

Applications of Nanotechnology in Forensic Science: A Comprehensive Review

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How to cite this article: Gouri Umale, Rakesh Mia, Dinesh Sharma. Applications of Nanotechnology in Forensic Science: A Comprehensive Review. *Medico-Legal Update* / Vol 25 No. 3, July - September 2025

Abstract

Nanotechnology is reshaping forensic science with new techniques that are faster, more sensitive, and more precise. This review highlights how the increasing use of nanomaterials in forensic investigations improves the detection, collection, and analysis of evidence. Nanoparticles like gold, silver, zinc oxide, and titanium dioxide have improved latent fingerprint visualization, showing clearer ridge detail even on difficult surfaces.

The increasing use of nanotechnology in forensic investigations is promising and could soon be the tipping point in the discipline. Applications mainly have been related to evidence identification and analysis, such as single-crystalline semiconductor CdS nano slabs for explosives detection, functionalized TiO₂ nanorods for organophosphorus chemical warfare agents in Forensic Chemistry, the use of Nanopowders for latent print visualization in and gold nanoparticle protein nanopore for detection of single-stranded DNA in Forensic biology. In recent years, nanotechnology has also been used to identify illegal drugs. Due to the restricted tools available for evidence analysis, these and other applications of nanotechnology offer sensitive and selective techniques for identifying evidence, as well as quick and accurate results with fewer procedures.

Nanotechnology is also being used in document authentication, postmortem interval estimation and microbial forensics. But there are challenges to overcome, standardization, cost-effectiveness and environmental impact. This review brings together findings from recent studies to provide a comprehensive overview of how nanotechnology is revolutionizing forensic science and outlines the steps needed to further integrate these tools into routine forensic practice.

Keywords: Forensic Science, Nanotechnology, Fingerprint, DNA analysis, GSR, Drugs, Toxicology, Questioned document, Nanoparticles.

Introduction

Nanotechnology involves exploring and working with materials, devices, and systems by controlling matter on an extremely tiny scale—so small that it's measured in nanometers. The word 'nano' comes from the Greek meaning 'dwarf.' Usually, a nanostructure is something between 1 and 100

nanometers in size. When materials are this small, they often have special properties that are quite different from what we see in larger pieces. These unique features can make things more efficient and effective. The idea of nanotechnology was first introduced back in the 1980s by Dr. Richard Feynman. In forensic science, nanotechnology is

used mainly in two ways: first, for analyzing and detecting samples at the tiny, nanometer level; and second, by using nanomaterials with special features to help gather and identify evidence. Whether used alone or alongside other tools, nanotechnology is showing huge promise in fields like security, drug testing, finding explosive residues, examining fingerprints, analyzing questioned documents, and DNA testing. The progress in creating nano-sensors and tiny devices for detecting small or hard-to-find evidence is pushing the frontiers of forensic science and opening new doors to solving crimes faster and more accurately. ⁽¹⁾

Forensic science's broad field has embraced the latest methods of the natural sciences to acquire criminal or other legal evidence, one being Nanotechnology Applications, and knowledge derived from nanotechnology has led to the new branch or sub-field in forensics called Nano-forensics, which has borrowed methodologies from nanotechnology in assisting investigations to be further enhanced. Some methods and instrumentation applied in the forensic lab were taken advantage of in the emerging application of nanotechnology for nanomaterials' characterization. They consist of the Atomic Force Microscopy, Scanning Electron Microscopy, Raman Micro Spectroscopy, and the Transmission Electron Microscopy.

