APPLICATIONS OF NANOMATERIALS IN FORENSIC SCIENCE

Abstract

The convergence of nanotechnology and forensic science has paved the way for transformative advancements in evidence analysis, crime scene investigation, and overall investigative methodologies. This chapter delves into the applications of nanotechnology within the realm of forensic science, elucidating its pivotal role in enhancing the accuracy, sensitivity, and efficiency of various forensic processes. Nanotechnology's unique ability to manipulate and characterize materials at the nanoscale has propelled its integration into forensic science This paper provides an extensive overview of the fundamental applications of conventional nanotechnology tools in examining questioned documents, determining the age of bloodstains, estimating time since death, and enhancing various forensic processes. Additionally, it investigates their roles in optimizing polymerase chain reaction (PCR) efficiency, refining DNA analysis techniques, and advancing explosive detection mechanisms. The study also emphasizes the emerging potential of sophisticated nanotechnology instruments in screening illicit drugs. These applications transcend the limitations of traditional methods, enabling the identification and analysis of previously undetectable evidence.

Keywords: Nanomaterials, nanotechnology, forensic science, applications, fingerprints, pesticides, questioned documents

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I. INTRODUCTION

To determine the truth about the alleged incident, forensic science applies the theories, principles, laws, and techniques of all the fundamental sciences to the recognition, identification, individualization, and reconstruction of physical evidence collected at a crime scene. Knowledge of forensic science is the set of information from the various sciences like chemistry, Anthropology, Medicine, Psychology, Physics, Biology., etc, in order to solve crimes and identify and locate the culprits or suspects[1]. The place where the crime has happened is called a crime scene and the objects which are involved or created by the crime are called evidence. The evidence may be Biological, Chemical, or Digital.There are various prominent and practically relevant branches of forensic science which include, Forensic Toxicology, Forensic serology, Forensic Odontology, Forensic Physics, and Forensic chemistry, etc., which drives the principles and techniques from various sciences which help in the identification of various types of evidence which encounter at crime scenes that provides the link between the suspect or culprit and victim. Numerous samples and subjects have been collected for investigation at crime scenes, and forensic technology is important in assisting a team of forensic scientists inthe analysis of the evidence, judges, and prosecutors to present evidence against culprits in a court of law [2].The existing traditional methods and techniques in forensic analysis are progressively getting less effective, prompting the development of novel and advanced tools and techniques. Potentialevidence like Bloodstains, Fiber, Gunshot Residues, Fingerprints, Kinfe, Chemicals,Explosives, and Other digital evidence are some prevalent evidence substrates frequently encountered in forensic analysis. Fingerprints and Bloodstain evidence play an important role in the characterization and individual identification.

II. APPLICATIONS OF NANOMATERIALS IN FORENSIC SCIENCE

Traditional forensic analysis methods are becoming less effective over time, prompting the development of new, cutting-edge tools and techniques. Nanotechnology has continued to demonstrate its supremacy with numerous applications to traditional methods in medical, electrical, engineering, and other disciplines. The advancement of nanotechnology has significantly contributed to the field of forensic science by introducing enhanced nanosensors, nanomanipulators, and nanoimaging tools. These innovations offer exceptional precision and sensitivity, while also reducing the time needed for various processes. As a result, nanotechnology has the potential to enhance and optimize conventional forensic techniques, leading to increased efficiency and improved outcomes. Figure 1 depicts the possible applications of nanotechnology in forensic science.

