

Interdisciplinary perspectives on chemistry in crime detection and law enforcement



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ABSTRACT

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There is a growing need to protect society from harmful industrial, environmental, and service-related practices through clear, equitable, and effectively enforced legislation. This review aims to provide interdisciplinary perspectives on the role of chemistry in crime detection and law enforcement, emphasizing its contribution to justice, social order, and sustainable development. A qualitative literature survey was conducted using Google Scholar, Scopus, and PubMed, resulting in the inclusion of 65 relevant references. The analysis synthesizes insights from forensic chemistry and legal scholarship to examine how scientific investigation supports the collection of direct and indirect, as well as substantive and demonstrative, evidence in criminal proceedings. The findings highlight the interconnectedness of forensic chemistry and the justice system, underscoring the importance of rigorous chemical analysis, aggressive enforcement of the law, and data-driven conclusions in maintaining societal balance and public trust. The review also reveals the complexities and challenges faced by professionals operating at the interface of chemistry and law, particularly in ensuring evidentiary reliability and legal compliance. These insights have practical implications for policymakers, legal practitioners, and forensic scientists by informing legislative reforms, strengthening investigative frameworks, and promoting evidence-based decision-making to safeguard justice and foster sustainable societal progress. In summary, this manuscript highlights the importance of interdisciplinary perspectives on forensic chemistry in crime detection and law enforcement, emphasizing the need for a collaborative approach to the identification of persons and items and the effective implementation of laws to promote peace in society.

Contribution/ Originality: This review uniquely synthesizes forensic chemistry and legal frameworks through an interdisciplinary lens, emphasizing their societal and civilizational implications. Unlike prior studies, it integrates chemical evidence typologies with justice, sustainability, and policy enforcement, offering a holistic “bird’s-eye” perspective on chemistry’s role in maintaining social order.

1. INTRODUCTION

Chemistry education, laboratory training, and experience help in answering specific questions in criminal investigations of suspected individuals or samples that help in the administration of justice in law enforcement. Forensic chemistry and law have complementary roles in finding criminals (Freeland, 2014; McEldowney & McEldowney, 2011; Van Klink & Taekema, 2012). The faculties developed by research are those most needed in an investigation and the identification of persons. The art of forensic investigation and the importance of active law practice can provide legal evidence, eventually helping to put criminals behind bars (Lee & Pagliaro, 2013). The joint

application of the experimental approach of chemistry, along with the legal systems of the land, can help solve a particular case. The progressive development of forensic research laboratories worldwide and several amendments to criminal laws facilitated the proper identification of criminals (Sapse & Kobilinsky, 2011). The fruits of research in everyday legal practice have been fundamental to many major criminal cases in their critical evaluation (Ludwig, 2016). In this paper, we establish the interconnectedness of chemistry and law, demonstrating how this relationship enables the systematic identification of criminals and delivers a clear message to society through appropriate punishment. This article highlights the need for the joint application of chemistry and law, particularly addressing criminal issues. The link between forensic research and the law is also emphasized as essential for the effective application of scientific advances to a legal case. Chemical investigations serve as a critical component in many areas of law enforcement, and high conviction rates based on factual evidence ultimately enrich jurisprudence (Woodman, Spiranovic, Julian, Ballantyne, & Kelty, 2020).

Chemistry plays an increasingly important role in courts of law by helping establish the innocence or guilt of individuals and serving as an essential tool in law enforcement through interdisciplinary collaboration. Forensic chemistry aids in the detection, investigation, and control of crime within society. Moreover, perspectives beyond the legal field are crucial for a comprehensive understanding of the criminal justice system, as scholars from diverse disciplines contribute clarity to complex legal and forensic issues (Bachman & Schutt, 2019). The logic and discipline of chemistry can be applied to the study and practice of law. Patent Law, Environmental Law, Food and Drug Law, and Product Liability encompass numerous aspects of chemistry and law. Learning law and chemistry through relevant quality content is essential to creating future citizens of society. Chemical investigations using sophisticated instruments confirm the actions of the offender/s and/or victims and identify the exact nature of the samples as evidence of crime in a criminal case. The presentation of scientific evidence is crucial for the justice administration in law enforcement (Cato, 1974). Chemists can appear in court as expert witnesses using chemical principles and techniques to examine all materials to determine whether a suspect is innocent or guilty, fostering far better legal outcomes (Bjur & Richardson, 2020). Law has the power to transform society by providing retribution, deterrence, prevention, and reform, enabling people to live with dignity and respect. To achieve our full potential as individuals and nations, it is wise to reflect deeply on creating a more civilized world order, one guided more by human connection than by technology.

