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Review

Forensic nanotechnology: Innovations, challenges, and legal considerations

Kartikay Singh Nayal[1], Kasturee Hajra[2,3], Divya Tripathi[1,*], Dipak Maity[4,5,*]

[1] School of Health Sciences, University of Petroleum and Energy Studies, Uttarakhand 248007, India
[2] School of Public Health, SRM Medical College, Kattankulathur, Tamil Nadu 603203, India
[3] Center for Chronic Disease Control, New Delhi 110016, India
[4] Integrated Nanosystems Development Institute, Indiana University, Indianapolis, IN 46202, USA
[5] Department of Chemistry and Chemical Biology, Indiana University, Indianapolis, IN 46202, USA
*** Corresponding author:** Divya Tripathi, divya.tripathi@ddn.upes.ac.in; Dipak Maity, dipakmaity@gmail.com

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Abstract: Forensic science fundamentally centers on detecting and interpreting clues, many of which are extremely small, easily degraded by environmental conditions, or intentionally concealed. Traditional forensic methods remain reliable and legally accepted; however, they increasingly struggle to address emerging forms of highly minute and complex evidence. In response, researchers are turning to nanotechnology to enhance forensic capabilities. Working at the nanoscale offers improved sensitivity, selectivity, and accuracy, enabling forensic scientists to detect, visualize, and analyze trace evidence with greater precision. This review examines the expanding role of nanotechnology across diverse forensic domains, including fingerprint visualization, gunshot residue detection, DNA analysis, document authentication, drug-related investigations, and postmortem interval estimation. Rather than suggesting that nanotechnology will replace established approaches, this article compares nanoscale methods with conventional techniques, highlighting their respective advantages, limitations, and practical considerations. Key challenges, such as validation, reproducibility, interpretation of results, and admissibility in court, are critically discussed. By assessing how nanotechnology can both support and complicate forensic workflows, this review provides a balanced perspective on its realistic contributions and shortcomings. Through integrating recent scientific advances with an understanding of forensic constraints, the article aims to clarify how nanoscale technologies may meaningfully strengthen forensic science while upholding the evidentiary standards demanded by the justice system.

Keywords: nanotechnology; nano-forensics; DNA; gold nanoparticles; microanalysis; advanced analytical techniques

1. Introduction

Forensic science is a case-based or multi-case-based, research-oriented, scientifically grounded discipline focused on the study of traces and remnants of past activities, such as an individual's presence or actions. These traces are detected, recognized, recovered, examined, and interpreted to reconstruct anomalous events of public interest, including crimes and security incidents [1].

The term *nano* originates from the Greek word for "dwarf" [2,3]. Nanotechnology refers collectively to the design, synthesis, development, manipulation, improvement, and industrial application of materials, systems, and devices through the controlled manipulation of matter at the nanoscale (10^{-9} m) [4]. Materials or structures with dimensions between 1 and 100 nm are classified as nanostructures [5]. At this scale, materials often exhibit novel or enhanced physicochemical properties compared to their bulk counterparts, making them advantageous for a wide range of applications [6].

The conceptual foundation for nanotechnology was first articulated in the 1980s by Dr. Richard Feynman, whose pioneering ideas laid the groundwork for the field's development.

There are two ways that nanotechnology can be used in forensic science [7]:

a) **The Primary Method:**

The primary method follows the principle of recognizing and analysing the test samples and pieces of evidence at the nanoscale.

b) **The Secondary Method:**

The secondary procedures involve using advanced nanomaterials with new characteristics to help find and characterize shreds of evidence.

Nanotechnology is being used in forensic science to help distinguish the reactive material [7,8], and the development of microchip technology [9], nano-manipulators [10], and visualization tools and techniques. Security, testing for narcotics, detection of explosives, fluorescent finger-mark analysis, the study of questionable documents and forgery identification, and DNA analysis are all areas where nanotechnology has a considerable application, either in combination with other technologies [11] or natively alone [12]. One innovative forensic application of nanotech is the manufacture of nano-sensors and nano-devices assisting in recognizing anonymous evidence [13].

Different forms of physical, chemical, and biological sciences are brought together under nanotechnology to research and develop numerous phenomena at the nanometre scale (1 nm) [14]. Science fiction literature and speculative research at secret laboratories centred on nanotechnology a few years ago. Among the technologies currently in use, nanotechnology is one of the most promising yet debatable new technologies [15]. In the forensic sciences, research is a sequential processing area that involves task investigation and information collection at the crime scene using a certain technique. The employment of forensic sciences will drastically alter the investigative process by making it simpler, faster, more accurate, impactful, and user-friendly.

1.1. What is forensic science?

The framework outlined in *"Organization of Scientific Area Committees (OSAC) for Forensic Science"* emphasizes the critical need for scientifically validated methodologies, reproducible results, and inter-laboratory standardization across forensic disciplines (**Figure 1**). As modern criminal investigations increasingly encounter trace-level, highly degraded, or chemically complex forms of evidence, traditional analytical techniques often reach the limits of their sensitivity and discriminatory power. This growing technical demand has accelerated interest in nanoscale technologies as complementary tools capable of enhancing analytical precision, detection limits, and overall reliability within standardized forensic workflows.

Nanotechnology operates within the 1–100 nm dimensional range, where materials exhibit size-dependent physicochemical properties that differ markedly from their bulk forms. At this scale, effects such as quantum confinement, increased surface-to-volume ratios, tunable surface functionalization, and localized surface plasmon resonance significantly enhance molecular recognition and signal amplification. These nanoscale phenomena translate directly into forensic advantages. Functionalized gold nanoparticles enable highly sensitive colorimetric and plasmonic detection of nucleic acids and explosive residues; quantum dots provide exceptional photostability and multiplexing capability for biological tagging, thereby improving DNA profiling sensitivity; and nanostructured substrates enhance latent fingerprint visualization by increasing selective adhesion and improving contrast resolution.

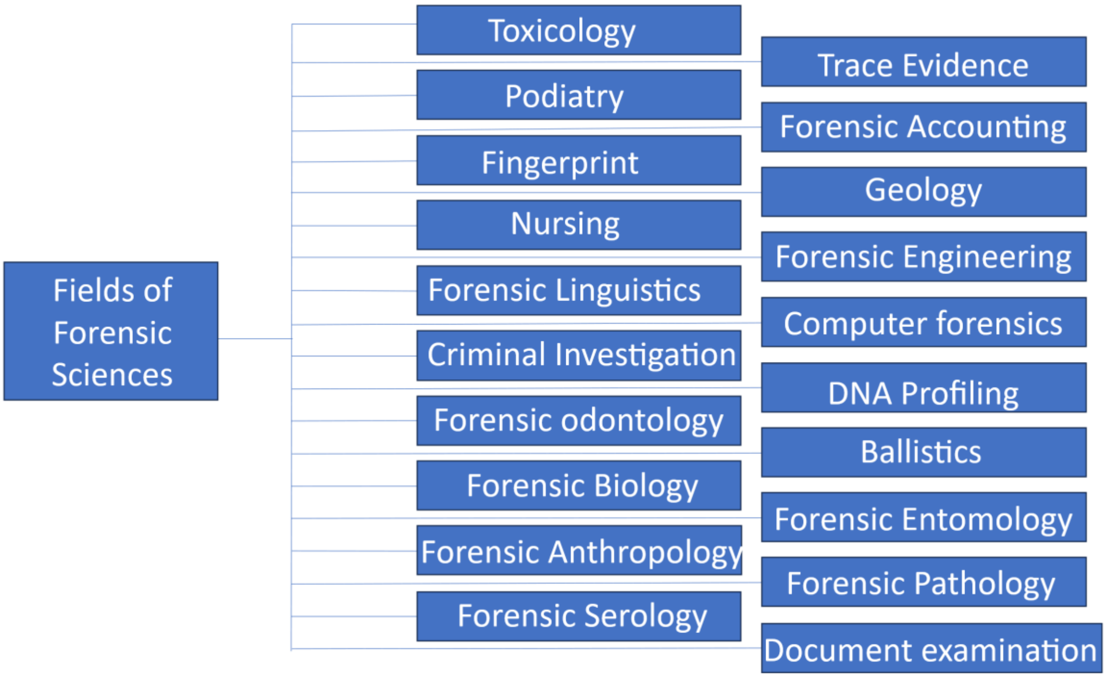

Figure 1. Fields of Forensic Sciences.

