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Review Article

A review on forensic profiling of rhinoceros horn

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ABSTRACT

The relentless escalation of rhinoceros horn trafficking represents a profound and immediate threat to the survival of rhinoceros populations across Africa and Asia. This illicit trade, driven by persistent demand in certain consumer markets, undermines global conservation efforts and poses significant challenges for law enforcement agencies worldwide. This review comprehensively explores the pivotal role of forensic profiling as an indispensable tool in combating rhino horn trafficking. Forensic profiling, by applying advanced scientific methodologies to analyse the unique chemical, physical, and molecular signatures inherent to rhino horn offers critical capabilities in the detection of concealed contraband. Profiling can be used for the authentication of genuine horn against widespread counterfeits, and the increasingly sophisticated geographical sourcing of seized materials. This multi-faceted scientific approach could not only provide robust, admissible evidence for prosecution, but also generate vital intelligence to inform strategic interventions, disrupt illicit supply chains, and ultimately contribute to the long-term conservation of these endangered mega-herbivores.

1. Introduction

A high majority of the forensic profiling papers relate to DNA analysis (genetics). DNA profiling, particularly the RhODIS system, is the internationally recognised and most robust method used in court to link a confiscated horn to a specific poaching incident [17]. However, research into chemical profiling (isotopes, elemental analysis, and odour profiling) remains a significant and growing area for rapid, non-destructive screening to facilitate successful prosecutions, and ultimately function as a powerful deterrent to poaching of endangered species.

The majestic rhinoceros, an iconic symbol of African and Asian biodiversity, faces an existential threat from rampant poaching, driven by a lucrative illegal trade in its horn [23,29]. Türkiye is predominantly used as a transit hub (61 % of cases) in the illegal trade, connecting Africa with both Asia and Europe. It was also identified as an origin country in 26 % of cases and a final destination in 14 % [6]. Despite strict international regulations, primarily enforced through the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) which prohibits commercial trade in rhino parts, the black market continues to thrive, with rhino horn commanding prices that rival gold and narcotics [3,9,14,23,25]. This unprecedented demand, particularly from certain consumer countries in Asia, is fuelled by a combination of traditional medicinal beliefs despite the horn composed primarily of keratin with no scientifically proven medicinal properties and its emerging status as a symbol of wealth and social standing [31,33].

Despite some conservation success in countries such as India and Nepal, poaching, although a serious threat, is not the only challenge; habitat loss, climate change and diseases also present a real risk to the rhinoceros' species [30]. The escalating rhino poaching crisis has led to a dramatic decline in populations across all five extant rhino species, with several teetering on the brink of extinction [31,18]. This dire situation is compounded by significant challenges in law enforcement, which struggles with the clandestine nature of the trade, the difficulty in distinguishing genuine horn from sophisticated fakes, and the transnational scale of organised crime syndicates involved [6,19,23,45]. A morphological study discovered that characteristic filamentous unit was observed in all genuine rhino horns studied, but not in any fake horn. This is identified as the most unique and reliable feature for identification, even from small pieces [19]. However, horns are often transported and traded in processed forms such as powders, carvings, or fragments,

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that further complicates visual identification [3,13]. There is thus an urgent and recognised need for robust, scientifically validated tools to enhance enforcement, facilitate successful prosecutions, and ultimately function as a powerful deterrent to this illicit activity [13].

A South African university has completed a pilot study on the injection of radioactive material into the rhino horn. According to these researchers the procedure is harmless but will enable customs officers to detect poached horns [41]. In response to these critical demands, forensic analysis has emerged as a cornerstone of modern wildlife conservation and law enforcement. By applying principles and techniques from forensic science, investigators can extract invaluable information from seized rhino horn, moving beyond morphological identification to provide objective, scientific evidence [15,20,27]. This review specifically focuses on the application of chemical and molecular profiling methods for detection, authentication, and sourcing of rhino horn. This review will describe various analytical techniques capable of characterising the unique chemical and physical properties of rhino horn. An outline of the practical applications of these forensic approaches in combating illegal trafficking, discussing their role in border security, combating counterfeiting, and tracing the geographical origins of poached horn are provided. Furthermore, we will critically examine the inherent challenges and limitations associated with forensic profiling of rhino horn, including issues of sample integrity and method standardisation. Finally, we will propose future directions for research and development, emphasising the need for integrated, rapid, and field-deployable solutions to significantly enhance global anti-trafficking efforts.

