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Integrating DNA and Chemical Profiling to Trace Illicit Drug Manufacture and Distribution

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ABSTRACT: Illicit drug materials represent a valuable but underutilized source of forensic intelligence. While chemical profiling is routinely used to trace drug composition and origin, the recovery of trace DNA offers the potential to link these substances directly to individuals involved in their manufacture and distribution. This study evaluates the forensic utility of integrating DNA profiling with chemical analysis to improve source attribution across different drug formulations. Pharmaceutical-grade simulants in the form of capsules, tablets, and powders were handled by volunteers under controlled deposition scenarios. DNA was recovered using moistened cotton swabs, extracted via automated silica-based workflows, and analyzed using STR profiling. In parallel, chemical fingerprints were generated through GC-MS and LC-MS, with sample classification based on retention time and mass spectral data. Capsules yielded the highest DNA recovery (median: 310 pg), followed by tablets (230 pg) and powders (18 pg), with single-source STR profiles obtained in over 85% of capsule and tablet cases. Chemical profiling achieved 85% accuracy for capsules, 78% for tablets, and 65% for powders. When integrated, the combined approach significantly outperformed individual methods, achieving classification accuracies of 97% for capsules, 85% for tablets, and 72% for powders ($p < 0.01$). These findings demonstrate the enhanced evidentiary value of dual profiling, particularly in cases involving degraded or limited DNA. The proposed framework supports a more comprehensive forensic strategy, enabling biological and chemical linkage of drug materials to persons of interest and manufacturing sources. This integrative approach offers critical advantages for law enforcement and prosecution in disrupting drug trafficking networks.

Keywords: Forensic genetics; Forensic science; DNA profiling; STR profiling; Trace DNA; Touch DNA; DNA recovery; Chemical profiling; Illicit drugs; Chemical fingerprinting; GC-MS; LC-MS; Forensic attribution; Trace evidence; Integrated forensics

1. Introduction

Touch DNA, also known as trace DNA, constitutes a critical source of genetic material frequently encountered at crime scenes and serves as a powerful forensic tool for associating suspects with criminal activity [1–6]. Typically transferred via incidental contact with frequently touched objects—such as tools, doorknobs, and clothing—it provides evidentiary value in the abse nce of bodily fluids [2,7–9]. However, Touch DNA presents unique challenges stemming from variability in the quantity and quality of recoverable material. Factors influencing these outcomes include the physicochemical properties of the substrate [10,11], exposure to environmental stressors [12–14], and inconsistencies in evidence collection techniques [10,11,15–18]. Variability in wetting agents and the number of adhesive lifts applied can further complicate recovery efficiency [19–25].

Beyond sampling inconsistencies, differences in DNA extraction and quantification methods [2,4,12,26–30], the risk of contamination, and inter-individual variability in DNA shedding rates all contribute to analytical complexity [31–38]. Recovery success is highly dependent on the selection of appropriate collection tools. Studies underscore the need to tailor tools such as cotton swabs, nylon swabs, or adhesive tapes to the type of surface encountered [10,11].

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Smooth, non-porous surfaces like plastic and glass favor swabbing techniques [10,20], whereas porous materials like fabric often require tapelifting approaches for optimal results [39–44].

To address the limitations of conventional sampling, recent innovations have introduced hybrid techniques, such as combining cotton and microFLOQ® swabs for direct amplification, employing microbial wet-vacuum systems, and using enhanced decontamination agents [23,44–46]. These advancements mark rapid progress in trace DNA recovery technologies. Importantly, the variability in DNA yields across surface types and environmental conditions underscores the necessity of deploying site-specific, adaptive collection protocols [47–50].

Aligning emerging casework evidence with flexible forensic workflows is essential for responding to evolving crime trends. This further reinforces the importance of integrating technological innovation with adaptive sampling strategies to meet the demands of contemporary forensic practice [51,52]. Traditional DNA workflows, particularly those based on silica column extraction, are prone to DNA loss, which becomes a limiting factor when working with low-template or degraded samples [1,53]. In response, direct amplification techniques—which bypass extraction and quantification—have gained interest for preserving limited material while streamlining analysis [17,22,54].

Illicit drug use remains a pervasive global issue, with significant societal and public health ramifications. Law enforcement efforts to curb drug trafficking have predominantly relied on the chemical profiling of seized substances, aiming to identify constituent compounds and trace their synthetic origins [55]. While effective, this strategy provides limited insight into the individuals involved in the drug production and distribution pipeline.

Previous forensic studies have demonstrated the feasibility of recovering DNA from the outer surfaces of drug packaging [56–58]. However, such samples often originate from handlers at the final stages of the supply chain, such as street-level dealers. While informative, this downstream DNA fails to illuminate the earlier phases of drug manufacturing and upstream distribution. Identifying DNA from individuals involved in production could significantly enhance investigative leads and offer strategic intelligence. Coupling this with chemical profiling may yield a more complete forensic picture, aiding the dismantling of trafficking networks and disrupting illicit supply chains.

