# Toward the Development of the STR Utility Index (SUI): A Conceptual Framework for Quantifying Pre-Analytical Biological Evidence Utility

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**Abstract**
Forensic biological evidence remains one of the most widely relied upon forms of physical evidence in criminal investigations, particularly through short tandem repeat (STR) analysis for human identification. Despite substantial advances in forensic DNA interpretation, uncertainty quantification remains largely confined to post-analytical stages, after biological material has already been consumed through extraction, amplification, and electrophoretic analysis. This limitation creates operational inefficiencies, contributes to laboratory backlogs, and may result in the irreversible expenditure of finite biological evidence without prior assessment of likely evidentiary value.
This paper introduces the conceptual foundation for a proposed STR Utility Index (SUI), a pre-analytical framework designed to estimate the likelihood that biological evidence will yield interpretable and actionable STR profiles prior to full laboratory processing. The framework integrates measurable variables associated with DNA degradation, including biological source, substrate type, environmental exposure, preservation conditions, estimated time since deposition, and postmortem interval, into a structured probabilistic model of evidentiary utility. By extending uncertainty quantification into earlier stages of forensic workflows, the SUI offers a theoretical mechanism for improving evidence triage, resource allocation, and decision transparency across forensic laboratories and law enforcement agencies. This conceptual framework establishes a foundation for future empirical development, computational modeling, and operational validation.
*Keywords:* STR Utility Index, forensic DNA, uncertainty quantification, evidence triage, degraded biological evidence, forensic decision-making

**Keywords:** STR Utility Index (SUI), Forensic DNA Analysis, Biological Evidence, Short Tandem Repeats (STR), Pre-analytical Assessment, Evidence Triage, DNA Degradation, Probabilistic Decision-Making, Forensic Evidence Management

## 1. Introduction

Forensic biological evidence remains one of the most widely relied upon forms of physical evidence in criminal investigations, particularly through the use of short tandem repeat (STR) analysis for human identification. Advances in forensic DNA analysis have significantly improved the sensitivity and discriminatory power of STR profiling, allowing analysts to recover informative genetic profiles from increasingly limited biological material (Gill et al., 2015). These developments have strengthened investigative capabilities across violent crime, missing persons investigations, and disaster victim identification. Despite these advancements, the evidentiary value of biological material is often shaped long before laboratory analysis begins, as biological samples remain vulnerable to degradation, environmental exposure, and handling conditions that may compromise DNA integrity.

Biological degradation presents a persistent challenge in forensic DNA analysis. Factors such as heat, moisture, ultraviolet exposure, microbial activity, substrate interaction, and prolonged environmental deposition may reduce DNA quantity and quality, ultimately affecting amplification success and profile interpretability (Ballou et al., 2013; National Institute of Justice [NIJ], 2023). These factors often act simultaneously and variably, producing uncertainty regarding whether biological evidence is capable of yielding useful STR profiles.

The finite nature of biological evidence further complicates this problem. Once biological material is consumed during extraction and amplification, it cannot be restored. Samples that ultimately fail to produce interpretable profiles may still consume valuable laboratory resources, contributing to casework inefficiencies and forensic backlogs (National Institute of Justice [NIJ], 2011; National Research Council, 2009).

Although forensic DNA interpretation has increasingly incorporated probabilistic genotyping, likelihood ratio methodologies, and activity-level assessments, these frameworks primarily address uncertainty after analytical processing has occurred (Aitken et al., 2020; Taylor & Kokshoorn, 2023). Comparatively little attention has been given to structured assessment of biological evidence utility prior to full laboratory processing.

This paper introduces the conceptual foundation for the STR Utility Index (SUI), a pre-analytical framework designed to quantify the probable utility of biological evidence for STR analysis before full laboratory processing occurs. By extending uncertainty quantification into earlier stages of forensic workflows, the SUI seeks to establish a structured approach to biological evidence triage, resource allocation, and evidentiary preservation. If empirically validated, such a framework may improve laboratory efficiency, strengthen evidence management practices, and increase transparency in pre-analytical forensic decision-making.