The purpose of forensic analysis is to establish facts, identify individuals, provide evidence, and resolve disputes. Applying chemical principles to legal matters provides crucial evidence for investigations and court proceedings, helping to solve crimes and deliver justice (Wish & Gropper, 1990). The identification and characterization of chemicals present in blood or drug samples collected from crime scenes provide investigators with valuable clues. Forensic chemists often serve as expert witnesses in court, presenting their findings and explaining analysis methods used by juries and judges with ink and intellect. Forensic chemistry plays a crucial role in the justice system by identifying suspects and victims, reconstructing crime scenes, imparting justice based on scientific evidence, providing evidence to support or refute claims, offering expert testimony, and collaborating with legal practitioners. The connection between science and law becomes clear when forensic science experts work closely with lawyers, detectives, and other legal professionals to understand the legal context of forensic findings and present evidence effectively in court. Some common examples of forensic chemistry use include identifying poisons and drugs in bodily fluids and tissues, identifying and quantifying illegal substances, trace evidence analysis (hair/fibers/paint chips), firearms and ballistics analysis, and determining the cause of fires via fire debris analysis. Digital forensics examines computer data or other digital evidence to reconstruct events or identify perpetrators. Powerful microscopes enable us to examine evidence, such as hairs or fibers found at a crime scene, comparing them with those related to known individuals. DNA analysis of samples helps identify individuals or establish connections to a crime scene. Bloodstain pattern analysis, examining the size, shape, distribution, and location of bloodstains, helps understand the dynamics of bloodshed and reconstruct the sequence of events. A thorough scientific analysis using standard operating

procedures (SOPs) and established analytical methods provides accurate results. Forensic chemists can present their findings in the courtroom as expert witnesses and narrate the scientific evidence for admission, as outlined in the Evidence Act, Expert Witness Testimony, and Scientific Evidence Admission.

1.1. Spirit of Justice System

The rules and standards administer all aspects of society. Law exists to regulate society, and it can affect many aspects of daily life via the justice system, from police stations to courtrooms (Fisk, 2017; Kapoor, 2015; Rahayu, Faisal, Sari, & Satrio, 2020). Laws deal with every aspect of life, from traffic offenses to mass murder. It is a fundamental element of all societies, and every culture has evolved into a system of rules and regulations. The legislature makes and passes laws, whereas the judiciary interprets, implements laws, and resolves disputes (Baude & Sachs, 2016; Rubin, 1989). Regulating spending and taxation, approving appointments of executives/judges, and overseeing the government's administration also come under the legislature. Protecting rights and liberties, ensuring legal certainty, upholding the rule of law, and providing advice are essential to promote social peace. The police and courts are responsible for enforcing the law. It is a legal requirement to wear a seat belt while driving. Breaking laws is liable to prosecution. Long-suppressed mass aspirations of the people in a country certainly have consequences and could lead to public unrest.

When laws are broken, it leads to a state of chaos. Courts are particularly influential in developing the law. The examination of evidence (written/spoken evidence, actual object-murder weapon, scientific data, blood samples) is essential in legal trials. Jurisprudence is the science or philosophy of law that seeks to ascertain regularities in human behavior. Civil/Criminal/Family/Religious laws deal with taxation, property, inheritance, and medical law (damage to property, person, or reputation), buying/selling a home, acts of violence (assault and murder), theft, traffic offenses, and public disorder, juvenile crime, drug dealing or fraud, the relationship between couples, parents, and children (divorce settlements, custody of/access to children, and Sharia (The Path). Ultimately, a humanistic worldview of hope and light must prevail, and universal human values (UHV) must be practiced by law-abiding global citizens (Kostina, Kretova, Teleshova, Tsepkova, & Vezirov, 2015).

1.2. Perspectives on the Judicial System

Truth is subject to confirmation/contradiction on inquiry. Veiling power hides the real (manipulates truth), and projection power reveals other things than the real (creates an illusion). There are several issues and concerns in law-making and its enforcement bodies (Amer, 2014; Ghavanini, 2020): i) frequent disturbances disrupting proceedings ii) forced adjournments for several days at a stretch iii) heavy absenteeism witnessed in the parliament iv) public servants becoming the source of power and patronage with vested interests, and v) essential bills not moved due to various reasons. General disorder in the neighborhood leads to increased antisocial behavior and eventually to serious crime, resulting in law-breaking. If a civil disorder is eliminated, then grave crimes will drop, and it is crucial to explore the right perspectives on the judicial system. It is essential to enhance the quality of people elected to parliament, and an alert, intelligent public opinion plays a pivotal role in the nation-building task. People must take an active part in the political process and decision-making, and elected representatives must take practical actions considering public moods and mass aspirations. At the same time, establishing fast-track courts, mobile courts, rural courts, or special courts would help provide timely justice to the victims and prevent unlawful activities. Similarly, judicial education, trial court practice, and training and mercilessly rooting out judicial corruption, matter in the long-term public welfare and progress (Fisman & Golden, 2017). Directing the energy of the younger generation into constructive channels fosters lasting social changes. Awareness programs involving people's participation utilizing improved technology will encourage them to engage in lawful activities. Lawyers should act as a strong force in society's reformation in the letter and spirit of the law.