In clandestine laboratory settings, where anti-contamination protocols are generally absent, DNA and other biological materials are readily deposited onto or within drug products [34]. Cellular debris, dust, and microorganisms may become incorporated into powders or settle on capsule and tablet surfaces at various points in the production process. During synthesis of compounds such as methamphetamine or MDMA, airborne deposition—resulting from speaking, coughing, or breathing—is a viable pathway for DNA transfer [59], highlighting that direct contact is not a prerequisite for DNA contamination. Air-drying drugs on trays further facilitates DNA deposition from the ambient environment.

Manual operations, including capsule encapsulation or tablet counting and bagging, increase the likelihood of transferring DNA from handlers to the product surface. These touchpoints render capsules and tablets promising substrates for trace DNA recovery. Additionally, examining DNA embedded within powders could offer insights into earlier drug synthesis and handling stages.

This study investigates the feasibility of recovering DNA from both the outer surfaces of capsules and tablets and from within powdered substances. It explores the mechanisms influencing DNA transfer, persistence, and recovery in these drug forms. By integrating DNA profiling with chemical analysis, the study aims to establish stronger links between drug materials and the individuals involved in their production and distribution. The findings have the potential to inform a more comprehensive and robust forensic approach to combat organized drug trafficking networks.

2. Materials and Methods

2.1. Materials

2.1.1. Drug Simulants and Components

To simulate the chemical and physical properties of illicit drug formulations encountered in forensic settings, pharmaceutical-grade powders—including lactose and microcrystalline cellulose—were used as primary components. Additional sugar- and starch-based fillers were incorporated to replicate the diversity of cutting agents typically found in street-level drug samples. Encapsulated and compressed drug forms were prepared using empty gelatin capsules and a laboratory-scale tablet press. This dual formulation strategy enabled comprehensive DNA transfer, retention, and persistence assessment under varied manufacturing and handling conditions.

2.1.2. Human DNA Sources

Trace DNA was obtained from ten volunteer donors under ethically approved and controlled laboratory conditions. Three DNA deposition methods were employed: (i) direct contact with bare hands, (ii) indirect contact via gloved handling, and (iii) airborne deposition. For gloved handling, volunteers wore nitrile gloves for four hours to allow accumulation of skin cells, sweat, and biological residues. The gloves were then inverted and used to manipulate the drug simulants, simulating realistic cross-contamination during drug production. Airborne deposition was achieved by instructing volunteers to speak and breathe over the powder samples during preparation, reproducing contamination events common in clandestine laboratory environments.

2.1.3. Chemical Profiling Reagents

High-purity solvents and reagents were used for Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography-Mass Spectrometry (LC-MS) analyses. These included methanol, acetonitrile, and deionized water containing 0.1% formic acid. Solvents were selected to ensure full solubilization and stability of chemical constituents during sample preparation, enabling precise identification of compound-specific signatures.

2.2. Experimental Design

2.2.1. Capsule and Tablet Preparation

Fifty capsules per batch were manually filled with simulated drug powders and handled by volunteers to simulate DNA transfer during encapsulation and packaging. Capsules were stored in zip-lock polyethylene bags to replicate real-world storage and transportation conditions. Tablets were produced using a high-pressure tablet press, compressing the pharmaceutical-grade powder into solid dosage forms. As with capsules, volunteers simulated counting, sorting, and packaging processes to promote realistic DNA transfer to tablet surfaces.

2.2.2. Powder Preparation

To simulate DNA contamination during production, powder simulants were rubbed with pre-worn gloves under controlled conditions. This contact was designed to mimic real-world DNA deposition during manufacturing stages. The powders were subsequently homogenized to simulate an even distribution of DNA throughout the mixture, providing a consistent and representative model for evaluating DNA persistence and recovery from bulk powder forms.

2.3. Sample Analysis

2.3.1. DNA Sampling and Analysis

Surface DNA was collected from capsules and tablets using Copan 150C cotton swabs (Copan Diagnostics Inc.; Murrieta, CA, USA), pre-moistened with 100 µL of sterile distilled water via a plastic spray bottle. Powder samples were collected directly into sterile, DNA-free microcentrifuge tubes. Samples were processed immediately or stored at −20 °C to preserve DNA integrity until extraction.

DNA extraction was conducted using the PrepFiler Express™ kit on an AutoMate Express instrument (Applied Biosystems/Thermo Fisher Scientific; Waltham, MA, USA), following the manufacturer's protocol. Full swab heads and powder aliquots were processed, and final DNA elution was performed in 50 µL volumesDNA quantification was carried out using the Quantifiler® Trio DNA Quantification Kit on a QuantStudio 5 Real-Time PCR system (Applied Biosystems/Thermo Fisher Scientific; Waltham, MA, USA). Amplification was performed with the GlobalFiler™ PCR Amplification Kit on an ABI GeneAmp® 9700 thermocycler (Applied Biosystems/Thermo Fisher Scientific; Waltham, MA, USA) using 29 cycles. Electrophoretic analysis of amplified products was performed on an ABI 3500 Genetic Analyzer (Applied Biosystems/Thermo Fisher Scientific; Waltham, MA, USA) with a 36-cm capillary array and POP-4™ polymer.

