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MINI REVIEW

Technological Evolution in Latent Fingerprint Detection: From Nanomaterials to Artificial Intelligence

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Latent fingerprints are one of the most important forensic pieces of evidence in criminal investigations due to their uniqueness and persistence throughout an individual's life. Technological developments in latent fingerprint detection and analysis methods have advanced significantly, especially through the application of nanotechnology, artificial intelligence and spectroscopic techniques. This study aims to systematically evaluate innovations in latent fingerprint detection methods that have been developed between 2015 and 2025. The literature review shows that the integration of nanoparticle-based technologies, optical sensors and digital image processing has improved the sensitivity and effectiveness in latent fingerprint visualisation. In addition, Artificial Intelligence (AI), especially deep learning and machine learning, has accelerated and improved the accuracy of matching fingerprints with forensic databases. However, while these innovations offer more adaptive and efficient solutions, challenges remain, especially in the aspects of method standardisation, technology scalability as well as cost-effectiveness. With a multidisciplinary approach combining chemistry, physics and artificial intelligence, this research highlights the potential for developing more advanced, efficient and environmentally friendly latent fingerprint identification methods.

Keywords: Latent fingerprints, Forensic science, Nanotechnology, Artificial intelligence, Spectroscopy.

INTRODUCTION

Latent fingerprint analysis remains one of the fundamental pillars in forensic science, serving as an important tool in criminal investigations. In recent decades, technological advancements have led to significant advancements in latent fingerprint detection, development and analysis methods [1]. Visualisation techniques that were initially dominated by traditional methods, such as the use of powders, have now evolved into more sophisticated techniques with both optical and chemical approaches/techniques. These innovations aim to improve the clarity, resolution and sustainability of latent fingerprints on various media, thus strengthening reliability in the forensic investigation process [2].

The 2015-2025 period marks tremendous progress in this field, especially through the integration of nanotechnology and eco-friendly materials in forensic methodologies. Cross-disciplinary collaborations including materials science, chemistry and biology, have enriched latent fingerprint detection techniques and provided solutions to challenges, such as detection on irregular surfaces or under difficult environmental conditions [3]. These advancements have not only scientific but also societal impacts, as improved techniques can increase the scope and reliability of forensic investigations [4].

However, despite these advances, there are still challenges in the development of latent fingerprint techniques. Some traditional chemical methods use toxic reagents, which pose potential environmental and health risks [5]. In addition, some techniques still face obstacles in producing consistent results on complex surfaces, such as porous or colourful surfaces. These challenges demand more adaptive and rebeoust innovations to overcome various detection conditions [6]. One promising solution is the utilisation of nanomaterials, which offer high optical and chemical sensitivity, thus enabling latent fingerprint visualisation with better resolution and higher efficiency.

Nanotechnology involves understanding, manipulation and control of matter at the atomic and molecular levels, allowing for the development of new materials, devices and structures with distinct characteristics [7]. Nanotechnology has become a transformative element in latent fingerprint analysis. The use of organic-inorganic hybrid nanoparticles, for example, has been shown to improve the clarity of fingerprints on various surfaces. In addition, biocompatible fluorescent graphene nanosheets provide a safer alternative to traditional reagents without compromising their effectiveness [8]. Another significant innovation is the application of green nanoparticles based on sustainable resources, which is in line with global environmental standards and overcomes toxicity issues from conventional methods.

A review of the literature from 2015 to 2025 shows a research trend that increasingly focuses on nanomaterial-based techniques for latent fingerprint detection. Although various studies have proven the effectiveness of nanoparticles in enhancing detection, there are still limitations in terms of scalability and cost-effectiveness [9]. In addition, inconsistent results when applying eco-friendly nanoparticles highlight the need for the development of standardised protocols for optimisation and validation of this technique.

This research aims to investigate recent advances in the latent fingerprint detection techniques, focusing on the use of nanotechnology and eco-friendly materials. By systematically analysing developments from 2015 to 2025, this research seeks to identify key trends, evaluate the methodologies used and propose solutions to existing challenges. An interdisciplinary approach is key in overcoming technical barriers and expanding the application of these techniques in forensic science. By emphasizing the sustainability aspect, this research also aims to encourage the adoption of more environmentally friendly methods in forensic practice. Therefore, the development of safer and more efficient techniques is expected to improve the reliability of forensic evidence in the justice system, given the central role of fingerprints in criminal investigations.