The majority of the methods from nanotechnology and Nano-forensics are either used to analyze evidence of Nano-scale size or employ the effect of the nanomaterial in detecting evidence for criminal investigation. With specific reference to the development of tools as a new arena of nano-forensics, Nano-sensors have emerged as a novel tool for the investigator to conduct investigations. This, alongside numerous other products and impacts of nanotechnology, has assisted in deciphering numerous mysteries surrounding some crimes through the detection and analysis of evidence, which previously would not be identified or would have taken extended durations in identification and analysis. ⁽²⁾

Applications of Nanotechnology in Forensic Science

Nanotechnology in Latent Fingerprint Detection

For many years, latent fingerprint detection has made use of nanoparticles. By enhancing the ridge characteristics and detecting sweat pores, the nanoparticles interact with the fingerprint's tiny ridges. Silver nanoparticles are an example of a developer that can be used to visualise latent prints. The silver nanoparticles interact with the natural component of fingerprints, developing the print in a darkish grey to black silver colour on the porous surface. Gold nanoparticles also have value in latent fingerprint analysis since they're inert, selective, and sensitive. The latent prints produced by the use of gold nanoparticles can be preserved for a longer duration of time. Gold nanoparticles can also be used to enhance the visibility of the latent pattern with the aid of generating multi-metallic deposition (MMD) ⁽³⁾. Quantum dots can also be used to visualise bloody fingerprints, as it is far common for bloody fingerprints to smear and contaminate the deposition of fingerprints, which could damage ridge details in those prints. The analysis shows that a small quantity of ZnO-SiO₂ nanoparticles introduced to the powder substantially enhances the visible development of latent prints to third-level ridge detail of the prints. Carbon nano powder has additionally been developed for the visualization of prints on multi-colored or patterned backgrounds. ⁽²⁾

Drug Detection and Analysis using Nanoparticles

Drug detection using nanoparticles typically occurs using colorimetric, fluorescence, and electrochemical sensors. The fabrication of a dipstick assay using the AuNP-labeled single-chain fragment variable (scFv) antibody for the morphine determination was made. ⁽⁴⁾ A colorimetric sensor based on aptamer and molybdenum disulfide (MoS₂)-gold nanoparticles (AuNPs) can be employed for cocaine detection. ⁽⁵⁾ This sensor was rapid, cost-effective, and could detect a highly sensitive amount. A recent study showed that if the perpetrator or victim of the crime had been under the influence of drugs or alcohol, a combination of microextraction

by packed sorbent (MEPS) and direct analysis at real time (DART) Tof-MS was applied. The techniques enhanced not only the rate of extraction of drugs from urine (< 2 minutes) but also the rate of drug detection (< 1 minute). The study presents the potential to detect extremely low levels of drugs, days after consumption, in a person's urine. The method could be regularly employed in forensic science, whereby screening a close to unlimited number of drug metabolites could be achieved.⁽⁶⁾

Nanotechnology in the Analysis of Questioned Documents

Nanoparticles play a role in the creation of ink and writing ink formulations. The SEM images of the writing and printing inks, viewed at different magnifications, reveal the elemental composition and the pigment structure in writing and printing inks. To ensure the confidentiality and preservation of sensitive information, self-erasing inks and media were created. The self-erasing inks are metallic nanoparticles. The dimensions of the gold and silver nanoparticles are approximately 5nm. The gold and silver nanoparticles clump together when exposed to UV radiation, changing colour visibly. The vanishing ink effect is caused by the clumps being dispersed by the visible light. A gel film with organic particles and incorporated gold or silver nanoparticles is the self-erasing medium. The barcode used for military security is printed using confidential inks. The radio frequency identification tags are produced using a gold nanoparticle-based ink that is enclosed within an alkanethiol layer.⁽¹⁾ The nanomaterials that can be found in the document can be examined using Atomic Force Microscopy (AFM). When it comes to ink saturation, crossing depth, ink amplitude variations, and ink phase changes on paper, AFM can provide qualitative information about a questioned document. It offers crucial details to ascertain the order in which lines created by ball pen ink and ribbon dye intersect. Additionally, phosphorescent nanoparticles like quantum dots or nano-sized luminescent phosphors and up-converters could be included as an additional security tagging in the security document to enhance their security and discourage counterfeiting.⁽⁶⁾