## 2. Literature Review

The interpretation of forensic DNA evidence has increasingly evolved toward probabilistic and statistically informed methodologies, particularly in response to the challenges posed by low-template DNA, degraded biological samples, and complex DNA mixtures. Historically, forensic DNA interpretation often relied on threshold-based determinations of profile quality and analyst-driven categorizations of interpretability. While these approaches provided practical operational value, they frequently simplified the probabilistic nature of biological evidence and may have inadequately represented the uncertainty present throughout the analytical process (Gill et al., 2015).

The introduction of probabilistic genotyping has significantly advanced forensic DNA interpretation by allowing analysts to evaluate evidentiary weight through likelihood-based models rather than categorical inclusion or exclusion. These systems have improved the interpretation of complex mixtures, partial profiles, and stochastic phenomena such as allele dropout, peak imbalance, and amplification variability (Gill et al., 2015). More recently, forensic interpretation has expanded beyond source-level propositions into activity-level evaluations, recognizing that evidentiary meaning must also account for transfer, persistence, and recovery under competing scenarios (Taylor & Kokshoorn, 2023). These developments have strengthened the scientific foundation of forensic DNA analysis by formalizing uncertainty within post-analytical interpretation.

Despite these advancements, the broader forensic DNA workflow remains largely reactive. Quantitative uncertainty is typically addressed only after biological material has undergone extraction, quantification, amplification, and electrophoretic analysis. This creates an important limitation, as the decision to proceed with full laboratory processing is often made before any structured assessment of probable profile utility has been established. In cases involving compromised biological evidence, this pre-analytical uncertainty may be substantial, particularly when degradation factors such as environmental exposure, preservation conditions, and temporal deposition have already affected DNA integrity (Ballou et al., 2013).

In many forensic and investigative settings, pre-analytical decisions are often informed by practical heuristics, contextual assumptions, or prior experience rather than formalized predictive assessment. This may result in implicit binary viability decisions, where evidence is viewed as either likely or unlikely to yield useful STR profiles. However, biological degradation exists on a continuum rather than within discrete categories. Samples perceived as highly compromised may still produce partial or probative genetic information, while samples presumed viable may ultimately fail due to inhibition, stochastic effects, or insufficient template quantity (Gill et al., 2015).

Aitken et al. (2020) emphasize that forensic evidence evaluation must remain grounded in statistical reasoning that explicitly accounts for uncertainty at each stage of the evidentiary process. Reliance on categorical thresholds without probabilistic modeling may oversimplify complex evidentiary dynamics and weaken both scientific rigor and judicial defensibility. This perspective reinforces the need for pre-analytical frameworks capable of extending uncertainty quantification earlier in forensic workflows.

The consequences of this limitation extend beyond laboratory efficiency. Premature exclusion of biological evidence may result in missed investigative opportunities, while unnecessary processing of low-probability samples contributes to reagent consumption, analyst workload, and casework backlog accumulation (National Research Council, 2009; National Institute of Justice [NIJ], 2011). More importantly, the absence of structured pre-analytical assessment may obscure the uncertainty underlying these decisions, limiting transparency in both forensic resource allocation and evidentiary accountability.

Together, these limitations highlight a significant gap in forensic biological evidence management. While forensic science has developed increasingly sophisticated tools for interpreting uncertainty after DNA evidence has been generated, comparatively little attention has been given to structured assessment of whether interpretable DNA evidence can be generated at all. This gap forms the conceptual basis for the development of pre-analytical utility frameworks in forensic DNA analysis.

## 3. Conceptual Foundation of the STR Utility Index (SUI)

The STR Utility Index (SUI) is proposed as a pre-analytical framework designed to estimate the probable utility of biological evidence for short tandem repeat (STR) analysis prior to extraction, amplification, and full laboratory processing. Conceptually, the SUI is intended to quantify the likelihood that a given biological sample will yield interpretable and potentially actionable STR information based on measurable pre-analytical variables. Rather than functioning as a replacement for laboratory analysis, the SUI is intended to serve as a structured decision-support mechanism for evidence triage, preservation, and resource prioritization.

