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NARRATIVE REVIEWS

Advances in Nanotechnology for Latent Fingerprint Detection

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Abstract

Nanotechnology has become a transformative tool in forensic investigations, offering enhanced capabilities for detecting and examining materials of evidentiary relevance. Owing to their physicochemical features, nanomaterials have proven beneficial in identifying latent fingerprints, detecting illicit drugs, and tracing explosive residues. Their integration into molecular biology techniques like polymerase chain reaction has improved accuracy and sensitivity of DNA analysis. Sophisticated analytical procedures, such as atomic force microscopy, scanning electron microscopy–transmission electron microscopy, dynamic light scattering, Raman micro-spectroscopy, and time-of-flight mass spectrometry, are used to detect forensic traces at microscopic and nanoscopic levels. Although latent fingerprints are vital forensic evidence, their recovery from difficult surfaces such as textured vehicle dashboards remains limited. No universally accepted method exists to reliably extract prints from such complex substrates at crime scenes. Conventional visualization techniques use fingerprint powders, followed by lifters or molding materials to transfer impressions. Cyanoacrylate fuming and fluorescent dyes, such as Rhodamine 6G, are also used to enhance contrast and visibility. However, the effectiveness of lifters and casting materials on uneven surfaces is not studied extensively and presents an area for research. Collection, processing, and interpretation of fingerprint evidence should be conducted by trained forensic experts to ensure accuracy. When applied correctly, fingerprint identification remains one of the most reliable methods for linking individuals to criminal acts. It can substantiate witness testimonies, corroborate forensic findings, and exclude individuals from suspicion, helping investigators allocate resources effectively.

1. Introduction

The study of nanotechnology concerns the manipulation and use of particles measuring between 1 and 100 nanometers (nm) in size [1]. It readily lends itself to a wide variety of applications in modern forensic science [2]. This occurs because, at this scale, particles begin to show unique and typically improved properties; these include a large surface area, quantum behavior, and, above all, smaller particle size [3]. They are commonly used in a diverse range of applications and processes, such as scanning tunneling microscopy, microscale chemical technology, nanoelectronics, biochemistry, calorimetry, electro-optics, and so on [4]. This accounts for their increasing application in multidisciplinary fields of science, especially the life sciences [5].

These materials, therefore, have potential for special applications in detection systems (enlarged latent fingerprint development, nanoscale bomb and drug particle detection, etc.) [6]. The need for more accurate detection systems is growing. Issues of national security and civil safety, including prison security, make it

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necessary for latent fingerprints to be easier to identify, have more details, and to have markings that last longer and do not change or disappear over time [7]. This is particularly important in prevention and crime-solving [8]. The increasing importance of these areas has generated a clear need for the development of nanotechnology in forensic sciences, particularly when detecting latent fingerprints [9]. We intend to provide a brief review of these developments so that they can be referred to as part of a larger composite in future [10].

2. Background

Nanotechnology is concerned with the nanoscale manipulation of matter, typically between 1 and 100 nanometers in size [1,5]. This field has emerged as a powerful interdisciplinary science that intersects physics, chemistry, biology, and materials science [11,12]. In forensic science, nanomaterials offer unique advantages because of their high surface area–volume ratio, optical properties, and reactivity, making them particularly useful in detection and enhancement [39,92].

Fingerprint detection, especially latent fingerprint visualization, is a crucial element in forensic investigations. Traditional techniques include powder dusting, ninhydrin spraying, and cyanoacrylate fuming, which rely on physical or chemical interactions with components of fingerprint residues, such as sweat, amino acids, or oils [27,28]. While effective, these methods often suffer from limitations, such as environmental sensitivity, low contrast on certain surfaces, and reduced accuracy over time because of degradation of print components.

Recent advancements in nanotechnology have led to the development of a variety of novel techniques to overcome these challenges. Nanoparticles (NPs), such as quantum dots (QDs), carbon nanotubes (CNTs), metal oxides, and magnetic nanostructures, are now employed to improve visualization and enhance contrast, even on challenging surfaces such as textured plastics or fabric. These materials can bind selectively to fingerprint residue components, offering greater sensitivity and specificity [27,29,31].

One significant innovation is the use of polymer dots (Pdots) with near-infrared (NIR) fluorescence properties. These Pdots can be engineered to bind with amino acids present in fingerprint residues, offering enhanced visualization under specific lighting conditions. Figure 1 outlines how the synthesis of functionalized Pdots can lead to high-contrast fingerprint images by combining optical sensitivity and chemical specificity [21,54,55]. The process involves synthesizing a conjugated polymer, stabilizing polymer, and a chemical used for detecting amino acids in latent fingerprints. Pdots exhibit strong NIR emission, making them suitable for high-contrast visualization under specific lighting conditions. The method combines chemical sensitivity and optical fluorescence, enhancing fingerprint detection and forensics analysis.

