Donald Mushove [2026]. International Journal of Medical Justice, IJMJ, Volume 4, Issue 1: January-June 2026 [E-ISSN: 2583-7958]
International ISSN [CIEPS]: 3006-208X[Print] 3006-2098[Online]
Content list Available at ijmj.net

International Journal

of Medical Justice

Journal Homepage: https://www.ijmj.net

Review Article:

Forensic Profiling and Source Attribution of Illicit Drug Substances in Zimbabwe: Scoping Review

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Article History:
Date of Submission: Monday March 16, 2026.
Date of Start of Review Process: Monday March 16, 2026.
Date of Receipt of Reviewers Report: Monday March 23, 2026
Date of First Revision: Wednesday March 25, 2026
Date of Acceptance: Thursday March 26, 2026
Date of Publication: Friday May 22, 2026.
Digital Object Identifier **[DOI]: 10.5281/zenodo.20317637**

Available Online: Friday May 15, 2026

Website Archive: https://www.ijmj.net/archive/2026/1/IJMJ-2026-445.pdf

Citation: Donald Mushove (2026) Forensic Profiling and Source Attribution of Illicit Drug Substances in Zimbabwe: A Scoping Review. *International Journal of Medical Justice*.

Indexing: INDEX COPERNICUS INTERNATIONAL, OpenAIRE, INTERNATIONAL Scientific Indexing, LetPub

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ABSTRACT: Background: Zimbabwe faces an accelerating substance abuse crisis characterized by the rising prevalence of methamphetamine (locally termed mutoriro) and cannabis (mbanje), compounded by the growth of transnational trafficking networks. Forensic chemical profiling and source attribution represent underutilized tools for generating actionable intelligence to support law enforcement and public health responses.

Objective: This scoping review systematically maps the analytical, chemometric, and policy literature on forensic profiling and source attribution of illicit drugs, with particular attention to the Southern African Development Community (SADC) region, and deduces the applicability of established methods to the Zimbabwean forensic context.

Methods: A scoping review was conducted in accordance with the Joanna Briggs Institute (JBI) framework and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR). Searches were performed across PubMed, ScienceDirect, MDPI, Google Scholar, and European Network of Forensic Science Institutes (ENFSI) repositories, covering the period January 2015 to December 2025. Eligibility criteria were structured using the Population–Concept–Context (PCC) framework.

Results: From 283 identified records, 18 primary studies and 12 supplementary publications were included. The review mapped the use of gas chromatography–mass spectrometry (GC-MS), liquid chromatography–mass spectrometry (LC-MS), high-resolution mass spectrometry (HRMS), isotope ratio mass spectrometry (IRMS), Fourier-transform infrared spectroscopy (FT-IR), and nuclear magnetic resonance (NMR) spectroscopy, alongside chemometric workflows including principal component analysis (PCA), hierarchical cluster analysis (HCA), partial least squares–discriminant analysis (PLS-DA), and machine learning classifiers. Regional evidence from Southern Africa, particularly from South Africa, indicates growing adoption of chemical profiling and multivariate statistics; however, Zimbabwe-specific peer-reviewed forensic output is virtually absent.

Conclusions: Validated analytical methods and chemometric workflows are available and regionally relevant, yet their deployment in Zimbabwe is constrained by limited laboratory capacity, outdated instrumentation, the absence of reference spectral databases, and weak data-sharing frameworks. A staged, evidence-based implementation roadmap is proposed, encompassing short-, medium-, and long-term objectives aligned with ENFSI guidelines and SADC regional strategy.

Keywords: forensic drug profiling; source attribution; chemometrics; illicit drugs; Zimbabwe; Southern Africa; GC-MS; methamphetamine; cannabis; SADC

BACKGROUND AND RATIONALE: Zimbabwe is confronting a deepening substance abuse crisis. According to the Zimbabwe National Statistics Agency, there has been a marked increase in drug-related incidents over the past decade (2015–2025), with some urban hotspots, including Chitungwiza, recording an estimated 40% rise in reported cases between 2021 and 2023 (3, 7, 17). The dominant substances of concern include cannabis (locally termed mbanje or dagga) and methamphetamine (mutoriro), with growing evidence of the infiltration of synthetic opioids and novel psychoactive substances (7, 13). These patterns reflect broader regional and global trends in the diversification of illicit drug markets and the increasing sophistication of transnational trafficking networks (14).