2. The nature of rhino horn and its chemical and volatile profile

Rhino horn, unlike true bone, is a dense, fibrous structure composed predominantly of keratin, the same protein found in hair, nails, and hooves [13,19,33]. This protein matrix is densely packed with calcium deposits and melanin, providing its characteristic strength and colour. Beyond this basic composition, rhino horn contains a complex array of other organic compounds and inorganic elements, which contribute to its unique chemical "fingerprint" [33].

Forensic profiling efforts exploit these nuanced chemical characteristics. While the Ewart et al. [13] study focuses on DNA, their introduction also references chemical profiling approaches. Volatile Organic Compounds (VOCs) are a critical component of this profile, as they are responsible for the distinctive odour associated with biological materials, including horn [33]. The specific mixture and relative abundance of these VOCs can vary, offering potential for forensic discrimination. Similarly, the mineral profiles within rhino horn, including trace elements, reflect the animal's diet and environment [13,36].

Crucially for forensic analysis, these chemical profiles are not static and can be significantly influenced by a range of factors. While all rhino horn is primarily keratin, subtle differences in the genetic makeup and physiological processes across the five extant rhino species (Black, White, Indian, Sumatran, Javan) can lead to species-specific variations in the precise composition of amino acids, lipids, and trace elements within the horn [33,34,40].

As an animal ages, its metabolic processes and cumulative exposure to environmental factors can subtly alter the chemical composition of its horn, potentially leaving age-related markers [19]. The specific diet of a rhinoceros, which varies depending on its geographical habitat, directly influences the uptake and incorporation of various trace elements and isotopic ratios into its horn [2].

Browsers (like black rhinos) and grazers (like white rhinos) will exhibit distinct dietary signatures. This is one of the most significant factors influencing the chemical profile. Differences in soil geochemistry, water sources, and vegetation across distinct geographical regions lead to unique elemental and isotopic signatures (e.g., strontium, oxygen, carbon isotopes) that are incorporated into the horn during its growth [2,34]. These regional "fingerprints" are invaluable for sourcing poached horn back to specific areas. Similar work, in combating the international illegal ivory trade, was done to showcase how integrating DNA and isotopic data allows law enforcement to trace illegal wildlife products back to their source population [7].

Critically, the condition of the horn after the animal's death plays a substantial role. Drying, storage conditions (e.g., humidity, temperature, exposure to light), and processing methods (e.g., grinding, carving, boiling, chemical treatment) can dramatically alter the chemical profile [10,28]: 51). Degradation processes can lead to the loss of volatile compounds, oxidation of lipids, and changes in the structural integrity of proteins, masking or modifying the original biological signatures. These post-mortem alterations present a significant challenge for consistent and reliable forensic analysis, necessitating robust methodologies that account for such variability [10,28]: 50,53. Key volatile compounds contributing to the rhino horn profile included phenol, *p*-cresol, indole, and skatole. These compounds are commonly associated with animal matter and may be characteristic of the keratin in the horn [44].

3. Analytical techniques for chemical profiling in a forensic context

The development and application of advanced analytical techniques are paramount for extracting meaningful forensic intelligence from rhino horn samples. These methods allow for the precise characterisation of horn composition, enabling detection, authentication, and sourcing.

3.1. Chromatographic analysis

Gas Chromatography-Mass Spectrometry (GC-MS) is a powerful, versatile analytical technique used to both separate and identify/quantify components in complex mixtures, particularly for organic compounds and gases with molecular weights below 1250 g/mol. The technique works on the principle of combining two separate methods: GC is the separation step, where the sample components, which must be volatile and thermally stable, are vaporised and carried by a mobile gas phase through a column containing a stationary phase. Compounds separate based on their differential affinity for the stationary phase, eluting from the column at different rates [42]: 68–87; [39]:15, 62–63, 85–86. As each component elutes from the GC column, it enters the MS. The MS operates under a reduced pressure (vacuum) and functions by converting the molecules into ions and then separating them based on their mass-to-charge ratio m/z. The resultant fragmentation pattern is unique, acting like a fingerprint for the molecule, allowing for its unequivocal qualitative identification. The MS also allows for quantification of known analytes [39]: 8, 89–126; [42]: 99–141.

