *et al.*, 2008; Xu *et al.*, 2019).

Advanced sensor systems also possess multiplexing capabilities, enabling the simultaneous detection of multiple toxicants within a single analysis. This multi-analyte detection significantly enhances the efficiency of forensic investigations by providing comprehensive toxicological profiles in a single test, reducing the need for multiple assays. Multiplexed biosensors, for instance, can concurrently detect a range of drugs of abuse, poisons, and metabolites in biological fluids, improving diagnostic accuracy and streamlining forensic procedures. The integration of nanotechnology, micro fluidics, and artificial intelligence has further enhanced the sensitivity and specificity of multiplexed sensors, ensuring precise identification of toxicants even at trace levels (Smith, 2004; Figueiredo *et al.*, 2016).

Ethically, the use of sensor technologies in forensic toxicology aligns with the principles of justice, accuracy, and non-invasive evidence collection. Rapid and reliable toxicological assessments help ensure fair legal proceedings by providing objective, scientifically validated data. Additionally, non-invasive sensor-based methods, such as saliva or breath analysis, reduce the need for intrusive sample collection techniques, improving compliance and ethical acceptability in forensic investigations. The give Fig. 3 showing the advantages of sensor technologies continue to evolve, their role in forensic toxicology will expand, further enhancing the accuracy, efficiency, and accessibility of toxicological assessments in various legal, medical, and investigative contexts.

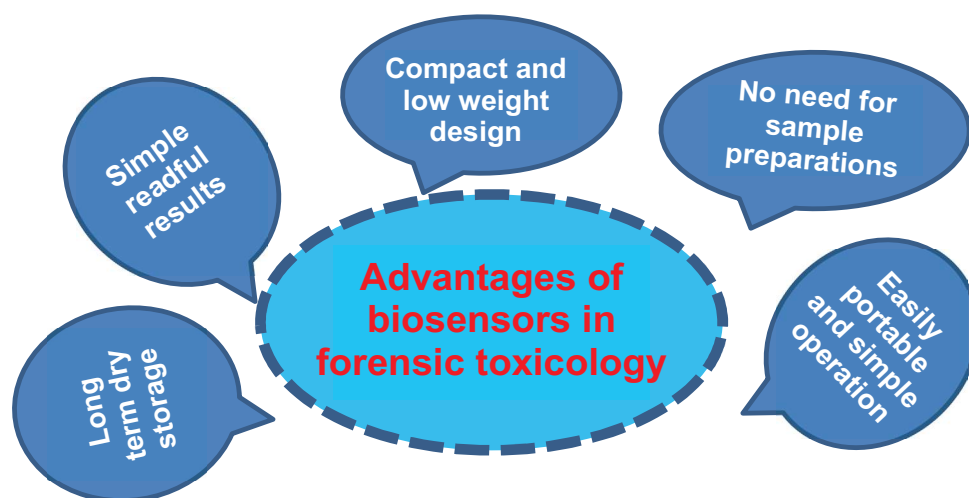


Fig. 3: Illustrates the advantages of sensor technology in forensic toxicology

CHALLENGES AND FUTURE PROSPECTIVE

Despite their numerous advantages, sensor technologies in forensic toxicology face certain limitations that must be addressed to enhance their reliability and applicability. One of the primary challenges is related to sensitivity and specificity. While sensors are designed to provide rapid and cost-effective toxicological assessments, they may not always achieve the level of sensitivity and specificity required for accurate toxin identification, particularly in complex biological samples such as blood, urine, or tissues. Interference from other substances present in these matrices can lead to false positives or false negatives, potentially compromising forensic investigations. The need for highly selective recognition elements, such as advanced nanomaterials or engineered biomolecules, is critical to improving sensor performance and ensuring precise toxin detection.

The future of sensor-based toxicological analysis in forensic science is poised for significant advancements with the integration of emerging technologies. The miniaturization of sensor technologies, facilitating the development of portable, point-of-care diagnostic tools for forensic toxicology. The advent of compact, field-deployable sensors could enable rapid on-site detection of toxins, particularly in remote or resource-limited settings where access to sophisticated laboratory equipment is restricted. Such advancements would not only expedite forensic investigations but also improve the accessibility and efficiency of toxicological screening in emergency situations. By addressing current limitations and integrating cutting-edge innovations, sensor-based technologies have the potential to revolutionize forensic toxicology, making toxic substance detection faster, more accurate, and more widely accessible. One of the most promising developments is the incorporation of artificial intelligence (AI) to enhance the analytical capabilities of sensors. AI-driven algorithms can process complex datasets, identify subtle patterns, and improve the accuracy of toxicological assessments, enabling more reliable and automated detection of toxins. By leveraging machine learning models, forensic scientists can refine sensor outputs, reduce false positives, and improve decision-making in forensic investigations.