Methodology

This study employed a systematic literature review (SLR) methodology following PRISMA guidelines to critically examine recent advancements in latent fingerprint identification techniques. The SLR approach was selected due to its structured, transparent and reproducible framework, which enables rigorous identification, evaluation and synthesis of scientific evidence in forensic science. The review focuses on latent fingerprint detection, enhancement and identification methods, emphasizing their effectiveness, practical applications and challenges across different substrates and environmental conditions.

Data sources and search strategy: A comprehensive literature search was conducted for articles published between 2015 and 2025, covering both conventional and technology-driven approaches, including AI-based methods. Searches were performed across multiple reputable databases: Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, Web of Science and Wiley Online Library.

The search strategy employed combinations of the following keywords applied to titles, abstracts and keywords: "Latent Fingerprint Detection", "Fingerprint Identification Techniques", "Forensic Fingerprint Analysis", "Chemical Methods for Latent Fingerprints", "Optical Enhancement of Fingerprints", "Machine Learning in Fingerprint Identification", "Nanoparticles", "Deep Learning", "Spectroscopy", "FTIR".

This strategy ensured comprehensive coverage of both traditional and state-of-the-art latent fingerprint methodologies.

Study selection process: The study selection followed the PRISMA (preferred reporting items for systematic reviews and meta-analyses) framework to ensure transparency and reproducibility. The selection process consisted of four stages: (1) **Initial search**: Around 5,800 articles were identified from all databases; (2) **Title and Abstract Screening**: 1,750 articles remained after excluding irrelevant studies; (3) **Full-Text Evaluation**: 480 articles underwent in-depth assessment for methodological rigor and relevance; (4) **Final Selection**: 155 articles met all inclusion criteria and were included for the detailed analysis.

To provide a visual overview of the study selection procedure, a PRISMA flow diagram was constructed (Fig. 1).

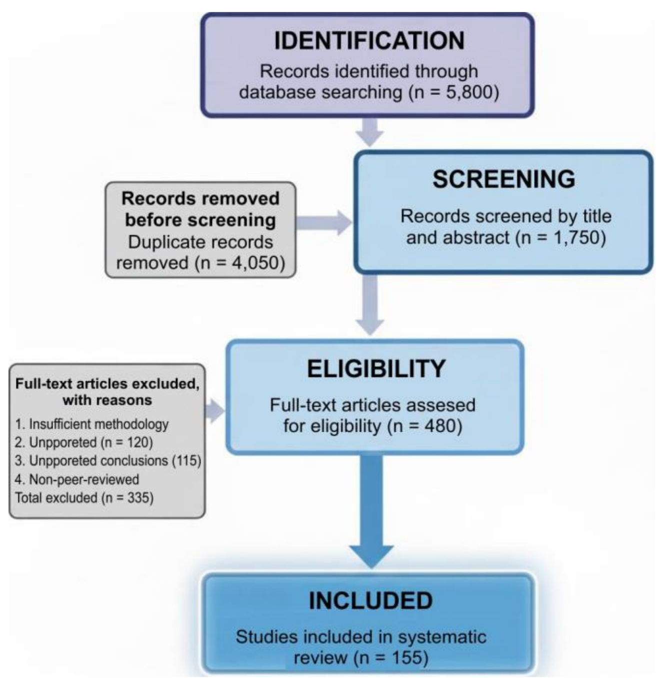

Fig. 1. PRISMA flow diagram of the systematic literature review process, showing the identification, screening, eligibility assessment and final inclusion of 155 articles

Inclusion and exclusion criteria: In this study, every article retrieved from academic databases and consulted libraries was given an equal opportunity to be considered for inclusion. To minimize selection bias, a clear set of inclusion and exclusion criteria was established and applied consistently (Tables 1 and 2). The inclusion criteria ensure that only studies with high academic value and direct relevance to latent fingerprint investigation were analysed, while the exclusion criteria remove studies that are irrelevant, methodologically weak or duplicated.

TABLE-1
INCLUSION AND EXCLUSION CRITERIA

Inclusion criteria	Exclusion criteria
The study focuses on technologies, acquisition methods, enhancement, reconstruction, matching and the impact of latent fingerprints in forensic systems.	Irrelevant to latent fingerprint detection or identification.
The article has undergone a peer-review process and has been published in reputable academic journals or conferences.	Not peer-reviewed.
The study is written in English or Indonesian.	Insufficient methodological details or unsupported conclusions.
The article is a research paper or a survey paper.	Duplicate publications.
The article is available online.	Non-English/Indonesian publications if language barrier prevents analysis.