In the context of rhino horn, GC-MS is employed to establish a "chemical odour profile" Techniques such as headspace analysis or Solid-Phase Microextraction (SPME) are commonly used to extract VOCs directly from the horn sample without extensive preparation, making them suitable for forensic applications. The distinct patterns of VOCs identified by GC-MS can differentiate authentic rhino horn from fakes and may even provide clues about the horn's species or its processing history [44].

High-Performance Liquid Chromatography-Mass Spectrometry (HPLC-MS) is a fundamental and highly effective analytical technique in the biomedical field, owing to its ability to seamlessly couple the separation power of liquid chromatography with the high sensitivity and molecular specificity of mass spectrometry [5]: 330. The key to its versatility was the development of Atmospheric Pressure Ionisation (API) techniques [5]: 332, most notably Electrospray Ionisation (ESI) [5]: 332; [22]: 64, which efficiently produces charged ions from complex solutions, allowing for the analysis of both small molecules and large, polar, non-volatile biomolecules like peptides. After chromatographic separation, the ions are channelled into a mass analyser to precisely measure the mass-to-charge ratio (m/z). To increase specificity

and obtain structural information, techniques like tandem mass spectrometry (MS/MS) are utilised, which are central to achieving high-confidence measurements in complex matrices ([5]: 337–342; [22]: 298). In the biomedical arena, LC-MS applications focus on crucial areas like drug metabolism and pharmacokinetic (PK) studies and comprehensive analysis in metabolomics and biomarker discovery ([5]: 330, 354), with instrumental approaches continually being refined to increase throughput and speed using new methodologies like ultra-high-performance liquid chromatography ([5]: 349–350; [22]: 37).

HPLC-MS can be particularly valuable for investigating the protein and lipid profiles of horn, identifying specific biomarkers for species identification, or detecting masking agents and contaminants [33].

3.2. Spectroscopic analysis

X-ray fluorescence analysis (XRF) is a versatile, non-destructive, multi-elemental technique utilised across a wide range of practical applications ([4]: 3). The fundamental process tracks the path of a photon, which begins at an X-ray source to excite the sample, is modified by an optic, and is finally registered by an X-ray detector ([4]: 4). The resultant characteristic fluorescence radiation is analysed in the crucial step of quantitative analysis, where the observed photon rate is used to determine the weight fraction of the element or the thickness of single or multiple layers in a structure ([4]: 309). Since the measured photon rate is also a function of the specimen's matrix (the accompanying elements) and the spectrometer's geometric setup, complex quantification approaches, such as the theoretical Fundamental Parameter (FP) method, are often employed to convert the measured X-ray intensity into an accurate compositional value ([4]: 309, 311).

For rhino horn, XRF can provide a "fingerprint" of major and trace elements (e.g., Ca, S, Zn, Cu, Sr) without damaging the sample. This is particularly useful for geographical sourcing, as the elemental composition reflects the animal's environment [34]. Portable XRF devices are also available, offering rapid screening capabilities in field settings [26].

Inductively Coupled Plasma (ICP) spectrometry is a core technique for elemental analysis that begins with the sample, typically a liquid solution, being converted into a fine aerosol using a nebuliser and spray chamber for efficient transport into the plasma ([11]: 78–80). The fundamental component is the plasma itself, a high-temperature energy source sustained by radiofrequency power, which serves to thermally decompose the sample matrix and promote the resulting elements to excited or ionized states ([11]:102). The high temperatures within the plasma, described by characteristic gas, excitation, and ionisation temperatures, are crucial for this process ([11]: 96). Following atomisation and ionisation, the elemental species can be detected by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), which samples the ions and measures them according to their mass-to-charge ratio using mass analysers like Time-of-Flight or Triple Quadrupole systems ([11]: 142, 152). Accurate determination of the unknown concentration relies on calibration using analytical standards, calibration standards, or the technique of standard addition ([11]: 25, 164).