To contextualize these advancements, Table 1 provides a comparative overview of traditional fingerprint detection techniques and those enabled by nanotechnology. Key differences lie in the methods employed, environmental safety, detection mechanisms, and performance across various surface types. This comparison highlights the transformative potential of nanoscale materials in forensic science [27,92].

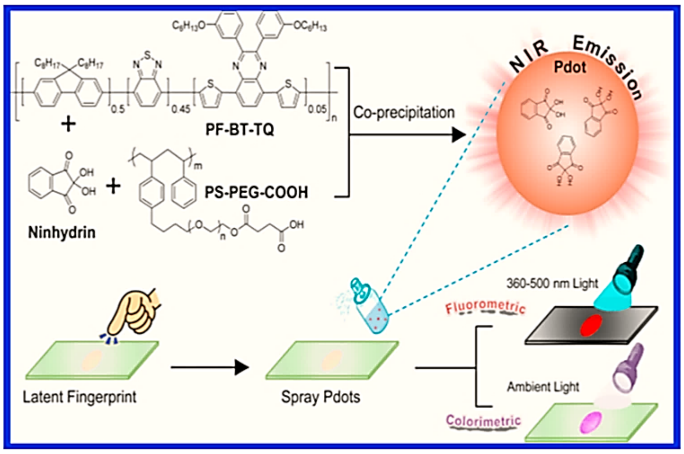

Figure (1): Process for improving latent fingerprint detection using polymer dots (Pdots) with near-infrared (NIR) emission [26].

Table (1): A comparison table summarizing traditional techniques and nanotechnology-based approaches for latent fingerprint detection.

Aspect	Traditional methods	Nanotechnology approaches
Chemical use	Involves harmful chemicals (e.g., ninhydrin, cyanoacrylate) [28]	Uses low-toxicity, environment-friendly nanomaterials [31]
Detection basis	Physical interaction with sweat, oil, and amino acids [29]	Molecular-level interaction and nanoscale binding [32,33]
Surface compatibility	Less effective on texture or porous surfaces [31]	Works well even on rough and complex substrates [32,34]
Clarity & sensitivity	Limited contrast and resolution	High-detail, high-sensitivity detection [29]
Technological progress	Limited innovation over recent years	Rapid advancements using smart, adaptive materials [30,32]
Tools used	Powders, chemical sprays, lifting tapes	Quantum dots, nanostructured films, fluorescent nanoparticles [32,33]
Environmental impact	Often unsafe or polluting [26]	Green chemistry principles with improved safety [30]
Future prospects	Incremental improvements expected	Strong potential for miniaturized, on-site forensic tools [34]

Despite these advances, broader implementation remains limited by factors, such as cost, complexity of synthesis, and regulatory concerns. Nonetheless, nanotechnology is poised to redefine latent fingerprint detection through its adaptability, sensitivity, and precision.

3. Principles of Latent Fingerprint Detection

Detecting latent fingerprints, such as invisible traces left behind by natural secretions, is one of the foundational techniques in forensic science. Two widely used methods to visualize them are fuming and application of chemical dyes [13].

In the solvent entombment method, a solvent, typically an ester, penetrates the dehydrated fingerprint residue, encapsulating it for further treatment [14]. The print is then exposed to a fluorescent dye. After absorption, the latent print becomes visible under a secondary light source, such as ultraviolet (UV) light, creating a fluorescence effect that highlights ridge patterns [15,16]. To make print permanent, it is often dusted with powder. However, this multi-step process can be sensitive. Overprocessing, poor surface quality, or examiner's experience can reduce clarity of the print [17–19].

Fuming, particularly with cyanoacrylate, works by releasing vapors that form a polymer coating on fingerprint's ridges [20]. This polymerization enhances ridge visibility. More advanced techniques now use coated luminescent fuming, which incorporates fluorescent agents to improve details' recognition [21]. These methods allow for clear identification of second-level details such as ridges, furrows, and bifurcations [11,22]. The resulting contrast, typically white ridges on a darker background, makes the print highly visible [23]. Combined with dye treatment, the fumed print can form a well-defined three-dimensional (3D) map of ridge details [24,25].

