

Review

Imaging and Artificial Intelligence in Forensic Reconstruction and PMI/PMSI Estimation of Human Remains in Terrestrial and Aquatic Contexts

Alessia Leggio ^{1,2,*} , Ricardo Ortega-Ruiz ³  and Giulia Iacobellis ⁴ 

¹ Forensic Sciences Unit of “Malta Life Sciences Park (MLSP)”, European Forensic Institute, 3000 San Gwann, Malta

² Legal Medicine Unit, Department of Interdisciplinary Medicine, University of Bari “Aldo Moro”, 70121 Bari, Italy

³ Faculty of Criminology, Universidad Internacional Isabel I, 09003 Burgos, Spain; ricardo.ortega@ui1.es

⁴ Radiology Unit, Department of Clinical and Experimental Medicine, University of Foggia, 71122 Foggia, Italy; giulia.iacobellis@unifg.it

* Correspondence: a.leggio@eufor.eu

Abstract

The application of advanced imaging techniques, particularly computed tomography (CT), photogrammetric scanning, and three-dimensional reconstructions of body surfaces and skeletal remains, is becoming a crucial component of Forensic Anthropology. These tools enable a non-invasive and highly standardized analysis of both intact cadavers and human remains recovered from terrestrial or aquatic environments, providing reliable support in identification processes, traumatological reconstruction, and the assessment of taphonomic processes. In the context of estimating the Post-Mortem Interval (PMI) and the Post-Mortem Submersion Interval (PMSI), digital imaging allows for the objective and reproducible documentation of morphological changes associated with decomposition, saponification, skeletonization, and taphonomic patterns specific to the recovery environment. Specifically, CT enables the precise assessment of gas accumulation, transformations in residual soft tissues, and structural bone modifications, while photogrammetry and 3D reconstructions facilitate the longitudinal monitoring of transformative processes in both terrestrial and underwater contexts. These observations enhance the reliability of PMI/PMSI estimates through integrated models that combine morphometric, taphonomic, and environmental data. Beyond PMI/PMSI estimation, imaging techniques play a central role in anthropological bioprofiling, facilitating the estimation of age, sex, and stature, the analysis of dental characteristics, and the evaluation of antemortem or perimortem trauma, including damage caused by terrestrial or fauna. Three-dimensional documentation also provides a permanent, shareable archive suitable for comparative analyses, ensuring transparency and reproducibility in investigations. Although not a complete substitute for traditional autopsy or anthropological examination, imaging serves as an essential complement, particularly in cases where the integrity of remains must be preserved or where environmental conditions hinder the direct handling of osteological material. Future directions include the development of AI-based predictive models for PMI/PMSI estimation using automated analysis of post-mortem changes, greater standardization of imaging protocols for aquatic remains, and the use of digital sensors and multimodal techniques to characterize microstructural alterations not detectable by the naked eye. The integration of high-resolution imaging and advanced analytical algorithms promises to further enhance the reconstructive accuracy and interpretative capacity of Forensic Anthropology.



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1. Introduction

Forensic Anthropology involves the analysis of human remains to reconstruct identity, ante-, peri- and post-mortem events, and taphonomic modifications related to the depositional environment. In recent decades, the development of digital imaging techniques has revolutionized this field, providing non-invasive tools capable of documenting intact cadavers and skeletal remains from both terrestrial and aquatic contexts in an objective, standardized, and reproducible manner [1–5]. The integration of computed tomography (CT), photogrammetry, and three-dimensional reconstructions of body surfaces and osseous structures has enabled a detailed analysis of anatomical features and taphonomic processes without the need for physical manipulation of the remains.

These methodologies are particularly valuable for estimating the post-mortem interval (PMI) and the post-mortem submersion interval (PMSI), one of the most complex challenges in forensic investigations (Figure 1). Advanced imaging facilitates the monitoring and quantification of transformations in residual soft tissues, the accumulation and distribution of decomposition gases, osseous alterations, and degradation patterns influenced by the environmental context. For remains recovered from terrestrial environments, CT and 3D reconstructions allow for the observation of skeletal progression, modifications induced by scavenging fauna, and interactions with the soil. In aquatic environments, imaging aids in identifying specific characteristics of aquatic decomposition, such as skin slippage, alterations to adipose tissues, saponification phenomena, and damage caused by aquatic macro- and microfauna.



Figure 1. (A) Terrestrial decomposition within the context of Post-Mortem Interval (PMI) estimation. (B) Marine decomposition within the context of Post-Mortem Submersion Interval (PMSI) estimation.

Computed tomography (CT) and three-dimensional reconstructions represent advanced methodologies for taphonomic analysis in forensic anthropology, enabling non-invasive and detailed documentation of decomposition processes in both terrestrial and aquatic environments [6–10].