Fourier Transform Infrared (FTIR) spectroscopy is a widely utilized analytical technique essential for identifying the characteristic functional groups present in various materials, including gases, liquids, and solids ([21]: 2). The fundamental concept of the method is rooted in the interaction of infrared radiation with matter; when a molecule is exposed to IR, it absorbs energy at specific wavelengths, inducing changes in its molecular vibrational and rotational energy levels ([21]: 3). Unlike traditional dispersive instruments, FTIR utilises a Michelson interferometer to collect all IR wavelengths simultaneously, resulting in a raw signal called an interferogram, which is then mathematically transformed *via* the Fourier Transform algorithm into the final spectrum ([21]: 5). The resulting infrared spectrum plots the absorbed energy against the frequency (wavenumber), yielding a unique chemical "fingerprint" that facilitates the qualitative analysis and structural elucidation of the sample ([21]: 4, 5). Building on established methods, the successful application of chemometric analysis (specifically PCA and LDA) to differentiate species based on subtle chemical variations in avian keratin [16] strongly suggests the feasibility of extending this technique to analyse rhino horn, which is also composed primarily of keratin, for equivalent forensic species identification. A study done in 2007 by Espinoza, Baker and Berry[12], specifically mention infrared spectroscopy as a method previously used for rhino horn identification, although this method had not been validated for use, as forensic evidence in court. Another study by Power et al. [32] describes the evaluation of a rapid analytical technique designed for the discrimination of rhinoceros horn and ivory samples originating from various mammalian species. The methodology leverages the synergistic combination of Near-Infrared (NIR) spectroscopy and chemometric analysis. The combined NIR spectroscopy and chemometrics approach yielded a proof-of-concept classification model, achieving an overall correct classification rate of 73.5 % for the differentiation of all tested samples.

Raman spectroscopy is an analytical technique utilised for structural identification and characterisation of materials, which fundamentally relies on the inelastic scattering of monochromatic light, known as the Raman Effect ([38]: 77). When a sample is irradiated, most photons undergo elastic Rayleigh scattering, retaining their original energy; however, a minute fraction of the incident photons interact with the molecule's vibrational modes, causing a shift in energy, either lower (Stokes scattering) or higher (Anti-Stokes scattering) ([38]: 78, 80). These shifts, which are measured in wavenumbers, correspond precisely to the specific vibrational energy changes within the molecule, and are independent of the excitation wavelength ([38]: 81). For a vibrational mode to be Raman active, the molecular polarisability must change during the vibration, meaning Raman and IR spectroscopies often provide complementary information, as they adhere to different selection rules ([38]: 82).

FTIR (observing amide bands) and Raman spectroscopy (observing C-C, C-H, C═O, and S-S disulfide bonds) can potentially be used to identify the presence of keratin, differentiate it from other materials, and potentially detect adulterants or binders in processed horn products.

3.3. Mass spectrometry

ICP-MS is a highly sensitive technique for comprehensive elemental analysis. While ICP requires sample digestion, it provides highly accurate and precise quantification of a broad spectrum of trace elements and isotopes present in the horn. ICP-MS, in particular, is crucial for isotopic analysis (e.g., $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$), which are powerful markers for diet and geographical origin [2,15].

Direct Analysis in Real Time Mass Spectrometry (DART-MS) is a fast, non-invasive screening tool that can quickly analyse the chemical profile of a sample (e.g., rhinoceros' horn, wood) to determine if it is authentic, synthetic, or from a non-regulated species [37]. The DART-MS instrument works by directing a stream of heated, ionised gas onto a confiscated sample—such as rhinoceros' horn—which rapidly desorbs and ionises the volatile or semi-volatile chemical compounds on the material's surface. These resulting ions are then passed into the mass spectrometer, generating a unique chemical profile or "fingerprint" (a mass spectrum) of the sample's composition. This rapid chemical profiling capability makes DART-MS an appealing tool for the preliminary screening and classification of regulated species, allowing law enforcement to quickly distinguish genuine or specific wildlife products from counterfeits or other materials based on their distinct chemical signatures [8].

3.4. Emerging technologies

Electronic Noses (E-noses) are devices engineered to mimic the mammalian olfactory system, utilising an array of chemical sensors to detect and recognise complex odour patterns. E-noses offer rapid, non-

destructive, and potentially portable screening for suspected rhino horn, alerting authorities to the presence of characteristic volatile signatures [47]. While still under development for this specific application, their potential for high-throughput screening at border crossings is significant [48].