Nanotechnology and Forensic DNA Analysis

Nanoparticle-based methods now take center stage in DNA analysis because of their low cost and ease of automation. Specifically, magnetic nanoparticles are now being used to extract DNA due to their increased sensitivity and yield of DNA. The use of Fe₃O₄ nanoparticles to extract nucleic acid from four sources (bacteria, yeast, human blood, and virus) yielded the highest yield and relatively pure nucleic acids.⁽⁷⁾

Sensor-based DNA detection methods like the gold nanoparticles, are used because of their optothermal property. Using the optothermal property of Au nanorods, researchers converted the near-infrared energy into thermal energy in a microfluidic chip, which results in the lysis of pathogens and eventually in the extraction of DNA.⁽⁸⁾ Other than gold nanoparticles, silica nanoparticle-based assay also detects DNA with sensitivity. The NanoPCR, a nanoparticle-assisted PCR, is gaining attention due to its specificity, reaction rate, and speed. Several types of nanoparticles have been introduced into PCR technology, including carbon tubes, quantum dots, and metal nanoparticles.⁽⁹⁾

Explosives Detection using Nanotechnology

Explosive-based crimes are increasingly becoming common due to their ease of manufacture and immense destructive potential. An explosive becomes difficult to detect because of the large number of explosive types and their uses. Trace vapors or particulate matter go through collection with initial detection, subsequently being analyzed by their highly sensitive sensors. The conventional way is much tedious, thus implying a need for sensors with higher sensitivity, selectivity, and cheapness, having lower detection levels.⁽¹⁰⁾ Nanostructured sensors have recently catapulted and brought an increased level of sensitivity, precision, and response time. Nano-curcumin probes, electronic noses, nanowires, nanotubes, and plasmon nanocavities usher in specific targeted detection. A cheap method has been developed to detect traces of TNT using nano-curcumin.⁽¹¹⁾ Surface Enhanced Raman Spectroscopy (SERS) has also been proven to be a reliable, non-destructive method of explosive detection.

Estimation of Time Since Death using Nanotechnology

Time since death has been estimated soon after death using a variety of biochemical and physiological changes, particularly the physiology of specific fluids, including blood, spinal fluid, pericardial fluid, aqueous and vitreous humor, and synovial fluid. (12) Vitreous humor can be examined in a deceased individual, and its composition remains relatively stable for an extended period following death. Consequently, this implies that metabolic alterations in VH that affect the concentration of amino acids in the fungus and the cadaver occur at a relatively slow pace. (13) This assessment can predict TSD over the next 96 hours, where the VH cysteine levels significantly rise, and the increase in TSD follows a linear pattern. The impact of TSD was assessed by assessing the rate of DNA degradation in the brain and spleen over 96 hours. In the future, researchers will measure and quantify the concentration of VH using fluorescent nanoparticles and flow cytometry. This innovative technology would surpass the accuracy of traditional TSD estimation methods. (14)

Nanotechnology and Examination of Bloodstains

Bloodstains found at the crime scene are clear indicators of someone or something being harmed, and when analyzed, they can identify either the victim or the suspect through DNA profiling. Furthermore, bloodstain patterns can help crime scene investigators determine what happened at the crime scene and reconstruct the occurrence. This has spawned studies on forensic age estimation of bloodstains using Atomic Force Spectroscopy (AFS) to establish the age of a bloodstain at a crime scene, to help estimate the time of occurrence. (15) AFM has been employed in the estimation of time since death (TSD) of erythrocytes in bloodstains. (16) Since AFM is a quickly progressing tool, potentially providing forensic investigations with more information, therefore, it has been utilized to measure the elasticity of the blood by recording a force-distance curve. The change in bloodstain during the drying and coagulation stages is most likely responsible for the steady drop in elasticity pattern. The age of bloodstains may be ascertained and will be useful for supporting criminal investigations

once the AFM creates a calibration curve of elasticity over time. (17)