TABLE-2
SOURCES OF ARTICLES IN LATENT FINGERPRINT INVESTIGATION

Article sources	No. of articles	Percentage (%)
Science Direct	34	21.94
Scopus	26	16.77
IEEE Xplore	17	10.97
Springer	28	18.06
Web of Science	14	9.03
Google Scholar	19	12.26
Wiley Online Library	17	10.97
	155	100

Tables 1 and 2 provide a clear framework for selecting relevant studies. The inclusion criteria ensure that only articles with suitable focus, quality and accessibility are considered, while the exclusion criteria systematically remove studies that do not meet these standards. This approach strengthens the rigor and transparency of the systematic review process.

Data extraction and quality assessment: Data extraction was performed systematically to ensure reliability and minimize bias. For each selected study, the following information was collected: Research objectives and scope; Latent fingerprint acquisition, enhancement and identification methods; Experimental design and substrate types; Performance metrics (*e.g.*, sensitivity, specificity, accuracy); AI or technology-based techniques used.

Two independent reviewers conducted the data extraction and quality assessment, resolving discrepancies through discussion. The quality evaluation criteria included: Clarity of research objectives; Appropriateness of methodology; Adequacy of data analysis; Relevance and contribution of findings. Articles with low methodological quality or insufficient evidence were excluded from the final synthesis, ensuring that the review is based on high-quality studies.

Literature review and background

Role of latent fingerprints in forensic science: Latent fingerprints represent one of the most reliable and enduring forms of forensic evidence used in criminal investigations due to their inherent uniqueness and permanence throughout an individual's lifetime [10]. Extensive forensic research has consistently demonstrated that no two individuals, including identical twins, possess identical fingerprint patterns, reinforcing the evidentiary strength and long-standing legal admissibility of fingerprint evidence. Consequently, fingerprints remain a cornerstone of both traditional and modern forensic identification systems.

Beyond individual identification, latent fingerprints play a crucial role in reconstructing criminal events and establishing associative links between suspects, victims and crime scenes. The forensic value of fingerprint evidence is highly dependent on the use of scientifically validated detection and analysis procedures to ensure accuracy, reliability and reproducibility [11]. In addition to confirm an individual's presence at a particular location, fingerprints may provide insights into the sequence of actions during criminal activity, thereby strengthening their investigative and evidentiary significance within judicial processes.

Latent fingerprint detection methods: Latent fingerprint detection aims to visualize invisible ridge patterns deposited on various surfaces through interactions between fingerprint residues and detection agents. Conventional detection techniques, including powder dusting, ninhydrin and cyanoacrylate fuming, remain widely used due to their simplicity, affordability and high technological maturity [12]. Powder-based methods rely on physical adhesion mechanisms to enhance contrast on non-porous substrates, while ninhydrin selectively reacts with amino acids on porous materials. Cyanoacrylate fuming produces polymerised ridge structures on non-porous surfaces, which can be further enhanced using fluorescent dyes [13].

Recent advancements have significantly expanded the scope of latent fingerprint detection. Optical- and chemical-based innovations have improved visualisation on complex and previously challenging substrates. In particular, the incorporation of nanotechnology has markedly enhanced detection sensitivity and ridge contrast. Luminescent nanoparticles and fluorescent graphene-based materials have demonstrated improved signal intensity and ridge visibility, especially on non-porous and multicoloured surfaces [14]. Importantly, these materials may also reduce health and environmental risks associated with conventional chemical reagents.

Fingerprint analysis and chemical characterisation: Fingerprint analysis has evolved beyond ridge visualisation toward the extraction of structural and chemical information from developed fingerprints. Spectroscopic techniques such as Fourier transform infrared (FTIR) and Raman spectroscopy enable non-destructive chemical characterisation of fingerprint residues, facilitating the identification of organic and inorganic compounds within the fingerprint matrix [15]. These chemical signatures may indicate prior contact with drugs, explosives, or other substances of forensic relevance.

While spectroscopic techniques provide valuable complementary information not accessible through traditional visualisation techniques, challenges related to equipment cost, technical expertise and laboratory-based operation limit their routine application. Nevertheless, chemical characterisation techniques remain essential in advanced forensic investigations where molecular-level information is required to support evidentiary conclusions.

Fingerprint matching and recognition technologies: Fingerprint matching and recognition involve comparing acquired fingerprint patterns with reference databases to establish individual identity. Digital image processing techniques, including Gabor filtering and contrast enhancement algorithms, improve ridge clarity and suppress background noise, enabling more accurate feature extraction from degraded or low-quality latent fingerprints.