The trend in forensic science is towards miniaturised, robust, and field-deployable versions of established laboratory instruments. Hand-held XRF devices are already available [26,35]. Ongoing research aims to develop portable GC-MS systems or integrated multi-sensor platforms that can perform rapid, on-site chemical profiling, reducing reliance on central laboratories and speeding up the investigative process [24].

3.5. Sample preparation considerations for forensic samples

Effective sample preparation is critical for obtaining accurate and reliable results, especially given the typically small and often degraded nature of forensic samples. Since horn is a heterogeneous material, obtaining a representative subsample for analysis is crucial. This may involve grinding a small portion of the sample into a fine powder to ensure homogeneity for elemental or isotopic analysis [36].

Strict chain-of-custody protocols and cleanroom conditions are essential to prevent exogenous contamination from human DNA [13], other biological materials, or environmental chemicals, which could compromise the integrity of the chemical profile [20,27].

For VOC analysis, samples must be handled and stored in airtight, inert containers, often at low temperatures, to prevent the loss or degradation of volatile compounds. Whenever possible, non-destructive techniques (e.g., XRF, FTIR, E-noses, headspace analysis, SPME) are preferred, especially for valuable or limited seized items, as they preserve the evidence for further analysis or as court exhibits.

4. Applications in combating illegal trafficking

Forensic chemical profiling, in conjunction with other forensic disciplines, provides a powerful arsenal for law enforcement agencies actively engaged in combating the illegal rhino horn trade.

4.1. Detection at border crossings/seizures

One of the most critical applications of forensic profiling is the detection of concealed horn at border crossings and seizure points. The unique chemical "odour profile" of rhino horn, driven by its distinctive blend of VOCs, serves as a primary target for detection. Electronic noses and portable chemical detectors, when further developed and validated, could offer rapid, high-throughput screening capabilities for luggage, cargo, and mail suspected of containing horn. These devices can alert customs officials to the presence of illicit material, even when traffickers employ sophisticated concealment methods or masking agents [43].

The remarkable efficacy of bio-detection (sniffer dogs) in detecting rhino horn is a testament to the power of olfaction. These highly trained canines exploit their superior sense of smell to identify specific chemical signatures associated with rhino horn [44]. Understanding the exact chemical basis of the odours they detect (i.e., identifying the key VOCs) can inform the development of more targeted and effective artificial detection systems, complementing and enhancing canine unit capabilities.

4.2. Authentication and discrimination

A pervasive challenge in combating the rhino horn trade is the widespread proliferation of fraudulent products designed to mimic genuine horn. These fakes, often made from resin, bovine horn, or other animal horns, can deceive untrained eyes [13,19]. Forensic chemical profiling provides the scientific rigor needed for authentication and discrimination. Techniques like GC-MS, HPLC-MS, XRF, ICP, and FTIR can identify distinct chemical markers that reliably differentiate authentic rhino horn from counterfeits [33,36]. For instance, the specific keratin structure, unique lipid profiles, or precise trace elemental compositions will vary significantly between real rhino horn and, for example, water buffalo horn or a plastic replica [19]. This initial authentication step is crucial for establishing whether a criminal act has occurred and for initiating legal proceedings [13].

4.3. Geographical origin determination

Establishing the geographical origin of seized rhino horn is a powerful intelligence tool, enabling law enforcement to identify poaching hotspots, map trafficking routes, and allocate conservation resources more effectively [14]. This application primarily leverages the elemental and isotopic profiles within the horn. As rhino horn grows, it incorporates elements and isotopes from the animal's diet and local environment. By analysing stable isotopes (e.g., $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$) and trace elements (e.g., Sr, Ba, Zn) using techniques such as ICP-MS and XRF, a "geochemical fingerprint" for a specific region or even a particular rhino population can be developed [2,15]. While challenging due to the need for extensive reference databases and environmental variability, the potential of linking forensic profiles to specific populations offers invaluable intelligence for targeted anti-poaching strategies [19].