Crucially, the integration of nanoscale detection systems aligns with OSAC's priorities related to methodological rigor, reproducibility, and validation. While nano-enabled assays offer heightened sensitivity, they also require stringent calibration, robust reproducibility assessments, and well-defined standard operating procedures to ensure their reliability and admissibility in courtroom settings. Within validated forensic frameworks, nanotechnology does not replace conventional methods; rather, it strengthens them by lowering detection thresholds, improving analytical robustness, and enabling rapid, high-throughput analysis of trace evidence.

Thus, the convergence of nanoscale engineering with forensic standardization represents a significant step toward more sensitive, reproducible, and scientifically defensible investigative practices.

1.2. Nanotechnology platforms and emerging applications in forensic science

The conceptual foundations of nanotechnology trace back to Richard Feynman's landmark lecture, *"There's Plenty of Room at the Bottom"* [16], in which he envisioned manipulating individual atoms and molecules with precise, controllable instruments. He noted that at the nanoscale, intermolecular forces such as surface tension and Van der Waals interactions dominate gravitational effects [17], and materials exhibit behaviors markedly different from their bulk forms. Gold, for example, is chemically inert at the macroscopic level but becomes catalytically active at the nanoscale. These principles ultimately shaped the modern field of nanotechnology.

According to the U.S. National Nanotechnology Initiative, nanotechnology involves the understanding and control of matter between 1 and 100 nm, where novel physicochemical phenomena enable transformative applications. Materials at this scale often display dramatically altered melting points, optical properties, and chemical reactivity. Gold nanoparticles (1.5–2 nm), for instance, melt near 300 ℃, far lower than bulk gold at 1064 ℃, and exhibit size-dependent colors ranging from pink to purple rather than a metallic sheen. Comparable nanoscale transformations occur in copper, aluminum, platinum, and silicon, demonstrating how conventional material properties shift in this dimensional regime.

A wide array of nanomaterials has since been developed, including carbon nanotubes, peptide nanotubes, semiconductor quantum dots, and numerous metal-based nanoparticles. These platforms now support applications across medicine, catalysis, environmental monitoring, advanced communications, and quantum technologies.

Their utility in forensic science is increasingly evident. Nano-platforms have enhanced narcotics detection [18–20], homeland-security screening [21], explosive-residue identification [22], and DNA analysis for similarity mapping [23]. Such tools allow investigators to detect highly minute, degraded, or chemically complex evidence that often falls below the sensitivity of conventional methods. Understanding their capabilities, limitations, and potential risks remains essential for integrating nanomaterials into routine forensic practice.

Specialized nano-enabled devices, such as nano-sprayers and lab-on-a-chip systems, further expand forensic capabilities. Lab-on-a-chip platforms enable multiple biochemical analyses using minimal sample volumes, while nano-sprayers enhance trace-element recovery at crime scenes [24]. As materials used in criminal activities become more refined and less detectable, improved nanoscale trace-evidence technologies will be critical. Some nano-enabled systems can already detect single DNA molecules [25].

The emergence of portable nanoscale instruments may eventually supplement or partially replace traditional laboratory workflows. On-site biochemical analyses could accelerate investigations by allowing rapid screening and preliminary interpretation at the crime scene. Lab-on-a-chip systems also require minimal user training and can produce faster, more reliable results than many existing laboratory assays [26]. Broader public access to these technologies may further accelerate the development and validation of new forensic methodologies [27].

Nanotechnology also contributes to multifunctional smart devices and integrated forensic tools. Consolidating multiple laboratory functions into a single nanoscale platform can reduce contamination risks and streamline evidence processing [28]. The inherent sensitivity and selectivity of nano-tools have demonstrated substantial potential to enhance security, prevent fraud, and counter organized crime and terrorism [29], particularly in regions with persistent criminal activity.

Forensic science relies fundamentally on scientific principles to identify, individualize, and interpret evidence [30], enabling accurate reconstruction of crime scenes and supporting legal adjudication [31]. Nanotechnology has become increasingly important in these efforts. Instruments such as Transmission Electron Microscopes (TEM), Atomic Force Microscopes (AFM), Scanning Electron Microscopes (SEM), and Raman Micro-Spectroscopy (Micro-Raman) now form essential components of forensic analysis. Subsequent sections of this review discuss these instruments, associated nanotechnologies, and their established forensic applications in greater depth.

2. Role of nanotechnology in attributes of forensic investigation and evidence collection

Fingerprints have been used as distinctive identifiers since antiquity, with evidence of their application on Babylonian clay tablets for business transactions [32]. In modern forensic practice, fingerprint powders are expected to adhere selectively to the residues left by a suspect's fingertips on evidence surfaces, thereby revealing the characteristic ridge patterns that enable individual identification. Ideally, these powders should not adhere to the background surface, particularly on non-porous materials. Conventional latent-fingerprint development relies on fluorescent or contrasting powders, such as aluminium flakes for dark backgrounds and carbon black for light surfaces [33]. A significant limitation of these materials is their tendency to adhere not only to the fingerprint residues but also to the underlying substrate, often reducing the clarity of the developed impression [34].

This challenge has motivated the integration of engineered nanoparticles into fingerprint detection. Nanotechnology offers promising opportunities for improving evidence collection and analysis, enabling forensic professionals to recover physical traces that may connect a suspect to a crime or, conversely, establish innocence. Once collected, evidence must typically be secured, transported, and analyzed in a laboratory, a process that is time-consuming and introduces potential for human error.

Advancements in analytical techniques have further supported fingerprint visualization. Micro–X–ray fluorescence (micro-XRF) has been shown to reveal latent fingerprints by detecting inorganic components within fingerprint residues [35]. This non-destructive technique provides precise and reliable imaging without altering the chemical stability of the sample [36]. Analyses using micro-XRF have identified elements such as silicon, aluminium, and calcium in fingerprint residues, although the approach requires specialized equipment and trained personnel.

To address these constraints, nanotechnology-based methods are being developed for rapid, on-site evidence assessment. Various nanopowders have now been incorporated into forensic procedures to enhance latent fingerprints on multiple surface types [37]. Photoluminescent CdS semiconductor nanocrystals capped with dioctylsulfosuccinate have been explored to improve fingerprint visualization [38]. Additionally, researchers have synthesized a novel $ZnO–SiO_2$ nanopowder using conventional heating techniques. This nanopowder has been applied through powder dusting and small particle reagent (SPR) methods to develop fingerprints on both moist and dry surfaces, including porous, semi-porous, and non-porous substrates. Results demonstrate that $ZnO–SiO_2$ nanopowder provides superior ridge detail compared to commercially available white powders, positioning it as a highly effective alternative for latent-fingerprint development [39].

