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MOLECULES, BONES, AND THE BIOLOGY OF DEATH: BRIDGING FORENSIC BIOLOGY, ANTHROPOLOGY, AND MEDICINE IN HUMAN IDENTIFICATION AND DEATH INVESTIGATION

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ABSTRACT

Background: Complex death investigations require the interpretation of biological traces, skeletal remains, and pathological findings within a shared evidential framework. Fragmented examination can obscure the distinction between identifying a person and explaining their death.

Objective: To critically examine the complementary roles of forensic biology, forensic anthropology, and forensic medicine in human identification, trauma assessment, and postmortem reconstruction.

Approach: A targeted narrative synthesis of selected primary studies and authoritative forensic guidance was undertaken, emphasizing validation and interpretive limitations.

Synthesis: Genetic analysis supports identity and kinship assessment; anthropology contributes skeletal profiling, recovery, and contextual interpretation; forensic medicine evaluates injuries, disease, and potential causes of death. Their integration is particularly valuable for decomposed, fragmented, and commingled remains. Postmortem imaging, microbial succession, and stable isotope analysis expand investigative possibilities, but their evidential value depends on appropriate reference data, sampling, and validation. A proposed workflow links coordinated recovery, evidence-preserving examination, independent specialist assessment, and multidisciplinary reconciliation.

Conclusion: Effective integration requires question-specific interpretation rather than uncritical accumulation of apparently concordant findings. Transparent uncertainty, preservation of contradictory evidence, and separation of identity from causal conclusions are essential to scientifically defensible death investigation. The proposed framework offers a practical basis for collaborative casework and future validation studies.

Keywords: Forensic biology; Forensic anthropology; Forensic medicine; Human identification; Medicolegal death investigation; Evidence integration.

1 INTRODUCTION

A death investigation must answer several related questions: who died, what happened, when it happened, and whether the available evidence supports a particular explanation. Each question draws on different observations. A genetic association may support identity without explaining a fatal injury, while a skeletal defect may indicate trauma without identifying its recipient. The central challenge is therefore to connect evidence while preserving the boundaries of what each method can establish. Forensic biology addresses biological material and genetic relationships. Forensic anthropology examines human remains, particularly when decomposition, fragmentation, or loss of soft tissue restricts conventional examination. Forensic medicine applies medical knowledge to legal questions, including injury interpretation and death investigation. This review concentrates on its postmortem branch, forensic pathology; it does not attempt a comprehensive review of clinical forensic medicine. The Minnesota Protocol provides an authoritative context for multidisciplinary investigation of potentially unlawful deaths [1]. The practical value of collaboration is illustrated by INTERPOL disaster victim identification guidance, which incorporates multiple specialist examinations and reconciliation of antemortem and postmortem information [2]. However, procedural coordination alone does not guarantee sound inference. Examiners must also recognize uncertainty, avoid importing investigative expectations into measurements, and distinguish identification evidence from evidence about the circumstances of death. This review critically examines these connections and proposes a question-led workflow. Its contribution is an organizational synthesis: specialist findings should be integrated according to the proposition they address, the quality of their underlying evidence, and their dependence on other findings. The workflow is proposed for future evaluation, rather than presented as a validated diagnostic system.