1.3. Upholding Legal Principles

Foundational concepts that guide the interpretation and application of laws, ensuring fairness, justice, and consistency in legal systems, are called legal principles. The key legal principles include the rules of law, separation of powers, and equality. The rule of law ensures that everyone in power is subject to and accountable under the law, promoting fairness and preventing misuse of power. The separation of powers divides legislative, executive, and judicial authority to prevent one branch from becoming too powerful. Treating all individuals equally under the law is an important principle. The concept of legal certainty ensures that laws are clear, predictable, and applied consistently, promoting fairness and preventing confusion. The hierarchy of legal norms establishes a ranking of legal rules in the order of constitutions, statutes, regulations, and judicial precedents. The principle of legality implies that actions can only be punished if they are prohibited by law. Other essential principles include fairness, justice, accountability, proportionality, responsibility, precedent, contract, administration of justice, and alternative liability (Gyöngyi, 2020; Mathew, 2020).

To stimulate reliable judgment, the sequence of concrete action steps should be logical (particular subject areas), the proper people should be involved (specialized expertise or experience), and the deadlines should be reasonable to rationalize specific reasons to complete quickly (time management). Passion is the energy that drives excellence and superior results. It is essential to motivate and inspire learners to help them maximize their potential to lead more stable, productive lives. It is essential to change people's mindset from negative to positive thinking and work towards the ideals of social justice and harmony. It is better to curb some social issues, such as nepotism, favoritism, racism, casteism, terrorism, separatism, regionalism, sexism, linguism, exclusivism, and religious fundamentalism that turn humans against each other. A deliberate misuse of power/authority, by targeting various corporate entities or politicians to extort money with criminal intent, is against the interests, goals, and values of society. It is vital to expedite the delivery of justice, as justice delayed is justice denied. A proper legal perspective on biomedical waste management, environmental/biodiversity protection, prevention and pollution control, and making/breaking of laws has a profound impact on the reformation of society in the right spirit. The transition from prison inmate to a contributing citizen via reintegration into society, rehabilitation, and reformation is essential for the greater good of society (Gideon & Sung, 2011; Khan, Shah, & Kanwel, 2023).

1.4. Reflections on the Legal Field

We have to change the system by realizing the following: i) realize the need to fight for justice/democratic values, ii) pay extra attention to social well-being, iii) youngsters have to enter politics in large numbers, iv) be more active in terms of citizen participation, v) demand our parliamentarians to do more, vi) embrace the modern scientific thinking and hard-work culture, and vii) use Natural resources sustainably and become a prosperous, harmonious democracy. The journey to success depends on how we learn to identify root causes and acknowledge and navigate these challenges with courage and grace, unified efforts, and collective humanity leading to achievement. Ultimately, fostering a scientific culture that values scientific spirit, diverse perspectives, and integrity over pseudoscience and sycophancy is essential for the long-term health of the nation and the public welfare. Purpose and passion, policies and schemes for public welfare, training, and certification, quick decision-making and rapid implementation, and developing a deeper connection with our natural ecosystem help create future-ready learners/professionals. Artificial intelligence is transforming our society, and legal professionals are leveraging AI-powered tools for different tasks, including legal knowledge/research, reasoning, predictive analytics, decision-making, and contract review. Future-ready solutions include expanding the availability and accessibility of legal services through innovative models that deliver practical and affordable assistance. These solutions encompass online legal consultancy and related digital services, as well as free legal aid for senior citizens (Casey, 2013).

When rules and specific regulations are poorly drafted, multiple interpretations can arise, complicating matters and often leading to disputes and increased litigation within the justice delivery system (Collins, 2010). No timely

justice, judicial corruption, misconduct by judges, misuse of laws, money laundering, anti-national activities, inflammatory speeches, terror, civil disorder, injustice and crimes, disproportionate assets, and organized crime often lead to senseless violence and pose a significant danger to a healthy society. Activities of organized crime include gambling, money laundering, narcotics distribution, prostitution, kidnapping for ransom, human trafficking, bank robberies, drug trafficking, destructive arson, illegal sale or distribution of firearms, illegal land hoarding, and blackmail. Sometimes, we must agree to disagree to demonstrate tolerance for conflicting viewpoints that are more relevant than ever before. Strife and struggle, tension and turmoil, shooting and looting, suffering and suffocating, hatred and violence, dissonance and injustice, war and loss of dignity, civil disorder and crime, terror and trafficking must be significantly reduced by working towards ideals of social justice and harmony using body, mind, and intellect. Other critical concerns include terrorism, cybercrime, public health legislation, torture behind bars, capital punishment, accident cases, cheque bounce cases, tax evasion, financial fraud, illegal immigration, digital arrest scams, ragging, and redefining environmental jurisprudence (Boulot, 2012; Powell, Stratton, & Cameron, 2018). Massive delays in convictions, low conviction rates, lack of witness protection programs, uncooperative or hostile witnesses, flawed investigations, and misuse of laws contribute to case backlogs and undermine justice. Promoting public awareness of laws is essential to fostering an orderly society free from wrongdoing and injustice. Better policing, speedy justice, stringent punishments, independence of institutions, public interest litigation, and preventive measures can have a profound impact on people and help avoid legal problems. Environmental degradation, the content/conduct of government policy, violation of fundamental human rights of the poor, violation of religious or other fundamental rights, and compelling municipal people to perform a public duty are essential for changes in society or social welfare. Exploiting technicalities, loopholes, and ambiguous legal language undermines the very intention for which the law was enacted. It is paramount to develop a professional culture (attorney/judge) as there is no replacement for experience/competitive edge/quality judgment. Rational thinking, innovative strategies, peaceful protests, sustainable judicial practices, raising voices against injustice, preventing future legal issues, transparency/accountability/responsibility, social activism, and novel technologies make things better and have a positive impact on other people's lives. It is better to comply, not just with the letter of the rules and regulations, but also with the spirit behind why these rules are implemented. Sensitizing the public about the laws of the land is vital to maintaining discipline and order in society. In a just society, the principles of accessibility and access to healthcare, opportunities, and justice that empower people to lead dignified lives are significant (Daniels, 2008).