The integration of artificial intelligence (AI), particularly machine learning and deep learning approaches, has transformed fingerprint recognition systems. Convolutional neural networks (CNNs) and artificial neural networks have demonstrated high accuracy in automated fingerprint classification and matching, significantly reducing examiner subjectivity and processing time [16]. Despite their analytical advantages, AI-based systems require substantial computational resources, high-quality training datasets and standardised validation protocols, which challenges remain for widespread implementation in resource-limited forensic settings.

Implications and future research directions: The development of safer, more efficient and eco-friendlier techniques in forensic analysis is fundamental to minimise the negative impacts of evidence collection processes. With increasing awareness of environmental sustainability, research and innovation in this field must focus on creating methods that are not only effective but also ecologically responsible [17]. In forensic science, nanotechnology has emerged as a primary approach to improving the reliability of evidence within the judicial system. Moreover, the application of green analytical methods has been proposed to reduce the use of hazardous substances, making forensic processes safer for the environment while maintaining their effectiveness. Consequently, the exploration of innovative methods that integrate advanced technology with social and environmental responsibility has become the primary direction for future developments in this field.

An interdisciplinary approach is also a crucial aspect in advancing latent fingerprint detection techniques [18]. The combination of techniques from chemistry, physics and material science has proven to produce more efficient methods while enhancing the accuracy of fingerprint identification. The synergy between these scientific disciplines has contributed to significant innovations in detection methods, reducing the time and resources required for forensic analysis. Furthermore, nanomaterials show great potential in future forensic applications, particularly in improving evidence detection and analysis. For instance, recent studies indicate that nanoparticles can be utilised to develop highly sensitive and specific sensors for detecting chemical and biological substances relevant to forensic investigations. These innovations present substantial opportunities for the advancement of forensic technology, making it more reliable and efficient in supporting criminal investigations.

However, the implementation of new techniques and materials in forensic analysis must be accompanied by rigorous evaluation and testing to ensure their effectiveness under diverse and often challenging field conditions [19]. Furthermore, additional research is needed to establish protocols and standards that ensure the application of nanomaterials in forensic systems aligns with regulatory requirements, thereby maintaining the integrity of judicial processes. This process includes material selection, application methods and long-term impact assessment of the technologies being utilised. Therefore, the development of innovative forensic analysis techniques must consider effectiveness, efficiency and environmental impact simultaneously [20]. Through interdisciplinary collaboration and cross-sector partnerships, forensic science can continuously adapt to technological advancements, ensuring the sustainability and enhancing reliability in criminal investigations.

RESULTS AND DISCUSSION

After applying the rigorous selection procedure outlined in the previous section, each selected article was systematically reviewed by extracting relevant information. Table-2 provides a breakdown of the distribution and percentage of the 155 selected articles obtained from various academic databases. ScienceDirect is the largest contributor with 34 articles (21.94%), followed by Springer with 28 articles (18.06%) and Scopus with 26 articles (16.77%). Google Scholar contributed 19 articles (12.26%), while IEEE Xplore and Wiley Online Library both provided a significant portion with 17 articles (10.97%) each. Finally, Web of Science accounted for 14 articles (9.03%). These figures highlight the diversity of reputable sources used in this study to ensure comprehensive coverage of the latest developments in latent fingerprint investigation, including technology-driven methods such as AI and nanotechnology.

The diversity of sources used in this study indicates that research on latent fingerprints is multidisciplinary, encompassing various scientific approaches from different journals. This broad approach enables a more thorough review of techniques and methodologies used in latent fingerprint investigations. This analysis confirms that a multidisciplinary approach is crucial in latent fingerprint research [21]. By integrating methods from fields such as forensics, artificial intelligence and image analysis, this study provides deeper insights and more innovative solutions for forensic investigations. Therefore, selecting articles from various academic sources is not only intended to ensure broad coverage but also to enrich perspectives in understanding and improving latent fingerprint investigation techniques.

The multidisciplinary approach in the latent fingerprint research reflects the evolving methodologies and technologies used to enhance detection and analysis. These advancements include the application of analytical chemistry in residue detection, material science in surface analysis and artificial intelligence in data processing [22]. For instance, numerous studies have demonstrated that colloidal polymer nanoparticles could be used as smart ink for authentication and latent fingerprint indication, improving the effectiveness of conventional methods such as fingerprint powdering. This finding confirms that combining chemical and material science techniques contributes to better visualisation of latent fingerprints. Moreover, several researchers suggested that DNA-based technologies and mathematical approaches could enhance fingerprint verification security. They emphasized that fingerprint enhancement methods could affect DNA recovery, clarifying the relationship between physical and chemical methods in forensic analysis. Consequently, a multidisciplinary approach serves as the foundation for developing more advanced and effective fingerprint detection methods.