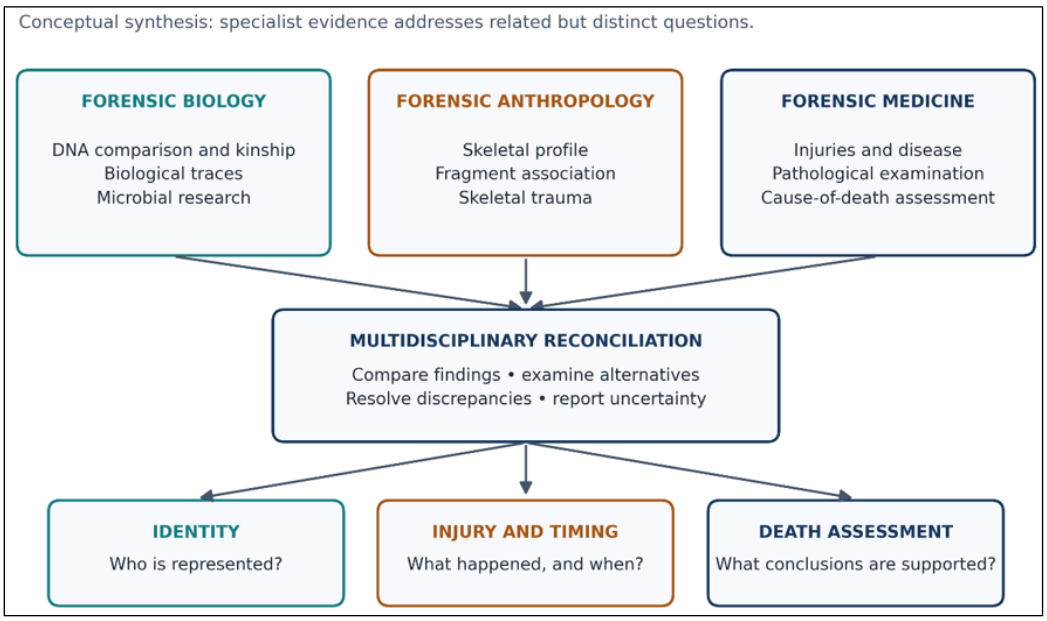


Figure 1: Complementary roles in death investigation

Figure legend: Forensic biology, anthropology, and medicine contribute different observations to multidisciplinary reconciliation. Their combined interpretation supports separate conclusions about identity, injury and timing, and death assessment. This is a conceptual synthesis, not a validated diagnostic model.

2 REVIEW APPROACH AND OBJECTIVES

Targeted web-assisted literature searches were conducted on 6 October 2026 using terms relating to forensic anthropology and DNA identification, skeletal sex and age estimation, fracture timing, postmortem imaging, cadaver microbial succession, stable isotopes, and forensic evidence interpretation. Sources were located through PubMed-indexed records, journal websites, and official INTERPOL, OHCHR, and NIST publications. Selection was purposive, emphasizing directly relevant primary research and authoritative guidance. Bibliographic information and accessible abstracts or source text were checked; not every publication was available for full-text assessment.

This is a narrative review, not a systematic review or meta-analysis. No exhaustive database export, duplicate screening, formal risk-of-bias instrument, or pooled effect estimate was undertaken. The cited literature should therefore be understood as an illustrative, critically selected evidence base rather than a complete inventory.

The objectives are to explain disciplinary complementarity, examine selected validation evidence, distinguish routine from emerging applications, and propose an auditable integration process. Before journal submission, the literature search should be expanded and adapted to the target journal's requirements.

Table 1: Complementary questions and interpretive limits

Investigative question	Forensic biology	Forensic anthropology	Forensic medicine	Interpretive limit
Who is represented?	Genetic comparison and kinship	Skeletal profile and specimen association	Medical comparison information	Profile compatibility alone does not establish identity.
What injury is present?	Associated biological traces	Skeletal defects and damage patterns	Injury and pathology examination	Trace association does not establish injury causation.
When did events occur?	Research microbial predictions	Preservation and contextual observations	Postmortem observations	Different methods may concern different intervals.
What caused death?	Relevant ancillary findings	Surviving skeletal injury evidence	Medical causal assessment	Identity evidence cannot substitute for causal evidence.
Which life-history leads apply?	Biomolecular and isotope results	Skeletal contextual assessment	Available medical history	Regional compatibility is not unique identification.

2.1 Human Identification: Linking Skeletal and Genetic Evidence

Anthropological profiling can guide the search for potential identities, but resemblance to a demographic profile is not equivalent to individual identification. In a validation study of DSP2, Brůžek and colleagues used pelvic measurements and probabilistic classification, retaining an indeterminate category when a specified probability threshold was not reached [3]. This illustrates an essential principle: a method should be allowed to abstain when evidence is insufficient. Sex estimation from skeletal morphology also should not be reported as a determination of gender identity. Age assessment has a different uncertainty structure. Meindl and colleagues tested pubic symphyseal aging methods in documented skeletal samples and identified systematic underestimation in existing approaches [4]. For integrated interpretation, age should be treated as an estimated range with method-specific limitations. A discrepancy between a missing person's documented age and a skeletal estimate warrants review of the method, reference sample, and observations rather than automatic rejection or adjustment of the estimate.

DNA examination can then test identity or kinship propositions. The Romanov investigation reported by Coble and colleagues combined mitochondrial DNA, autosomal short tandem repeats, and Y-chromosomal markers to support the familial assignment of remains from a second grave [5]. Importantly, the genetic results did not resolve which of two sisters was represented. This distinction demonstrates that strong family-level evidence does not necessarily answer every individual-level question.