The integration of these advanced approaches is illustrated in **Figure 2**, which highlights the diverse roles of functionalised nanomaterials within modern forensic science.

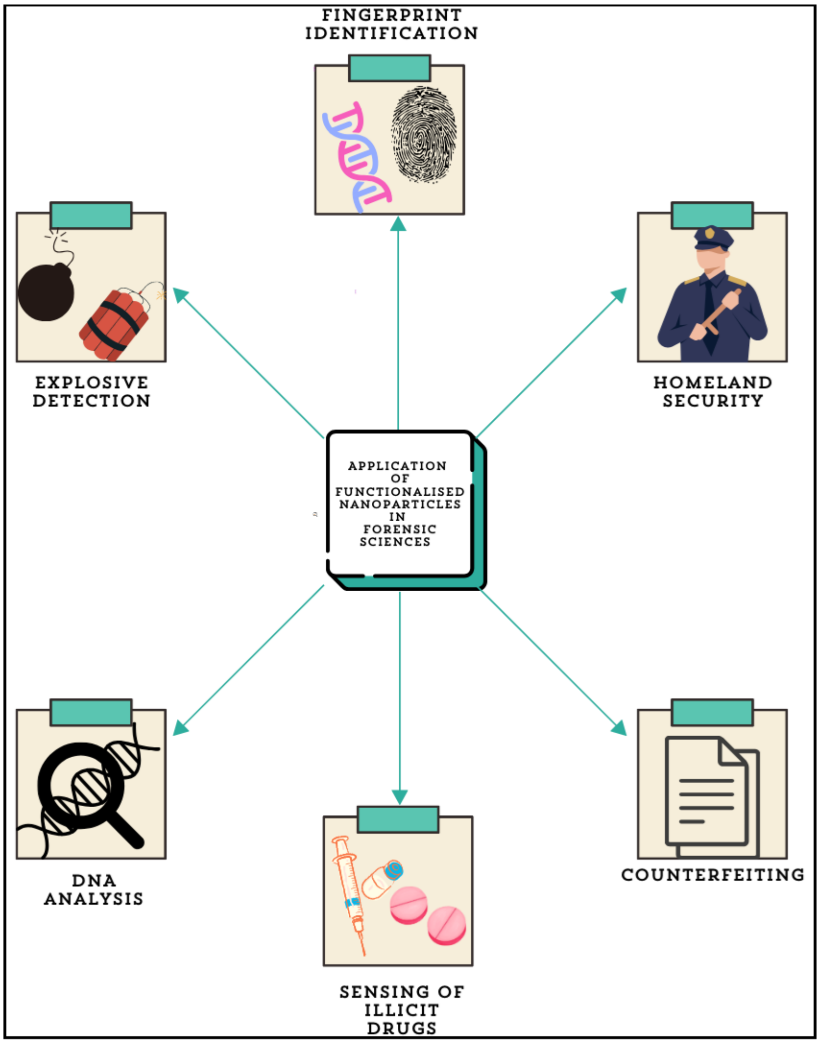

Figure 2. Role of Functionalised Nanomaterials in Forensic Science.

2.1. Nanotechnology-enabled detection of explosives and gunshot residue

Terrorism remains a significant global threat, driven in part by the ease with which explosive-based weapons can be manufactured, deployed, and used to inflict large-scale damage [40]. Detecting trace quantities of explosives, however, presents major forensic challenges due to factors such as limited amounts of unexploded residue, variability in collection methods, and contamination of samples at the crime scene [41]. During an explosion, intact fragments of energetic materials may remain at the site, while other residues can disperse over a wide radius. Locating these unfragmented components is often difficult, and insufficient evidence may prevent investigators from establishing a definitive link between a suspect and the crime scene. In such cases, nanotechnology-assisted analytical strategies offer valuable detectability enhancements. For example, nanoscale materials enable the identification of minute gunpowder and explosive particles on a suspect's hands or clothing [42].

Conventional gunshot residue (GSR) detection methods relying on scanning electron microscopy (SEM) and X-ray spectrometry remain effective but involve time-intensive procedures, specialized instrumentation, and susceptibility to analytical errors [43]. Furthermore, the investigative outcome is often influenced by the type of explosive used and its inherent lethality. Recent advancements demonstrate that charged nanoparticles and quantum dots can improve the detection of ballistic materials, providing investigators with additional trace-level indicators [44]. Surface-enhanced Raman scattering (SERS) has proven especially useful for identifying explosive constituents, such as nitroaromatics and nitrate esters, due to enhanced Raman signal intensities afforded by nanostructured substrates [45].

Nano-enabled approaches facilitate the detection of extremely small amounts of GSR on shooters' hands, clothing, and surrounding surfaces, offering investigative leads when traditional methods fail. Nanoparticles and engineered nanostructures can amplify chemical signatures, enabling the identification of explosive residues at concentrations far below conventional limits of detection. Despite these advantages, challenges remain. Environmental conditions may degrade residue or alter nanomaterial performance, and false positives or negatives can occur. Continued validation and standardization are essential to ensure scientific reliability and forensic admissibility. Nano-enabled detection systems should therefore be considered complementary tools that enhance but do not replace established forensic protocols.

Figure 3 illustrates an integrated Raman spectroscopy system equipped with a CCD (charge-coupled device) spectrometer for analyzing ballistic samples treated with nanoparticles to enhance the detection of nitro-containing explosive materials. A 785 nm laser source is employed to minimize fluorescence interference while maintaining sufficient Raman scattering intensity. The laser beam is directed through precision optical filters and mirrors to ensure spectral purity before interacting with the sample surface, enabling high-resolution differentiation of explosive signatures.