At its conceptual foundation, the SUI recognizes that biological evidence utility is influenced by multiple interacting factors known to affect DNA persistence, degradation, and recovery. These variables may include biological source, substrate type, sample handling, environmental exposure, preservation conditions, estimated time since deposition, and, where applicable, postmortem interval. Existing forensic literature has consistently demonstrated that such variables influence DNA quantity, quality, and amplification success, often in ways that directly affect profile interpretability (Ballou et al., 2013; Taylor & Kokshoorn, 2023). By organizing these variables into a structured pre-analytical framework, the SUI seeks to establish a more transparent basis for assessing evidentiary potential before biological material is consumed.

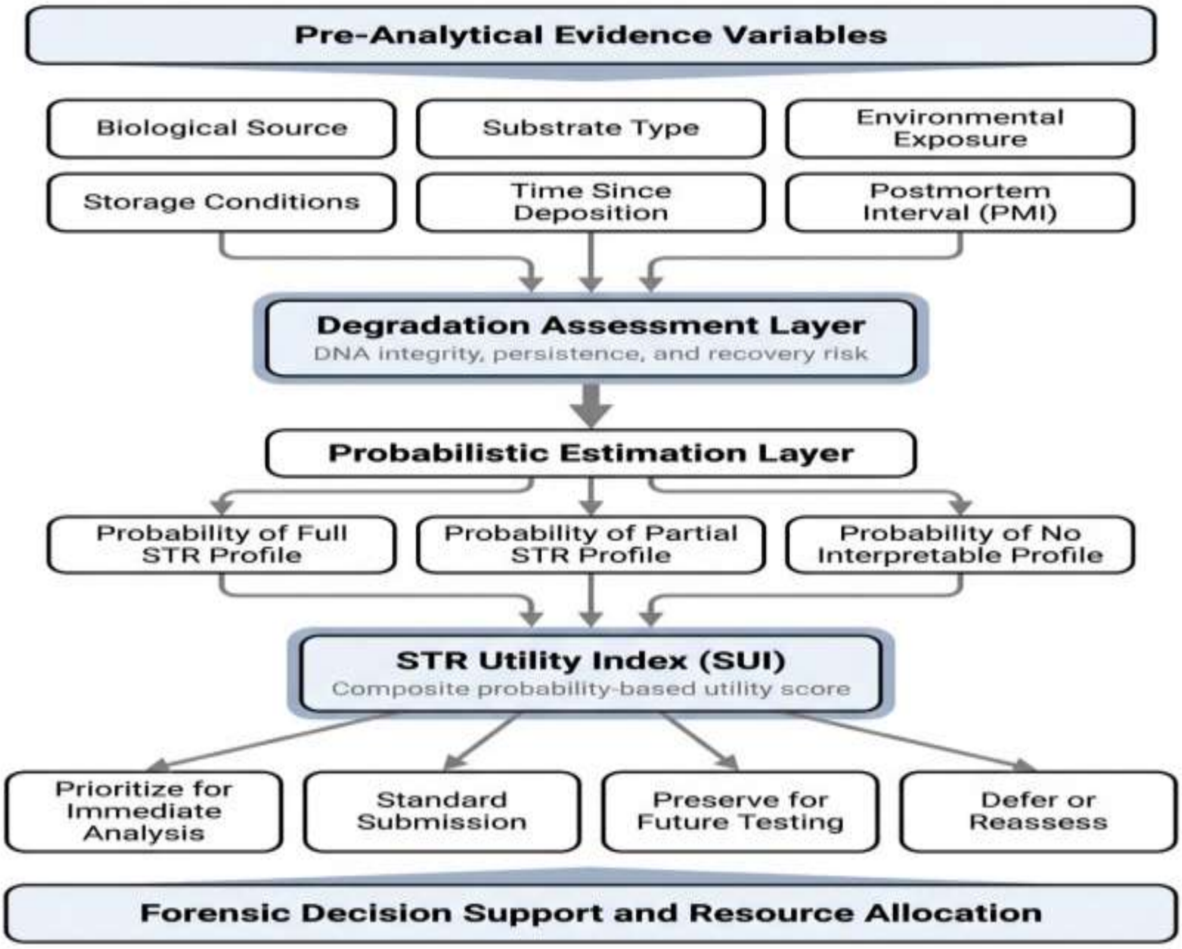


**Figure 1**. *Conceptual framework of the proposed STR Utility Index (SUI), illustrating how pre-analytical biological evidence variables may be integrated into a structured assessment of degradation, profile utility, and downstream forensic decision-making.*

Unlike probabilistic genotyping systems, which evaluate uncertainty within observed genetic data, the SUI shifts uncertainty assessment upstream by focusing on the probability that useful genetic data may be generated at all. Conceptually, this framework recognizes multiple possible outcomes, including the generation of full STR profiles, partial profiles, or non-interpretable results. This distinction is important, as partial DNA profiles may still retain investigative or evidentiary value depending on case context and comparative utility (Nozownik et al., 2025).

Importantly, the SUI is not intended to create deterministic decisions regarding whether evidence should or should not be analyzed. Rather, it is intended to provide structured probabilistic guidance capable of supporting earlier-stage forensic decision-making. By formalizing biological evidence utility as a measurable construct, the SUI establishes a conceptual bridge between biological degradation research, probabilistic reasoning, and practical forensic workflow management.

The SUI is currently under active interdisciplinary development, with future work focused on computational modeling, empirical validation, and operational implementation. As such, the present framework represents the theoretical foundation of a broader translational research effort aimed at improving forensic evidence triage through earlier-stage uncertainty quantification.