4.4. Correlating with other forensic methods

Forensic chemical profiling is not a standalone solution but forms a crucial part of a holistic forensic approach, complementing other established methods such as DNA analysis and genetic individualisation [1,13,17,20,27]. While DNA provides definitive species identification and, in some cases, individual identification and population assignment, chemical profiles offer additional layers of information. For example, if DNA confirms a sample is white rhino horn, complementary VOC analysis might reveal the presence of masking agents or suggest specific processing techniques, while isotopic analysis can provide robust evidence for its geographical origin. This integration of diverse techniques including DNA, stable isotope analysis, elemental profiling, and chemical odour profiling creates a comprehensive and robust forensic intelligence package, significantly enhancing the evidential value in court and providing actionable intelligence for investigators [17,20,27].

5. Challenges and limitations

Despite its immense potential, forensic profiling of rhino horn faces several significant challenges and limitations that must be systematically addressed to maximise its utility and ensure the admissibility of scientific evidence in legal proceedings.

5.1. Sample integrity

5.1.1. Degradation

Rhino horn, being a biological material, is highly susceptible to degradation over time and under adverse environmental conditions such as high temperatures, humidity, or exposure to sunlight and microbes [44]. This degradation can alter the chemical composition, leading to the loss or modification of volatile organic compounds, changes in protein structure, and leaching of elements. Such alterations can mask original signatures, complicate interpretation, and potentially render profiles unusable or misleading [10].

5.1.2. Contamination

Forensic samples are inherently vulnerable to contamination from various sources, including human DNA, handling residues (e.g., fingerprints, oils), packaging materials, and environmental pollutants [20,27]. Exogenous chemical contaminants can introduce extraneous signals into the analytical data, obscuring the true profile of the horn and leading to erroneous identifications or misleading sourcing conclusions. The risk of

contamination is particularly high with samples that have passed through multiple hands or transport routes [10,17].

5.1.3. Masking agents used by traffickers

A critical challenge is the deliberate use of masking agents by traffickers to evade detection. Strong perfumes, chemical treatments (e.g., bleaching, dyeing), or other substances may be applied to horn to alter its characteristic odour or chemical signature, making it difficult for sniffer dogs or chemical detectors to identify [37]. These agents can interfere with analytical instruments and complicate data interpretation, requiring sophisticated extraction and separation techniques to isolate the genuine horn profile.

5.2. Variability

5.2.1. Intra-species variability

Even within the same rhino species, there can be natural variations in chemical profiles (e.g., trace element concentrations, VOCs) due to individual genetic differences, age, sex, physiological state, and variations in localised diet within the same geographical range [44]. This intra-species variability necessitates the collection of extensive reference datasets from diverse individuals within a population to establish a robust baseline.

5.2.2. Inter-species variability

While forensic profiling aims to exploit inter-species differences for identification, some overlap in chemical signatures between different rhino species or even between rhino horn and other animal horns (e.g., domestic bovine horn, equine hooves) can occur [36]. This overlap can lead to false positives or ambiguous results, underscoring the need for highly specific analytical markers and multivariate statistical approaches for robust discrimination.

5.2.3. Environmental factors affecting chemical profiles

The precise elemental and isotopic composition of rhino horn is inextricably linked to the animal's environment [7]. Variations in soil geochemistry, water mineral content, and the specific plant species consumed in different ecosystems will directly influence the horn's chemical signature [2,15]. While this variability is leveraged for geographical sourcing, it also demands comprehensive, geographically extensive baseline databases to accurately interpret the origin of seized samples. The complexity of environmental gradients can make pinpointing a precise origin challenging without sufficient reference data.

5.3. Standardisation

5.3.1. Lack of standardised methods for sampling and analysis

A major impediment to the widespread and consistent application of forensic profiling in wildlife crime is the absence of internationally standardised and validated protocols for sample collection, preparation, and analysis [13,20,27]. Without uniform methods, results generated by different laboratories may not be directly comparable, undermining the reliability and admissibility of evidence in cross-border legal proceedings. The validation efforts undertaken by Ewart et al. [13] for DNA analysis highlight the critical need for such standardisation across all forensic profiling techniques.

5.3.2. Need for comprehensive reference databases

The effectiveness of comparative forensic analysis hinges on the availability of comprehensive, curated reference databases of known-origin samples with well-characterised chemical profiles. Currently, such extensive databases for rhino horn, encompassing diverse species, populations, and geographical origins, are limited [43,46]. Building and maintaining these robust databases require significant international collaboration, funding, and long-term commitment [43,46].