The proposed interpretation sequence is therefore to record skeletal observations independently, evaluate a candidate identity through appropriate comparison evidence, and explicitly state which uncertainties remain. When skeletal and genetic findings conflict, specimen labels, sample association, laboratory controls, and reference information should be re-examined. A multidisciplinary conclusion should preserve the disagreement until an evidential explanation is established.

2.2 Sampling as the Critical Interface

Sampling is where disciplinary decisions become physically consequential. Pinhasi and colleagues demonstrated substantial differences in endogenous ancient DNA recovery between regions of the petrous bone [6]. Their study concerns archaeological specimens; it should not be interpreted as proof that petrous sampling is optimal in every contemporary forensic case. Nevertheless, it shows why anatomical knowledge and molecular requirements need to be considered together.

This review proposes a specimen-priority meeting before destructive sampling. The team should identify what each specimen may contribute to trauma interpretation, identification, and other examinations; document it photographically or by imaging where appropriate; and record why a particular sampling location was chosen. A sample taken through a diagnostically important defect may remove evidence that another specialist still needs. The same logic applies to fragmented and potentially commingled remains. Each item should retain a distinct identifier until association has been evaluated.

Sampling and reporting should separate an observation about one fragment from an inference about an entire individual. Reserve material and a record of specimen consumption would allow later reassessment without suggesting that repeat testing is always possible. These are proposed coordination measures, not experimentally established improvements in identification yield.

2.3 Trauma, Pathology, and Causal Interpretation

Skeletal trauma provides valuable observations but requires caution about timing. Wheatley's experimental study of deer femora found that commonly described fracture features were unreliable for distinguishing perimortem from postmortem damage in that model [7]. The animal model limits direct extrapolation to human cases, but it challenges the assumption that a single morphological feature can establish timing. For the proposed workflow, the anthropologist describes the defect, its distribution, preservation, and competing explanations before the team considers its relationship to death.

The forensic physician then evaluates the finding alongside available soft-tissue examination, medical information, and ancillary results. Where tissues have been lost, the limitation itself must remain visible in the final conclusion. An injury observation, a probable injury mechanism, and a cause-of-death opinion are distinct outputs. A fracture can be real while its timing remains uncertain; an injury may be severe without the surviving evidence proving that it caused death. Likewise, the absence of a skeletal lesion should not be converted into an exclusion of every possible fatal process.

Integrated reporting should identify the inferential step connecting an observation to a causal opinion and state when that step is unsupported. Biological evidence also requires proposition-specific interpretation. NIST's DNA mixture review distinguishes questions about genetic contributors from questions about the activities that produced the trace [8]. A DNA association should therefore not automatically be described as proof of the timing, mechanism, or criminal significance of contact. In this review's framework, such claims require their own contextual evaluation.

2.4 Postmortem Imaging as a Shared Examination Platform

Postmortem imaging can provide a common anatomical record for specialist discussion, but its capacity to determine cause of death must be evaluated separately. In a validation study of adult deaths, Roberts and colleagues compared CT and MRI findings with autopsy. Major cause-of-death discrepancies occurred in 32% of CT assessments, 43% of MRI assessments, and 30% of consensus radiology assessments [9]. These figures apply to that study population and protocol; they are not universal performance estimates for all imaging approaches. The study supports a cautious position: imaging may complement an examination strategy without being assumed to replace every component of it.

This review proposes that imaging questions be specified in advance – for example, locating a defect, documenting anatomical relationships, or selecting an area for further examination. The report should distinguish a visible structural abnormality from an opinion about its causal significance. Retaining annotated images alongside the original dataset could facilitate independent review and help explain specialist disagreements.

2.5 Postmortem Interval: Biological Change Within Environmental Context

Microbial succession is an important research connection between forensic biology and postmortem investigation. Metcalf and colleagues characterized microbial community assembly and metabolic function during mouse and human decomposition and identified reproducible decomposer networks [10].

Burcham and colleagues subsequently followed 36 human cadavers at three locations, identifying a conserved interdomain network despite environmental variation and evaluating its potential for predicting time since death [11]. Together, these studies support further investigation of microbial models rather than a claim that decomposition is governed by a universal, error-free clock.

The proposed multidisciplinary approach treats each temporal estimate as conditional on its measurement context. A microbial prediction should be accompanied by the sampling site, laboratory method, environmental information, model version, and applicability limits. Its relationship to morphological observations should be explored without assuming that all estimates measure the same interval or are statistically independent.

Repeated samples from one body present a particular design challenge for future machine-learning studies. The present review recommends separating training and evaluation data by individual and testing performance in external environments. Models should report uncertainty and identify conditions outside their validated scope. Research on local climatic settings could be especially valuable, but establishing a new regional model requires actual measured data; neither a simulated dataset nor a transferred model establishes field validity.