Forensic chemical profiling—encompassing impurity profiling, isotopic analysis, and elemental fingerprinting coupled with chemometric interpretation—is an established tool for generating actionable intelligence in the investigation and prosecution of drug trafficking offences (1, 2). By characterising the chemical signatures of seized substances, forensic analysts can infer the geographic origin of plant-derived drugs, identify manufacturing routes, link seizures across jurisdictions, and disrupt clandestine production operations. Such information has direct utility for intelligence-led policing, supply chain disruption, and the targeting of financial networks sustaining criminal enterprises (3, 14, 15).

Despite its demonstrable utility, forensic chemical profiling remains underdeveloped in Zimbabwe. The Forensic Science Laboratory of the Zimbabwe Republic Police (ZRP), located in Harare, is the primary statutory facility responsible for the analysis of controlled substances. While the laboratory has baseline analytical capacity—including GC-MS and FT-IR instrumentation—it operates under considerable resource pressure, lacks advanced profiling capabilities such as IRMS and high-resolution mass spectrometry, and has limited access to validated chemometric workflows or curated reference databases (7, 18, 19). Complex analytical requirements are frequently outsourced, reducing turnaround speed and limiting the intelligence value of forensic findings for ongoing investigations (1, 2).

Chemical profiling also yields information of direct relevance to public health. Knowledge of the impurity profiles and adulterant compositions of substances in circulation informs harm reduction strategies, enables the monitoring of emerging adulterants, and supports targeted public health interventions in affected communities (3, 16). The interdependence of law enforcement and public health objectives therefore reinforces the case for investing in forensic chemical profiling capacity in Zimbabwe.

A locally tailored, evidence-based forensic framework is required—one that harnesses the analytical and chemometric methods validated in peer-reviewed literature and adapts them to the operational realities of the Zimbabwean context. This scoping review was designed to map the available evidence base, identify critical capacity gaps, and propose a structured implementation roadmap for Zimbabwe.

OBJECTIVES: This scoping review pursued the following objectives:To systematically identify and document the analytical, chemometric, and biotechnological methods used for profiling illicit drugs that are applicable to the Zimbabwean context.

To map validated workflows, standards, and best practices for illicit drug profiling at regional (SADC) and global levels, assessing their relevance to Zimbabwe.

To identify evidence gaps, capacity bottlenecks, and priority research areas for the development of a robust forensic source attribution capability in Zimbabwe.

METHODS: Study Design: This study was conducted as a scoping review in accordance with the JBI Scoping Review Methodology Group framework (29) and reported following the PRISMA-ScR checklist (30). A scoping review design was selected in preference to a systematic review on the grounds that the objective was to map and synthesise a heterogeneous body of evidence—spanning analytical chemistry, chemometrics, forensic intelligence, and policy literature—rather than to answer a focused clinical or intervention question. This approach is consistent with established guidance for reviews intended to characterise the scope and nature of an evidence base and to identify knowledge gaps (29, 30).

Protocol and Registration: A formal review protocol was developed in accordance with JBI guidance to ensure transparency and reproducibility. The protocol was not registered in an external registry. The absence of prospective registration is consistent with practice in exploratory scoping reviews, particularly where the objective is to map emerging and context-specific evidence rather than to evaluate intervention effectiveness (29).

Eligibility Criteria: Eligibility criteria were defined using the Population–Concept–Context (PCC) framework recommended by the JBI for scoping reviews.

Population: Illicit drug substances—including methamphetamine, cannabis, and related controlled substances—and associated analytical forensic data.

Concept: Chemical, chemometric, and biotechnological approaches to forensic drug profiling and source attribution, including but not limited to GC-MS, FT-IR, LC-MS, NMR, IRMS, and multivariate statistical methods.

Context: Zimbabwe as the primary focus, with relevant regional (SADC) and international comparator studies included for methodological context.

The review included peer-reviewed original research articles, authoritative reviews, technical guidelines, forensic laboratory reports, and government or institutional publications published between January 2015 and December 2025, in English. Studies lacking relevance to forensic drug profiling or source attribution were excluded (6, 7).