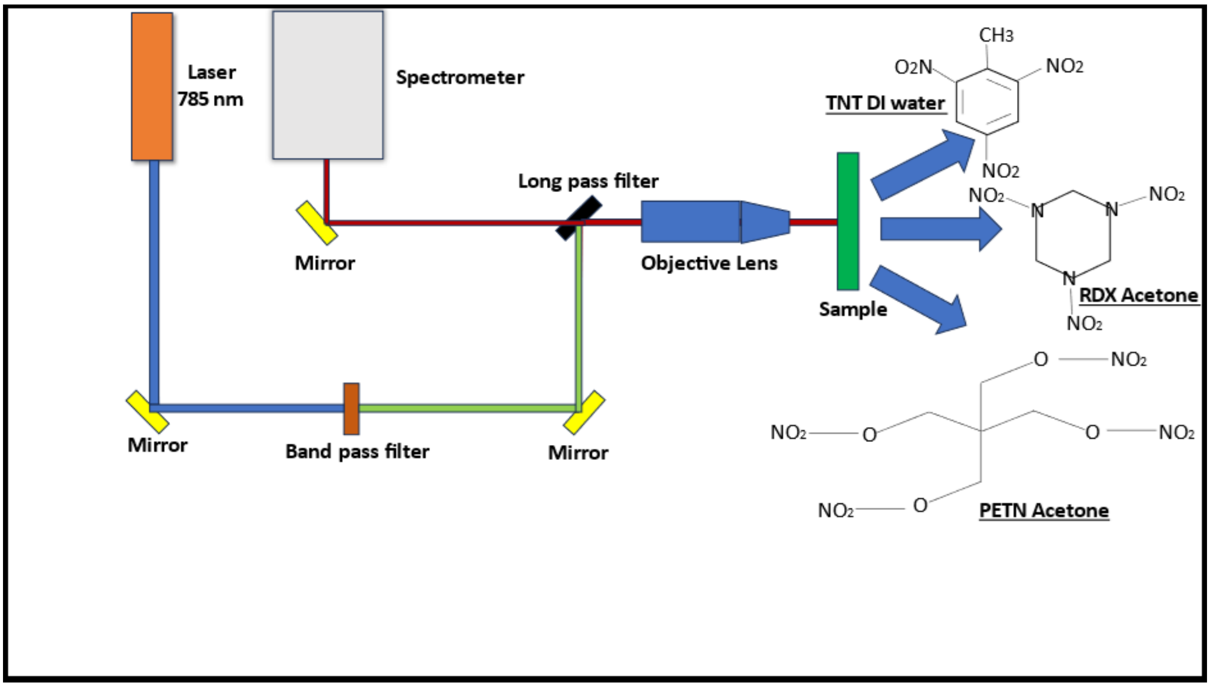

Figure 3. Using a CCD spectrometer to analyze a sample plate containing ballistics infused with nanoparticles for differentiating between nitro-containing ballistic materials.

2.2. Nanoscale approaches for forensic DNA detection and analysis

The rise in violent and complex crimes has intensified the need for highly sensitive forensic analytical tools. Among all forms of biological evidence, DNA remains one of the most powerful identifiers of human presence at a crime scene, whether originating from a victim or an offender [46]. Recent advances in nanotechnology have introduced new opportunities for recovering, extracting, and analyzing DNA from a wide range of biological materials, including hair, blood, semen, skin cells, and saliva, using magnetic nanoparticles and other nanoscale platforms [47].

Nanotechnology-assisted instruments have also expanded possibilities for direct DNA sequencing at the molecular level. For example, placing extracted DNA molecules onto graphite (carbon) nanotubes enables high-resolution nanoscale interrogation using atomic force microscopy (AFM). This approach supports precise visualization of DNA strands collected from diverse sample types such as skin, saliva, blood, and other trace biological residues. Carbon nanotube-assisted AFM imaging has demonstrated the ability to reveal DNA structure while causing minimal physical damage to the underlying genetic material, making it advantageous for forensic investigations that rely on preserving the integrity of the evidence [48]. Alternatively, DNA can be immobilized onto gold surfaces and subsequently characterized by AFM or related nanoscale analytical techniques, offering additional versatility in forensic DNA analysis.

Despite these advancements, most nano-enabled DNA analysis techniques remain in the research or proof-of-concept stage. Established polymerase chain reaction (PCR)–based methods continue to serve as the forensic gold standard due to their demonstrated robustness, validation across laboratories, and widespread legal acceptance in judicial systems. Consequently, nanotechnology-based DNA approaches should currently be regarded as complementary rather than replacement methodologies. Their greatest potential lies in improving trace-level DNA recovery, enabling direct nanoscale characterization, and supporting analyses when conventional techniques face limitations due to sample degradation or scarcity.

Figure 4 illustrates the preparation and AFM characterization of amine-functionalized DNA (NH_2-DNA) conjugated with gold nanoparticles for nanoscale analysis. The procedure begins by incubating gold nanoparticles with NH_2-modified DNA strands, where the amine (–NH_2) groups form strong coordination and electrostatic interactions with the nanoparticle surface. After approximately 12 h of incubation, stable gold–DNA conjugates are produced, enabling efficient immobilization and high-resolution AFM imaging for forensic characterization.

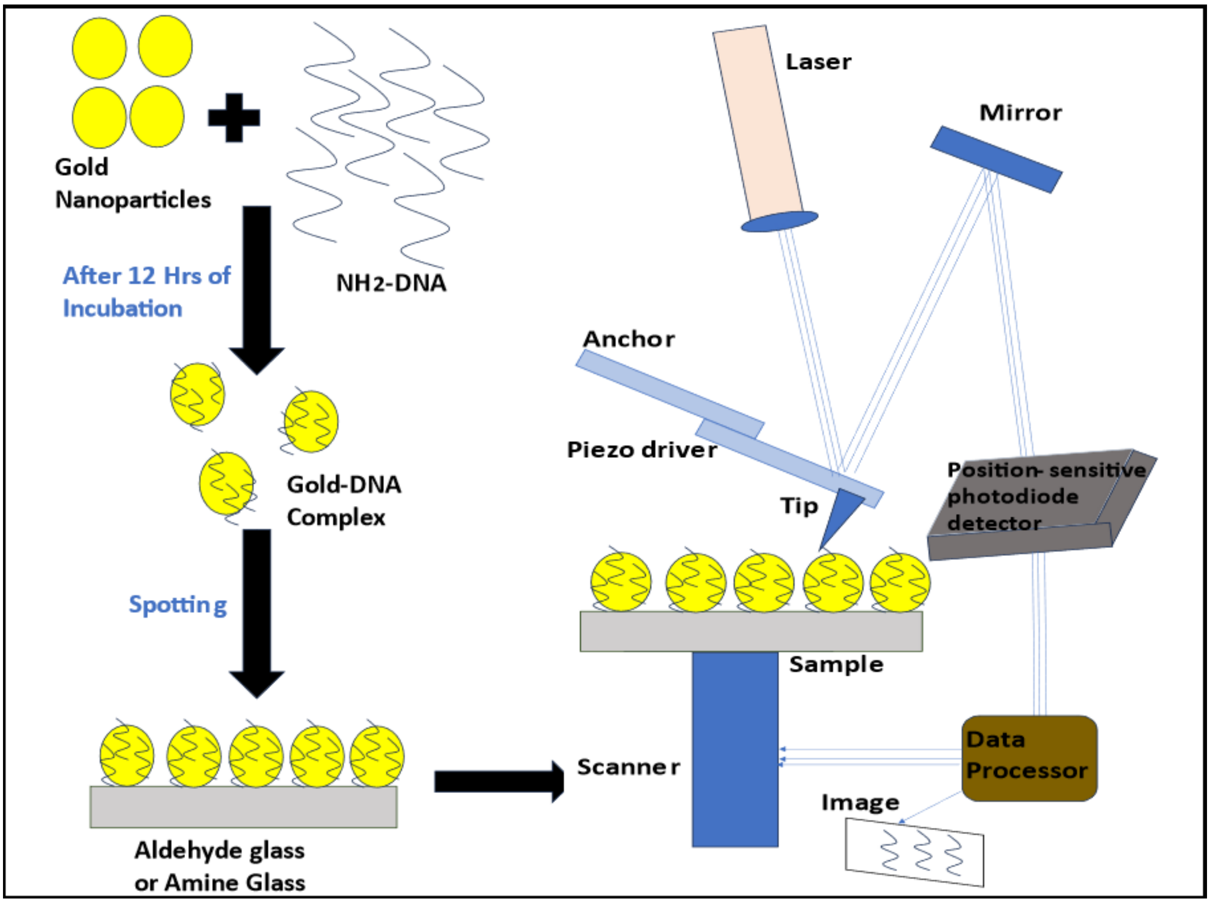

Figure 4. Gold Nanoparticles infused NH2-DNA strand analysed under AFM for analysis.