1.5. Exploiting Technology and Science for Criminal Activities

It is essential to understand the duality of technology as a double-edged sword (Clarke, 2004). For instance, rocket technology helps launch satellites for remote sensing and communication applications and develops missiles with specific defense needs. Aviation technology helps develop passenger jets and reach remote areas quickly during disasters. At the same time, it created fighter and bomber aircraft that defend a country. Chemical engineering developments allow fertilizers to increase crop yield and generate chemical weapons. Nuclear science is applied in nuclear medicine/nuclear power generation, and nuclear irradiation for the preservation of agricultural products. Further, it also creates atomic weapons of mass destruction. Mobile, an instrument of empowerment and communication, could be a source of harassment. Dynamite is used to help build roads, tunnels, and canals worldwide, and it can also be used as an instrument of war. Chemistry plays a pivotal role in pharmaceuticals and life-saving drugs, while performance-enhancing drugs play a negative role in sports events, which are prohibited. Technology is undoubtedly transforming human life, making it easier, more convenient, and faster, and at the same time, it leads to social isolation, including pseudo-progress and insensitivity.

Criminals are leveraging scientific knowledge and technological advancements to plan, execute, and conceal crimes and exploiting scientific principles for creating weapons or explosives. Computer science knowledge is used to launch cyber attacks, steal classified data, and commit online fraud. They can create fake documents, manipulate

databases, and steal personal information, including bank details. Some criminals even use their chemistry knowledge to create improvised explosive devices (IEDs) or dangerous weapons. They can use modern synthetic methods to prepare and distribute illegal drugs or insecticides (drug trafficking). Criminals may alter or destroy evidence such as DNA or fingerprints, falsifying documents using scientific knowledge to avoid prosecution (crime scene manipulation). They can use plastic surgery to change their appearance or to create false identities. They can create fake pieces of great artists that are difficult to distinguish from the original artwork. Criminals can use DNA analysis to identify potential victims or targets, or use fingerprint analysis to fake fingerprints or cover up their own. Similarly, knowledge of toxicology can be used to poison victims or to create fake evidence. Intellectual property rights (IPR), including patents, copyrights, trademarks, and trade secrets, can be misused by offenders, leading to violation of exclusive rights, infringement, or misappropriation, potentially harming inventors and businesses. Property rights crimes, involving actions that damage, misuse, or steal, such as document forgery, criminal trespass, burglary, breach of trust, fraud, extortion, vandalism, auto theft, and cheating, may occur using applied science knowledge.

1.6. Physical Evidence in Court

Tangible items, such as weapons (guns, knives), fingerprints (latent, visible, plastic), or DNA samples (blood, hair, bodily fluids) found at a crime scene, can be presented as evidence to prove or disprove facts in a case (Dugan, 2011). Other common types of physical evidence include tools (Screwdrivers), trace evidence (fibers, hair, soil), impressions (footwear and tire tracks), documents (Audio records, emails, text messages, photographs, videos, contracts, receipts, invoices), digital evidence (computers, phones, electronic devices), and crime scene evidence (bones, teeth, tissues).

1.7. Biological Evidence in Proceedings

Biological evidence can include bodily fluids (blood, urine, saliva, semen, vaginal secretions, feces), tissues and organs (hair, tissue, bone, teeth), and items containing these biological materials (clothes, beds) (Kaye, Bieber, & Primorac, 2014; Stotler & Bell, 1997). This evidence used in court helps to identify individuals and establish a link between them and a crime scene. It can be used to support or refute claims made by witnesses or suspects. It can also help reconstruct the sequence of events of a crime or the location of the actions.

1.8. Chemical Evidence in Legal Framework

Chemical evidence includes qualitative and quantitative analyses of various substances found at crime scenes (Levinson, Buchnik, Ariel, & Domb, 2024; Neumann, Kaye, Jackson, Reyna, & Ranadive, 2016). It can be used to identify substances, trace their origins, establish impairment levels, and determine the circumstances of an event, eventually supporting legal proceedings. Common types of chemical evidence used in court include trace evidence (arson and fire residues, gunpowder residue, controlled substances, explosives, paints, solvents), biological evidence (discussed above), and forensic chemical analysis (toxicology, forensic chemistry, forensic DNA analysis, forensic ballistics). Chemistry expert witnesses can explain the results of chemical analysis and their implications for the case at hand, helping to identify suspects. Chemical analysis can provide crucial evidence to support or refute claims made by the prosecution or the defense.