Cutting-edge technologies such as deep learning have been employed to recognize fingerprint patterns with greater accuracy, while material science plays a role in identifying the chemical composition of fingerprint residues [23]. Researchers also highlighted the importance of detecting metabolites in latent fingerprints for medical and forensic purposes. Moreover, deep learning algorithms have enabled the separation of overlapping fingerprints, which remains a significant challenge in fingerprint analysis. These innovations demonstrate significant progress in forensic technology.

The diversity of fingerprint detection methods is also crucial in adapting techniques to various field conditions. The challenges in detecting fingerprints are also highlighted on certain surfaces prone to rapid fading. They revealed that fluorescent dye techniques might be less effective on semi-porous surfaces [24]. Understanding these limitations contributes to more efficient on-site investigations while reducing operational costs. Collaboration between academics, forensic practitioners and technology developers also plays a key role in innovating fingerprint detection methods. Biometric sensors could provide surface texture data to improve the fingerprint analysis. Also, integrating machine learning algorithms has proven to enhance fingerprint processing accuracy. Such collaborations support the development of safer and more efficient techniques while addressing the complexity of diverse fingerprint patterns.

However, challenges remain in mitigating fingerprint degradation due to environmental factors. The effectiveness of fingerprint recovery methods heavily depends on sample collection conditions [25]. It was observed that using nanomaterials could enhance fingerprint recovery success under various conditions. Therefore, a cross-disciplinary approach is essential in finding innovative solutions to improve the effectiveness of forensic methods. The combination of emerging technologies with conventional techniques has also led to significant advancements in this field. Silica-based fluorescent nanoparticles could enhance the contrast of latent fingerprints, facilitating easier identification and analysis. By integrating traditional techniques with modern innovations, forensic research can produce more reliable and relevant results for criminal investigations.

In this context, it is essential to consider the surface variations and environmental conditions when developing the latent fingerprint detection methods. Fingerprints can fade quickly on certain surfaces, emphasizing the need for adaptive techniques. Furthermore, challenges in establishing new standards for fingerprint verification remain a major concern. Looking ahead, the combination of advanced data processing and innovative materials will drive the development of new forensic science methods [26]. As more complementary techniques emerge, research is expected to yield more efficient and effective approaches for latent fingerprint analysis. With the continuous support of modern technology and multidisciplinary collaboration, forensic research will continue to evolve, producing more accurate and applicable methods for criminal investigations in the future.

Comparative performance of conventional and modern detection method: A comparative synthesis of fingerprint acquisition and analysis techniques is presented in Table-3, which consolidates findings from multiple studies rather than reporting isolated results.

Conventional methods, for example, powder dusting, ninhydrin and cyanoacrylate fuming, remain dominant in

TABLE-3
LATENT FINGERPRINT ACQUISITION AND ANALYSIS TECHNIQUES

Technique	Main substrate	Advantages and performance metrics	Limitations and maturity level
Powder	Non-porous (glass, plastic)	Low cost, high portability, rapid application; moderate resolution	Low sensitivity for aged prints; highly mature
Ninhydrin	Porous (paper, fabric)	High sensitivity to amino acids; good ridge contrast	Long processing time, low portability; mature
Cyanoacrylate fuming	Non-porous & semi-porous	Stable ridge patterns; moderate–high resolution	Environment-dependent; over-polymerisation risk; mature
Light excitation/fluorescence	Various, complex backgrounds	High sensitivity, non-destructive	High equipment cost; limited portability; emerging
UV-Vis spectroscopy	Optically responsive substrates	Absorption-based detection; high contrast	Substrate-dependent; emerging
Infrared spectroscopy (FTIR)	Wide range	Chemical characterisation; high analytical resolution	Expensive instrumentation; laboratory-based; emerging
Gabor filter	Digital images	Enhanced ridge clarity and contrast	Dependent on image quality; mature
Artificial neural networks (deep learning-based classification models)	Digital biometric systems	High accuracy; automated analysis	Requires large datasets and computing power; emerging
Machine learning	Large-scale databases	Fast processing; scalable identification	Complex implementation; emerging

operational forensic contexts due to their low cost, portability and legal maturity [27,28]. However, across the reviewed studies, their performance consistently declined under conditions involving aged fingerprints, contaminated surfaces or high humidity conditions.