2.3. Ion beam analysis in forensic science

Ion beam analysis (IBA) is an advanced instrumental technique increasingly applied to the examination of forensic evidence [49]. It enables the detection, classification, and characterization of materials such as explosive residues, firearm discharge products, soil, inks, and even latent fingerprints. By comparing elemental composition profiles of evidence recovered from a crime scene with reference materials, IBA assists investigators in establishing associations between suspects, objects, and criminal events. Unlike many conventional analytical methods, ion beam analysis offers exceptionally high sensitivity and the ability to quantitatively examine a broad range of elements simultaneously [50]. Operating with ion beams in the millielectron-volt (meV) energy range, the technique allows both identification of elemental species and determination of their concentration depth profiles at the sub-monolayer level, typically within a depth resolution of several to tens of nanometers [51]. This nanoscale depth sensitivity makes IBA particularly valuable when working with trace or layered samples. When a charged ion beam strikes the surface of a specimen, it interacts with the electrons and nuclei of the constituent atoms, causing the emission of secondary radiation or particles in characteristic patterns. By analyzing these emissions using spectrometric techniques, investigators can determine which elements are present, their relative abundances, and their spatial distribution within the sample. Spectral peaks and their optical densities provide information on elemental identity, concentration, layer thickness, and material composition [52]. Depending on the forensic question and sample type, a variety of IBA modalities, such as Particle-Induced X-ray Emission (PIXE), Rutherford Backscattering Spectrometry (RBS), or Nuclear Reaction Analysis (NRA), may be selected. Ion beam analysis offers several important advantages: it is non-destructive, highly sensitive, and capable of resolving elemental distributions within extremely thin surface layers, much like examining tree rings to understand a material's layered structure. These capabilities are particularly useful for analyzing microscopic residues, such as a thin smear of explosive material or a trace soil deposit, that might otherwise go undetected. However, IBA is not without limitations. The equipment is expensive, requires specialized laboratory infrastructure, and demands a high level of technical expertise to operate and interpret results. Consequently, ion beam analysis is not typically used in routine forensic casework. Instead, it is reserved for high-stakes or complex investigations in which precise elemental characterization is essential for advancing the inquiry.

2.4. Nano-trackers and nanotechnology-enabled anti-counterfeiting systems

Nanotechnology has enabled the development of nanoscale trackers, barcodes, and security markers (**Figure 5**) designed to support law enforcement and enhance crime-prevention strategies [29]. These nano-engineered identifiers can be incorporated into merchandise, packaging, and high-value assets to create covert patterns or pictograms that deter theft and facilitate the recovery of stolen materials. When illuminated or analyzed under specific investigative conditions, these nano-markers enable rapid and reliable verification of an item's origin, ownership, or authenticity.

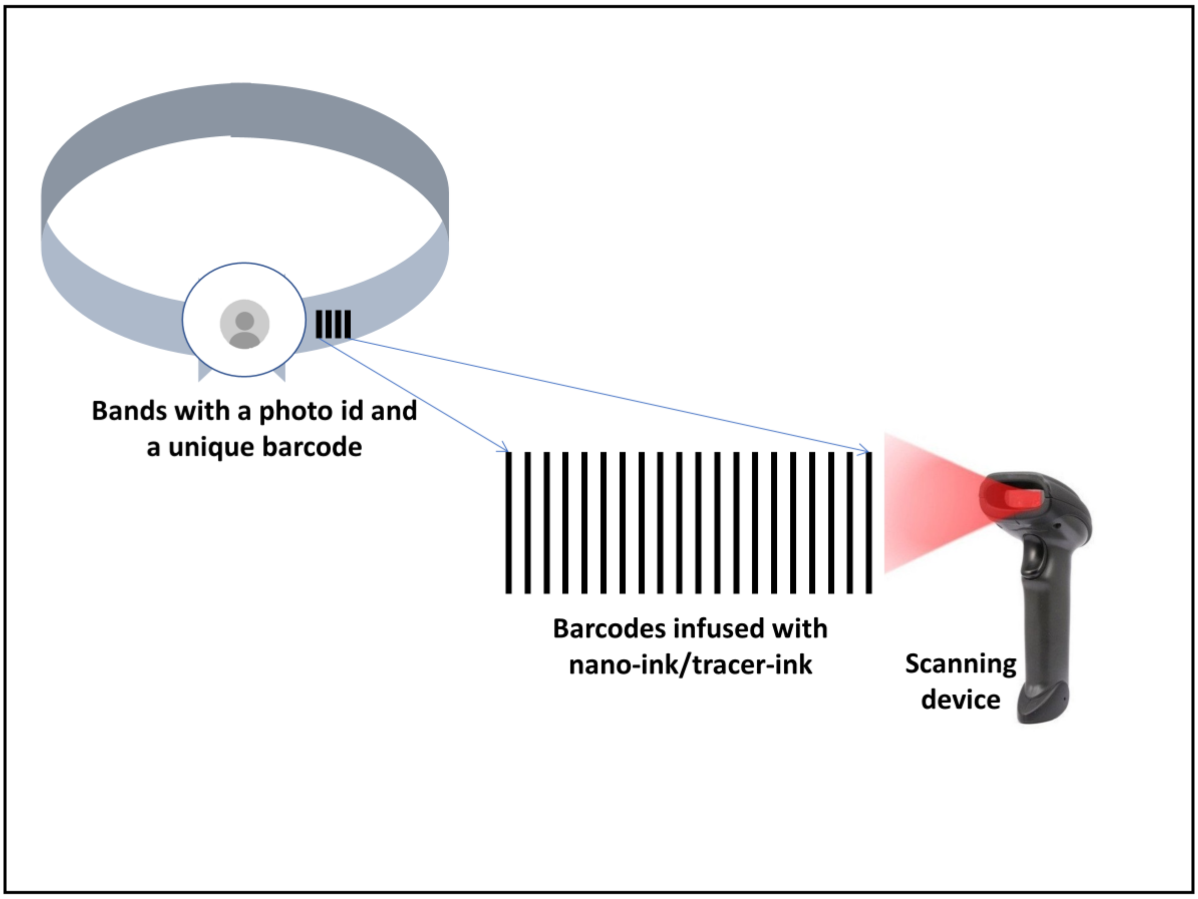

Figure 5. Specialized Bands for prison inmates with distinct nano-trackers.

Beyond theft prevention, nano-trackers play an increasingly important role in combating product counterfeiting. Counterfeit goods inflict significant economic losses, undermine consumer trust, and damage corporate and national reputations. To address this challenge, manufacturers are integrating nanofibers, nanodots, luminescent nanoparticles, and nanoscale watermarks into items and documentation as embedded security features [53]. These structures exhibit unique optical or spectral signatures that are difficult to replicate and can be authenticated using specialized forensic illumination sources or spectroscopic methods.

Such nano-enabled markers create a robust security framework for distinguishing genuine products from sophisticated counterfeit replicas. Their covert nature and high specificity make them especially valuable for protecting pharmaceuticals, currency, identification documents, electronics, luxury goods, and critical supply-chain assets.