1.9. Miscellaneous Evidence Examples

Demonstrative evidence could include visual aids (diagrams/charts) to illustrate aspects of the case, while associative evidence, such as blood/body fluids/fingerprints, links a person to a crime scene or victim. If the visual aid establishes facts, it would be used as substantive evidence (number and location of wounds, electronic documents). If it is used solely to illustrate testimony, it is demonstrative evidence only (e.g., computer animations). Class physical evidence is associated with a group of people or objects rather than an individual. Crime scene evidence includes any

objects found at the crime scene. Direct evidence will prove a point without inference or interpretation of circumstances (eyewitness, video), while indirect evidence/circumstantial evidence requires inference and interpretation (fingerprints, behavior). Primary evidence refers to the original document, a photograph, or the object in question, while secondary evidence is a copy or substitute when the original is unavailable in legal contexts (photocopy, certified copy). Evidence collected in real time and that collected while stored is admissible in the court. Other types of evidence include oral evidence, factual evidence, hearsay evidence, and judicial/non-judicial evidence (Albright, 2023).

1.10. Chemistry in Crime Detection

Chemistry plays a pivotal role in the air we breathe and the food we eat. The interconnected nature of chemistry and law involves learning across disciplines (Esseiva et al., 2007; Fakayode, Mayes, Kanipes, Johnson, & Cuthbertson, 2017; Gibbs, Gore, McGarrell, & Rivers III, 2010; Jeffery, 2017; Kanu et al., 2015; Kaplan, 2019; Katz & Halámek, 2016; Payne, 2016). Identifying unique DNA can help apprehend criminals, and chemistry experts can offer scientific opinions and provide crucial scientific evidence. Kitchen chemistry courses taught at some well-known universities and a book on using food to stimulate interest in the chemistry classroom by Keith Symcox, published by Symcox (2013b), serve as 'food for thought' to replicate such courses elsewhere (Symcox, 2013a). The nutritional value of the food decreases, and toxicity increases in our bodies when we consume adulterated food. Chemical adulterants can cause health risks and carcinogens. Forensic chemistry is the application of chemistry and forensic toxicology in a legal setting that helps in crime scene analysis. A forensic chemist assists in identifying unknown materials found at a crime scene. Fibers, footprints, and skin/hair/blood samples are used to identify people in forensic detection. Forensic chemistry is handy in testing athletes for drugs, investigating product safety, establishing the cause of suspicious fires, comparing document ink compositions, and analyzing alcohol, poisons, or drugs in body fluids/tissues. It is practical in identifying toxic chemicals maliciously added to foods or public water supplies. Illicit drug traffic is the root cause of many issues. Chemistry is helpful in mob-control with strong disabling chemical sprays/tear gas.

The purpose of forensic analysis is to establish facts, identify individuals, provide evidence, and resolve disputes. Applying chemical principles to legal matters provides crucial evidence for investigations and court proceedings to solve crimes and deliver justice. The identification and characterization of chemicals present in blood or drug samples collected from crime scenes provide investigators with valuable clues. Forensic chemists often serve as expert witnesses in court, presenting their findings and explaining analysis methods used by juries and judges with ink and intellect. Forensic chemistry plays a crucial role in the justice system by identifying suspects and victims, reconstructing crime scenes, defending justice based on scientific evidence, providing evidence to support or refute claims, offering expert testimony, and collaborating with legal practitioners. The connection between science and law becomes clear when forensic science experts work closely with lawyers, detectives, and other legal professionals to understand the legal context of forensic findings and present evidence effectively in court. Forensic chemistry applications include identifying poisons and drugs in bodily fluids and tissues, identifying and quantifying illegal substances, trace evidence analysis (Hair/fibers/paint chips), firearms and ballistics analysis, and determining the cause of fires through fire debris analysis. Digital forensics examines computer data or other digital evidence to reconstruct events or identify perpetrators. Powerful microscopes are utilized to examine evidence such as hairs or fibers found at a crime scene, comparing them with those related to known individuals. DNA analysis of samples helps identify individuals or establish connections to a crime scene. Bloodstain pattern analysis, examining the size, shape, distribution, and location of bloodstains, helps understand the dynamics of bloodshed and reconstruct the sequence of events.