4. Traditional Techniques vs. Nanotechnology

Traditional fingerprint detection methods, such as powdering, ninhydrin spraying, and cyanoacrylate fuming, depend on physical or chemical interaction with fingerprint residues such as sweat, oils, and amino acids [12,27]. While these methods are widely used, they have limitations: low sensitivity on aged or textured surfaces, poor environmental adaptability, and reliance on potentially hazardous chemicals [28].

Nanotechnology offers a more advanced solution. Materials engineered at nanoscale, such as quantum dots, metallic nanoparticles, and carbon-based nanostructures, interact more precisely with fingerprint residues because of their small size and high surface area [29]. These nanomaterials can bind to specific components in the residue, providing stronger contrast, enhanced resolution, and greater adaptability across various surfaces [30].

Researchers are also exploring biomimetic systems that imitate natural structures to improve adherence and image clarity. These innovations not only reduce the environmental impact but also overcome challenges posed by complex or deteriorated surfaces [31,32]. The integration of smart nanotechnologies is pushing the boundaries of what is possible in forensic detection [33].

5. Nanoparticles and Their Role in Fingerprint Detection

Nanoparticles are materials that measure less than 100 nanometres in at least one dimension and bridge the gap between atomic-scale matter and bulk materials [34,35]. These particles can be composed of metals, non-metals, liposomes, quantum dots, carbon structures, or biomolecules [36]. Owing to their minute size, nanoparticles exhibit unique optical, magnetic, and chemical properties that differ significantly from their larger counterparts, making them powerful tools in forensic imaging and detection [37,38]. They are typically synthesized through techniques such as chemical reduction, thermal decomposition, or deposition methods, each affecting their morphology and functionality [39].

In forensic science, particularly fingerprint detection, nanoparticles are making a transformative impact. For example, gold nanoparticles can be synthesized from natural plant extracts, such as *Drimia indica* (*D. indica*), providing an eco-friendlier route to production of nanoparticles [40]. A notable development involves DITMSA (a specific nanoparticle formulation), which has demonstrated excellent optical properties, zeta potential, and UV response, making it ideal for detecting fingerprints [41]. When applied using laser-assisted electrodeposition, these nanoparticles turn latent fingerprints into silver-metal imprints, offering enhanced contrast and clarity [42]. Experimental studies using DITMSA, coffee powder, and household dust yielded 100% detection accuracy, showcasing their practical reliability in forensic scenarios [43].

6. Nanotechnology-Based Imaging Techniques

Recent advances in nanotechnology have introduced new imaging tools into forensic science, supplementing traditional Raman spectroscopy. These include hyperspectral imaging, chemical vapor imaging, and scanning probe microscopies that offer nanoscale resolution [44]. Although only a few of these have seen widespread forensic use so far, technologies such as atomic force microscopy (AFM) and tunnel molecular force microscopy are gaining traction because of their capacity for high-detail visualization [45].

Advanced infrared techniques have shown potential in detecting luminescent fingerprints on treated paper, especially those doped with elderberry extracts and metallic agents such as titanium or lanthanides. These modifications create high-contrast nanocomposites that are particularly useful for aged fingerprints or complex surfaces [46,47].

7. Surface-Enhanced Raman Spectroscopy (SERS)

Surface-enhanced Raman spectroscopy is a highly sensitive variation of Raman spectroscopy that uses metallic nanoparticles, commonly gold or silver, as substrates to amplify signal responses [48,49]. These nanoparticles can detect even faint fingerprints on smooth or reflective surfaces, such as glass or plastic [50]. For example, silver nanoparticles embedded in silk films or on paper substrates have demonstrated strong enhancement of fingerprint ridge detail [51,52]. In one method, silver nanoparticles are deposited onto reduced graphene oxide (rGO) and polyvinyl alcohol (PVA) films using a microwave-assisted technique. The resulting composite exhibits high flexibility, uniform nanoparticle growth, and excellent adhesion, making it ideal for latent fingerprint detection [53,54].

8. Quantum Dots in Fingerprint Detection

Quantum dots are semiconductor nanocrystals known for their bright and tunable luminescence, offering a clear advantage over traditional dyes [55]. They are especially useful in fingerprint detection because of their sensitivity to excitation light and robust stability [56]. Quantum dots combined with silver nitrate and surfactants are now used to produce fingerprint powders that can detect prints on glass, metal, and plastic [57].