## 4. Potential Applications in Law Enforcement and Forensic Practice

The practical value of pre-analytical biological evidence assessment extends beyond forensic laboratories and into the operational decision-making environments of law enforcement agencies. In many jurisdictions, investigators, crime scene personnel, and evidence technicians are responsible for determining which biological samples are collected, preserved, and submitted for forensic analysis before any formal assessment of evidentiary viability can be made. These decisions may significantly influence investigative outcomes, laboratory workloads, and the preservation of finite biological material.

One of the most immediate applications of the STR Utility Index (SUI) lies in evidence submission triage. In cases involving multiple biological samples, agencies are often required to prioritize which items should be submitted for laboratory analysis based on investigative relevance, available resources, and practical judgment. A structured pre-analytical framework may assist in identifying biological evidence with greater probable utility, allowing agencies to make more informed submission decisions while reducing unnecessary expenditure of forensic resources.

This application may be particularly valuable in violent crime investigations such as homicide and sexual assault, where complex scenes often generate numerous biological evidence items of varying quality and condition. In such cases, prioritization of biological material may directly influence case progression and laboratory turnaround times. A structured assessment framework may support earlier evidence ranking while preserving potentially valuable biological material for later analysis if needed.

Cold case investigations present another important operational application. Biological evidence in unresolved cases is often subject to prolonged storage, uncertain preservation conditions, or prior analytical limitations. Before finite material is reintroduced into modern testing workflows, agencies may benefit from a structured pre-analytical assessment capable of estimating probable STR utility. This may support more strategic case reopening decisions and reduce unnecessary consumption of aged or limited evidence.