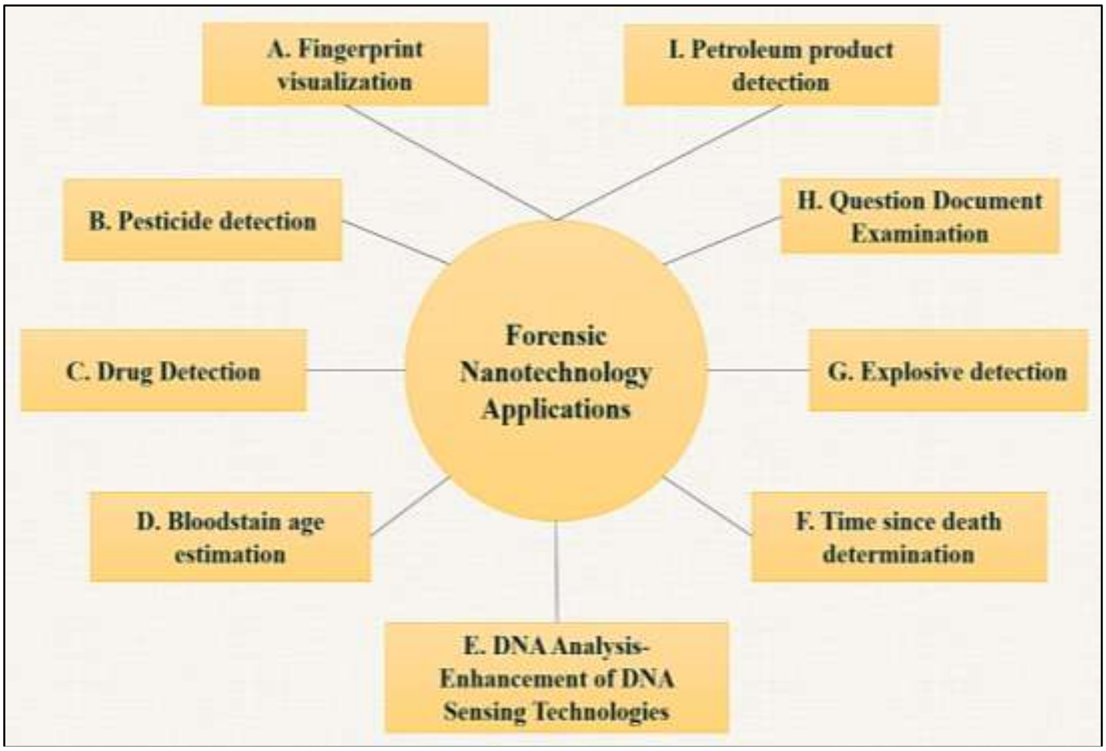

Figure 1: Possible applications of nanotechnology in forensic science.

III. APPLICATIONS OF NANOMATERIALS IN FINGERPRINTS VISUALIZATION

Fingerprints left at the scene of the crime or on any object that was touched by hands during the crime may be used to identify the culprit. Considering fingerprints are distinct, permanent, universal, unique, and classifiable, utilizing collected fingerprints from a crime scene can assist validate an individual's identification. Fingerprint identification will totally depend upon the fingerprint minutiae. Some of the common fingerprint minutiae are shown in Figure 2. A fingerprint is a verified form of trace evidence that serves as essential proof for establishing an individual's identity, given its partial representations of the unique ridge pattern present on the fingers of humans.Patent and Plastic fingerprints are visible kinds of fingerprints, whereas Latent Fingerprints (LFPs) are one of the most often encountered types of fingerprints in scenes of crime because They remain invisible to the naked eye. which leads to the development of visualization techniques [3]. Patent fingerprints can be visible to the naked eye because they may be formed by contacting any object with paint, blood, dirt, grease, or ink. There are multiple methods of preserving patent fingerprints, including photography, whereas plastic fingerprints may be formed by pressing the fingers on tar, soap, wax, or clay. Regarding latent fingerprint impressions (LFPs), the powder dusting method stands out due to its notable effectiveness and user-friendly nature, making it the most convenient and commonly employed technique for enhancing LFPs at crime scenes. Regular polymers, metallic, and luminous powders are the three categories under which fingerprint powders are categorized based on their composition and characteristics, whereas metal powders and magnetic powders are two of the most common types of powders used in the powder-dusting method[4]. The conventional powder dusting technique employs traditional powders to reveal latent fingerprints effectively under standard conditions. However, this approach faces growing difficulties due to the powders' low contrast, lack of fluorescence, limited sensitivity, heightened susceptibility to background colours, and intricate patterns [5]. In the field of forensic science, a significant ongoing challenge revolves around achieving optimal effectiveness, strong contrast, precise selectivity, and minimal background interference when working to develop latent fingerprints. The considerable surface area nanoparticles have peculiar physicochemical characteristics. In addition to that, the optical characteristics of Nanopowders depend on their size, and the distinct colours they exhibit are a result of absorption in various visible spectrum regions [6-7].

Figure 2: Detailed fingerprint ridge characteristics.