STR profiles were analyzed using GeneMapper® ID-X Software (v1.5), applying an analytical threshold of 75 RFUs as validated internally. In cases involving mixed DNA profiles, deconvolution was performed using STRmix™ (v2.8.0) (ESR, New Zealand; University of Auckland, Auckland, New Zealand), and likelihood ratios (LRs) were calculated to quantify the strength of the DNA evidence for both single-source and mixed profiles.

2.3.2. Chemical Sampling and Analysis

Tablets were ground into fine powders using a sterile mortar and pestle. Approximately 10 mg of powdered tablet or simulant was weighed for each chemical analysis. Samples were dissolved in methanol, acetonitrile, or water containing 0.1% formic acid depending on expected compound properties. Dissolutions were vortexed and sonicated for 5 to 10 minutes to ensure complete solubilization, then passed through 0.22 μm PTFE syringe filters to remove particulate matter.

For GC-MS analysis, 1 μL aliquots were injected into the instrument using a capillary column under a programmed temperature ramp. LC-MS analysis was conducted using 5 μL sample injections and a reverse-phase column with a binary solvent gradient for optimal separation. In both cases, mass spectral data were used to generate compound-specific fingerprints based on retention times and fragmentation patterns. These profiles were then compared across batches to assess chemical consistency and infer source linkages.

2.4. Statistical Analysis

DNA recovery efficiencies across capsules, tablets, and powders were statistically compared using the Kruskal–Wallis test, with a significance threshold of $p < 0.05$. Likelihood ratios derived from STRmix™ were used to assess the probative value of both single-source and mixed profiles. Bayesian modeling was employed to evaluate the combined contribution of DNA and chemical profiling data in establishing forensic linkages between drug materials and individual sources. This integrated statistical framework provided a robust method for quantifying evidentiary strength in simulated drug seizure scenarios.

2.5. Ethical Considerations

All volunteer participation was conducted under informed consent protocols approved for laboratory-based trace DNA studies. Stringent contamination control procedures were maintained throughout the study, including the use of DNA-free consumables, validated workflows, and cleanroom-standard laboratory environments. Negative controls were incorporated in all DNA and chemical analyses to detect procedural contamination. All reagents and consumables were verified as DNA-free before use.

3. Results

3.1. DNA Recovery

The results demonstrated that sustained contact—lasting approximately 3–5 s—during handling of drug formulations was sufficient to transfer measurable amounts of DNA suitable for short tandem repeat (STR) profiling. Each sample group consisted of 20 replicates, enabling robust comparison of DNA yield across drug forms.

Capsules yielded the highest median DNA concentration, averaging 310 pg per sample, with a corresponding median likelihood ratio (LR) of 5.8×10^{28} for known contributors (Figure 1). Tablets followed, with a median yield of 230 pg and median LR of 3.1×10^{28}. Powdered samples, in which DNA was integrated during simulated manufacturing, produced a significantly lower median yield of 18 pg, with a corresponding median LR of 3.2×10^{5}.

Over 85% of capsule and tablet samples yielded single-source STR profiles, meeting the minimum detection threshold of 75 RFUs as validated during in-house development. Single-source profiles provide high evidentiary value due to their unambiguous attribution to individual contributors within forensic databases. Approximately 15% of capsule samples produced mixed DNA profiles, indicating the presence of DNA from two or more individuals, likely resulting from cross-contamination during handling. While mixed profiles may be more challenging to interpret, they offer forensic value by revealing multiple contributors' involvement.

By contrast, most powder samples yielded partial profiles, typically recovering 6 to 10 STR loci from the whole panel. These incomplete profiles were often the result of low DNA quantity and potential degradation during synthesis and exposure to environmental conditions. Such partial profiles may still be used for intelligence purposes or partial database matching, but present greater limitations in court-admissible identification.

A Kruskal–Wallis test confirmed significant differences in DNA recovery across the three sample types ($p < 0.01$), with capsules and tablets significantly outperforming powders in yield and STR profile completeness. The relatively narrow interquartile ranges in capsule and tablet groups reflect consistency in deposition and recovery. In contrast, the wide variability in powder samples likely reflects uneven distribution, dilution effects, and degradation.

These findings reinforce the utility of solid dosage forms—particularly capsules and tablets—as optimal substrates for trace DNA recovery in drug-related forensic investigations. Their high yield and STR quality make them strong

candidates for identification and database integration, especially when combined with complementary chemical profiling techniques.