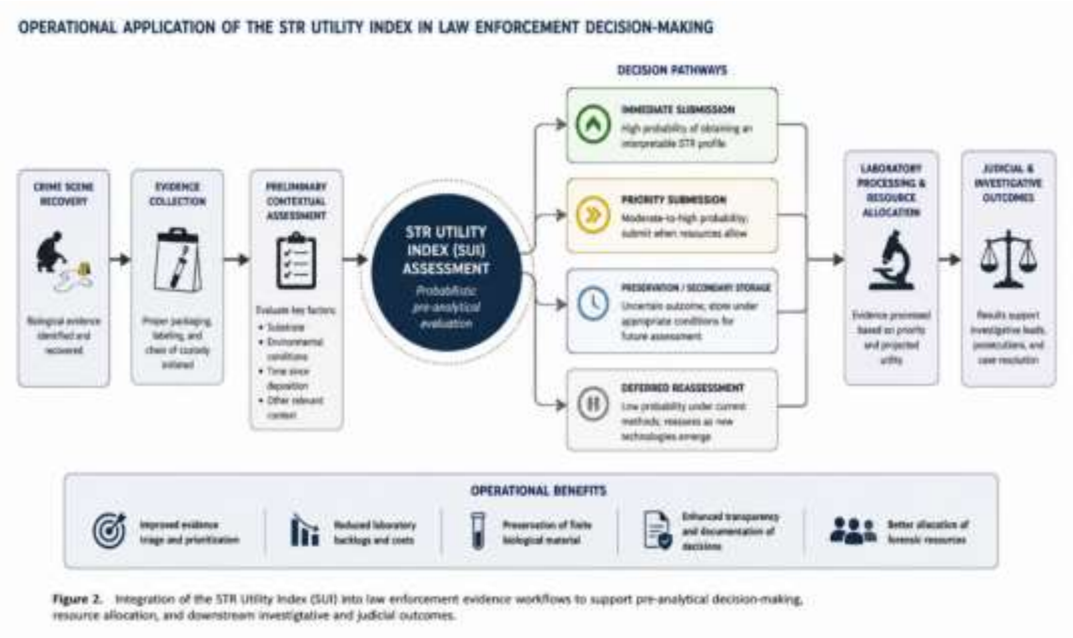


**Figure 2.** *Proposed integration of the STR Utility Index (SUI) into law enforcement evidence workflows, illustrating its role in evidence triage, submission prioritization, and downstream forensic and judicial decision-making.*

Similarly, in high-volume property crime and touch DNA investigations, where biological evidence frequently yields partial or low-template profiles, a utility-based framework may improve submission efficiency by helping distinguish between samples with stronger potential evidentiary value and those less likely to produce useful results. This may be particularly relevant for agencies operating under limited budgets or constrained laboratory access.

Beyond operational efficiency, the SUI may contribute to greater transparency and accountability in agency-level evidence decision-making. Such documentation may strengthen evidentiary continuity and support later justification of submission decisions in judicial review. Documented pre-analytical reasoning may provide a clearer basis for explaining why biological evidence was prioritized, deferred, or preserved, strengthening both investigative documentation and interagency communication with forensic laboratories. As forensic workloads continue to expand, structured frameworks capable of supporting earlier-stage evidence decisions may represent an important advancement in the relationship between law enforcement operations and forensic science practice.

## 5. Comparative Framework

The introduction of the STR Utility Index (SUI) represents a conceptual shift from reactive biological evidence processing toward earlier-stage probabilistic triage. Traditional forensic DNA workflows generally begin with evidence submission and proceed through extraction, quantification, amplification, and interpretation before uncertainty can be formally assessed. In contrast, the SUI proposes the introduction of structured utility assessment before analytical resources are committed. This distinction may improve efficiency, preserve finite evidence, and strengthen decision transparency.

**Table 1.** ***Comparison of Traditional Forensic DNA Workflow and SUI-Informed Workflow***

| Aspect | Traditional Workflow | SUI-Informed Workflow |
|---|---|---|
| **Timing of Utility Assessment** | After laboratory processing | Before laboratory processing |
| **Decision Structure** | Reactive | Pre-analytical and predictive |
| **Evidence Viability Assessment** | Often informal or experience-based | Structured probabilistic assessment |
| **Resource Commitment** | Initiated before utility is known | Guided by estimated utility |
| **Evidence Preservation** | Greater risk of unnecessary consumption | Improved preservation of finite material |
| **Submission Prioritization** | Often based on case urgency or judgment | Informed by probable STR utility |
| **Documentation of Deferral Decisions** | Often limited or absent | Structured rationale for triage decisions |
| **Workflow Transparency** | Variable across agencies and laboratories | More standardized and explicit |
| **Legal Defensibility** | Variable and often undocumented | Structured documentation supporting evidentiary accountability |
| **Operational Efficiency** | Risk of unnecessary backlog accumulation | Improved prioritization and reduced unnecessary processing |
| **Judicial Accountability** | Limited rationale for triage decisions | Auditable decision records for review |