In the past few decades, various types of nanoparticles that have different characteristics were developed and used in investigations. They are highly recommended for their significant surface area, small size, distinct spectral properties, and ease of surface modification using various binding agents for the visualization of Fingerprints. Due to their characteristics, these substances are well-suited for engaging with fingerprint residues on surfaces that are either porous or non-porous. By utilizing hydrophilic interactions with the fingerprint residues present on these surfaces, nanomaterials produce more detailed and distinct fingerprint impressions, all the while reducing any potential disruption from the background[8]. One key advantage of nanomaterials is their ability to detect both recent and aged fingerprints on a diverse array of surfaces.

In latent fingerprint (LFP) detection, nanomaterials assume a crucial function by capitalizing on electrostatic interactions among amino acids, fatty acids, and silver particles. Specifically, the application of colloidal silver particles proves exceptionally efficient on porous surfaces, owing to their potent affinity for organic compounds. [9]. These substances, derived from sweat and encompassing lipids and fatty acids, exhibit durability on porous materials found at crime scenes. Consequently, this fingerprint imaging technique yields high-quality LFP images even after a substantial period of time. The resulting images, which are dark and black in low-light conditions, depict fingerprints vividly [10]. The use of redox reagents like iron salt generates oxidation-reduction reactions that produce images. Sol-gel techniques were applied in the presence of Bimetallic deposition of nanoparticles to create a variety of substrates with enhanced visibility [11]. When iron salt is employed as an oxidizing agent, it converts silver nitrate to metallic silver, resulting in a black and dark-grey latent fingerprint image as a result of interactions with the fingerprint's lipid and fatty acid residues. Along with these techniques, the TiO2 nanoparticles have been reviewed in comparison to other commercial powders that are easily available for the development of fingerprints [12]. The revelation was made that distinct photographs capturing furrows, whorls, arches, bifurcations, and sweat pores could be successfully produced. The level-3 sweat pore supported the TiO2 powders for the detection of blood fingerprints even after 180 days [13]. TiO2 nanoparticles were thereby used in forensic science for fingerprint identification. Although metal ions supported on substrates have fallen out of favour of Fingerprints in fingerprint detection, the utilization of silver nanoparticle powder as a physical developer has been prevalent for the past three decades. By employing iron salt as an oxidant, silver nanoparticles are reduced, creating clear images in shades of grey and dark colours on porous surfaces due to oxidation and reduction processes [14].

Silica nanoparticles readily receive dye coatings, enhancing latent fingerprint (LFP) detection. This phenomenon arises from the establishment of hydrogen bonds and electrostatic interactions with amino acids, proteins, and lipids within fingerprint residues adhered to various substrates. [15]. In recent advancements,Multimetal Deposition (MMD) is an advanced technique employed in fingerprint detection within the realm of forensic science. This method involves the controlled deposition of multiple metal layers onto latent fingerprints, enhancing their visibility and aiding in accurate identification [16]. For example, gold nanoparticles can also be coated on silica nanoparticles which involve the electrostatic interaction mechanism between the fingerprint sweat and gold nanomaterials in acidic media [17]. On the other hand, using hybrid Nanopowders and gold nanoparticles functionalized by Poly (styrene-alt maleic anhydride)-b-Polystyrene (PSMA-b-PS), latent fingerprints on patterned or multi-coloured surfaces can be clearly identifiable [18]. Conversely, nanomaterials such as zinc oxide, europium oxide, quantum dots like cadmium sulphide (CdSQDs), cadmium selenide (CdSeQDs), and cadmium telluride (CdTeQDs), carbon dots (CDs), polymer dots, fluorescent silica nanoparticles, as well as fluorescent mesoporous silica nanoparticles, and aggregation-induced emission luminous molecules known as conjugated-polyelectrolyte dots (CPEDs) which encompass rare earth metals – have found utility in the realm of forensic applications. These fluorescent nanoparticles serve as a means of visualizing fingerprints, aiding in the development of latent fingerprints directly at the crime scene[19-21].