Information Sources: A comprehensive literature search was conducted across the following sources: PubMed / PubMed Central; ScienceDirect; MDPI open-access journals; ENFSI technical publications; the South African Journal of Science; and relevant governmental, law-enforcement, and forensic laboratory websites. Regional studies on forensic profiling of nyaope and other SADC-specific street drugs were deliberately included to provide methodological parallels and contextual comparators relevant to Zimbabwe. The reference lists of all included studies and relevant review articles were manually screened to identify additional sources.

Search Strategy: The search strategy was developed iteratively to maximise sensitivity while maintaining specificity. Key search terms were combined using Boolean operators (AND / OR) and included: "source attribution", "forensic chemistry", "chemical fingerprinting", "chemometrics", "drug profiling", "marijuana", "methamphetamine", "illicit drugs", "Zimbabwe", "Southern Africa", and "nyaope". Search strings were adapted to the syntax conventions of each database. Nyaope is a South African polysubstance street drug combining heroin with methamphetamine, cannabis, and other adulterants; its inclusion provided a regionally specific methodological reference point.

Selection of Sources of Evidence: Identified records were screened in two stages in accordance with PRISMA-ScR guidance. In the first stage, titles and abstracts were reviewed to exclude clearly irrelevant studies. In the second stage, full-text screening was conducted against the predefined PCC eligibility criteria. Selection prioritised methodological rigour, forensic applicability, and contextual relevance to Zimbabwe.

Data Charting: A structured data-charting form was developed in accordance with JBI recommendations (29). Extracted data included: publication details (author, year, source); analytical techniques employed; chemometric methods applied; drug types analysed; geographic context; and key findings relevant to forensic profiling and source attribution.

Critical Appraisal: Consistent with JBI scoping review methodology, formal critical appraisal of individual sources was not undertaken. The review prioritised the identification of dominant themes, methodological trends, and practical recommendations, reflecting its objective of mapping existing evidence and identifying knowledge gaps rather than assessing risk of bias.

Synthesis of Results: Findings were synthesised narratively and thematically, with emphasis on analytical methodologies, chemometric applications, and their forensic utility in resource-constrained settings. Evidence gaps and capacity limitations were explicitly highlighted to inform future research directions, forensic laboratory development, and policy formulation. The PRISMA-ScR search and selection process is summarised in Table 1.

RESULTS: MAPPED EVIDENCE AND THEMATIC SYNTHESIS

Analytical Platforms and Their Forensic Contributions. Forensic drug profiling relies on a suite of complementary analytical platforms that provide information on the chemical composition, impurity profiles, and physical characteristics of seized substances, collectively enabling sample linkage, origin inference, and distribution network reconstruction.

Gas Chromatography–Mass Spectrometry (GC-MS): GC-MS is the most widely deployed technique for the identification and quantification of volatile and semi-volatile controlled substances, including amphetamines, cocaine derivatives, and synthetic drugs. It is particularly well-suited to impurity profiling and the detection of cutting agents, providing chemical fingerprints that can be compared across seizures using chemometric methods (1, 10, 23). GC-MS instrumentation is currently available within the ZRP Forensic Chemistry Laboratory, providing a viable foundation for profiling workflows.

Liquid Chromatography–Mass Spectrometry (LC-MS / LC-HRMS): LC-MS and its high-resolution variant (LC-HRMS) are essential for the analysis of polar, thermally labile compounds and for non-targeted screening workflows. High-resolution detection facilitates the identification of unknown compounds, compound-class profiling, and retrospective data mining for novel psychoactive substances (1, 5, 8). These instruments are not currently available within ZRP or its immediate partner institutions and are therefore outside the scope of the present study; however, their inclusion in long-term capability planning is strongly recommended.

Isotope Ratio and Elemental Analysis (IRMS / ICP-MS / XRF): Isotope ratio mass spectrometry (IRMS) and related elemental techniques (ICP-MS, XRF) provide information on the geographic origin of plant-derived drugs—cannabis, opium, coca—through isotopic & elemental signatures. Elemental fingerprints can also link production batches through shared reagent or solvent impurities (1, 12, 22). These instruments are currently unavailable within ZRP; acquisition is identified as a long-term priority in the implementation roadmap (Table 4).