1.11. Chemical Intricacies Involved

A crime cannot occur without a transfer of material between the criminal and something at the crime scene, though the ways and means of criminals are becoming sophisticated. Samples such as blood, building materials, cosmetics, documents, drugs, fabrics, flammable liquids, glass, hair, inks, intoxicating compounds, metals, paints, perspiration, rubbers, saliva, seminal fluid, soil, and urine provide the much-needed evidence. Forensic chemistry is the application of chemistry and forensic toxicology in a legal setting. A forensic chemist can assist in identifying unknown materials at the crime scene. No two people, not even identical twins, share the same fingerprint. Qualitative analysis can be used to detect the chemical composition of unknown substances found at a crime scene. Quantitative analysis is used to determine how much of each component is present. The application of sophisticated analytical instruments for data collection and measurement using chemical principles provides detailed information about the crime incident. Fingerprints are a reliable means of identifying individuals. When we touch an object, some sticky films of sweat and natural oils stick to the object, leaving behind a fingerprint. A latent print of friction ridges is recorded with a black printer's ink rolled across a contrasting white background, and patterns of ridges can be observed with a bright flashlight. The cloth pieces left at the crime scene provide helpful evidence of the solvents' action on natural or synthetic fibers. Similarly, paper, glass, metal, paints, firearms, grease and oils, cement, cosmetics, drugs, body secretions, and hair and nails also provide practical evidence for solving a crime. Many substances in trace amounts can be detected through careful chemical analysis and provide vital information/evidence (Deadman, 2003; Houck, 2003). Forensic science is valuable at various stages of litigation, including discovery, extraction, examination, identification of evidence, and its presentation in the courtroom. It is related to the discovery of truth in the crime scene investigation. It is the intricate interplay between the principles of forensic sciences, ensuring scientific rigor and fundamental principles of fairness and reliability of legal proceedings, that matters in the ultimate justice. Thus, forensic chemistry is handy in detecting and curbing crime in society.

1.12. Techniques of Forensic Chemistry

Analytical chemistry is invaluable in criminal investigations, as it provides scientific evidence used in criminal cases (Bell, 2009; De Araujo et al., 2018; Silva, Braz, & Pimentel, 2019). Analytical tools in crime detection include DNA fingerprinting (Cells from blood/hair root/bone) in establishing maternity/paternity, family relationships, and identifying missing children and soldiers killed in a war. Atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) assist in analyzing heavy metals and traces of Pb, Ba, and Sb from firearm residues. Chromatographic techniques such as thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) are essential in drug metabolite separation and identification, and qualitative and quantitative analysis of petroleum products, inks, paints, and explosive residues. Fluorescence spectroscopy is applicable in detecting inks, invisible laundry marks, seminal stains, saliva, urine, and perspiration. Infrared and ultraviolet spectroscopy are instrumental in distinguishing pigments and dyes, and the identification of rubbers, plastics, and organic compounds. X-ray fluorescence and X-ray absorption fine structure (XAFS) spectroscopy are beneficial in analyzing samples from bullet holes, hair, glass fragments, clothing, building materials, paints, inks, and firearms residues. X-ray diffraction and laser-induced breakdown spectroscopy (LIBS) help identify explosive residues, alloys, and soils. Electrophoresis analysis is applicable in analyzing wet or dry blood samples to determine factors that make them unique (individualization). Radioimmunoassay is used for the chemical identification of suspected samples.

1.13. Role of LC-MS in Forensic Science

Advanced techniques such as liquid chromatography-mass spectrometry (LC-MS) are used for identifying and quantifying substances (Jackson & Barkett, 2023; Kuwayama et al., 2019). It is a powerful tool in forensic chemistry, used to identify drugs, explosives, and trace materials, providing crucial information for investigations and legal

proceedings. Identification of drug metabolites in biological samples (Blood/urine), screening for drug abuse (Amphetamines/cannabinoids), determination of the concentration of drugs in samples, analysis of complex mixtures, analysis of dyes and pigments, analysis of components of explosives, and analysis of environmental samples that are crucial for understanding the extent/comprehensive picture, helping to link suspects to the crime scene. LC-MS can be used to identify and characterize polymers and to analyze flammable liquids, which can be helpful in forensic investigations involving plastics/arson. It can be used to identify oil additives and determine the source of oil spills, a case in oil spill environmental forensics, allowing stricter penalties for environmental damage. The advantages of LC-MS include high sensitivity and specificity, versatility, rapid analysis, and the ability to analyze polar and thermally labile compounds. These features enable the detection and identification of trace amounts of substances, the analysis of a wide range of samples, rapid results, and the examination of materials that are difficult to analyze using other techniques.

1.14. Miscellaneous Techniques

Other emerging technologies, such as automated firearm identification, blood pattern analysis software, DNA phenotyping, 3D scanning and printing, micro-XRF analysis, steam thermography, frontal X-rays, bacterial oral decomposition, and 3D fingerprinting, are used for qualitative identification and quantitative determination, allowing for detailed examination and reconstruction. Diatom analysis helps determine the cause of death in drowning cases. Tire and skid mark analysis involving tire impressions and skid marks can reveal vehicle identity in crime scenes and help reconstruct events to present evidence in court. Identification of applied cosmetics in hair forensic analysis using FTIR spectroscopy helps analyze evidence and identify criminals. Cyber forensics is used to analyze digital evidence and to identify cyber criminals. Other techniques, such as microscopy, chemometrics, and DNA analysis, are used by forensic chemists (Ahlinder, Nordgaard, & Lindström, 2015; Kumar & Sharma, 2018; Morton, 1993). AI programs used in law enforcement work during the preparation/presentation of evidence include predictive profiling, probabilistic genotyping, facial recognition, and other machine learning-based processes. There is a need for strategic change in the face of rapid technological advancements, particularly in artificial intelligence (AI) (Campbell, 2023; Reiling, 2020).