IV. APPLICATIONS OF NANOMATERIALS IN PESTICIDE DETECTION

The term "pesticide" refers to any agent used to control, eliminate, or prevent organisms that are considered to be disruptive or causing damage to crops. This phrase includes biocidal products and plant protection products.These are chemical compounds or mixes of chemical substances that differ in one another's physical, chemical, and eerily similar qualities [22]. They are therefore categorized according to their characteristics. These describe several groups of pesticides, such as insecticides, herbicides, fungicides, rodenticides, wood preservers, garden chemicals, and house disinfectants, which are used to prevent or deter pests. Additionally, pesticides can be classified into groups based on their chemical composition, mode of entry, and level of toxicity [23]. Pesticides can either be synthetic (such as inorganic and organic (organochlorines, organophosphates, carbamates, and pyrethroids) substances) or natural (such as mineral oils and plant-based agrochemicals).A global study published in BMC Public Health reveals that approximately 44% of the world's 860 million farmers are lost annually due to pesticide-related fatalities [24]. According to scientific evidence published in research, pesticides are responsible for the death of 11,000 people every year and 385 million people are mostly farmers and employees in the agricultural industry. An estimated 6,000 deaths each year, or 60% of all fatalities, occur in India [25]. Human pesticide poisoning has long been regarded as a severe matter of public health. Around one million unintentional pesticide poisonings with severe symptoms are anticipated to occur annually, with around 20,000 fatalities, according to a World Health Organisation task committee's estimate from 1990 [26].Interestingly, abuse and accidental pesticide releases can cause pesticides to persist in food, animals, and the environment, which causes bioaccumulation and spread up food chains since certain pesticides have longer half-lives [27]. More specifically, chronic exposure to pesticides may result in reduced immunity power, imbalances in hormones, and drug resistance.

Traditional analytical techniques have played a crucial part in detecting the presence of pesticides during the last few decades, including gas chromatography (GC), high-performance liquid chromatography (HPLC), and mass spectrometry (MS) [28]. The development of simple and reliable sensing techniques for pesticide detection is of vital importance due to the drawbacks of conventional methods. Fluorometric sensors have the benefits of simplicity in usage, rapidity, and high sensitivity in the analysis of samples, which makes them a suitable option for pesticide analysis [29]. In addition to the synthesis of advanced practical materials, carbon nanomaterials including diamond, graphene, amorphous carbon, fullerene C60, carbon nanotubes, carbon dots (CDs), and organic framework materials have set up a completely novel path for the advancement of fluorometric sensing methods [30]. Fluorescence carbon nanomaterials, such as zero-dimensional (0-D) CDs/graphene quantum dots (GQDs), two-dimensional (2-D) carbon nitride nanosheets (g-C3N4 NSs), and three-dimensional (3-D) carbon-based metal/covalent organic frameworks (MOFs/COFs), are emerging substitutes that may exceed certain drawbacks of semiconductor quantum dots and organic other dyes with fluorescent properties [31].

Along with this, by utilizing a newly developed nanotechnology-based electrochemical biosensing platform based on the inhibition of the acetylcholinesterase (AChE) enzyme [32]. Lately, there has been a growing trend in utilizing various nanoparticles for enhancing biosensor advancements in pesticide detection. These nanoparticles encompass cadmium sulphide nanoparticles (CdS NPs), gold-platinum (AuPt) bimetallic nanoparticles, pure gold nanoparticles, as well as composite materials like Prussian blue (PB) and zirconium dioxide (ZrO2) incorporated into chitosan films [33,34]. Pesticide exposure is frequently associated with forensic suicide or attempt suicide investigations. The existence of pesticides or their byproducts in biological samples such as blood serum or urine is used to determine prior pesticide exposure [35]. In the process of confirming the existence of these harmful pesticides, conventional techniques necessitate the preparation of an extensive array of samples. To address this challenge, metal ferrite nanoparticles have been innovated as auxiliary agents within surface-assisted laser desorption/ionization mass spectrometry (SLDI-MS). This advancement is aimed at detecting pesticide residues in human blood serum, offering a solution to this issue. [36]. For example, ZnFe2O4, CuFe2O4, and MnFe2O4 nanoparticles were produced using the cooperating method, and they were then characterised using a variety of analytical techniques, such as X-ray diffraction, UV- Vis

Spectroscopy, X-ray Photo-electron Spectroscopy, Transmission electron Microscopy, and the Brunauer-Emmett-Teller method[37].These biosensors assist the scientific community by being quick to use, lightweight, cost-effective, highly specific and sensitive, and user-friendly and can replace the traditional methods in forensic laboratories [38].