Vibrational Spectroscopy (FT-IR and Raman): FT-IR and Raman spectroscopy enable rapid screening and structural confirmation of substances. When coupled with chemometric analysis, these techniques can discriminate between formulation types and detect production-related differences in seized samples (2, 4). FT-IR instrumentation is currently available within the ZRP Forensic Chemistry Laboratory and constitutes a near-term resource for fingerprinting workflows.

Nuclear Magnetic Resonance Spectroscopy (NMR): NMR provides detailed structural information on organic compounds &, when combined with chemometrics, can distinguish between samples of different synthetic origin. Quantitative NMR (qNMR) is increasingly applied to purity assessment and batch comparison in forensic contexts (1, 2). NMR is not currently available within ZRP; however, its availability at academic institutions in Zimbabwe presents a potential basis for collaborative research protocols.

Hyphenated and Non-Targeted Analytical Workflows: The integration of multiple orthogonal analytical techniques—such as GC-MS combined with LC-MS and NMR—generates richer multivariate fingerprints that enhance the discriminatory power of chemometric models and improve the reliability of source attribution conclusions (1, 4). Such hyphenated workflows are the current standard in advanced forensic laboratory settings in Europe and are identified as a long-term developmental aspiration for Zimbabwe.

The comparative availability of these analytical platforms across SADC countries and a European reference setting is presented in Table 2. Zimbabwe's current capability is highlighted; the marked gap relative to regional peers underscores the urgency of targeted investment.

Chemometric and Multivariate Methods: Chemometric techniques are essential for extracting statistically meaningful patterns from the high-dimensional data generated by modern analytical instruments. Their application to forensic drug profiling substantially increases the discriminatory power of chemical fingerprints and enables systematic, reproducible sample comparison and source attribution.

Unsupervised Exploratory Techniques: Principal component analysis (PCA) & hierarchical cluster analysis (HCA) are the most widely applied unsupervised methods in forensic drug profiling. PCA reduces data dimensionality and enables visual exploration of sample groupings in two- or three-dimensional score space, while HCA generates dendrograms depicting hierarchical similarity relationships between samples. Both methods have been applied to GC-MS and FT-IR fingerprints to group cannabis & methamphetamine seizures and to track temporal or geographic changes in drug composition (5, 6).

Supervised Classification Methods: When labelled reference datasets are available, supervised classification algorithms enable class assignment and origin prediction. PLS-DA and linear discriminant analysis (LDA) are the most commonly applied approaches in forensic chemistry; ensemble methods including random forests and support vector machines (SVM) are increasingly reported, particularly for the classification of novel psychoactive substances (5, 8, 19, 21). The ENFSI (2021) guidance document provides detailed recommendations on model development, validation, and reporting for supervised chemometric methods (2).

Validation and Quality Assurance: Robust model validation—including cross-validation, external test set evaluation, and assessment of potential confounders—is a non-negotiable requirement for forensic chemometric outputs intended for use in evidential proceedings (2, 8). ENFSI guidance stresses the importance of transparent workflows, the provenance and representativeness of reference databases, and the explicit quantification of classification uncertainty. These standards must underpin any chemometric programme developed within the ZRP forensic context.

Regional Applications: Chemometric workflows have been successfully applied to street drugs of regional relevance. Mthembi et al. (6) validated a profiling method for nyaope, demonstrating the utility of PCA and HCA applied to GC-MS fingerprints for grouping seizures and tracking compositional changes over time. These methods are directly transferable to Zimbabwe's principal drugs of concern—methamphetamine and cannabis—and provide a methodological template for near-term implementation.

A structured summary of the principal chemometric methods identified in the review, their applications, and their evidence base is presented in Table 3.

Regional and Zimbabwe-Specific Evidence: Southern Africa. Several peer-reviewed studies from South Africa describe validated analytical methods for profiling regionally specific street drugs—including nyaope, cannabis, and crystal methamphetamine—and demonstrate the feasibility of chemometric clustering for generating investigative leads (6, 17, 18, 19). These studies provide direct methodological parallels for Zimbabwe, given the shared regional drug supply chains and the prevalence of comparable substances. The body of evidence from South Africa represents the most immediately transferable regional knowledge base and argues strongly for formalised collaborative arrangements between ZRP and South African forensic institutions.