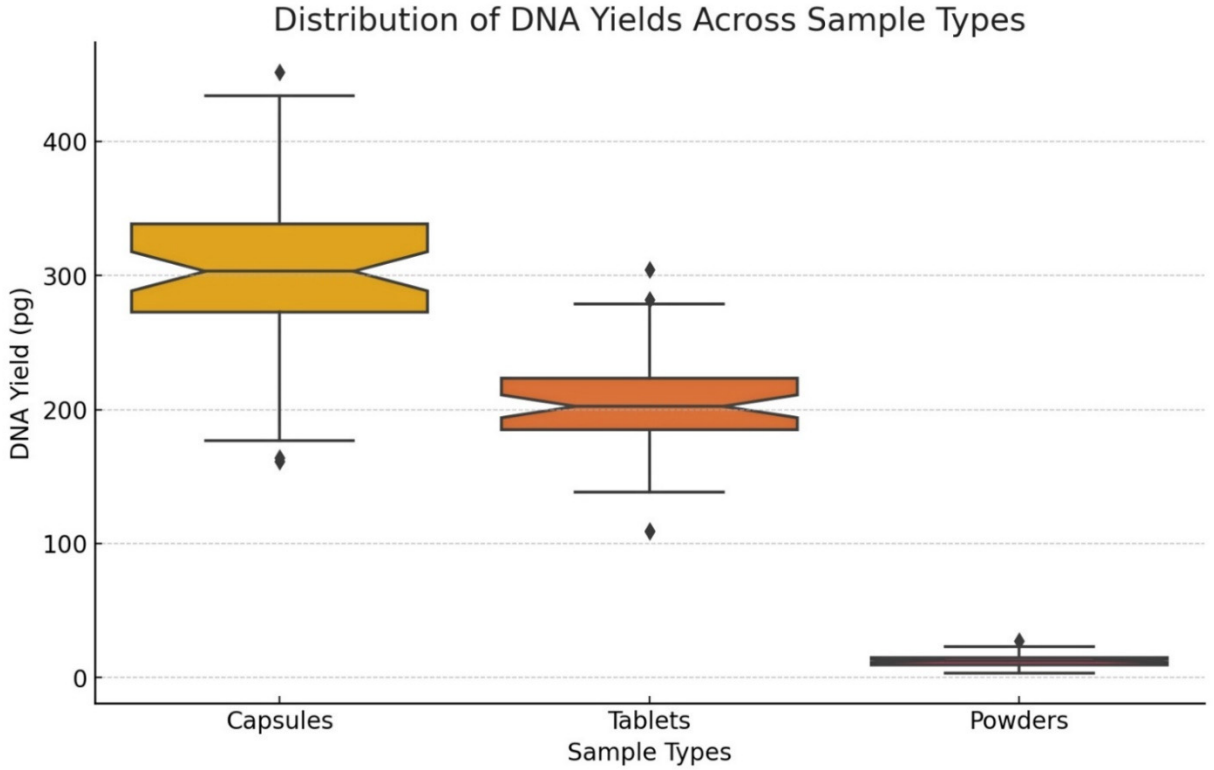

Figure 1. Boxplot showing the distribution of DNA yields (in picograms) recovered from capsules, tablets, and powders (n = 20 per group). Capsules yielded the highest DNA quantities, with a median of 310 pg (IQR: 300–315 pg), followed by tablets (230 pg, IQR: 220–235 pg), and powders (18 pg, IQR: 14–24 pg). The narrow interquartile ranges for capsules and tablets indicate consistent DNA transfer during handling and packaging. In contrast, powders exhibited a wider spread in DNA yields, likely due to variable contamination, dilution effects, and degradation during synthesis and environmental exposure. A Kruskal–Wallis test confirmed statistically significant differences in DNA recovery across sample types ($p < 0.01$). These findings underscore the superior reliability of solid dosage forms for trace DNA recovery in forensic drug investigations.

3.2. Chemical Profiling

Chromatographic analysis using Gas Chromatography–Mass Spectrometry (GC-MS) and Liquid Chromatography–Mass Spectrometry (LC-MS) produced distinct chemical fingerprints for capsules, tablets, and powders. Each formulation type was analyzed in 20 replicate samples, aligned with those used for DNA profiling. Capsules and tablets prepared under standardized conditions exhibited highly consistent retention times, with intra-batch variation of less than 0.1 minutes across replicates. These findings reflect the chemical stability of solid dosage forms and the low variability introduced by packaging or manual handling.

In contrast, powder samples displayed greater chromatographic variability, with retention time shifts of up to 0.3 min between replicates. This inconsistency likely results from environmental exposure, uneven mixing during synthesis, and lack of controlled formulation, all of which are common in clandestine drug manufacturing settings. Internal retention time standards were included in each run to normalize for instrument drift and support accurate comparison of chemical profiles.

In addition to retention times, fragmentation patterns from mass spectra were analyzed to ensure compound-level consistency. Fragmentation spectra showed minimal deviation across replicates for capsules and tablets, further supporting batch homogeneity. Powder samples, however, exhibited spectral variability indicative of chemical instability and heterogeneity in composition.