V. APPLICATIONS OF NANOMATERIALS IN DRUG DETECTION

Drug-facilitated crime (DFC) is the term used to describe crimes involving illegal drugs. The primary goal of this crime is to impair the behaviour, cognitive abilities, or interpersonal abilities of the drug-impaired individual. The detection of illicit narcotics is a major challenge because DFC also encompasses serious offences including rape, sexual assault, burglary, and robbery [39-40]. Drug detection becomes challenging for forensic professionals since the drug cannot be accessed in its original form in the sample that was provided to the forensic laboratory for examination and the standard methods of drug testing are associated with several drawbacks, including sensitivity, equipment limits, and cost-effectiveness [41]. Therefore, Nanotechnology makes it an essential tool for the detection of illegal substances.In the current scenario, nanotechnology is effectively used in forensic toxicology for the detection and quantification of various toxic compounds from various forensic evidence such as blood, hair, saliva, urine, vitreous, and even fingerprints and cadaver bones.

In the past few decades, due to their exceptional biocompatibility and distinctive optical and electrochemical features, gold nanoparticles (AuNPs) have drawn significant interest and are often used in nanotechnology [42]. Researchers developed a technique to detect a drug called clonazepam which is used in the treatment of anxiety disorders. This technique is based on gold nanoparticles (AuNPs), which are extremely sensitive, selective, and economical approaches for the detection of minute amounts of a drug called clonazepam in the presence of melamine [43-44]. As a result. Clonazepam and melamine's hydrogen bonding interactions caused AuNPs to aggregate, changing their colour from wine red to blue. This suggested plan was further backed by this method and can also be used with real samples, including blood and skeletal remains, to demonstrate the applicability of the designed Nano sensor through a series of empirical research [45-46].Advanced techniques like HPLC, XPS, and Tof-MS which are embedded with nanotechnologies are used in the detection of a wide range of substances, including both legal drugs like paracetamol and illegal narcotics like heroin, cocaine, and other barbiturates [47-48].Additionally, the advancement utilizes capillary electrophoresis in combination with nano-gold (Au-NPs), nano-titanium dioxide (TiO_2) particles and silver nanoparticles in conjunction with FTIR, SEM and TEM [49-50]. Likewise, For the detection of many different substances and their metabolites, such as morphine (a metabolite of heroin), benzoylecgonine (a metabolite of cocaine), and others from latent fingerprints, functionalized magnetic particles containing antibodies were utilized [51-52]. Silver nanoparticles in a microfluidic device could help in the detection of traces of illegal narcotic drugs in saliva samples and in human urine samples can be identified by a quick technique of utilising the support vector machine (SVM) classification algorithm, gold nanorods (GNRs), and dynamic-surface enhanced Raman spectroscopy (D-SERS) [53].Newly conducted research reveals that drug identification from urine samples can now be accomplished in under a minute, while the extraction process takes less than two minutes. In addition to that, using citrate-stabilized Au-NPs as a probe and a "smartphone camera" as an analysis tool, a "smart" method was recently designed to rapidly detect and estimate the quantity of codeine sulphate. The smartphone's camera was able to identify exceedingly subtle colour changes or ultrasensitive colourimetric changes in the nanoprobe, depending on the presence of codeine sulphate [54]. This system of nanotechnology offered rapid, lightweight, to identify illegal narcotics drugs at the crime scene.

VI. APPLICATIONS OF NANOMATERIALS IN BLOODSTAIN AGE ESTIMATION

One of the most crucial pieces of evidence in forensic cases is thought to be bodily fluids. Blood, semen, and saliva might contain critical information for investigators, depending on their condition and location. There are several trustworthy techniques for identifying bloodstains during a forensic analysis of a crime scene [55]. The standard analysis still has issues with estimating the age of the bloodstains.Recent studies have successfully addressed a significant challenge in forensic science using Atomic Force Microscopy (AFM), allowing for the determination of the age of blood cells based on observable cellular and morphological transformations. AFM is a new possible technique for determining the age of bloodstains and the Time Since Death (TSD), therefore it may be able to assist legal and medical experts in solving crimes by providing them with crucial information [56]. AFM is a nanotechnology that may be used to produce forensic data. Nanoscale surface topography may be imaged using AFM methods. As a result, by capturing force-distance curves, AFM evaluates how changes in the morphology and surface elasticity of RBC. The elasticity pattern will decrease with time, which is more likely a result of bloodstains' normal coagulation and degradation processes. Therefore, it is possible to determine the age of the bloodstains by calibrating the elasticity curve with respect to time, which may assist a criminal investigation [57-58]. Along with this, silver nanomaterials were used to detect the blood stains on the cloths by spraying on the suspected blood stain cloth. In this process the solution of methanol and Mercaptosuccinic acid as a capping agent. Then these reagents help to visualize the suspected blood or semen samples which can be visualized under a UV light source [59-60].