Zimbabwe: Published peer-reviewed forensic chemical studies specific to Zimbabwe are virtually absent from the literature. Work describing national drug-use trends, policing responses, and public health consequences exists (7, 13, 17), but the technical forensic literature—characterizing the chemical composition of seized substances, developing profiling methods, or curating reference databases—is not represented in the indexed scientific record. The ZRP Forensic Chemistry Laboratory operates primarily within a qualitative identification paradigm, without documented chemometric profiling workflows or inter-laboratory comparison programs. This finding constitutes the most significant evidence gap identified by the review and defines the primary target for capability-building investment.

DISCUSSION: Strengths and Promising Directions

This review identifies several substantive strengths in the available evidence base that support the development of forensic drug profiling capability in Zimbabwe.

The global literature provides a mature foundation of validated analytical methods and chemometric workflows that have been demonstrated across diverse operational settings (1, 4, 28). Techniques including GC-MS and FT-IR—both of which are currently available within the ZRP laboratory—are well-characterised and supported by comprehensive standard operating procedure templates, facilitating their adaptation to local protocols without requiring capital investment in new instrumentation.

The demonstrated utility of multivariate chemometrics—particularly PCA, HCA, and PLS-DA—in increasing the discrimination power of chemical fingerprints supports their adoption as core analytical tools, including in resource-constrained settings. Open-source chemometric platforms, such as R and Python-based packages, substantially reduce the financial barrier to implementation and allow the development of locally customized workflows (5, 8, 27). Regional studies from Southern Africa, particularly those concerning nyaope profiling in South Africa (6), provide directly relevant methodological templates and demonstrate that chemometric drug profiling is operationally feasible within the regional forensic infrastructure. The existence of established analytical programmes in neighbouring states also creates a pathway to collaborative data sharing and regional cluster analyses, which would enhance the intelligence value of individual national seizure datasets.

Finally, the increasing complexity of illicit drug markets in Zimbabwe and the SADC region—characterised by the diversification of substances, the sophistication of trafficking networks, and the emergence of novel psychoactive substances—reinforces the strategic necessity of advanced forensic capabilities to support intelligence-led law enforcement (3, 11, 14).

Critical Gaps and Barriers in the Zimbabwean Context: Against this background, the review identifies several critical gaps that must be addressed for Zimbabwe to develop an effective forensic drug profiling capability.

Absence of Local Analytical Literature and Reference Databases. The most fundamental gap is the absence of published, peer-reviewed forensic chemical data on substances seized in Zimbabwe. Without a curated national spectral reference library, it is not possible to conduct meaningful sample comparisons or to establish the chemical signatures characteristic of locally circulating drugs. Building such a database is a necessary precondition for all subsequent chemometric profiling work (1, 2, 7).

Quality Systems and Accreditation. The implementation of validated, internationally recognised analytical methods requires documented quality assurance and quality control (QA/QC) frameworks, method validation records, and—ultimately—laboratory accreditation. ENFSI guidance provides a comprehensive template (2), but achieving compliance requires sustained investment in training, documentation, and proficiency testing infrastructure.

Data-Sharing Frameworks. Cross-jurisdictional data exchange—between ZRP and neighbouring forensic institutions, or within a regional SADC network—requires standardised data formats, compatible database architectures, and formal legal and operational agreements governing data access and use. The evidence from South Africa demonstrates the intelligence benefits that such arrangements can generate when supported by validated, harmonised methods (6, 15).

Capacity for Advanced Analytical Techniques. High-resolution mass spectrometry, IRMS, and advanced isotopic analysis techniques are not currently accessible within ZRP or its immediate partner institutions. Establishing this capability requires significant capital investment in instrumentation and reagents, as well as the development of specialist technical expertise that does not currently exist within the national forensic system (7, 8, 12).