CONCLUSION

The challenges associated with instrumental analysis methods currently employed in both crime scene investigations and laboratory-based forensic testing has highlighted the need for innovative techniques. These emerging approaches must offer rapid, highly sensitive, and specific detection of forensic analytes, ultimately enhancing the reliability and efficiency of toxicological assessments in forensic science. Sensor technologies have the potential to revolutionize forensic toxicology by offering faster, more efficient, and portable means of detecting a wide range of toxic substances. While challenges remain in terms of sensitivity, specificity, and regulatory acceptance, the advancements in sensor technology continue to improve, making them an increasingly valuable tool for forensic professionals. With ongoing research and development, sensors are poised to play a critical role in the future of toxicological analysis, simplifying the detection process and enabling more accurate and timely results in forensic investigations.

REFERENCES

1. Arduini, F., *et al.* (2017). Electrochemical sensors as an innovative approach for clinical and forensic toxicology. *Trends in Analytical Chemistry*, 97, 179-190.
2. Bahadir, E. B., & Sezgintürk, M. K. (2015). Applications of electrochemical biosensors to pharmaceuticals. *Analytical Biochemistry*, 478, 107-120.
3. Borkowska, E., & Kowalska, T. (2022). "AI-Powered Toxicological Screening: A New Era in Forensic Investigations." *Forensic Science International*, 314, 110380.
4. Britzi, M., Friedman, S., Miron, J., Solomon, R., Cuneah, O., Shimshoni, J. A., ... & Shlosberg, A. (2013). Carry-over of aflatoxin B1 to aflatoxin M1 in high yielding Israeli cows in mid-and late-lactation. *Toxins*, 5(1), 173-183.
5. Dhawan, D., & Garg, A. (2021). "Biosensors for Detection of Toxicological Agents in Forensic Investigations." *Sensors and Actuators B: Chemical*, 329, 129089.
6. Fan, X., *et al.* (2008). Sensitive optical biosensors for unlabeled targets: A review. *Analytica Chimica Acta*, 620(1-2), 8-26.
7. Figueiredo, R., *et al.* (2016). Advances in mass spectrometry for forensic toxicology. *Trends in Analytical Chemistry*, 85, 1-10.

8. Gao, A. (2024). Advances in biosensors for poison detection applications. In E3S Web of Conferences (Vol. 553, p. 05002). EDP Sciences.
9. Johnson, P. E., & Miller, M. R. (2020). "Mass Spectrometry in Forensic Toxicology: Recent Advances in Sensor Applications." *Forensic Science International*, 317, 110514.
10. Khan, R., Anwar, F., & Ghazali, F. M. (2024). A comprehensive review of mycotoxins: Toxicology, detection, and effective mitigation approaches. *Heliyon*.
11. Kumar R., Sheikh N., Bashir M., Vasudeva A., Kumar A., Yadav A., *et al.* (2023). *Journal of Family Medicine and Primary Care*. J. 12, 70.
12. Kumar, V., *et al.* (2019). "Biosensors in forensic toxicology: Current status and future trends." *Analytical and Bioanalytical Chemistry*.
13. Ligler F. S., Taitt C. R., Shriver-Lake L. C., Sapsford K. E., Shubin Y. S., Golden J. P. (2003). *Analytical and Bioanalytical Chemistry*. J. 377, 469.
14. López, M., *et al.* (2020). "Advances in biosensor technologies for toxin detection." *Journal of Toxicology*.
15. Parra, M., *et al.* (2020). "Recent Advances in Electrochemical Sensors for Forensic Toxicology Applications." *Trends in Analytical Chemistry*, 123, 115-123.
16. Ryan, M. A., & Smith, S. P. (2018). "Integrating AI and Mass Spectrometry in Forensic Toxicology." *Journal of Forensic Toxicology*, 36(5), 204-210.
17. Smith, R. D. (2004). Advances in mass spectrometry instrumentation. *Annual Review of Analytical Chemistry*, 1(1), 349-378.
18. Turner, A. P. F. (2013). Biosensors: Sense and sensibility. *Chemical Society Reviews*, 42(8), 3184-3196.
19. Ullah, M. F., Khan, Y., Khan, M. I., Abdullaeva, B. S., & Waqas, M. (2024). Exploring nanotechnology in forensic investigations: Techniques, innovations, and future prospects. *Sensing and Bio-Sensing Research*, 100674.
20. Wang, J. (2005). Electrochemical biosensors: Towards point-of-care cancer diagnostics. *Biosensors and Bioelectronics*, 21(10), 1887-1892.
21. Xu, X., *et al.* (2019). Advances in fluorescence-based biosensors for food safety detection. *Trends in Food Science & Technology*, 91, 240-252.
22. Yáñez-Sedeño, P., Agüí, L., Villalonga, R., & Pingarrón, J. M. (2014). Biosensors in forensic analysis. A review. *Analytica chimica acta*, 823, 1-19.
23. Yang, L., *et al.* (2022). "Optical Sensing in Forensic Toxicology: A Review." *Journal of Forensic Sciences*, 67(2), 578-591.
24. Zhang, Y., *et al.* (2019). "Advances in Portable Sensors for Toxicological Analysis in Forensic Investigations." *Sensors*, 19(24), 5478.
25. Zhu, Z., *et al.* (2021). "Deep Learning in Mass Spectrometry for Forensic Toxicology." *Nature Biotechnology*, 39(8), 1052-1060.