Within forensic science, the use of nano-trackers is therefore best characterized as a material-authentication and anti-counterfeit technology [54]. Incorporating nanostructured signatures into products provides investigators with verifiable forensic traceability and strengthens the evidentiary chain when illicit goods are seized.

It is important to clarify that popular narratives describing nano-trackers implanted into individuals for continuous surveillance are speculative and fall outside standard forensic practice. Such concepts raise substantial ethical, legal, and human-rights concerns and are not supported by contemporary forensic methodologies or policy frameworks. Current and legitimate forensic applications remain firmly centered on object-based authentication, supply-chain protection, and counterfeit prevention, rather than the monitoring of persons.

In summary, nano-trackers and nanotechnology-enabled barcoding systems represent powerful tools for deterring theft, preventing fraud, verifying authenticity, and supporting forensic investigations. Their integration into modern security infrastructure highlights the growing role of engineered nanomaterials in strengthening both public safety and economic resilience.

2.5. Nano-enabled approaches for screening drug-facilitated crimes

Drug-facilitated crime (DFC), often associated with "date rape," but also involving robbery, extortion, and assault, refers to offenses committed against individuals whose cognition or decision-making capacity has been compromised by psychoactive substances [55,56]. These drugs impair motor coordination and awareness, making victims vulnerable to coercion or violence across all age groups.

Detecting substances used in DFC cases remains a major forensic challenge. Many incapacitating agents are rapidly metabolized, present at extremely low concentrations, or degraded by the time victims seek assistance. Matrix effects, delayed reporting, and specimen variability further hinder the detection of these compounds. Although conventional toxicological methods remain reliable, their effectiveness is limited by sensitivity constraints, costly instrumentation, and labor-intensive workflows [57].

Nanotechnology offers promising solutions to these analytical limitations. Nanoparticles, quantum dots, nano-biosensors, and nanostructured detection platforms exhibit unique physicochemical properties that enhance sensitivity, selectivity, and signal amplification. These systems enable the detection of trace drug concentrations and metabolites that may evade standard screening. Additional benefits include miniaturization, rapid analysis, automation potential, and improved cost-effectiveness, making nano-enabled methods attractive for preliminary DFC screening [58].

Recent innovations include "smart" nanosensing systems that combine gold nanoparticles with smartphone-based detection. For example, citrate-stabilized gold nanoparticles have been used in a colorimetric platform capable of rapidly identifying codeine sulfate using only a smartphone camera for RGB-based quantification [26,59]. **Figure 6** depicts this nano-enabled sensing strategy for detecting narcotics and hallucinogenic substances frequently implicated in DFC cases.

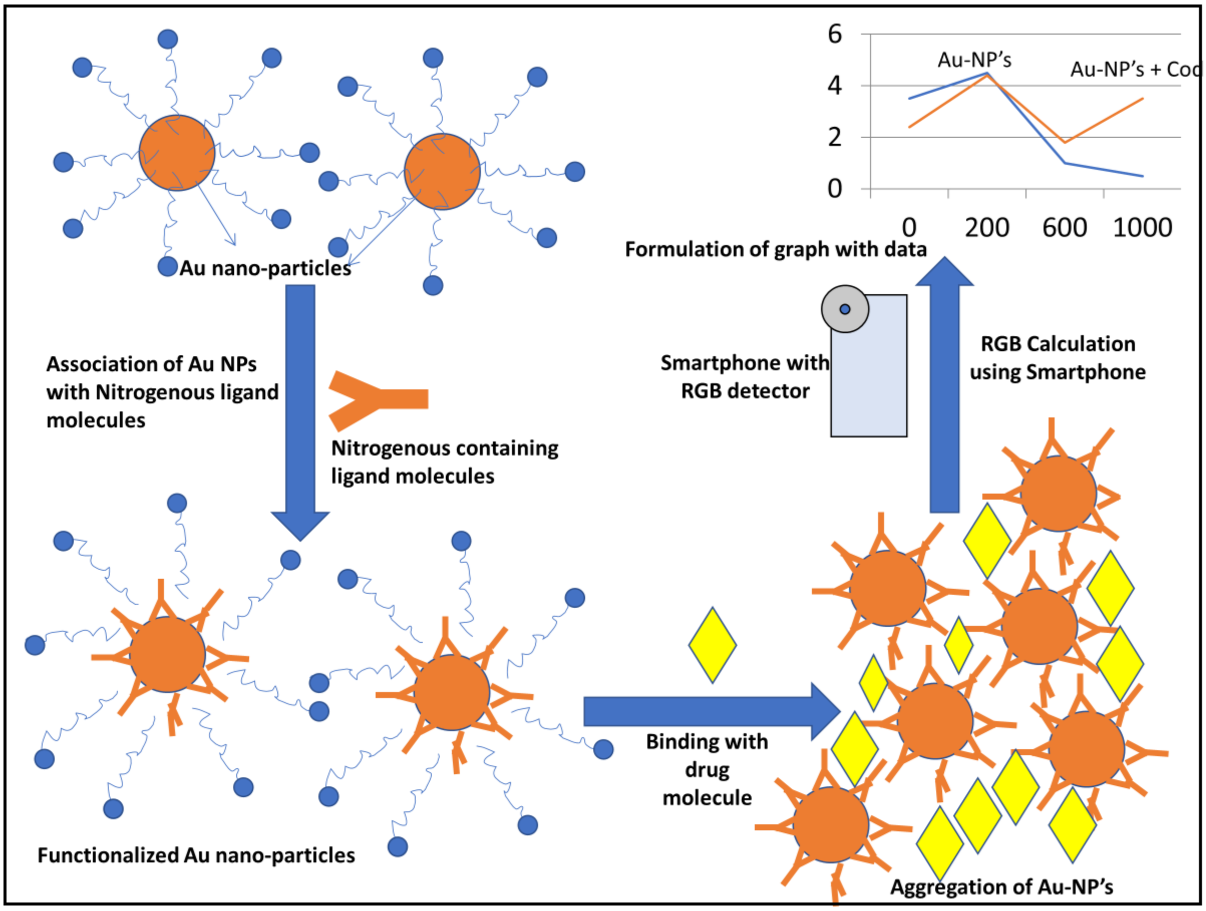

Figure 6. Detection of Drug Facilitated Crimes using advanced RGB Detection by smartphone cameras by conjugation of narcotics/hallucinogens with Au NP's.

Despite their promise, nano-based toxicological methods are not yet suitable as confirmatory forensic techniques. Nanoparticle behavior varies across biological matrices, and endogenous compounds may interfere with nanosensor performance. The field also lacks standardized protocols, inter-laboratory validation, and regulatory frameworks necessary for courtroom admissibility. Consequently, concerns remain regarding reproducibility, quality assurance, and legal reliability.

For these reasons, nano-enabled toxicological tools should be regarded as complementary innovations, well-suited for rapid preliminary screening, early case triage, and guiding targeted confirmatory tests, but not as replacements for validated forensic toxicology methods. As research advances and standardization improves, nano-assisted platforms may play an increasingly integrated role in forensic toxicology, supporting more efficient and sensitive detection of drugs used in DFC investigations.

2.6. Nano-enabled approaches for estimating the time since death

Accurate estimation of the time since death (TSD), also referred to as the post-mortem interval (PMI), is a critical component of medico-legal investigations. Traditional TSD estimation relies on observable physiological and biochemical changes such as algor mortis, rigor mortis, livor mortis, decomposition stages, ocular changes, gastric emptying, and alterations in bodily fluids. Although these parameters offer useful approximations, they are influenced by environmental and individual factors, which limit their precision.