2.6 Isotopic Evidence and the Reconstruction of Life History

Stable isotope analysis can add geographic and dietary information when conventional comparison records are limited. Ehleringer and colleagues developed a model linking hydrogen and oxygen isotope ratios in human scalp hair with geography, drawing on drinking-water and dietary inputs [12]. Thompson and colleagues examined modern hair from China, India, Mongolia, and Pakistan, demonstrating the importance of investigating these relationships in Asian populations [13]. For integrated casework, isotopic evidence is best framed as a lead about compatible life-history or geographic scenarios rather than a person's unique identifier. A proposed use is to prioritize searches for antemortem information or suitable comparison samples while documenting competing geographic explanations. The inference should be connected to the sampled tissue, relevant reference data, and the assumptions used in the assignment. Combining such information with DNA and skeletal evidence may improve investigative targeting, but this review does not claim that a validated combined accuracy has been demonstrated.

2.7 Disaster Identification and Humanitarian Investigation

Disasters illustrate the operational need for integration. INTERPOL identifies friction-ridge examination, dental comparison, and DNA as primary identification approaches and organizes work around scene, postmortem, antemortem, and reconciliation phases [2]. Anthropology can assist examination of fragmented remains, while medicine addresses pathological questions. Identity reconciliation should remain distinct from determining how a disaster occurred or assigning legal responsibility.

Potentially unlawful deaths have an additional human-rights context. The Minnesota Protocol emphasizes effective, thorough, independent, and impartial investigation and provides guidance for examination of bodies and skeletal remains [1]. Technical conclusions must be documented sufficiently to permit scrutiny, while communication with families should respect dignity and the limits of the evidence.

The proposed framework adds a practical separation of tasks: one record tracks the identification status of each item or individual; other tracks opinions about injury and death circumstances. Linking these records permits coordination without allowing a confident identity conclusion to imply unwarranted confidence about cause or manner of death.

2.8 A Proposed Framework for Evidence Integration

The central proposal is a six-stage process: define questions, coordinate recovery, preserve and prioritize specimens, obtain specialist assessments, reconcile evidence, and report bounded conclusions. Table 2 translates these stages into reviewable outputs. This is an author-proposed synthesis and has not been prospectively validated.

At the interpretation stage, a claim-evidence record should state the proposition, supporting observations, relevant alternatives, method limitations, and whether another finding depends on the same underlying data. For example, a skeletal sex estimate used to select a missing-person candidate cannot subsequently be counted as wholly independent confirmation of that candidate without considering selection effects. Similarly, collecting more tests does not necessarily provide more independent evidence. Several outputs may be derived from the same specimen, image, or model assumption. The present review recommends an explicit dependency check before any quantitative combination. A narrative reconciliation may be preferable where dependence cannot be adequately modelled.

Specialists should initially record observations and method outputs separately, while receiving information necessary for safe and appropriate examination. A later case conference can then assess agreement and discrepancies. This arrangement is intended to make the reasoning auditable. Its actual effect on errors, turnaround time, and evidential quality should be tested rather than assumed. An unresolved result is a legitimate outcome. A useful report may establish identity while leaving cause of death undetermined, or describe trauma while retaining uncertainty about timing. The objective is to communicate the strongest conclusion the evidence supports, alongside the questions it cannot resolve.

Table 2: Proposed workflow and auditable outputs

Stages	Proposed action	Reviewable output
1. Define questions	Separate identity, timing, injury, and causation propositions.	Written question list with alternatives.
2. Coordinate recovery	Coordinate item numbering and contextual documentation.	Item-specific recovery record.
3. Preserve and prioritize	Agree examination order before specimen consumption.	Sampling rationale and specimen-consumption log.
4. Specialist assessment	Record observations, outputs, and limitations separately.	Discipline-specific provisional reports.
5. Reconcile evidence	Review contradictions and shared data dependencies.	Claim–evidence record and discrepancy decisions.
6. Report conclusions	State separate conclusions and unresolved questions.	Bounded multidisciplinary report.