When STR profiles were degraded, partial, or inconclusive, chemical profiling served as a valuable alternative for batch-level attribution. As shown in Figure 2, classification accuracy was defined as the percentage of samples correctly matched to their known manufacturing batch based on retention time and fragmentation pattern similarity. Capsules

achieved ~85% accuracy, reflecting their chemical uniformity. Tablets followed with ~78%, while powders showed reduced accuracy at ~65%, underscoring the analytical challenges presented by their inherent variability.

These findings affirm the utility of chemical profiling as a complementary forensic tool. Even in scenarios where DNA yields are insufficient or degraded, reproducible chromatographic signatures—especially in capsules and tablets—can facilitate linkage between drug samples and their manufacturing sources. When combined with DNA evidence, chemical profiling enhances the evidentiary value of seized drug materials, supporting both investigative leads and prosecutorial outcomes.

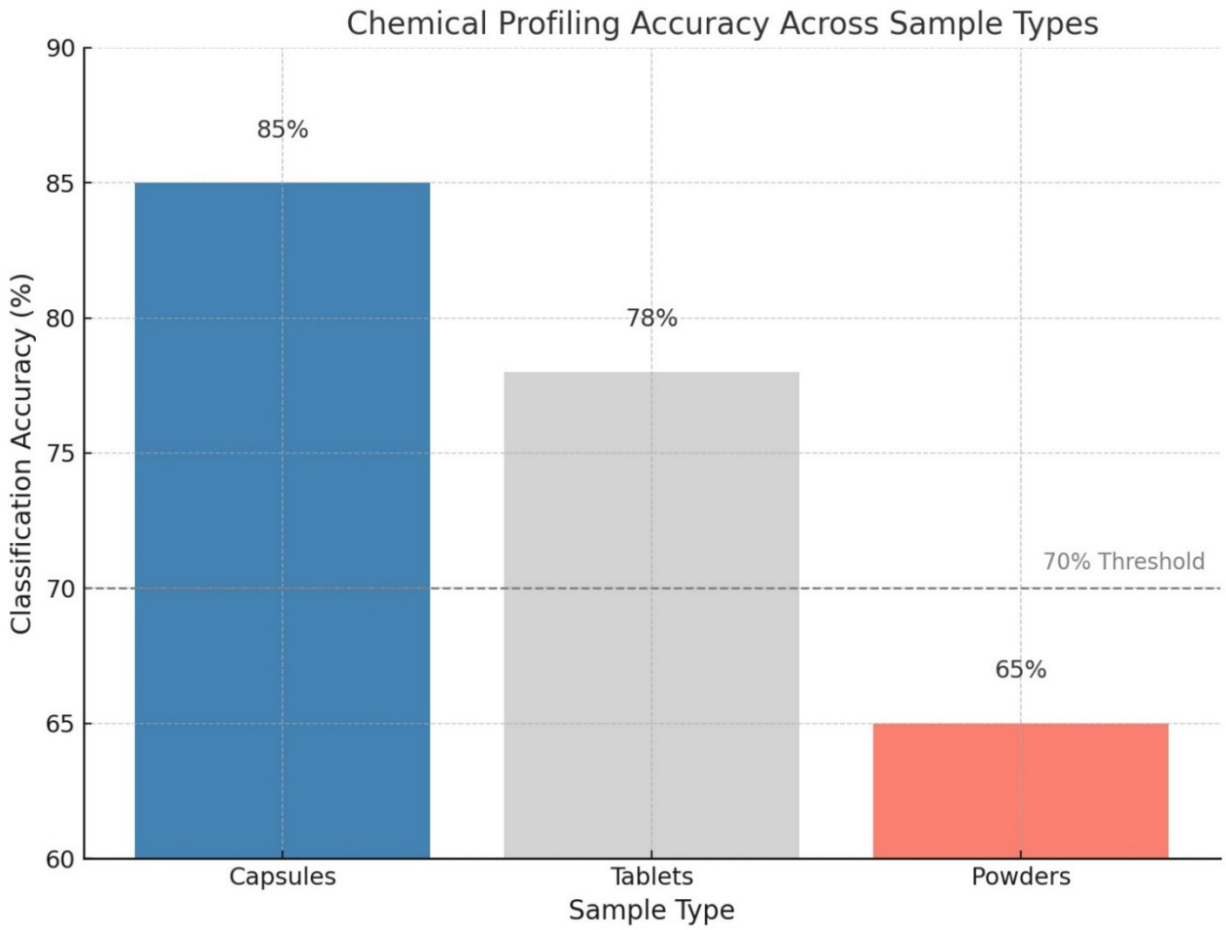

Figure 2. Bar chart comparing the classification accuracy of chemical profiling for capsules, tablets, and powders ($n = 20$ per group). Accuracy was defined as the percentage of samples correctly matched to their known manufacturing batch using retention time and fragmentation pattern similarity in GC-MS and LC-MS analyses. Capsules achieved the highest accuracy (85%), followed by tablets (78%) and powders (65%). These values reflect the greater chemical uniformity and reproducibility of solid dosage forms, which are typically produced under controlled conditions. In contrast, the lower performance for powders highlights their susceptibility to environmental variability, inconsistent mixing, and degradation. A dashed horizontal line at 70% indicates an interpretability threshold for forensic attribution.