Among post-mortem fluids, the vitreous humor (VH) is particularly valuable because it is isolated, slow-changing, and relatively protected from environmental contamination. Research has shown that certain biochemical markers within VH, particularly amino acids, exhibit gradual and predictable post-mortem changes, making them useful for refining TSD estimation. One such biomarker is cysteine, whose concentration changes slowly enough to allow for more accurate assessments of TSD compared with several other fluids [8].

Recent advancements in nanotechnology and microfluidics have introduced lab-on-a-chip systems that offer sensitive, rapid, and cost-effective detection of cysteine levels in VH. These nano-enabled analytical platforms can detect biochemical shifts up to 96 h before substantial increases in cystine concentration occur, potentially supporting earlier and more precise TSD estimations. Such systems also allow for scalable microfluidic integration, which could eventually improve the accuracy and efficiency of TSD assessments by correlating biomolecular patterns with post-mortem timelines.

However, it is essential to recognize that nano-enabled methods for PMI estimation remain experimental. While they show significant scientific promise, they are not yet validated for routine forensic casework. Current limitations include variable nanoparticle behavior across biological matrices, potential interference from endogenous compounds, and the lack of standardized protocols or admissibility frameworks within forensic laboratories. Consequently, nano-enabled techniques are more valuable for understanding post-mortem biochemical processes than for providing the legally defensible TSD estimations required in court.

Looking ahead, the most realistic and impactful role of nanotechnology in PMI estimation will likely emerge through integration with established forensic tools. When used within multidisciplinary frameworks that also include histological, entomological, biochemical, and environmental evidence, nano-assisted platforms may eventually contribute to the higher precision and reliability that forensic practice seeks.

3. Security, governance, and ethical considerations of nano-enabled forensics

Nanotechnologies have the potential to modernize forensic investigation and security operations by reducing time, skill barriers, and cost, while improving analytical accuracy and field accessibility through nano-enabled sampling and detection devices [60]. Despite this promise, applied research in forensic nanotechnology remains nascent, and many anticipated applications still require demonstrated validation, standardization, and legal acceptance before routine adoption.

3.1. Technical maturation and standardization needs

Current challenges include inconsistent terminology and classification, variable performance across biological and environmental matrices, and gaps in quality assurance protocols. Health and safety considerations associated with the production, handling, and disposal of nanomaterials also require clear guidance. More broadly, concerns have been raised that the unchecked proliferation of "nanomaterials" could shift technological leverage toward entities with privileged access, complicating global equity and power dynamics [7]. Addressing these issues demands interdisciplinary standards, robust validation studies, and alignment with forensic quality systems.

3.2. Public understanding, policy, and oversight

A persistent obstacle is limited public awareness of how nano-enabled tools are used in security and forensic contexts. This knowledge gap can be mitigated through transparent communication, evidence-based outreach, and privacy-preserving access to personal data. However, improved access must be matched with clear regulations to prevent unauthorized use, data disappearance, or mission creep. As nanotechnologies grow more complex, regulatory capacity must keep pace, particularly if core capabilities are increasingly concentrated in private organizations that hold the technical know-how. Effective oversight requires independent auditing, clear accountability mechanisms, and public-interest safeguards.

3.3. Privacy, surveillance, and data protection

The miniaturization and covert detectability of some nano-devices raise well-known privacy and surveillance risks. Hypothetical misuse includes clandestine data collection on individuals or firms using discrete nanoscale sensors. Such practices would present serious threats to informational self-determination and due process, particularly if government or corporate actors gain disproportionate ability to access sensitive personal data without robust legal controls [61]. Forensic adoption must therefore be bound by strict authorization regimes, data minimization, proportionality, and independent oversight to maintain public trust and legal defensibility.

3.4. Responsibility, agency, and human factors

Questions of accountability arise when technologies can influence human behavior or shape investigative judgments. Determining intent and agency becomes more complex if external technological factors affect decisions or outcomes. Intersections between neurotechnologies and nanoscale tools, occasionally discussed in speculative contexts, underscore the need for ethical review, forensic restraint, and judicial caution. Even where nanotechnology may offer insights into cognitive states or behavioral correlates, its use must respect human rights, avoid overinterpretation, and remain within accepted scientific validity thresholds.

3.5. Path forward: Risk mitigation and responsible integration

Historically, technological risks have been addressed and outweighed by careful design, targeted regulation, and continuous oversight. The same applies to nanotechnologies, which offer meaningful security and forensic benefits when paired with:

- Clear legal frameworks tailored to nanospecific risks,
- Standards for validation, inter-laboratory reproducibility, and chain-of-custody,

- Health, safety, and environmental (HSE) protocols across the lifecycle of nano-materials,
- Privacy-by-design safeguards and data-protection impact assessments,
- Independent audits and accountability structures to deter misuse.

By embedding these controls, stakeholders can leverage nano-enabled innovation to enhance security and forensic capability while protecting civil liberties and upholding evidentiary rigor.

4. Nanotechnology in questioned documents and nanoscale analytical methods

4.1. Nanotechnology and questioned documents

Nanomaterials are increasingly incorporated into writing and printing inks to enhance performance and enable forensic discrimination. Scanning electron microscopy (SEM) of ink cross-sections reveals morphology and elemental composition of nanopigments, supporting source attribution and authenticity assessments [62].

Security printing has leveraged nanotechnology to develop self-erasing inks and papers composed of ~5 nm gold or silver nanoparticles embedded in organic gel films. These systems undergo controlled aggregation-induced color changes under UV exposure and photo-induced disassembly, enabling temporary marking for confidential documents [63,64].

Further, gold-nanoparticle inks functionalized (e.g., with alkanethiols) have been used in RFID and military security barcodes, while luminescent nanoparticles (quantum dots, nano-phosphors, upconverters) serve as covert tags in high-security documents to deter counterfeiting [65].

At the document surface, atomic force microscopy (AFM) provides qualitative, high-resolution information about depth, amplitude, and phase at ink–paper interfaces, aiding reconstruction of stroke order (e.g., ballpoint vs ribbon dye) and revealing microstructural features not accessible with conventional optical methods [65].

Nevertheless, while nano-enabled document examination markedly improves resolution and sensitivity, results should be interpreted alongside established forensic criteria; specialized expertise and careful sample preparation are often required. These techniques are best viewed as adjuncts to, not replacements for, traditional document examination.

4.2. Nanotechnology-based analytical applications in forensics

A suite of nanoscale and microanalytical tools supports the characterization of inks, papers, biological traces, and other evidentiary materials:

(1) *Atomic Force Microscopy (AFM):*

Beyond document analysis, AFM assesses 3D surface morphology and nanomechanical properties (e.g., roughness, adhesion) due to its capability of high spatial resolution and nanomechanical insights It has been applied to stroke order determination in questioned documents [66], post-mortem interval (PMI) studies via erythrocyte nanomechanics (force–distance curves documenting elasticity changes in dried bloodstains) [67], and trace evidence analysis (e.g., textile fibers, pressure-sensitive adhesives) through quantitative surface texture parameters [68]. However, AFM is best suited to targeted micro-analysis rather than high-throughput screening due to its limitation such as a small field of view and labor-intensive workflows.