In terrestrial contexts, this technology enables the objective monitoring of progressive decomposition stages, quantifying soft tissue loss, the distribution of decomposition gases,

and the emergence of post-mortem fractures. It is fundamental for identifying alteration patterns left by scavenging fauna, such as characteristic bone erosion from insects or the sharp margins from rodent gnawing, accurately distinguishing them from antemortem trauma. Furthermore, it documents soil interaction, revealing sediment infiltration, compression imprints, and mummification processes. In aquatic environments, CT imaging elucidates the unique trajectories of decomposition, visualizing phenomena such as skin slippage and characteristic tissue transformations, including saponification and adipocere formation. Three-dimensional (3D) analysis facilitates the identification of bone alterations caused by aquatic fauna, distinguishing abrasions and biodegradation processes that are often indistinguishable from traumatic lesions through two-dimensional examination alone. Furthermore, this analytical approach enables the detailed magnification, refinement, and precise characterization of any osseous modification. The technology also allows for the detection of sediment distribution within bodily cavities and the presence of endocavitary gases, providing critical indices for immersion dynamics [11–16].

Beyond enhancing PMI/PMSI estimation, imaging techniques significantly contribute to bioprofiling and forensic reconstruction: they facilitate the estimation of age, sex, and stature; dental identification; the detection of antemortem or perimortem trauma; and the taphonomic documentation of post-mortem alterations. The digital nature of the data also allows for the preservation of a permanent archive, shareable across laboratories and valuable for comparative analyses, thereby promoting standardization, transparency, and reproducibility.

Future perspectives are oriented toward increasing integration between advanced imaging, predictive modelling, and artificial intelligence [17–19]. The automated analysis of morphological and taphonomic transformations will contribute to the development of algorithms capable of estimating PMI with greater precision across a wide range of environmental conditions, including particularly complex ones such as deep aquatic contexts or climates with high variability. Concurrently, improving the resolution of 3D techniques and adopting internationally standardized protocols will help consolidate digital imaging as an indispensable tool in contemporary Forensic Anthropology. In this evolution, imaging does not merely represent technological support, but a true investigative paradigm that is re-defining the way human remains are analysed and post-mortem processes are understood, substantially improving the accuracy and reliability of forensic reconstruction [20–25].

2. Materials and Methods

To conduct this narrative review and critically evaluate and synthesize the diagnostic potential of imaging in Forensic Anthropology, specifically assessing the extent to which advanced imaging techniques can contribute to a reliable estimation of the Post-Mortem Interval (PMI) across different recovery contexts, with particular focus on distinguishing between terrestrial and aquatic environments, an extensive literature search was performed. This comprehensive literature search was conducted across major biomedical and forensic databases, including PubMed/MEDLINE, Scopus, Web of Science, Embase, and Google Scholar.

This exploratory search employed key terms such as “Forensic Anthropology,” “post-mortem interval (PMI),” “forensic imaging,” “post-mortem computed tomography (CT),” “photogrammetry,” “taphonomy,” and “3D reconstruction.” The review focuses on original research, reviews, and case studies that demonstrate the methodological application of post-mortem imaging to human remains and its relevance for PMI estimation in both terrestrial and aquatic settings, prioritizing contributions with robust quantitative and methodological foundations. Only peer-reviewed articles within the forensic field were considered. Drawing upon this body of literature, this review aims to discuss and integrate

the findings concerning sample characteristics and the imaging methodologies employed, specifically post-mortem computed tomography (CT), 3D photogrammetry, and three-dimensional (3D) reconstruction techniques, in order to provide a critical and updated overview of the current state of the art.

3. Taphonomy of Human Remains in Terrestrial Environments and PMI Estimation

The estimation of the post-mortem interval (PMI) is one of the most complex and fundamental challenges in forensic investigations involving human remains recovered from terrestrial environments. Within this framework, taphonomy transcends its descriptive role to become a crucial interpretive science, providing the tools necessary to decipher the timeline connecting the time of death to the discovery [26–28]. Numerous taphonomic events (such as scavenging, post-mortem movement, or sudden environmental alterations) are intrinsically stochastic in nature, thanatochronology focuses on the study of specific biological and chemical processes (e.g., tissue decomposition, the succession of necrophagous insects) which, under a given set of conditions, can exhibit measurable temporal sequences, thus offering a potential “biological clock” for PMI estimation. Classical methods based on body cooling or livor mortis become obsolete within days, giving way to the analysis of decomposition and skeletonization phenomena. Here, forensic entomology is paramount among applied taphonomic sciences: the ecological succession of necrophagous arthropods (from calliphorid dipterans to dermestid beetles) and their developmental stages (eggs, larvae, pupae, adults) provide an exceptionally precise temporal indicator for PMIs ranging from a few hours to days and weeks. However, this succession is itself a taphonomic process, profoundly conditioned by both biotic (e.g., interspecific competition, predation) and abiotic factors. Assessing the decompositional stage (fresh, bloat, active decay, advanced decay, skeletonization) yields a coarse PMI estimate but must be calibrated against critical environmental parameters such as temperature, humidity, soil pH, and sun exposure, which can dramatically accelerate or decelerate the rate of degradation [29–31].