3.3. Combined Analysis

The integration of DNA and chemical profiling significantly improved the classification accuracy of drug samples by leveraging the complementary strengths of each method. Combined profiling was defined as a consensus-based approach, where classification was considered correct if either DNA or chemical data independently matched a sample to its correct source. This approach was evaluated using 20 replicates per sample type, and classification accuracy was calculated as the proportion of correctly attributed samples out of the total replicates.

The integrated method achieved 97% classification accuracy for capsules, surpassing DNA profiling alone (90%) and chemical profiling alone (85%). Tablets followed a similar trend, with combined profiling achieving 85%, compared to 78% (DNA) and 70% (chemical profiling). Powdered samples, which typically yielded partial STR profiles and inconsistent chemical signatures, benefitted most from the integrated method. Combined profiling achieved 72% accuracy, outperforming DNA alone (60%) and chemical profiling alone (55–60%).

As visualized in Figure 3, the performance enhancement from integrating both data types was statistically significant across all sample types ($p < 0.05$; Kruskal–Wallis post hoc comparisons). Combined analysis reinforced evidentiary strength for capsules and tablets—already demonstrating strong individual profiling outcomes. In contrast, powders showed the greatest relative improvement, illustrating the compensatory value of multimodal data fusion, particularly for chemically and biologically unstable samples.

These findings highlight the importance of cross-modal redundancy in forensic analysis. When one profiling modality is compromised by contamination, degradation, or data insufficiency, the other can augment classification confidence. The additive value of combining DNA and chemical signatures strengthens the reliability of forensic conclusions, particularly in complex case scenarios involving heterogeneous drug formulations or incomplete evidence.

Overall, the results validate integrated profiling as a superior strategy for forensic source attribution. Improving classification performance across all drug forms—especially in low-quality evidence cases—enhances investigative accuracy and evidentiary robustness in court proceedings.