(2) *Electron Microscopy (TEM/SEM):*

Transmission electron microscopy (TEM) uses high-energy electron beams to probe internal structure, lattice features, and nanoparticle morphology, often yielding 2D images and diffraction data. Scanning electron microscopy (SEM) maps surface topography and near-surface composition via secondary/backscattered electrons, producing quasi-3D surface imagery suited to ink/paper interfaces and nanoparticle distributions [62,65].

(3) *Infrared Micro-Spectroscopy and Micro-X-ray Fluorescence (MXRF):*

These modalities enable chemical functional group identification (IR) and elemental mapping (MXRF) at the microscale, providing complementary information to electron and probe microscopies in complex, layered samples (inks, coatings, substrates) [66–68].

(4) *Dynamic Light Scattering (DLS):*

Also known as photon correlation or quasi-elastic light scattering, DLS rapidly estimates hydrodynamic size distributions (≈0.8–6500 nm) and detects low-level aggregation (down to ~0.01% by weight) in nanoparticle formulations, which are useful for ink nano-additives and forensic nanoprobes [1].

(5) *Raman Micro-Spectroscopy (Micro-Raman):*

Raman maps vibrational signatures without extensive sample preparation and is relatively insensitive to water, making it suitable for intact materials (papers, inks, biological residues). Laser excitation, monochromation, and CCD/PMT detection enable non-destructive chemical identification and imaging at the microscale [66].

4.3. Summary and forensic integration

Nanotechnology has expanded the toolkit for questioned document examination and trace evidence analysis, enabling covert security features, enhanced anti-counterfeiting, and high-resolution, multimodal characterization of inks, substrates, and residues [62–68]. In forensic applications, the type of analytical methods should be selected based on each technique’s functionality: AFM provides topographical and mechanical detail; TEM/SEM yield structural and morphological insights; IR/MXRF provides chemical/elemental mapping; DLS verifies nano-ink stability; Raman offers non-destructive molecular fingerprints. In combination, these orthogonal methods deliver robust, multimodal characterization for questioned documents and trace evidence. Nevertheless, these techniques provide complementary datasets that, when integrated, strengthen attribution, authenticity verification, and reconstruction. Routine adoption should continue to emphasize validation, standardized protocols, and expert interpretation, ensuring nano-enabled findings are scientifically defensible and aligned with forensic best practices [1].

5. Ethical, legal, and safety considerations for nanotechnology in forensic analysis

The growing adoption of nanotechnologies in forensic science raises important ethical, legal, and safety considerations that must be addressed prior to widespread implementation. Because judicial outcomes rely heavily on forensic evidence, any nano-enabled method proposed for casework should demonstrate high reliability, transparency, and reproducibility under validated protocols. Although state-of-the-art nano-approaches offer advanced sensitivity and novel capabilities, they often involve complex workflows and non-intuitive measurement principles, which can be difficult to explain to non-experts (e.g., judges and juries) without rigorous validation and clear interpretive guidance.

5.1. Ethical considerations

- Risk of overinterpretation: As detection limits decrease, the likelihood of identifying trace-level contaminants or benign background compounds increases [69]. Such findings may lack probative value without appropriate contextualization (e.g., transfer mechanisms, persistence, environmental prevalence).
- Interpretive discipline: To avoid overstating sensitivity as evidentiary significance, nano-derived results must be linked to well-designed validation studies, uniform operating protocols, and predefined interpretive criteria tailored for forensic application [69].
- Transparency and explainability: Given method complexity, experts should be prepared to provide clear, lay-accessible explanations of principles, limitations, and uncertainty to support fair adjudication.

5.2. Safety considerations

- Material hazards: Engineered nanoparticles can exhibit enhanced reactivity and potential toxicity distinct from their bulk counterparts, particularly under chronic or repeated exposure [70].
- Laboratory controls: Forensic laboratories employing nanomaterials should implement formal risk assessments, engineering controls (e.g., containment and ventilation), standardized handling and disposal procedures, and appropriate PPE and training to protect personnel and the environment [69].

5.3. Legal considerations

- Admissibility standards: Courts typically assess scientific evidence under Daubert or Frye criteria, focusing on testability and replication, peer review, known or potential error rates, standards and controls, and general acceptance in the relevant scientific community [70].
- Current readiness: Many nano-forensic techniques are still maturing and may lack comprehensive validation or broad forensic acceptance, limiting their immediate suitability for courtroom use [69,70]. Until such benchmarks are met,

courts should exercise caution and require clear disclosures of limitations, uncertainties, and method performance.

5.4. Path to responsible adoption

To responsibly integrate nanotechnology into forensic practice:

- Establish standardized protocols, QA/QC frameworks, and inter-laboratory validation aligned with forensic standards.
- Report error rates, limits of detection, matrix effects, and uncertainty alongside results to support legal scrutiny [70].
- Maintain ethics-by-design and safety-by-design approaches, including life-cycle considerations for nanomaterial handling [69].
- Prioritize training for practitioners and clear communication for courts to ensure scientific transparency and public trust.

6. Limitations and future perspectives

Despite substantial promise, the adoption of nanotechnology in forensic science faces notable constraints that must be addressed before the routine implementation. Most nano-enabled applications remain early-stage, with limited forensic validation. Key gaps include inter-laboratory reproducibility, standard operating procedures (SOPs), and the long-term stability and reliability of nanomaterials under real-world forensic conditions. Cost and complexity further limit accessibility. Many nanoscale imaging and sensing platforms require specialized infrastructure, expert operators, and significant capital investment, which can be prohibitive, particularly for laboratories in resource-constrained settings [71].

Looking ahead, progress will likely come from improving portability, automation, and user-friendliness. Integrating nanotechnology with microfluidics, AI-assisted analytics, and standardized data pipelines could accelerate workflows while enhancing sensitivity and decision support. However, such advances must be matched by robust validation, quality assurance frameworks, and ethical oversight to ensure scientific defensibility and public trust.

Importantly, nanotechnology should be viewed as a complement to, not a replacement for, established forensic methods. Responsible integration will depend on sustained collaboration among forensic practitioners, materials scientists, legal experts, and regulatory bodies to align performance standards, admissibility criteria, and practitioner training for real-world casework.

7. Conclusion

Nanotechnology is no longer a future prospect. It is already reshaping forensic science. By enabling measurements and imaging at the nanoscale, it enhances the detection and interpretation of trace evidence across diverse domains, including latent fingerprint visualization, explosive residue identification, toxicology, DNA analysis, and post-mortem interval estimation [72]. These advances expand investigative sensitivity, specificity, and throughput, revealing probative details that were previously inaccessible.

Translating these laboratory innovations into routine casework, however, remains a central challenge. For nano-enabled methods to achieve courtroom admissibility, they must demonstrate rigorous validation, reproducibility, standardized operating protocols, and clear interpretability aligned with legal standards. Many techniques highlighted in this review show strong promise under controlled conditions, but they require comprehensive inter-laboratory studies, quality assurance frameworks, and transparent reporting of limitations before widespread forensic adoption.

Ultimately, nanotechnology should be viewed as a complementary evolution, not a replacement of established forensic techniques. By prioritizing method transparency, interdisciplinary collaboration, and standards development, the forensic community can responsibly integrate nano-enabled tools to strengthen evidentiary integrity and investigative reliability, while preserving the foundational principles that underpin the justice system.

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