Studies show that factors, such as UV excitation intensity, treatment duration, and environmental conditions, directly influence the luminescent intensity of quantum dot-based powders [58,59]. Sulfide coatings enhance this stability, preventing photodegradation and extending usability in field conditions [60,61]. Since conventional powders often lack the sensitivity needed for weak or partial prints, quantum dot-based solutions represent a significant upgrade for forensic practitioners [62–64].

9. Carbon Nanotubes and Graphene in Forensics

Carbon nanotubes and graphene are known for their strength, flexibility, and excellent electrical and thermal conductivity, which make them promising candidates in forensic applications [65]. These carbon-based nanomaterials are used to create new fingerprint detection systems and to enhance the performance of the existing ones [66]. However, their application must consider environmental and toxicity factors, including how different coatings influence their behaviour [67].

Researchers are investigating how to create safe and effective formulations for forensic use. For example, pre-oxidized multi-walled CNTs or those paired with organic adhesives can enhance fingerprint quality on substrates where traditional powders fail [68,69]. Graphene-based materials also overcome challenges associated with "invisible fingerprints" caused by surface texture or chemical interference [70,71]. Numerous studies have demonstrated that these advanced coatings produce clear and high-quality ridge details across a wide range of surfaces [72–74].

10. Advances in Nanopore Technology

Nanopore technology represents a cutting-edge approach to fingerprint detection. It operates through tiny pores in membranes and analyzes the size and composition of individual molecules in fingerprint residues [75]. These systems are highly precise, label-free, and non-destructive ideal qualities for forensic evidence analysis [76].

What makes nanopore technology especially exciting is its compatibility with flexible and wearable electronics. These developments could soon lead to wearable fingerprint detectors integrated into gloves or handheld devices used directly at crime scenes [77].

Traditional fingerprint detection methods are often time-consuming, expensive, or prone to damaging the print. In contrast, nanopore devices promise to deliver real-time analysis with minimal background noise or chemical interference [78,79]. Research is now focused on optimizing the fabrication of solid-state nanopores and integrating them with biocompatible sensors for use in real-world forensic environments [80–83].

11. Nanotechnology in Fingerprint Enhancement

Despite ongoing improvements, visualizing latent fingerprints remains a persistent challenge in forensics [84]. Traditional methods, such as lasers, powders, and chemical dyes, often fail on textured or dark surfaces and may damage the print in the process [85]. Nanotechnology, first introduced conceptually in 1959, has now matured to the point where its application in fingerprint enhancement is both practical and powerful [62].

Because nanoparticles have an incredibly high surface area–mass ratio, they bind effectively to fingerprint residues, increasing contrast and clarity [86]. Over the last decade, a wide variety of nano-powders, fluorescent, magnetic, or metallic, have been developed to improve detection across different surfaces and environmental conditions [87].

However, no universal method yet exists, and forensic experts often struggle to choose the most effective technique for a given case. Millions of latent prints may go undeveloped due to this limitation [88]. Research now focuses on creating nanoparticle-based "universal developers" capable of adapting to multiple surface types and residue conditions [88].

12. Nanotechnology in Fingerprint Visualization

Fingerprint visualization using nanotechnology relies on the use of specially engineered particles, often metallic or fluorescent, that can adhere to trace residues and render high-resolution prints [33]. These nano-powders are highly sensitive and provide superior visualization on both common and challenging surfaces [21,68,89].

Optimizing these particles for stability, cost, and surface compatibility remains an ongoing research priority. Different deposition temperatures and methods of synthesis can dramatically influence performance [90,91]. A growing body of work now focuses on improving these protocols to ensure consistent high-quality results across various crime scene environments [92].

13. Nanotechnology in Fingerprint Development

Latent fingerprints are some of the most valuable forms of physical evidence in criminal investigations, and nanotechnology has revolutionized how they are detected and developed [20,27]. Compared to traditional methods, nanoparticle-based approaches often yield higher-quality prints with better resolution, even under adverse conditions [28].

Today, forensic laboratories worldwide are testing a range of nanoparticles to evaluate their potential for replacing or enhancing older development techniques. These include chemical, physical, biological, and hybrid methods designed to increase the visibility and integrity of fingerprints on various surfaces [26,91]. Still, no single method works universally, highlighting the need for continued innovation and comparative analysis [93].

14. Nanotechnology in Fingerprint Lifting

Nanotechnology has significantly advanced both lifting and visualization of latent fingerprints, offering high-contrast, noninvasive, and non-destructive alternatives to conventional methods. These techniques use engineered fluorescent powders and photoluminescent materials to highlight ridge details without damaging the substrate [82]. However, despite their effectiveness, these methods are often costly and complex. In particular, the mass production of certain nanoparticle formulations is restricted by commercial or intellectual property concerns [16].