1.15. Examples of Analytical Chemistry

Arson Investigation: It is a fire investigation to ascertain the cause and origin of fire or explosion in fire-related incidents (Lentini, 2012; Stevens, 1953). The laboratory examination of the retrieved samples takes place after the investigation of the scene of the fire. Shorting of faulty electrical circuits in defective equipment, faulty fuel lines in car fires, or spontaneous combustion in an organic waste storage room are possible causes of fire. The residue sample collected from the crime scene is analyzed to determine the chemical structure. Liquid nitrogen could be used to trap residue and analyzed using a gas chromatography (GC) technique for compound identification and quantification. Forensic chemists analyze evidence for the presence or absence of explosive residues (gunshot residue), often leading to the identification of the type of explosive used. Capacity to extrapolate combustion chemistry concepts to real-life situations and apply acquired competencies in such incidents to generate solutions to specific fire-related problems. Identifying trinitrotoluene (TNT) in explosive devices and other types of explosives through analytical methods is a case study in the world of law.

Blood Alcohol Content Analysis: Determining the concentration of alcohol in a person's blood allows us to assess their level of intoxication and supports driving-under-the-influence investigations for legal purposes (Jones, 2019; Thompson, 1985). Blood alcohol concentration is measured in a wet chemistry laboratory as grams of alcohol per 100 mL of blood and is expressed as a percentage. The breathalyzer alcohol field test measures the amount of ethyl alcohol (ethanol- $\text{CH}_3\text{CH}_2\text{OH}$) in the exhaled breath, which is proportional to blood alcohol concentration. Urea and saliva tests are also used to determine alcohol levels in individuals. The amount of alcohol consumed can be used in forensic

investigations involving accidents or incidents where its consumption is a likely factor. Alcohol levels are used to determine cases of drinking and driving, where they reach the impaired judgment stage. It is often noticed that mixing methanol (CH_3OH) in spurious liquor causes deaths beyond lethal doses. It is essential to realize that the presence or absence of a $-\text{CH}_2$ group in different alcohols can make as big a difference between life and death as its practical implications for community welfare.

Drug Purity Analysis: High-performance liquid chromatography (HPLC) is the gold standard in drug purity analysis because of its precision and versatility. Other techniques, such as liquid chromatography (LC), gas chromatography (GC), thin-layer chromatography (TLC), and Fourier-transform infrared spectroscopy (FTIR), are used to identify and quantify chemical compounds from the samples collected at the crime scene, aiding in crime reconstruction and suspect identification (Davies, 2010; Michel, 2018). Accurate information on chemical composition and information on impurities present in drug samples helps a safer supply, reduces adverse effects, reduces trauma, overdoses, and deaths, increases quality control, and mitigates harm from criminalization. These chemical analysis reports on drugs help lawmakers formulate or develop better laws to solve the issues related to spurious drugs. The use of chemically/enantiomerically pure drugs reduces toxicity, leads to selective pharmacological profiles, decreases drug interactions, and improves therapeutic value. Analyzing the profiles of impurities in drugs such as cocaine, cannabis, and opium can determine the similarity between samples and their geographical origin. Forensic scientists analyze hair, blood, urine, and tissue samples for the presence and concentration of drugs, toxins, and other illicit compounds. Forensic chemical analysis helps investigators pursue legal action against individuals suspected of a drug-related crime. The above examples illustrate the critical role that forensic chemistry plays in the modern justice system. Forensic science is crucial in solving crimes and ensuring justice to rewrite the script of contemporary society. Advocating logical answers to crime-related questions, along with clarity, courage, and foresight in law-abiding leadership, and recognizing the interconnectedness of science and law, fosters welfare, goodness, friendship, peace, and prosperity, fulfilling the true aim and sole purpose of laws.

1.16. Challenges and Prospects

The spirit of the article is to advocate a better connection between science and law, creating a peaceful and just world, and providing a voice to the voiceless. Challenges include ensuring the accuracy and precision of forensic analysis, reliability of methods and spectral interpretations, communicating complex scientific findings to non-scientific audiences, maintaining the integrity of evidence, and keeping track of recent advancements in forensic science and technology. Future research directions in forensic investigations include advancements in sensitive micro-detection methods to detect minute amounts of substances, integrating 3D genomics with artificial intelligence, and utilizing nanotechnology for improved efficiency and accuracy. These developments could lead to breakthroughs in analyzing trace evidence, identifying patterns not immediately apparent to humans, and DNA or gunshot residue analysis. An integrated multi-dimensional approach involving forensic science and the justice system would give an edge to strengthening legal-level interventions toward protecting the rights and freedoms of individuals and maintaining order worldwide. Forensic science insights uphold fairness, impartiality, accountability, transparency, equality, justice, law and order, efficiency, and effectiveness. Advances in analytical chemistry techniques, analytical method development, and drug validation protocols help provide expert witness testimony and scientific evidence admission in the modern justice system. The interdisciplinary perspectives and intricate link between forensic chemistry and advanced knowledge in legal principles must be taught in higher education institutions for societal well-being. These new interdisciplinary approaches could offer valuable insights to the scientific community and lawmakers, helping them develop more effective laws to address current challenges.