In contrast, modern approaches based on fluorescence, spectroscopy and artificial intelligence exhibited higher sensitivity and analytical resolution, albeit with reduced portability and increased infrastructure requirements [29]. The synthesis indicates that no single technique offers universal applicability, reinforcing the growing consensus that hybrid strategies combining mature conventional methods with advanced analytical tools represent the most effective forensic solution [30,31].

Advances in latent fingerprint analysis technology: The technological advancements identified in the reviewed literature are systematically summarised in Table-4, highlighting their core functions, advantages and forensic readiness.

Multispectral imaging emerged as one of the most operationally mature advanced techniques, demonstrating high effectiveness on complex surfaces through wavelength dependent contrast enhancement [32,33]. Spectroscopic techniques such as Raman and FTIR spectroscopy provided molecular-level information, enabling the detection of drugs, explosives and metabolites within fingerprint residues [34]. However, their application remains largely laboratory-based due to the equipment cost and technical complexity.

Nanotechnology-based approaches, including fluorescent nanoparticles and SERS substrates, consistently demonstrated enhanced signal-to-noise ratios and improved ridge clarity on challenging substrates, although issues related to scalability and standardisation persist [38]. Collectively, these findings indicate a technological convergence toward high-sensitivity, non-destructive and information-rich fingerprint analysis.

Quantitative trends in detection methods: Trend analysis across the reviewed studies reveals a measurable shift in the latent fingerprint detection strategies over the past decade. As illustrated in Fig. 2, conventional chemical methods dominated fingerprint research prior to 2017 but exhibited a gradual decline thereafter.

Post-2020, AI-assisted image processing and spectroscopic techniques showed the steepest growth rates, coinciding with advancements in computational power and digital imaging technologies [39-42]. AI-based methods, particularly deep learning architectures, demonstrated superior performance in handling degraded and overlapping fingerprints, achieving significantly higher matching accuracy than traditional enhancement techniques.

Nanotechnology-based detection methods also exhibited steady growth, with studies consistently reporting improved performance under adverse environmental conditions [41]. These trends collectively indicate a paradigm shift toward computationally driven and analytically robust forensic methodologies.

Multidisciplinary integration and forensic implication: Based on the systematic synthesis of the 155 selected studies, the review demonstrates that the most impactful advancements in latent fingerprint identification are driven by multidisciplinary integration. Studies that combine forensic science with analytical chemistry, material science and artificial intelligence consistently report higher analytical reliability, adaptability and robustness across diverse forensic scenarios [43,44]. This integration enables fingerprint detection and analysis methods to address challenges related to substrate variability, environmental degradation and partial or overlapping impressions more effectively than single-discipline approaches.

TABLE-4
LATENT FINGERPRINT ANALYSIS TECHNOLOGY

Technology	Core function	Key advantages	Forensic readiness and applications	Ref.
Multispectral imaging	Improves fingerprint contrast on various surfaces Enhances fingerprint contrast across different wavelengths	Effective on complex and multicoloured surfaces; non-destructive	High readiness; increasingly used in forensic laboratories and crime scene analysis	[32,33]
Spectroscopic techniques (Raman & FTIR)	Chemical characterisation of fingerprint residues	Enables detection of drugs, explosives and metabolites; contactless analysis	Moderate readiness; mainly laboratory-based due to equipment cost	[34]
3D Fingerprint reconstruction	Captures depth information from uneven surfaces	Improved ridge detail on curved or textured objects	Emerging readiness; limited operational use due to hardware complexity	[34]
Artificial intelligence & machine learning	Automated fingerprint enhancement, matching and classification	High accuracy, fast processing, reduced human bias	High readiness in AFIS and biometric databases; requires quality datasets	[35,36]
Modern fingerprint sensors	High-resolution fingerprint acquisition	Improved accuracy, reduced spoofing	High readiness; widely used in biometric security and forensic identification	[37]
Nanotechnology-based detection (*e.g.*, fluorescent nanoparticles, SERS)	Improves sensitivity of latent fingerprint visualisation	High contrast, improved detection on challenging surfaces	Moderate readiness; promising but limited by scalability and standardisation	[38]
Surface-Enhanced Raman Scattering (SERS)	Amplifies Raman signal for trace detection	Ultra-high sensitivity for chemical residue analysis	Emerging readiness; mainly experimental forensic research	[38]
Nanopore Sensor Applications	Biomolecular interaction analysis	Potential for compound-level identification	Low–emerging readiness; still exploratory in forensic contexts	[38]