5.4. Cost and accessibility of technology

5.4.1. High cost of instrumentation

Many advanced analytical techniques, such as high-resolution mass spectrometry and ICP-MS, require substantial capital investment in expensive instrumentation. This high cost limits their accessibility, particularly for laboratories in developing countries that are often at the forefront of anti-poaching efforts [46].

5.4.2. Limited accessibility for field deployment

While portable instruments are emerging, many sophisticated forensic profiling tools remain primarily laboratory-bound. This necessitates the transportation of seized samples to central facilities, introducing logistical delays, potential for sample degradation, and increased chain-of-custody risks [35].

5.4.3. Expertise requirements

Operating and interpreting data from complex analytical instruments and applying advanced statistical methods for profile comparison demand highly specialised training and expertise. The availability of trained forensic scientists in wildlife crime laboratories, particularly in range states, can be a significant bottleneck [43,46].

6. Future directions and conclusion

The ongoing rhinoceros poaching crisis underscores the critical and evolving need for sophisticated forensic tools. Future advancements in forensic profiling hold immense promise for significantly strengthening global anti-trafficking efforts.

6.1. Development of robust, rapid, field-deployable detection systems

A primary future direction is the intensified development of robust, rapid, and field-deployable detection systems. This involves refining existing technologies and innovating new ones that can be utilised directly at points of interdiction, such as airports, seaports, and border crossings, or even in the field near poaching hotspots. This includes the development of more sensitive and specific electronic noses capable of detecting minute traces of rhino horn VOCs, even in the presence of masking agents [47,48]. Furthermore, the miniaturisation and ruggedness of analytical instruments like portable GC-MS or handheld XRF devices will enable on-site chemical profiling, significantly reducing reliance on centralised laboratories, minimising sample degradation during transport, and accelerating intelligence gathering [26,36].

6.2. Building comprehensive chemical profile databases for different rhino species and origins

To unlock the full potential of chemical profiling for authentication and geographical sourcing, a concerted global effort is required to build and populate comprehensive chemical profile databases for all rhino species and from diverse geographical origins [43]. This involves systematic, standardised collection of vouchered horn samples with verified provenance, followed by rigorous and multi-modal chemical analysis (e.g., VOCs, elemental, isotopic profiles). These databases, akin to the DNA sequence databases highlighted by Ewart et al. [13], will serve as indispensable reference libraries, allowing for highly accurate comparisons of seized horn and robust statistical assignments of species and origin. International collaboration among research institutions, conservation organisations, and law enforcement agencies will be crucial for establishing and maintaining such critical resources [15,20,27].

6.3. Integration with other forensic techniques

The future of forensic profiling in wildlife crime lies in a truly

integrated approach, where various forensic disciplines seamlessly complement each other. While DNA analysis provides definitive species identification [13,17,43] and individualisation, chemical profiling offers distinct insights into geographical origin, processing methods, and the presence of adulterants or masking agents. The combination of genetic, isotopic, elemental, and VOC analyses creates a powerful, multi-dimensional forensic intelligence package. For instance, a single seized horn sample could yield DNA for species and population ID, stable isotopes for precise geographical sourcing, elemental profiles for environmental correlations, and VOC patterns for indications of storage or treatment [10,20,27,43]. This integrated approach provides stronger evidential value in court and generates more actionable intelligence for anti-trafficking operations.

6.4. The potential for forensic profiles to significantly enhance anti-trafficking efforts

In conclusion, forensic profiling, through its capacity to characterise the intricate chemical and volatile signatures of rhinoceros horn, represents a transformative force in the global fight against illegal wildlife trade. Advanced methodologies possess the potential to significantly enhance anti-trafficking efforts by providing objective, scientifically defensible evidence for the detection of illicit products, the authentication of genuine horn, and the accurate determination of geographical origin. As research progresses to overcome current limitations related to sample integrity, natural variability, standardisation, and technology accessibility, forensic profiling will undoubtedly become an even more indispensable tool, empowering law enforcement, disrupting criminal networks, and ultimately safeguarding the future of the world's rhinoceros' populations for generations to come.

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Vuyelwa J. Tembu: Writing – review & editing. **Wilma A. Augustyn:** Writing – review & editing. **Johan Linde:** Writing – review & editing, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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