Green crime encompasses a wide range of illegal activities that harm the environment, threaten wildlife, and unsustainable fishing practices, and exploiting natural resources unsustainably can pose a significant threat to human health, the environment, and global security. Offenders involved in activities such as illegal logging, pollution and

hazardous waste disposal, destroying forests, illicit trade in wildlife products, and wildlife trafficking should be punished under environmental crimes. Corporations, small and medium-scale industries, and individuals involved in such ecological crimes must be held responsible for their wrongdoings, and periodic workshops on analysis of effluent samples from the very organizations should be conducted on their premises to create awareness and compliance. Integrating forensic science with social science methods to tackle real-world problems, especially those related to sustainable development and climate change, strengthens equitable public policies in the global context. It is always better to apply laws, regulatory frameworks, sustainability, environmental, social, and governance (ESG), and diversity, equity, and inclusion (DEI) principles in corporate strategies and decisions to reshape the legal map of the world (Antin & Hanawalt, 2025; Hoggatt, Black, & Vorbrodt, 2024).

2. CONCLUSIONS

A thorough scientific analysis utilizing standard operating procedures (SOPs) and established analytical methods provides accurate results that forensic chemists can present in the courtroom as expert witnesses and narrate the scientific evidence for admission as per the Evidence Act, Expert Witness Testimony, and Scientific Evidence Admission. Sustainable judicial practices and preventing future legal issues include facing change, taking risks, overcoming fear, and making critical decisions to provide high-quality solutions. If we look at the world from a different perspective on things, acts, and relations, truth alone can be justified. Lawyers can work with forensic chemists to analyze DNA/drug samples and other unknown substances and present scientific evidence in court. Chemists and lawyers must team up to get clues from sound, sight, form, taste, touch, language, culture, and religion in their crime-fighting roles. We need to maintain the dignity of human existence through rational thinking, autonomous choices, moral actions, and passion for the law and fairness. It is essential to develop a spirit of service and cleanliness through a series of impactful initiatives in educational institutions. Nurturing every learner's unique potential by integrating academic rigor with holistic character development will foster creativity, emotional intelligence, and critical thinking in individuals. Preparing learners for knowledge tests and equipping them with the skills and mindset necessary to navigate challenges of the future by creating a productive learning environment in educational institutions enhances academic performance and overall development.

Significant advances in scientific instrumentation, data-driven conclusions, enforcement of laws, and appropriate punishment or compensation based on the severity of the crime help minimize such incidents in the future and serve as a deterrent to others from engaging in similar illegal activities. The joint application of chemistry and law can solve some legal problems. It is essential to learn the intricacies of procedural law and chemistry practical procedures and work as a team, benefiting society. An interdisciplinary approach involving adequate planning, developing proper protocols, laboratory investigations, access to special equipment or a suitable method, the availability of an appropriate expert, collecting and recording data, data analysis, interpretation of results, compliance with the law, deciding the severity of punishment, exposing students to real-world scenarios all are essential in court proceedings and classroom sessions. Learning to assess situations critically, developing specialized skills and interests, and cultivating a keen sense of observation help reveal the attitudes and motives of individuals involved in criminal activities. A meticulously designed curriculum can give graduates a distinct professional advantage by integrating legal knowledge with forensic chemistry expertise. Mastery of forensic chemistry concepts, investigative protocols, laboratory report interpretation, and the role of forensic science in legal decisions, policy development, and social or global contexts provides an essential framework for refining cross-disciplinary perspectives. Mainstream journals provide recent information and often particular accounts of current research work, research-centric discussions, novel methodologies, and unusual but exciting cases. The qualitative and quantitative analyses must be accurate, reproducible, and less expensive. Further, the law must be practical, and the adequate degree of punishment required to produce the desired effect must be well-defined. The progress and advancement of the literature on chemistry and specific aspects of the law subject can be particularly valuable. Future developments in chemistry and law could lead

to identifying criminals from their fingerprints or more particular information in each context. We must engage in thoughtful reflection to reach our full potential as individuals, and for nations to build a more civilized, multipolar world order and foster meaningful globalization. The above interdisciplinary perspectives are futuristic and forward-looking to enhance strong scientific capabilities to resolve global legal challenges and promote the rule of law. Active collaboration between forensic chemists and lawyers is recommended, shaping a new world order and generating a new algorithm for sustainable progress in our living world.

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