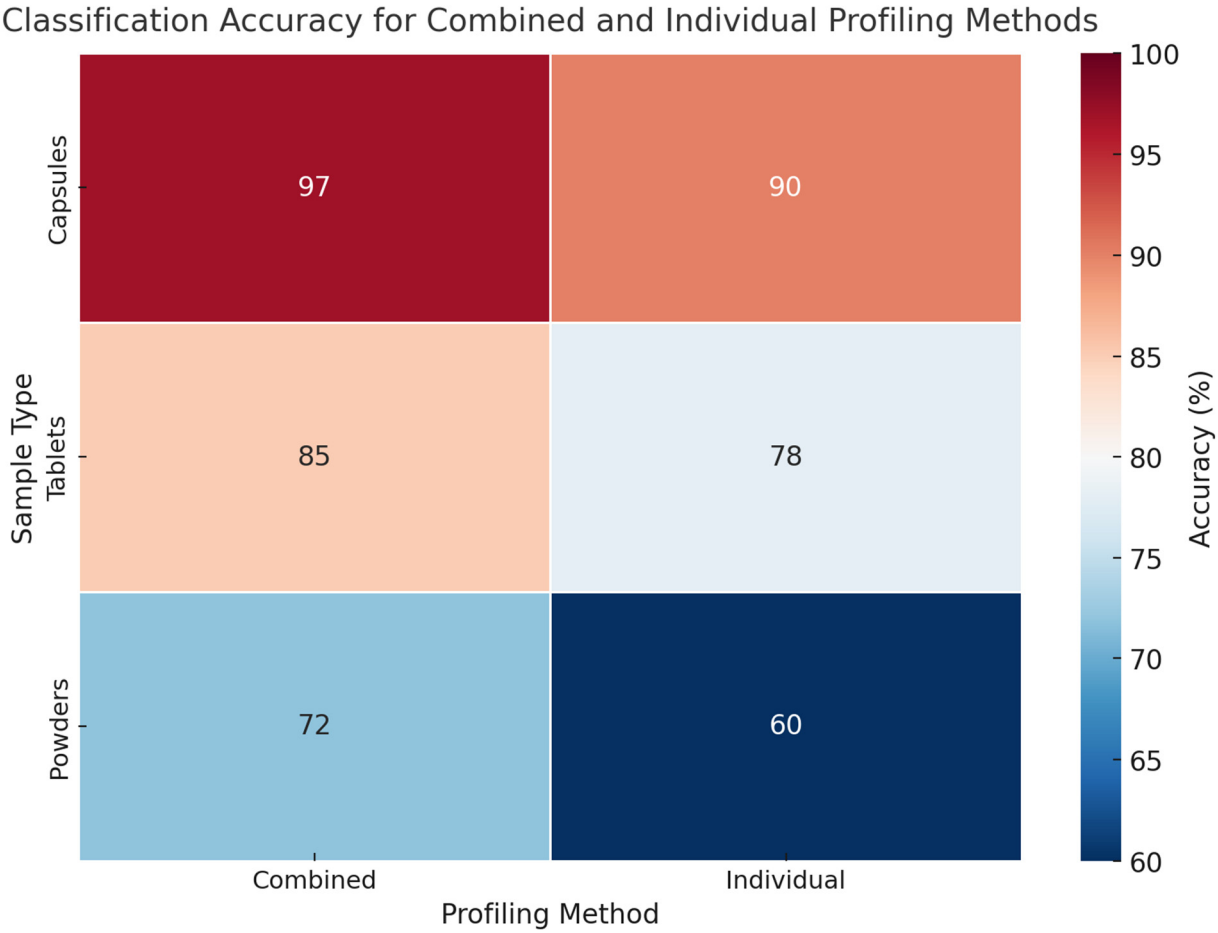

Figure 3. Heatmap displaying the classification accuracy (%) of combined (DNA + chemical) versus individual profiling methods across capsules, tablets, and powders ($n = 20$ per group). Combined profiling was based on a consensus model, in which a sample was correctly classified if either method successfully linked it to its manufacturing source. Capsules showed the highest combined accuracy (97%), followed by tablets (85%) and powders (72%). Individual methods yielded lower performance: DNA profiling alone resulted in 90% (capsules), 78% (tablets), and 60% (powders), while chemical profiling alone achieved 85%, 70%, and 55%–60%, respectively. A Kruskal–Wallis test with post hoc comparisons confirmed that combined profiling significantly outperformed individual methods across all sample types ($p < 0.05$). This heatmap highlights the synergistic benefit of integrating DNA and chemical data to enhance forensic linkage accuracy, particularly for complex or degraded samples.

4. Discussion

4.1. Overview of Findings

This study confirms the value of integrating DNA profiling and chemical analysis to enhance the forensic attribution of illicit drug materials. Consistent with recent research by Griffin et al. [60,61], brief contact—typically 1 to 3 s—with drug surfaces is sufficient to yield informative DNA profiles that can be uploaded to forensic databases.

Our findings show capsules consistently exhibited the highest DNA recovery, followed by tablets, with powders producing significantly lower yields. These results reinforce the importance of selecting appropriate substrates for DNA recovery in drug-related investigations.

The superior performance of capsules and tablets is likely attributable to direct handling during encapsulation, counting, and packaging, which facilitates the deposition of cellular material onto their surfaces [61]. Powders, by contrast, showed lower DNA yields due to environmental exposure, dilution, and less consistent DNA integration during synthesis. These observations align with Bertram et al. [62], who demonstrated that DNA integrity can be preserved even in drug residues. However, recovery efficiency can be influenced by material form and surface characteristics.

From an investigative standpoint, capsules and tablets offer significant forensic value. In our study, over 85% of samples yielded single-source STR profiles, which are highly reliable for matching individuals to drug materials. Approximately 15% of capsules produced mixed DNA profiles—likely due to multiple handlers—which, while more complex to interpret, can still provide actionable intelligence using probabilistic models. Griffin et al. [61] similarly found that surface and internal tablet DNA can be recovered, offering insight into individuals involved in manufacturing versus distribution.

The integration of DNA and chemical profiling offers distinct advantages. DNA profiles provide individual-level attribution, while chemical fingerprints reveal information about batch composition, origin, and synthetic pathway, especially when analysed via GC-MS and LC-MS. The dual modality enhances evidentiary value in intelligence-gathering and legal contexts, supporting broader efforts to dismantle drug distribution networks [60,63].

4.2. Implications for Chain of Custody and Contamination

Drug samples typically pass through multiple handling stages—seizure, transportation, storage, and laboratory examination—all of which pose contamination risks. Maintaining a robust chain of custody is crucial to preserving the integrity of trace DNA evidence [31]. Even minor lapses in documentation or handling protocol can compromise evidentiary reliability and risk exclusion from legal proceedings.

The presence of mixed profiles in capsule samples and partial profiles in powders in our study underscores the importance of implementing strict anti-contamination protocols. These include the use of single-use consumables, controlled lab environments, and thorough documentation of personnel contact with samples [33]. Bertram et al. [62] further emphasized that drug residues do not significantly inhibit DNA analysis, but mishandling and poor environmental controls can still degrade results.

Contamination is often unavoidable in real-world cases—especially involving clandestine laboratories due to the absence of hygiene standards. As noted in the literature [34], biological material may be unintentionally deposited through speaking, coughing, or environmental dust during synthesis. In our study, we modeled similar transfer pathways, including airborne deposition, to simulate realistic contamination scenarios, reinforcing the need for advanced precautions in field and lab settings.

4.3. Ethical Implications in Handling Drug Samples

Handling drug evidence that contains trace DNA raises important ethical considerations. While forensic practitioners aim to recover actionable intelligence, they must also ensure that the evidence is reliable, lawfully obtained, and interpreted responsibly. Mishandling during collection or lapses in the chain of custody not only increase the risk of contamination but can also lead to the wrongful implication of individuals, particularly when mixed or partial DNA profiles are involved.