Security Features in Official and Confidential Documents

Nations are constantly worried about protecting their priceless assets and sensitive information. Many strategies have been put out to increase security and reduce document fraud. Holograms, planchettes, fluorescent inks, color-shifting inks, security threads, passports, credit cards, and currency all contain various security elements. It is typical to discreetly label documents with inorganic and organic glowing powders known as phosphors and fluorophores. At present, bright nanoparticles like quantum dots (Q-dots) or nano-sized luminescent phosphors and up-converters are employed as security measures. These luminous nanoparticles are introduced into papers or inks to ensure document security. (18) Furthermore, the quick creation of a variety of bright nanoparticles has aided the rapid development of anti-counterfeiting inks. New, advanced nano-formulations are gradually replacing traditional fluorescent powders and dyes due to their more precise and complex security characteristics. (19)

Nanotechnology in Environmental Forensics

Aptamers are a group of biosensors that utilize DNA or RNA aptamers as the biological recognition elements for specific molecular entities. Different applications related to environmental toxicity can involve the utilization of various nanomaterials with aptamers. In the detection and quantification of diclofenac, an ibuprofen drug that is toxic to Gyps vultures, an electrochemical aptasensor was developed using carbon nanotubes functionalized with magnetic nanoparticles and graphene oxide. The aptasensor was selective and accurate in detection abilities up to the picometer range. Magnetic nanoparticles (Fe₃O₄) were inserted between graphene oxide layers and nanotubes. Water-soluble cadmium telluride quantum dots coated with thioglycolic acid are used to create an aptasensor to detect ibuprofen. Environmental forensics is likely to gain from the utilization of aptamer-based biosensors to identify drugs simply and rapidly

because they offer rapid, accurate, user-friendly, and selective analytical techniques. Aptamer-based test platforms for point-of-care diagnosis can be of great importance in the analysis of environmental and wildlife forensics. The long-term and chronic impacts of pharmaceuticals and heavy metals on non-target species and the environment have been supported by evolutionary evidence over time, perhaps because of low-level but chronic exposure. The utilization of aptasensors in the detection of trace amounts of such hazards is an important aspect of environmental forensics.⁽²⁰⁾

Nanomaterials in Cyber Forensics

The revolutionary data security breakthrough called Quantum encryption stands as the most important application of quantum materials. Security through quantum encryption functions better than classical encryption through quantum mechanics principles that develop impenetrable protection systems. Quantum Key Distribution represents a popular method in quantum encryption, which produces encryption keys through qubits (quantum bits). Quantum computers use qubits for performing advanced calculations at much higher speeds than traditional computers and consequently improve cybersecurity functions. Quantum computers present encryption method-breaking capabilities, but they can simultaneously allow researchers to develop secure cryptographic algorithms. New quantum-resistant algorithms must be adopted as they are specifically designed to shield against quantum computing breaches. The detection capabilities of quantum sensors scan network traffic for deviations that would indicate a cyberattack. Advanced detection systems made possible through this capability enable a more rapid identification and quicker security threat response to minimize the consequences of cyber incidents. Elucidating next-generation cybersecurity improvements emerges by a combination of silver nanoparticles with quantum materials, as well as predictive analytics approaches.⁽²¹⁾

Nano-trackers for crime prevention

In recent times, tracking devices and barcodes are being used as security measures against criminal

behaviour. Tracking devices function as preventive measures through their ability to embed secret patterns on products, which act as theft deterrents. Tracking devices deliver two functions: protection against theft and item identification after theft or disappearance. Tracking devices serve security functions by stopping prisoners from breaking out of their confinement. The bodies of inmates receive nano trackers, which enable authorities to track their movements when they attempt to escape. The tracking capabilities of nano trackers continue after release to monitor former prisoners and detect any potential criminal activity. Barcodes serve as a crime prevention tool.⁽²²⁾

