Nanotechnology Enhanced Forensic Chemistry: Revolutionizing Trace Evidence Detection and Toxicological Analysis

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Abstract

By allowing the ultra-sensitive, quick, and portable identification of trace evidence from explosives and illegal narcotics to poisons and latent biomarkers nanotechnology is revolutionizing forensic science. This study examines the analytical performance, field deployability, and legal acceptability of current (2023–2025) developments in nanomaterial-based sensors, including surface-enhanced Raman substrates, quantum-dot biosensors, graphene and MoS_2 nanosheets, and noble-metal nanoparticles. Limits of detection (LOD) now frequently approach sub-nanomolar levels, a 10^2–10^4-fold improvement over traditional techniques, according to comparative study (Table 1; Figures 1-2). Matrix interference, nanotoxicology, and standardization are the remaining issues we address. We also suggest future options, including AI-assisted spectrum interprettation and environmentally friendly, cadmium-free quantum dots.

Keywords

Nan forensics; surface enhanced Raman spectroscopy (SERS); quantum dots; graphene; trace evidence; toxicology; biosensors

1 Introduction

Techniques that can detect picogram-to-femtogram amounts of analytes in complicated, frequently degraded circumstances are essential for forensic research. Conventional spectroscopic and chromatographic techniques only partially address this issue. Nanomaterials provide potent new tools for pre-concentration, signal amplification, and selective identification because of their high surface-area-to-volume ratios, easily programmable electronic/optical characteristics, and simple surface functionalization. The transition from lab demonstrations to courtroom-ready methods is documented by recent reviews and case studies:

SERS substrates based on silver or gold nanostructures deliver single-molecule sensitivity for illicit drug residues and explosive particulates (1).

Microfluidics and electrochemical transduction are used in graphene-derived sensors to enable on-site TNT testing at ≤50 nM (2).
With LODs < 1 µM, quantum-dot (QD) chemodosimeters can detect biothiol in blood serum with the naked eye (3).
Hybrid nano-sorbents improve the visibility of latent fingerprints on rough polymeric or metallic surfaces (4).

Together, these advances herald a paradigm shift toward real-time, minimally invasive forensic analytics.

2 Current Performance Landscape

Figure 1 visualizes the logarithmic spread of these detection limits

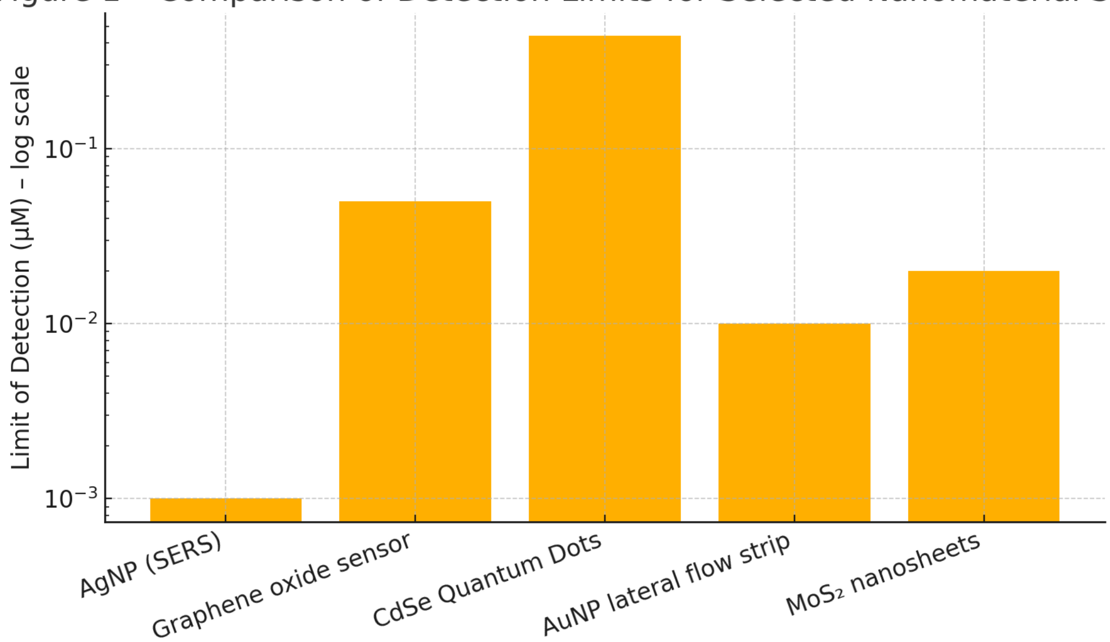
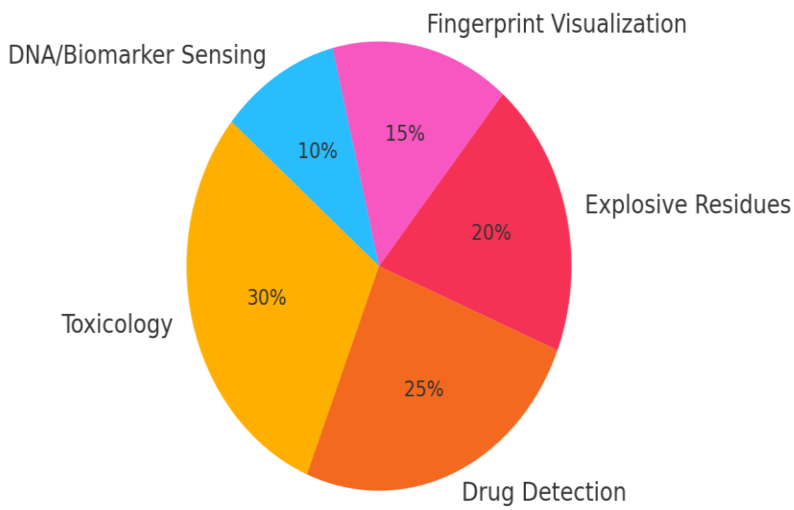


Figure 1 – Comparison of Detection Limits for Selected Nanomaterial Sensors

Figure 2 shows the relative share of application domains in recent literature

Figure 2 – Current Distribution of Nanotechnology Applications in Forensic Chemistry



3 Discussion

Focus area	Key advantages	Persistent hurdles	Emerging solutions
Drug & toxin screening	pM-to-nM sensitivity; portable readers	Matrix suppression; need for reference standards	AI-driven spectral deconvolution; machine-learning calibration models
Explosive residues	Rapid swab-to-result (<60 s); multiplexed panels	Environmental contaminants; weathering effects	Hierarchical plasmonic arrays; hydrophobic coatings
Latent prints	Multi-surface compatibility; dual use for DNA recovery	Nanoparticle toxicity; background fluorescence	Biocompatible GFP-based fluorophores
Bio-markers (DNA, proteins)	Attomole detection; label-free	Fragmentation in aged samples	CRISPR-coupled nano-electrodes; solid-state nanopores

Table:1

4 Conclusion

Forensic chemistry has entered a new age of ultrasensitive, field-deployable analytics because to nanotechnology. Together, SERS chips, graphene and MoS_2 nanosheets, quantum-dot tests, and noble-metal nano-lateral-flow strips expedite on-scene judgments and cut detection limits by orders of magnitude. Researchers must (i) standardize production and validation processes, (ii) thoroughly evaluate the environmental effect and toxicity of nanomaterials, and (iii) integrate nanosensors with reliable data-analysis pipelines in order to obtain routine judicial approval. It will need ongoing multidisciplinary cooperation between chemists, material scientists, law enforcement, and legal professionals to transform these lab achievements into widely accepted forensic instruments.

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