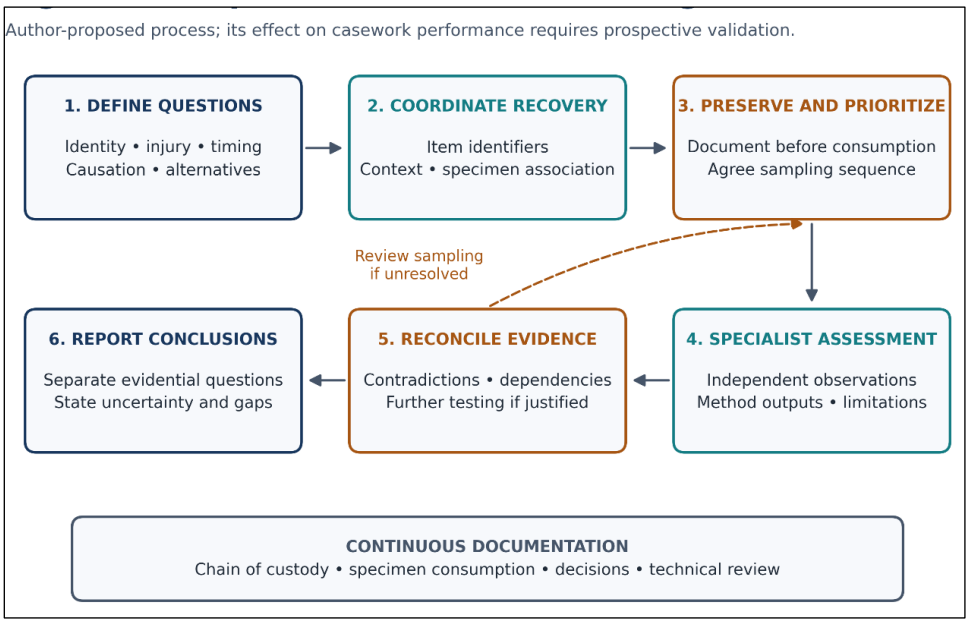


Figure 2: Proposed co-ordinated investigation workflow

Figure legend: The proposed workflow connects investigative questions, recovery, specimen preservation, specialist assessment, evidence reconciliation, and reporting. Unresolved discrepancies may require reconsideration of sampling or examination. Documentation continues throughout. The workflow requires prospective validation.

2.9 Scientific Limitations and Emerging Technologies

Three limitations constrain the proposed synthesis. First, the targeted literature selection may omit relevant studies and gives no quantitative estimate of overall performance. Second, the cited studies address different specimens, populations, and outcomes, so their findings cannot be pooled into a single accuracy measure. Third, proposed organizational improvements are plausible recommendations rather than validated interventions.

AI should be evaluated according to the task it performs. The microbial studies show one research application of predictive modelling [11]; they do not validate autonomous conclusions about identity, injuries, or manner of death. Future systems should be tested against defined reference outcomes and should retain an indeterminate output when evidence lies outside their scope. This review recommends prospective comparisons between assisted and unassisted examination rather than assuming that automation improves decisions.

The limits of one method also should not be obscured by placing it beside stronger methods. NIST's scientific foundation review found insufficient support for accurate bitemark source attribution, including exclusion or non-exclusion of

individuals [14]. This limitation should remain separate from the recognized role of dental comparison in identification [2].

Recovering biological material from a suspected injury and attributing that injury from its pattern are different evidential questions; combining them does not repair an unsupported inference. Other proposed safeguards include external validation across relevant populations, preservation of original observations, and explicit handling of contradictory results. Publication quality should be judged by transparent reasoning and reproducibility rather than by the number of technologies included.

Table 3: Selected evidence: implications and limits

Sources	Evidence or setting	Contribution	Key limitation
Brůžek et al. [3]	Pelvic metric validation	Probabilistic sex estimation	Applicability and indeterminate cases must be retained.
Pinhasi et al. [6]	Ancient petrous-bone samples	Anatomical variation in DNA recovery	Not universal forensic sampling validation.
Wheatley [7]	Experimental deer femora	Challenges fracture-timing assumptions	Animal model; limited direct human extrapolation.
Roberts et al. [9]	Adult imaging–autopsy comparison	Tests imaging for cause-of-death assessment	Results depend on population and protocol.
Burcham et al. [11]	Thirty-six cadavers at three sites	Microbial decomposition modelling	Requires evaluation in additional casework settings.
Ehleringer et al. [12]; Thompson et al. [13]	Human hair isotope studies	Geographic and dietary leads	Reference assumptions and regional transfer matter.
Sauerwein et al. [14]	NIST foundation review	Defines bitemark attribution limitations	Does not negate dental-record identification.