As illustrated in Table 1, the proposed SUI does not seek to replace traditional forensic DNA workflows but rather to supplement them by introducing earlier-stage assessment of biological evidence utility. This conceptual shift may allow agencies and laboratories to make more informed decisions regarding evidence prioritization, preservation, and analytical resource allocation. By formalizing pre-analytical uncertainty, the SUI may improve consistency and transparency across forensic evidence management practices.

## 6. Challenges and Scientific Limitations

Despite its conceptual promise, the STR Utility Index (SUI) faces several scientific and operational limitations that must be addressed before operational implementation. As with any predictive framework in forensic science, the reliability of utility estimation depends heavily on the quality, representativeness, and consistency of the data used during model development and validation. Without sufficient empirical grounding, predictive outputs may be vulnerable to error, misclassification, or overgeneralization.

One of the most significant challenges lies in the inherent variability of biological evidence. DNA degradation is influenced by numerous interacting factors, including temperature, humidity, ultraviolet exposure, microbial activity, substrate composition, and time since deposition (Ballou et al., 2013). These factors rarely operate in isolation and may vary significantly between cases. As a result, establishing universally applicable predictive relationships may prove difficult, particularly across different environmental or forensic contexts.

Another limitation involves the interpretive complexity of partial or degraded DNA profiles. Biological evidence perceived as low utility may still yield partial profiles capable of supporting investigative leads, database searches, or contextual associations. Conversely, evidence estimated as high utility may fail due to stochastic effects, inhibition, or previously unrecognized degradation factors (Gill et al., 2015). This variability reinforces the importance of avoiding deterministic interpretations of utility estimates.

Operationally, there is also risk of overdependence on predictive frameworks. If used improperly, pre-analytical utility assessments may influence evidence submission practices in ways that prematurely deprioritize biologically relevant material. This concern is particularly significant in serious violent crimes, cold case investigations, and cases involving limited evidence where the consequences of exclusion may be substantial.

Finally, model transparency and interpretability remain critical challenges. Any future computational implementation of the SUI must ensure that decision logic remains explainable and scientifically defensible, particularly if such outputs influence laboratory workflows or investigative strategy. These limitations underscore the importance of rigorous validation, external testing, and cautious integration before the SUI can be considered for routine forensic application.

## 7. Ethical and Legal Considerations

As predictive frameworks become increasingly integrated into forensic science, important ethical and legal considerations must be addressed to ensure their responsible use. Although structured utility assessments may improve efficiency and consistency, they also introduce concerns regarding transparency, accountability, and the potential overreliance on probabilistic outputs in investigative decision-making.

A central ethical concern involves the risk of treating predictive estimates as definitive rather than advisory. A low estimated probability of STR utility should not be interpreted as evidence of irrelevance, nor should it function as an automatic exclusionary mechanism. Biological evidence may retain contextual, corroborative, or future evidentiary value even when immediate analytical utility appears limited. Maintaining human oversight in all evidence triage decisions remains essential.

Transparency and explainability are equally important, particularly as forensic science increasingly incorporates computational and probabilistic systems. Recent scholarship has emphasized the need for explainable frameworks capable of articulating how predictive outputs are generated, especially where such outputs may influence legal proceedings or evidentiary strategy (Aalbers et al., 2023). Future computational development of the STR Utility Index (SUI) must prioritize interpretability alongside predictive performance to preserve scientific and legal defensibility.