Nano-sensors in the detection of counterfeit crimes

The authentication of products depends heavily on nanotechnology applications. Multiple industries can use this technology to protect against counterfeit and imitation goods. Artificial products threaten businesses and their countries by causing steep financial damage as well as reputation deterioration. A product's authenticity depends directly on the trustworthiness of the company because consumers who buy counterfeits or imitations will doubt the reliability of both products and the company's reputation. Watermarks function as a protective measure against product duplication because they help identify genuine products from counterfeits. Nanotechnology enables scientists to develop multiple instruments that help distinguish between authentic and fake products. Nanotechnology helps reduce counterfeiting activities through its implementation. Nanotechnology innovations have produced nanofibers and nanodots in different colors that serve as identification tools for counterfeit products. Nanodot and nanofiber examination requires forensic light sources that reveal their properties when employed by forensic technicians. Nanotechnology has demonstrated its effectiveness as a tool to fight counterfeiting activities.⁽²³⁾

Discussion

In this review paper, we have highlighted the applications of nanotechnology in terms of forensic science as well as the crucial use of sophisticated

nanotechnology instruments such AFM in multiple aspects of forensic science such as questioned documents, determination of time of death, age of stains of blood, DNA analysis, explosive detection as well as in drug analysis. This review article has also revealed the promising use of nanotechnology in various forensic investigations including nanosensors for detection of explosives, Au-NPs for DNA fingerprinting, quantum dots as luminescent materials and as security features in official and confidential documents, Au-NPs(gold), ZnS (zinc sulphide) and CdS-NPs (cadmium sulphide) for fingerprint enhancement with greater background selectivity etc.

Challenges and Future Prospects

Yet, nanotechnology does have its challenges, notwithstanding the advancements. Concerns regarding the health and safety of forensic scientists, environmental issues like bioaccumulation and toxicity, and the expensive development of equipment and research are a few important concerns. The high cost of implementing these novel methods including the purchasing of advanced instruments, specializes reagents, need for highly skilled personnel and long-term funding for interdisciplinary studies poses a major challenge particularly in developing countries. Governments and forensic organizations can collaborate to decrease the risk and cost. Additionally, the legal admissibility of evidence obtained using emerging technologies can be contentious as the court may question the reliability or standardization of such novel techniques. Privacy and ethical concerns may also arise from the use of highly sensitive nano-sensors or tracking devices capable of detecting biological traces at extremely low levels. Future developments would thus focus on creating portable tools that are field-ready and on extensive training to keep forensic scientists updated with nanotechnology developments.

Conclusion

In this review, we have demonstrated several instrumental and nanotechnology approaches in this work that can be applied to numerous

forensic investigation domains. Different kinds of nanoparticles are used to detect different forensic samples. The extreme sensitivity of nanosensors makes them useful in nano-forensics. Furthermore, the research procedure is now quick thanks to nano-forensics. According to the aforementioned techniques, nanotechnology is quick and precise for more dependable and secure systems related to forensic inquiry. To provide more sensitive and selective methods that can aid investigators in solving crimes more successfully, nanotechnology is expected to play a significant role in the future.

Source of Funding: This work did not receive any specific grant from funding agencies in the public, commercial or non-profit sectors.

Conflict of Interest: The author declares no conflict of interest related to the content or authorship of this manuscript.

Ethical Considerations: This article is based solely on previously published research papers and extensive literature review. It does not involve any studies with human or animal subjects performed by the authors. Hence, ethical approval was not required.