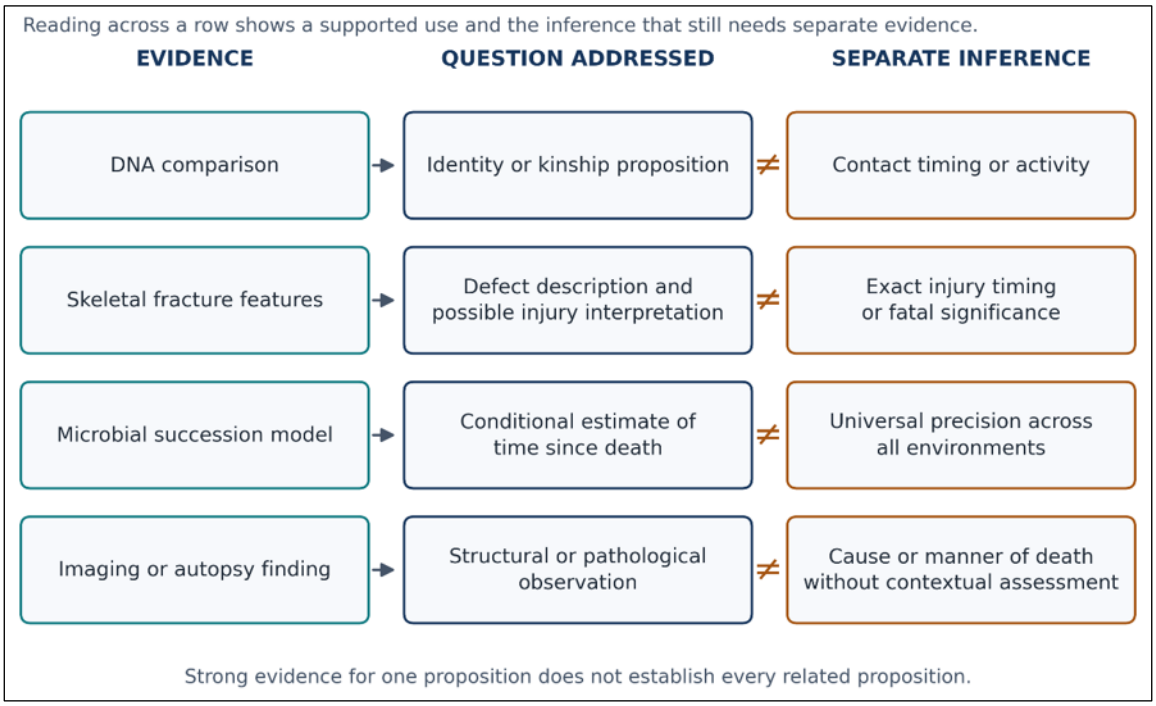


Figure 3: Evidence must remain tied to its question

Figure legend: Each row connects an evidence type with the question it can address and a related inference requiring separate support. The "≠" symbol means that support for the middle proposition does not automatically establish the proposition on the right. It does not indicate that the evidence can never contribute to that additional assessment.

2.10 Future Research Priorities

Future research should test integration directly. Prospective studies could compare coordinated and conventional workflows using predefined outcomes such as specimen consumption, association errors, unresolved discrepancies, turnaround time, and the quality of uncertainty reporting. Independent assessment and a clear reference standard would be needed to interpret any apparent improvement.

Regional validation is another priority. Indian research programs could examine the applicability of skeletal reference methods, isotopic assignments, and decomposition models across relevant environments and populations. Such work should avoid treating linguistic, cultural, or administrative categories as biologically uniform groups. Sampling plans and model assumptions must be justified for the actual research question.

Finally, future publications should report how findings were combined. A strong identification or death-investigation study should expose the reasoning between its observations and conclusions, including specimen associations, alternatives considered, and unresolved issues. Shared reporting templates may support this aim, but their usability and effect on examiner decisions should also be evaluated.

3 CONCLUSION

Forensic biology, anthropology, and medicine contribute different but complementary evidence to human identification and death investigation. Their most productive connection lies in a coordinated interpretation of biological material, skeletal observations, and pathological findings. Integration should begin before destructive sampling and continue through specialist assessment and reconciliation. The essential safeguard is to keep each conclusion tied to the question its evidence can answer. Identity, injury timing, postmortem interval, and cause of death should not acquire equal certainty merely because they appear in the same report. The proposed framework emphasizes evidence preservation, question-specific interpretation, explicit dependence, and transparent uncertainty. Its value now lies in providing a testable organizational model; future prospective research must establish whether it improves casework. Scientifically defensible collaboration depends on recognizing both the contributions and the limits of each discipline.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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