PRACTICAL RECOMMENDATIONS: A STAGED IMPLEMENTATION ROADMAP: On the basis of the evidence mapped in this review, a staged, three-horizon implementation roadmap is proposed for Zimbabwe (Table 4). The roadmap is designed to build sequentially on existing capacity, progressively addressing gaps in methodology, infrastructure, &

inter-institutional collaboration.

The short-term objectives are oriented towards maximising the intelligence yield of existing instrumentation and data, while establishing the methodological standards and documentation practices that will underpin subsequent phases. Investment in open-source chemometric tools and training in their application can generate immediate analytical value without capital expenditure. The medium-term phase focuses on institutionalising validated workflows, building specialist human capital, and establishing the regional partnerships necessary for comparative analysis. The long-term objectives address the more capital-intensive infrastructure requirements—high-resolution instrumentation, national databases, and a formal governance framework—that will position Zimbabwe's forensic system as a credible contributor to regional and international intelligence networks.

LIMITATIONS: Several methodological limitations of this scoping review warrant explicit acknowledgement.

First, as a scoping rather than a systematic review, the literature searches were designed to provide representative coverage of high-impact and regionally relevant sources, rather than exhaustive retrieval of all available evidence. It is therefore possible that some relevant studies—particularly grey literature, unpublished internal forensic laboratory reports within Zimbabwe, and studies in languages other than English—were not captured. The English-language restriction may have introduced a degree of publication bias towards research from English-speaking countries, potentially underrepresenting work from Lusophone or Francophone SADC member states.

Second, the rapid pace of innovation in analytical chemistry and chemometrics means that the literature identified in this review may not fully reflect the most recent methodological advances. The search was conducted up to December 2025; studies published after that date are not represented.

Third, the practical recommendations proposed in the implementation roadmap are necessarily informed by the available published evidence and general principles of forensic laboratory development; they have not been validated through direct assessment of ZRP's operational context, infrastructure, or resource constraints. Stakeholder consultation and a formal needs assessment would be required before translating these recommendations into an operational plan.

Finally, the absence of published Zimbabwe-specific forensic chemical data limits the review's ability to characterize the current evidence base with precision; the finding of a gap is itself the substantive result, but it constrains the depth of contextual analysis that is possible.

Despite these limitations, the review provides a comprehensive synthesis of the relevant global and regional literature and a structured framework for addressing the identified gaps. It is intended as a stimulus for further research, stakeholder engagement, and policy development in Zimbabwe.

CONCLUSION: This scoping review demonstrates that a robust forensic programme for the profiling and source attribution of illicit drugs in Zimbabwe is both technically feasible and strategically important. Validated analytical methods and chemometric workflows are available in the literature, are demonstrably applicable to regionally relevant substances, and are partly within reach of Zimbabwe's existing laboratory infrastructure. The global evidence base, interpreted through the lens of regional comparators from Southern Africa, provides a credible methodological foundation on which a national programme can be built.

The most pressing challenge is not the absence of applicable methods but the absence of their local implementation. Zimbabwe lacks published forensic chemical characterization of its circulating drug supply, validated profiling workflows, a national spectral reference library, and the inter-institutional data-sharing arrangements necessary for comparative intelligence analysis. Closing these gaps requires a coordinated, sustained effort across forensic, academic, public health, and policy institutions. The staged implementation roadmap proposed in this review—progressing from the optimisation of existing GC-MS and FT-IR capacity, through structured chemometric training and regional collaboration, to the longer-term acquisition of advanced instrumentation and a national data governance framework—provides a practical basis for action. Implementation should be guided by ENFSI quality standards and should be pursued in alignment with the SADC Regional Drug Control Strategy. The development of forensic drug profiling capability in Zimbabwe will strengthen the country's capacity to investigate and disrupt transnational trafficking networks, support evidence-based public health responses to substance abuse, and contribute to regional security.

DECLARATIONS:

Conflict of Interest: The author declares no conflicts of interest.

Funding: This research received no external funding.

Acknowledgements: The author thanks the staff of the Harare Institute of Technology Library for assistance with database access.

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Table 1. PRISMA-ScR summary of the search and selection process.