VII. APPLICATIONS OF NANOMATERIALS IN DNA ANALYSIS-ENHANCEMENT OF DNA SENSING TECHNOLOGIES

Nanomaterials have emerged as transformative tools in the realm of DNA detection, revolutionizing the sensitivity, specificity, and efficiency of this critical analytical process. Leveraging their unique physicochemical properties and high surface area-to-volume ratios, nanomaterials offer remarkable advantages for enhancing DNA sensing technologies. Various nanomaterials, such as gold nanoparticles (AuNPs), quantum dots (QDs), carbon nanotubes (CNTs), and magnetic nanoparticles, have been ingeniously integrated into DNA detection platforms. Functioning as adaptable foundational elements, these nanomaterials facilitate the creation of exceptionally sensitive and specific assays for DNA targets[61]. The exceptional optical properties of nanomaterials, like plasmonic effects in AuNPs and fluorescent emission in QDs, allow for label-free or fluorescent-based detection methods. These approaches enable real-time monitoring and quantification of DNA hybridization events. Additionally, the precise control over nanomaterials' sizes, shapes, and surface modifications facilitates the design of tailor-made probes for specific DNA sequences [62]. Nanomaterials' electronic properties have also been harnessed in electrochemical DNA sensors. CNTs, graphene, and conductive polymers serve as excellent substrates for DNA immobilization and electron transfer, enabling sensitive electrochemical detection. These systems exhibit rapid response times and can be easily integrated into portable devices for on-site DNA analysis [63]. Furthermore, the incorporation of magnetic nanoparticles imparts the capability for magnetic separation and manipulation of DNA molecules. This feature is pivotal in simplifying sample preparation and enabling efficient recovery of target DNA, enhancing both sensitivity and speed of detection methods [64]. Nanomaterial-based DNA detection holds tremendous promise across various applications. From medical diagnostics and genetic testing to environmental monitoring and forensic analysis, these technologies offer rapid and accurate results, often with reduced sample volumes and processing times. This integration of nanomaterials into DNA detection methodologies represents a paradigm shift in analytical sciences.

VIII. APPLICATIONS OF NANOMATERIALS IN THE DETERMINATION OF TIME SINCE DEATH (TSD)

The evaluation of the time elapsed since death (TSD) holds significant importance within medico-legal investigations. Accurate TSD assessment can prove valuable in establishing both the timing and cause of death. Conventionally, this assessment involves considering a range of factors, encompassing Algor mortis, ocular changes, post-mortem hypostasis, rigour mortis, decomposition alterations, contents of the stomach and intestines, urinary bladder contents, and anecdotal evidence[65].Out of these, Vitreous Humour (VH) is the fluid that endures and remains unchanged even after a long period of death. This indicates that VH's metabolic processes, which affect how much of the amino acid is present, fluctuate gradually. As a result, accurate TSD estimates may be achieved by examining these metabolic changes. In the near future, the amino acid composition from VH can probably be detected by fluorescent nanoparticles, and then quantification could be evaluated by flow cytometry, which would be an appropriate method to determine TSD efficiently[66]. Recent advancements in technology have made it possible to determine cysteine, an amino acid, with ease. This approach is smart, rapid, precise, cost-effective, and designed for lab-on-chip implementation. Utilizing this method, it becomes possible to ascertain the time since death (TSD) up to 96 hours prior to a noticeable increase in cystine concentration from VH. This increase demonstrates a linear correlation with the progression of TSD.The DNA degradation rate of the spleen and brain tissue was determined as well by a flow cytometry-based approach to estimate TSD for up to 96 hours [67-68]