Photoluminescence-based fingerprint lifting, where especially designed fluorescent nanoscale powders react with fingerprint residues, has shown promise but still faces practical barriers, such as the need for sophisticated laser systems that limit portability and field application [94]. In contrast, modified dusting powders using magnetic fluorescent nanoparticles are easier to apply across various surfaces and provide consistent results, making them suitable for both lifting and preserving prints [92].

The forensic field has seen notable progress from these innovations, but continued research is needed to adapt nano-enhanced powders to different surfaces and environmental conditions [94,95,60]. Interestingly, both secretors and non-secretors have been identified through powdered fingerprint residues, including those with trace DNA, suggesting that individual identification through such particles may soon become a routine [96].

15. Nanotechnology in Fingerprint Preservation

Preserving latent fingerprints is just as important as detecting them, especially in long-term forensic investigations. Recent innovations in nanotechnology are playing a key role here. Fluorescent nanoparticles and photoluminescent nanomaterials have not only enhanced detection but have also improved the stability and longevity of the preserved fingerprints [18,19,92].

These advanced materials enable the creation of durable fingerprint images through mineral transfer and crystallization, which help to maintain the print's structural integrity [97,98]. Effective preservation hinges on enhancing the print's contrast without compromising its original detail, something nanoparticle-based techniques achieve exceptionally well [99,100].

16. Challenges and Limitations of Nanotechnology in Fingerprint Detection

While the benefits of nanotechnology in fingerprint detection are undeniable, several challenges must be addressed before these methods are adopted universally. A key concern is toxicity. Some nanomaterials, especially when improperly capped, pose health risks, such as cellular damage, genetic mutation, and toxic buildup in organs [101–103]. For instance, fluorescent nanoparticles and metal conjugates have been shown to cause adverse effects in zebrafish embryos and mammalian liver cells during laboratory tests [104,105].

This underscores the urgent need for biocompatible alternatives and rigorous toxicity testing. The development of safe capping agents has already opened up safer applications, but regulatory frameworks must catch up. New safety standards should cover material composition, handling procedures, exposure routes (like inhalation or skin contact), and transportation protocols [106–108].

One overlooked issue is that some nanomaterials, such as CNTs, are harmful due to their geometry and electrical properties, making them dangerous when inhaled [109]. Despite known risks, comprehensive regulations or safety thresholds for their use in forensic contexts are still lacking. In future, it is essential that each nanomaterial used in evidence processing come with traceable certification, or a "passport," outlining its safety profile and production origin [60,91].

17. Future Directions and Emerging Trends

The use of nanotechnology in fingerprint science is still evolving but has already revealed enormous potential. From evidence collection at crime scenes to courtroom presentations, nanomaterials are changing how forensic scientists operate. One major trend involves simplifying current technologies to reduce costs and expand accessibility, especially in low-resource settings [92,72,109].

Researchers are also working toward multifunctional devices and tools that can detect, analyze, and store fingerprint data in one integrated unit. Such innovations would streamline investigative procedures and speed up case resolutions [110, 111]. Yet, this field is in its infancy. Greater collaboration across materials science, chemistry, and forensics is needed to push the boundaries further.

In future, we may witness real-time colorimetric fingerprint detection systems that can identify residues and ridge details within seconds. These advancements would not only enhance efficiency but also minimize sample destruction, preserving critical forensic evidence [112,113].

18. Conclusion

Nanotechnology is transforming forensic science by making investigations more sensitive, efficient, and versatile. A key advancement is in latent fingerprint detection, where nanoparticles allow for clearer ridge detail, even on difficult surfaces. These technologies also enable the development of compact portable systems that improve processing of on-site evidence.

Innovations, such as nano-trackers and nanoscale barcodes, already are being used for crime prevention and real-time tracking. In future, nanomaterials would play a larger role in identifying suspects, reconstructing crime scenes, and locating missing persons or stolen items.

However, concerns remain over the potential health risks of long-term exposure to certain nanoparticles, which can penetrate the body and damage DNA or tissues. Addressing these risks through proper regulation and safer materials is essential.

Despite these challenges, nanotechnology shows great promise in forensic science. It offers powerful tools for evidence collection and analysis from improved fingerprint detection to portable devices for rapid field testing, potentially reshaping the way crimes are solved.

Ethical approval

This study did not involve human participants or animals requiring ethical approval.

Author Contributions

All authors contributed significantly to the conception, design, data collection, analysis, and writing of the manuscript. All authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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