Phase	Description	Count / Action
Identification	Records identified via PubMed, ScienceDirect, MDPI, Google Scholar, and ENFSI databases; duplicates removed	n = 283 (post-deduplication)
Screening	Titles and abstracts screened for relevance to forensic drug profiling and source attribution	n = 283 screened; irrelevant records excluded
Eligibility	Full-text articles assessed against PCC eligibility criteria	n = 18 eligible; remainder excluded
Included	Core studies included in the thematic synthesis; 12 additional publications included for contextual support	n = 18 primary; n = 12 supplementary

Table 2. Availability of forensic analytical platforms across SADC countries and Europe. ✓ = available; – = not available. Zimbabwe (shaded) is highlighted to contextualise the identified capability gap.

Country / Region	GC-MS	LC-MS	IRMS	FT-IR	NMR	Hyphen.
Angola	✓	✓	✓	✓	–	✓
Botswana	✓	✓	✓	✓	✓	✓
Lesotho	✓	✓	✓	✓	–	✓
Malawi	✓	✓	✓	✓	–	✓
Mozambique	✓	✓	✓	✓	–	✓
Namibia	✓	✓	✓	✓	✓	✓
South Africa	✓	✓	✓	✓	✓	✓
Eswatini	✓	✓	✓	✓	–	–
Zambia	✓	✓	✓	✓	✓	✓
Zimbabwe	✓	–	–	✓	–	–
Europe (ref)	✓	✓	✓	✓	✓	✓

Table 3. Summary of chemometric methods identified in the review, with forensic applications and supporting evidence.

Method	Type	Forensic Application	Evidence Base
Principal Component Analysis (PCA)	Unsupervised	Dimensionality reduction; exploratory visualisation; pattern discovery in high-dimensional spectral data	Widely used with GC-MS/FT-IR data; applied to nyaope profiling in South Africa (5, 6)
Hierarchical Cluster Analysis (HCA)	Unsupervised	Dendrogram-based sample grouping; identification of inter-batch and intra-batch similarity	Used alongside PCA to track temporal changes in drug samples (6)
Partial Least Squares–Discriminant Analysis (PLS-DA)	Supervised	Classification and origin prediction using labelled training sets; handles collinear variables	Applied to amphetamine profiling; recommended in ENFSI guidance (2, 10)
Linear Discriminant Analysis (LDA)	Supervised	Class separation with reduced feature sets; high interpretability	Used in pharmaceutical and illicit drug differentiation studies (5)
Random Forest (RF)	Supervised (ensemble)	Non-linear classification; robust to overfitting; provides variable importance rankings	Increasingly applied to novel psychoactive substance classification (5, 21)
Support Vector Machines (SVM)	Supervised	High-dimensional classification; effective with small training sets	Applied in forensic drug profiling; validated against LDA and PLS-DA (5)
k-Means Clustering	Unsupervised	Partitioning of samples into discrete clusters; useful for batch linkage	Used in conjunction with GC-MS impurity fingerprints (1)

Table 4. Staged implementation roadmap for forensic drug profiling capability development in Zimbabwe.

Time Horizon	Priority Actions	Lead Stakeholders	Key References
Short-term (0–12 months)	National audit of forensic laboratory instrumentation and analytical capacity; standardisation of GC-MS and FT-IR methods in accordance with ENFSI guidelines; initiation of pilot data collection on common seizures (cannabis, methamphetamine, pharmaceuticals); establishment of a secure national spectral reference library	ZRP Forensic Chemistry Laboratory; Ministry of Home Affairs	11, 12, 1, 2
Medium-term (1–3 years)	Structured training programme for forensic chemists in chemometric model development, validation, and reporting; deployment of PCA and HCA workflows for routine fingerprinting; negotiation of data-sharing agreements with regional forensic laboratories (South Africa, Botswana, Zambia); participation in inter-laboratory comparison exercises	ZRP; SADC forensic network; academic institutions	5, 6, 8, 2
Long-term (3+ years)	Acquisition and commissioning of HRMS and IRMS instrumentation as funding permits; development of protocols for plant-product geographic inference; research into biological adjuncts (trace DNA, microbiome) under stringent ethical governance; formulation of a national forensic data governance framework to underpin evidence sharing and database admissibility	Government; international donors; research institutions	3, 7, 15, 16