IX. APPLICATIONS OF NANOMATERIALS IN EXPLOSIVE RESIDUE DETECTION

Terrorism has been characterized as illegal acts of violence which ignore public safety in order to create terror for their wrong ideologyExplosives such as bombs, grenades, and improvised explosive devices are known to cause widespread mass destruction. Explosives can be classified as nitroaromatics, nitrate esters, nitramines, and peroxides based on their composition as chemicals [69]. The most often used of these in both military operations and criminal activities are aromatic explosives with the combination of nitro group. Organic compounds that have one or more nitro functional groups (-NO2) are categorised as nitroaromatic explosives. Despite the considerable advancements and prevalent adoption of diverse detection methodologies for explosive materials, including techniques such as liquid and gas chromatography-mass spectrometry (LC/GC-MS), Fourier-transform infrared

(FTIR), surface-enhanced Raman spectroscopy (SERS), ion-mobility spectrometry, enzymatic assays, and electrochemistry, it is essential to acknowledge the intrinsic limitations inherent in these approaches [70-71]. These limitations primarily result from their intricate dependent on expensive and frequently large-scale instrumentation, complicated analytical procedures that are notable time consumption and expense, and limited feasibility when confronted with the need for on-site and real-time explosives detection circumstances.In this context, the integration of nano-based technology offers a valuable avenue for addressing enigmatic explosive cases.Several nanomaterials have been harnessed for the purpose of explosive residue detection, showcasing their efficacy in enhancing sensitivity, selectivity, and detection limits [72].

Noteworthy examples include Graphene, which is a single layer of carbon atoms arranged in a two-dimensional lattice, that exhibits exceptional electrical conductivity. Its high surface area and electrical properties make it suitable for creating sensors that can detect trace amounts of explosive residues with high precision [73]. Along with this, Carbon Nano Tubes (CNTs) are cylindrical structures composed of carbon atoms and Metal nanoparticles, such as gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs), which can be functionalized with specific molecules to selectively bind to explosive residues, leading to detectable changes in their optical or electrical signals. They possess remarkable electrical and thermal conductivity properties, enabling them to be employed as nanoscale sensing elements in various detection systems for explosives [74-75]. Semiconductor quantum dots (QDs) and Lanthanide-doped nanomaterials exhibit unique luminescent properties. They can be functionalized to bind with specific explosive compounds, resulting in changes in their luminescence that can be detected and quantified [76]. All these kinds of nanomaterials can be integrated into various sensor platforms, such as field-effect transistors, surface-enhanced Raman scattering (SERS) substrates, and optical sensors, to create powerful tools for the detection and identification of explosive residues in different scenarios [77-78].

X. APPLICATIONS OF NANOMATERIALS IN QUESTION DOCUMENT EXAMINATION

Questioned document analysis plays an important role in legal proceedings by establishing the authenticity and integrity of documents. The assessment of inks present on questioned documents holds critical significance, particularly in cases involving manipulated handwriting or text. The field of forensic science has faced persistent difficulties when it comes to analysing inks, largely due to the inherent difficulty in distinguishing between various compositions of ink. [79]. Nearly all inks share a fundamental composition, albeit with minor trace variations. These nuanced distinctions have proven difficult to leverage effectively for forensic purposes through conventional methods [80]. The integration of nanomaterials, characterized by their unique properties at the nanoscale, presents a novel approach to overcoming these limitations and a promising avenue to unlock the latent potential of ink analysis and ink ageing as advancing corroborative tools within the ambit of forensic investigations [81].Nanoparticles are incorporated into inks as luminescent markers to impart unique spectral signatures, related to fingerprints, to each ink formulation. When subjected to specific wavelengths of excitation light, these nanoparticles emit light at well-defined wavelengths, creating a luminescent pattern that can be captured and analyzed [82-83].Lanthanide ions, such as europium or terbium, can be doped into nanoparticles to create luminescent markers. These ions exhibit characteristic emission lines that are highly specific, akin to a chemical barcode. By incorporating lanthanide-doped nanoparticles into inks, forensic analysts can create a luminescent code unique to each ink formulation [84-85]. Exciting the nanoparticles with an appropriate energy source reveals distinct emission lines, enabling precise identification. Recent research states that Upconversion nanoparticles (UCNPs) are nanoscale materials that exhibit a unique phenomenon known as upconversion luminescence. By tagging different inks with UCNPs emitting unique colours, forensic analysts can discern ink variations and identify potential forgeries or alterations which is a non-destructive process [86]. Lanthanide-Doped Nanoparticles such as Yttrium (Y), Erbium (Er), and Ytterbium (Yb), are doped into nanocrystals like NaYF4 which are widely used for upconversion. These nanoparticles emit specific colours that are invisible under ambient light but can be detected using near-infrared excitation. Incorporating these nanoparticles into documents or banknotes adds a layer of authentication that is difficult to counterfeit and these nanomaterials are integrated into labels or tags as a means of anti-counterfeiting [87-90].