Ambiguous or partial profiles must be communicated with full transparency in court reports and expert testimony. As highlighted by Bond and Hammond [64], the evidentiary value of DNA depends not only on technical recovery but also on the quality and contextualization of the profile. Forensic analysts must guard against overstating the significance of low-template or mixed-source DNA evidence.

Moreover, ethical practice requires the appropriate use of integrated methods. While combined DNA–chemical profiling offers greater discriminative power, it also demands heightened documentation standards, procedural validation, and responsible reporting [33,34]. DNA recovered from drug surfaces or powders must be interpreted within the context of manufacturing and handling environments, especially when used to support legal actions against individuals across the drug supply chain.

5. Conclusions

This study demonstrates the significant forensic potential of integrating DNA profiling with chemical analysis to strengthen investigations into illicit drug manufacturing and distribution. Among the tested substrates, capsules and tablets consistently yielded the highest DNA recovery, producing high-quality single-source STR profiles that directly attribute handling to specific individuals. While more challenging due to environmental exposure and inherent variability, Powders still yielded valuable DNA evidence—especially when interpreted in conjunction with chemical signatures.

The complementary nature of DNA and chemical profiling enhances the evidentiary power of forensic analysis. DNA profiling links individuals to drug materials, while chemical profiling contextualizes those materials by identifying batch-level composition and synthetic pathways. Together, these modalities offer a more comprehensive approach to source attribution, enabling law enforcement and forensic practitioners to map personal and material connections across the drug supply chain.

Importantly, the study highlights the influence of sample form and handling on DNA transfer and persistence. Capsules and tablets, which undergo direct manual manipulation during encapsulation, counting, and packaging, exhibited significantly higher DNA recovery than powders, whose recovery was often hampered by surface area limitations, synthesis processes, and degradation. Nonetheless, even partial profiles from powders were forensically informative when combined with batch-level chemical data.

The operational implications of these findings are substantial. Integrated DNA–chemical profiling can augment strategic intelligence and evidentiary reliability in criminal prosecutions. Its application allows forensic scientists not only to establish links between individuals and seized drug materials, but also to identify potential manufacturing sources and track distribution networks—an essential advantage in dismantling complex trafficking operations.

To further improve outcomes, future research should focus on optimizing protocols for trace DNA recovery from chemically complex and environmentally unstable substrates. Standardized sampling procedures, rigorous contamination controls, and the adoption of advanced recovery technologies—such as vacuum-based touch DNA sampling and enhanced low-template amplification—will improve both yield and interpretation. Additionally, specialized training programs in trace evidence handling and probabilistic DNA analysis should be incorporated into forensic practice to ensure that partial and mixed profiles are interpreted accurately and ethically.

In conclusion, this study provides a scientifically robust and operationally relevant framework for combining DNA and chemical profiling in drug-related forensic investigations. To facilitate real-world implementation, a detailed visual guide is included as a supplementary file (Supplementary Methodology), outlining the step-by-step procedures followed in this study. By refining current methodologies and prioritizing multidisciplinary integration, forensic science can continue to provide powerful tools in the fight against illicit drug trafficking, supporting both investigative accuracy and prosecutorial strength provides.

Supplementary Materials

To support practical application, a comprehensive visual guide is provided as a supplementary file. It can be found at: https://www.sciepublish.com/article/pii/639. Supplementary Methodology: Integrated DNA and Chemical Profiling Workflow for Drug Evidence, presenting the step-by-step procedures used in this study.

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Author Contributions

S.K.A. was responsible for study design, coordination, forensic DNA analysis, data analysis, statistical interpretation, and drafting and finalizing the manuscript. A.A.K. contributed to sample collection, conducted forensic chemical profiling, and provided critical revisions and scientific input during manuscript development. Both authors reviewed and approved the final version of the manuscript.

Ethics Statement

This study was conducted in full accordance with the ethical standards and research governance protocols of the General Department of Forensic Science and Criminology, Dubai Police General Headquarters, Dubai, UAE. The research methodology—including participant involvement, DNA collection, handling of biological materials, and analytical procedures—was reviewed and approved by the relevant departmental oversight committee to ensure compliance with both institutional and internationally recognized ethical guidelines (Ref. No. STEMH 930, December 2024).

Informed Consent Statement

All volunteer participants provided informed consent prior to sample collection, and all experimental activities were carried out with strict adherence to protocols designed to protect participant anonymity, data integrity, and scientific transparency. The study upholds a strong commitment to ethical responsibility and scientific rigor, contributing meaningfully to the advancement of forensic science practice in both operational and research contexts.

Data Availability Statements

Not applicable.

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This research received no external funding.

Declaration of Competing Interest

The authors declare no conflicts of interest related to the conduct, analysis, or reporting of this research. There are no known financial, professional, or personal affiliations that could have influenced the study design, data interpretation, or conclusions drawn. All experimental procedures and analytical approaches were conducted independently and without external influence to ensure the objectivity and integrity of the findings presented.

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