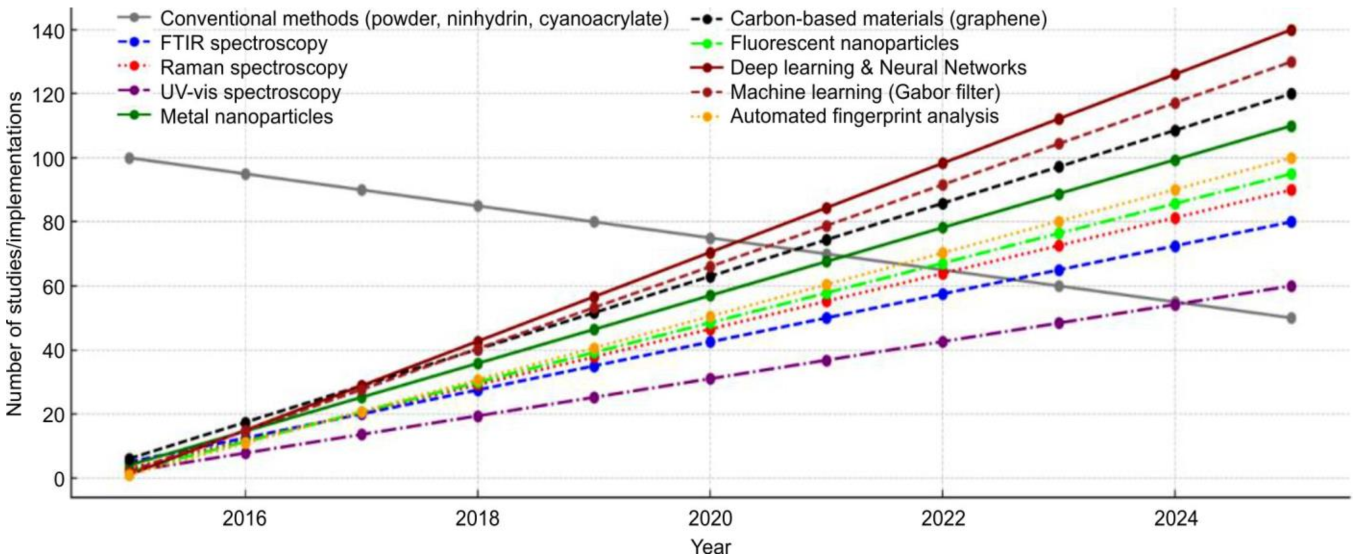

Fig. 2. Trends in latent fingerprint identification methods in forensics (2015-2025)

Despite these advantages, the reviewed literature highlights persistent challenges associated with training requirements, accessibility and methodological standardisation. While artificial intelligence and advanced spectroscopic techniques offer substantial analytical gains, their implementation often depends on skilled personnel, specialised infrastructure and institutional readiness. Consequently, future forensic systems must carefully balance technological sophistication with the operational feasibility, cost efficiency and legal admissibility to ensure successful adoption within routine forensic practice.

Role of forensic science in latent fingerprint identification: The synthesis further confirms that forensic science remains the foundational discipline in latent fingerprint identification, with continuous advancements driven by biochemical analysis, forensic statistics and analytical chemistry. Recent studies demonstrate that mass spectrometry and advanced chemical analyses can identify amino acids and lipid components within latent fingerprints, providing higher specificity and sensitivity compared to traditional visualisation methods [45]. In parallel, the development of biocompatible nanoparticles has significantly expanded detection capabilities, particularly on non-porous substrates that pose challenges for conventional techniques.

Beyond technological innovation, the reviewed studies emphasize the persistent issue of subjectivity and variability in fingerprint interpretation. Evidence indicates that even experienced forensic examiners may encounter inconsistencies in decision-making, underscoring the need for enhanced training programs and analytical support tools. Investments in automated fingerprint identification systems (AFIS) and the integration of machine learning algorithms are therefore regarded as critical strategies for reducing examiner bias and improving analytical consistency.

As forensic investigations become increasingly complex, the literature underscores the importance of continuous evaluation and validation of latent fingerprint identification techniques to maintain evidentiary reliability [46]. Emerging approaches involving DNA and protein separation from fingerprint residues further expand the evidentiary value of latent fingerprints, reinforcing the essential role of chemistry, biology and advanced analytical techniques in modern forensic science. Accordingly, future forensic frameworks must adopt comprehensive, technology-adaptive and responsive strategies to meet the evolving demands of criminal investigations.