References

1. Dominica RRaF. Application of Nanotechnology in Forensic Science. *Journal of Forensic Research*. 2022;; Volume 13: 8.
2. Paikrao Hariprasad DAPAAaTD. Nano-Forensics a Comprehensive Review. *Forensic Sci Add*. 2021.
3. Sweta Singh NS. Nanotechnology: A Powerful Tool in Forensic Science for Solving Criminal cases. *Arab Journal of Forensic Sciences & Forensic Medicine* 2021; Volume 3 Issue (2). 2021;; 273-296.
4. Gandhi S BIMPEs. A gold nanoparticlesingle-chain fragment variable antibody as an immunoprobe for rapid detection of morphine bt dipstick. *RSC advances* 8(3):. 2018;; 1511-1518.
5. Gao L XWDZSKWHea. Cocaine detection using aptamer and molybdenum disulfide-gold nanoparticle-based. *Nanomedicine* 15(4):. 2020;; 325-335.
6. Vandan Prasada SLLP. Emerging Forensic Applications of Nanotechnology. *International*

- Journal of Engineering and Allied Sciences (IJEAS). 2016;; ISSN: 2455-2054.
7. Ma C LCWFMNLXea. Magnetic nanoparticles-based extraction and verification of nucleic acids from different sources. *J. Biomed Nanotechnol* 9(4):. 2013;; 703-709.
 8. Cheong KH YDLJPKMea. Gold nanoparticles for one step DNA extraction and real-time PCR of pathogens in a single chamber. *Lab Chip* 8(5). 2018;; 810-813.
 9. Wang Y LB. Silica nanoparticle assisted DNA assays for optical signal amplification of conjugated polymer based fluorescent sensors. *Chem Commun* 34:. 2007;; 3553-3555.
 10. S. Kesarwani ea. Nano-forensic: new perspective and extensive applications in solving crimes. *Lett. Appl. NanoBioSci.* 10 (1). 2020;; 1792-1798.
 11. A. Pandya HGALSKM. A novel nanoaggregation detection technique of TNT using selective and ultrasensitive nanocurcumin as a probe. *Analyst* 137 (8). 2020;; 1771-1774.
 12. S.S. Kumar Vishal OGRKK. Changes in the levels of vitreous potassium with increasing time since death. *J. Indian Acad. Forens. Med.*26. 2004;; 136.
 13. L.M. Swann SLFSWL., Analytical separations of mammalian decomposition products for forensic science: a review. *Anal. Chim. Acta* 682. 2010;; 9-22.
 14. Williams Teddric SSWJCGTJG. Evaluation of DNA degradation using flow cytometry: promising tool for postmortem interval determination. *Am J Forensic Med Pathol* 36 (2). 2015.
 15. Smijs T,GF,aAAV. Forensic potential of atomic force microscopy. *Forensic Chemistry*, 2:. 2016;; 93-104.
 16. Cavalcanti DR,aSLP. Application of atomic force microscopy in the analysis of time since deposition (TSD) of red blood cells in bloodstains : A forensic analysis. *Forensic Science International*, 301. 2019;; 254-262.
 17. S. Strasser AZGKPHOPWMHAGNST. Age determination of blood spots in forensic medicine by force spectroscopy. *Forensic Sci. Int.* 170 (1). (2007);: 8-14.
 18. A. A. Cantu. Proceedings of SPIE-Int. society for optical engineering. *Proc. of SPIE.*, 7119. 2008;; 1-8.
 19. Shukla, Ritesh. (2013). Occupational Exposure of Nanoparticles In Forensic Science: A Need Of Safe Use. *International Journal of Forensic Science & Pathology.* 1. 1-6. 10.19070/2332-287X-130003.
 20. Dube S,SS,&RD. Aptasensors in environmental forensics: Tracking the silent killers. *WIREs Forensic Science*, 5(4). 2023;; e1482.
 21. Dita A, Shah NUR. The role of silver nanoparticles and quantum materials in predictive analytics for healthcare and cybersecurity in financial supply chains. 2024. doi:10.13140/RG.2.2.15193.12644.
 22. Pandya, A., Shukla, R.K. New perspective of nanotechnology: role in preventive forensic. *Egypt J Forensic Sci* 8, 57 (2018). <https://doi.org/10.1186/s41935-018-0088-0>
 23. Wang Y, Alocilja E. Sensor technologies for anti-counterfeiting. *Int J Comp Appl Crim Justice.* 2012;36(4):291-304. doi:10.1080/01924036.2012.726319.