Legal considerations also arise regarding evidentiary accountability and admissibility. Under reliability-based standards such as Daubert v. Merrell Dow Pharmaceuticals, Inc. (1993), forensic methodologies are subject to increasing scrutiny regarding validation, reproducibility, and methodological transparency. While the SUI is not intended as an evidentiary test itself, the decisions it informs may affect whether biological material is tested, preserved, or deferred. As such, the rationale underlying those decisions should remain documented and capable of review.

Similar concerns extend internationally, where expert opinion and evidentiary reliability are likewise subject to judicial scrutiny. Comparative legal systems increasingly emphasize transparency, methodological accountability, and procedural fairness in the evaluation of scientific evidence. These broader legal considerations reinforce the importance of ensuring that predictive utility frameworks remain advisory, explainable, and subject to professional oversight.

Addressing these ethical and legal issues will be critical to ensuring that pre-analytical utility frameworks strengthen forensic practice without undermining evidentiary fairness, scientific integrity, or judicial confidence.

## 8. Future Development and Research Directions

The STR Utility Index (SUI) remains in active conceptual and computational development as part of an interdisciplinary research effort aimed at improving pre-analytical biological evidence assessment. While the present paper establishes the theoretical framework, future work will focus on the empirical development and operationalization of the model through structured computational analysis and forensic validation.

A primary area of future research involves the systematic identification and weighting of pre-analytical variables known to influence DNA degradation, persistence, and recovery. This process will require retrospective case analysis, repository-based datasets, and controlled forensic data sources capable of establishing measurable relationships between evidentiary conditions and downstream STR outcomes. Such efforts will be critical in transforming the conceptual framework into a quantifiable and reproducible utility model.

Future development will also involve interdisciplinary collaboration between forensic scientists and computational researchers to explore predictive architectures capable of supporting utility estimation across varied forensic contexts. Additional collaboration with statisticians and artificial intelligence specialists may further strengthen predictive architecture and model explainability. This includes the potential integration of probabilistic reasoning, statistical modeling, and machine learning approaches to improve predictive reliability while maintaining transparency and interpretability.

External validation will remain essential for determining operational utility. Future studies should evaluate the performance of the SUI across diverse case types, environmental conditions, and biological substrates to assess generalizability and practical limitations. Attention should be given to how utility estimates vary across decomposed remains, touch DNA evidence, aged biological samples, and mixed-source evidence.

Additional research should also examine how structured utility estimates may be communicated effectively to forensic analysts, investigators, and legal stakeholders. The practical success of any pre-analytical framework will depend not only on predictive accuracy but also on its usability, explainability, and compatibility with existing forensic workflows.

As forensic science continues to move toward increasingly data-driven and uncertainty-informed methodologies, the continued development of the SUI represents an opportunity to expand structured decision-making into earlier stages of biological evidence management. The present framework serves as the foundational stage of that broader translational effort.

## 9. Conclusion

Forensic biological evidence remains one of the most powerful and widely utilized forms of physical evidence in criminal investigations, yet its utility is often complicated by degradation, environmental exposure, and incomplete genetic information. While forensic DNA interpretation has advanced considerably through probabilistic genotyping, Bayesian reasoning, and activity-level assessment, these developments have largely focused on uncertainty after analytical processing has already occurred. The pre-analytical stage, where critical decisions regarding evidence preservation, submission, and resource allocation are made, remains comparatively underdeveloped in its ability to formally assess biological evidence utility.

This paper has introduced the conceptual foundation for the STR Utility Index (SUI), a proposed pre-analytical framework designed to quantify the probable utility of biological evidence for STR analysis before full laboratory processing occurs. By extending uncertainty quantification into earlier stages of forensic workflows, the SUI offers a structured approach to biological evidence triage that may improve laboratory efficiency, support law enforcement decision-making, preserve finite biological material, and strengthen evidentiary transparency.

Although the SUI remains under active development, its conceptual framework establishes an important foundation for future empirical validation, computational implementation, and operational integration. As forensic science continues to evolve toward increasingly quantitative and data-informed methodologies, structured pre-analytical utility assessment may represent an important next step in improving the efficiency, reliability, and accountability of forensic biological evidence management.

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