Integration of artificial intelligence in fingerprint identification: Artificial intelligence has emerged as one of the most transformative components in latent fingerprint identification across the reviewed studies. Deep learning and machine learning techniques have been extensively applied to improve identification accuracy by automating ridge enhancement, noise suppression and feature extraction, thereby reducing reliance on manual and subjective evaluation. One of the most significant contributions of AI lies in its ability to address complex forensic challenges, particularly the separation of the overlapping latent fingerprints a longstanding limitation of conventional forensic methods. Deep learning based fingerprint separation models have demonstrated enhanced ridge continuity, improved clarity and increased individualisation potential in complex forensic scenarios [47].

Among AI-based approaches, convolutional neural networks (CNN) are the most widely adopted architectures for automated latent fingerprint classification and matching. CNN-based models enable rapid and precise recognition of ridge patterns through hierarchical feature learning, significantly reducing error rates associated with human interpretation and handcrafted feature extraction. Multiple studies report that CNN-driven fingerprint systems achieve markedly higher matching accuracy and robustness when compared to traditional feature-based methods, particularly for low-quality or degraded latent fingerprints [47,48].

Beyond classification and matching, artificial intelligence plays a critical role in enhancing the quality of degraded or incomplete latent fingerprint images. Deep learning–based super-resolution and image restoration techniques have been shown to reconstruct ridge details with improved spatial resolution, facilitating reliable analysis under challenging environmental conditions and on complex substrates [48]. The quantitative findings across the reviewed literature indicate that machine learning–assisted fingerprint analysis can reduce identification errors by up to approximately 30%, underscoring its substantial contribution to forensic accuracy and consistency.

Looking forward, the reviewed studies suggest that the continued integration of advanced image processing, adaptive learning algorithms and AI-driven decision support systems will further strengthen the efficiency, reliability and reproducibility of latent fingerprint identification. By fully leveraging artificial intelligence within validated and standardised forensic frameworks [49], future fingerprint analysis systems are expected to deliver more accurate, transparent and operationally robust solutions to support law enforcement investigations and judicial decision-making.

A future prospective for developing latent fingerprints: Latent fingerprint has a bright future, owing to the unfolding nanotechnology, image, processing and artificial intelligence trends that are likely to shape the domain. These devices provide better visualisation, sharper quality and the possibility of their automated analysis, improving at least in theory the forensic investigation efficiency. Although fingermark evidence has been employed for forensic purposes for over a century, research into its utility is ongoing. More innovations on enhancement methods, such as functionalised nanoparticles, may be seen soon by researchers. Spectroscopic fingerprint imaging is a rather novel field of science, but researchers can expect to see further development as technology gets more advanced. Spectroscopic techniques would seem to have the most potential for a 'universal' technique to detect and image latent marks and do so in a single step at the crime scene, a holy grail of forensic science. The study of the chemistry of fingermarks has provided an intriguing insight into potential information that may be retrieved regarding the leaver of a mark. Mass spectrometric methods are currently at the forefront of disclosing these imprint signals but if more sensitive spectroscopic methodology can be achieved, they may provide much more rapid, low-cost and accessible comparative data. Fingerprint artificial intelligence is also a popular technological trend that will enhance accuracy and security further. Artificial intelligence can comb through intricate trends, spotting anomalies that may signify that somebody is trying to commit fraud. By combining these technologies, one can enhance the identity verification and fraud detection process to keep pace with criminal and financial threat actors.

Conclusion

This review highlights recent innovations in latent fingerprint detection and analysis developed between 2019 and 2025, with particular emphasis on nanotechnology, artificial intelligence and spectroscopic approaches. The findings indicate that nanoparticle-assisted enhancement methods integrated with digital image processing and AI-based matching systems represent the most promising technologies for near-term forensic implementation, due to their improved sensitivity, compatibility with existing forensic workflows and increasing technological maturity. In the short term, AI-driven image enhancement and automated fingerprint matching offer realistic and scalable solutions for forensic laboratories and biometric databases. Conversely, advanced spectroscopic techniques and multifunctional nanomaterials, although highly promising for chemical residue analysis and enhanced selectivity, remain at an early or emerging stage of development because of challenges related to standardisation, instrumentation cost and operational scalability. However, despite substantial progress, the limitations in method harmonisation, accessibility and cost-effectiveness continue to restrict widespread adoption. A multidisciplinary and phased integration strategy, integrating chemistry, physics and artificial intelligence, is therefore essential to support reliable, efficient and sustainable latent fingerprint identification in modern forensic systems.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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