XI. APPLICATIONS OF NANOMATERIALS IN PETROLEUM PRODUCT DETECTION

Petroleum residues, often encountered in various crime scenes, pose unique challenges to forensic investigators due to their complex composition and widespread use. Petroleum residues are frequently encountered in forensic investigations, particularly in cases of arson, vehicular accidents, and environmental incidents. The intricate composition of petroleum products demands specialized techniques for accurate identification and source attribution [91]. Nanomaterial-based gas sensors exhibit remarkable sensitivity to volatile organic compounds (VOCs) emitted by petroleum residues. Functionalized Nanosensors can selectively interact with specific VOCs, enabling rapid on-site detection and source identification [92-93]. Nanoparticles functionalized with affinity ligands can selectively capture petroleum components from liquid samples, enabling precise qualitative and quantitative analysis. Techniques such as surface-enhanced Raman spectroscopy (SERS) using typical metal nanoparticles like gold or silver, to enhance the Raman scattering signal of molecules adsorbed on their surfaces. This technique can help in the identification of specific petroleum compounds based on their molecular vibrations, even at very low concentrations [94]. Gas chromatography (GC) and liquid chromatography (LC) are commonly used techniques in forensic analysis. Nanomaterials, such as carbon nanotubes or metal-organic frameworks, can be integrated into stationary phases to improve separation, reduce the analysis time, and enhance the detection of petroleum-related compounds[95-96]. Nanoparticles with unique optical or magnetic properties can be functionalized to selectively bind to petroleum residues. These tagged residues can then be tracked and visualized using techniques like fluorescence microscopy or magnetic resonance imaging (MRI), aiding in the mapping of residue distribution at crime scenes [97-98]. Surface-functionalized nanomaterial coatings can be applied to surfaces prone to petroleum contamination, such as fire-damaged structures or vehicle components. These coatings capture and stabilize residues, enabling subsequent analysis and aiding in source determination [99]. In recent years, nanotechnology is also used for the detection of iron oxide nanomaterials in petroleum products. By functionalizing iron oxide nanoparticles, researchers can create sensitive sensors that change properties when exposed to petroleum residues[100]. This technology enables rapid and precise detection of petroleum contamination in various samples, aiding in environmental monitoring and forensic investigations.

XII. DISCUSSION

This comprehensive chapter discusses the wide-ranging applications of nanotechnology within the field of forensic science and the integration of advanced nanotechnology tools, and their potential applications of nanotechnology like nanosensors which exhibit remarkable promise in the realm of explosive detection, opening avenues for enhanced security and safety measures and the utilization of nanoparticles, such as gold nanoparticles (Au-NPs), zinc sulphide nanoparticles (ZnS-NPs), and cadmium sulphide nanoparticles (CdS-NPs), for fingerprint enhancement. In the domain of DNA fingerprinting, gold nanoparticles (Au-NPs) offer intriguing possibilities, while quantum dots emerge as luminescent materials with potential applications in bolstering security features in sensitive documents which offer innovative solutions and tools for addressing complex challenges in the field. This chapter also discusses the future perspectives of forensic science with the combination of nanotechnology. This can be achieved by placing a robust emphasis on the development of educational research endeavours. This will play a pivotal role in furnishing a proficient workforce and the necessary infrastructure and tools, crucial for propelling nanotechnology to the more advanced technology by utilization of forensic laboratory instruments should be paralleled with the incorporation of equipment capable of conducting nanoscale analyses. In the near future, more sustainable and advanced nanomaterials will be synthesised as the growth towards sustainable living is the ultimate goal. This advancement will also have new tools for the solving and prevention of crimes as these devices will use special materials combined with nanotechnology will be more cost-effective, sensitive, and selective and will provide fast analysis.

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