For longer intervals (months, years, decades), the study of skeletal alterations becomes predominant. The interpretation of observable bone alterations requires careful scrutiny to distinguish among: (a) post-mortem taphonomic and diagenetic processes (e.g., biochemical degradation, weathering, scavenging marks); (b) pathological conditions or antemortem modifications; and (c) perimortem trauma. While the former provide contextual data on the post-depositional history of the remains, the accurate identification of perimortem trauma, understood as mechanical damage to the bone occurring temporally close to the time of death, is a primary diagnostic objective for reconstructing the circumstances of death. Therefore, an accurate terrestrial PMI estimate is contingent upon a holistic taphonomic analysis. This approach integrates entomological, botanical (e.g., vegetation growth around the body), chemical (e.g., the release of decomposition fluids into the soil), and anthropological data, modelling them according to the specific micro-environmental conditions of the recovery site (Figure 2). In this way, taphonomy transforms the body from static evidence into a dynamic system, enabling the reconstruction not only of the “when,” but also of the “how” and the “where” of post-mortem events [32–36].

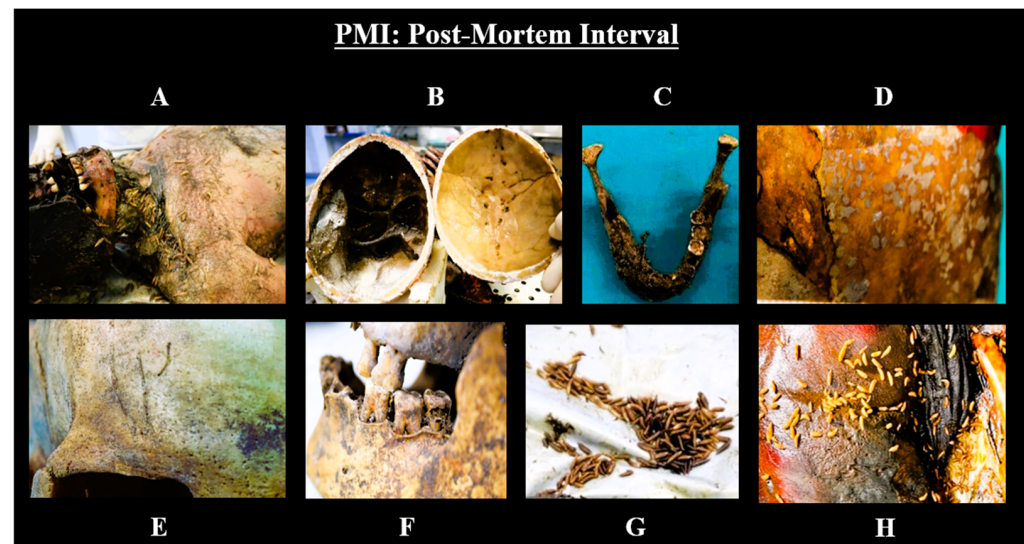


Figure 2. Examples of Terrestrial Taphonomy. Panel (A) depicts advanced decomposition with the presence of entomofauna. Panel (B) shows brain remains completely decomposed in a terrestrial environment. Panel (C) illustrates a mandible deteriorated by muddy terrain and debris. Panel (D) demonstrates the presence of fungi and lichens on the bone cortex of a skull. Panel (E) exhibits root etching on a cranial frontal bone. Panel (F) provides a detailed view of dental deterioration with altered pigmentation and embedded roots. Panel (G) displays a larval mass originating from advanced decomposition. Panel (H) presents larval contamination during the colliquative phase.

4. Taphonomy of Human Remains in Aquatic Environments and PMSI Estimation

The estimation of the post-mortem interval (PMI) for human remains recovered from aquatic environments represents one of the most complex frontiers in forensic taphonomy, where standard terrestrial parameters must be entirely recalibrated to adapt to a dynamic, dense medium governed by unique ecological rules. In this context, the very concept of PMI often bifurcates into “submersion time” (Post-Mortem Submersion Interval-PMSI) and “total PMI,” the latter encompassing the potential time spent on land prior to entering the water [37–39]. Aquatic taphonomic processes become the primary temporal indicators, yet their progression is significantly dictated by a critical triad of factors: water temperature, salinity, and movement. Decomposition typically proceeds more slowly and follows a different sequence compared to terrestrial settings, due to generally lower temperatures and the anaerobic conditions that inhibit the action of many bacteria and most necrophagous insects. Forensic entomology is supplanted by aquatic “necrof fauna”: crustaceans (amphipods, isopods, crabs) and fish produce distinct scavenging patterns whose characteristics, from initial lesions to complete defleshing, can provide coarse estimates of the PMSI (Figure 3). A crucial biological clock is the phenomenon of “flotation and sinking,” governed by the production and subsequent dispersion of putrefactive gases. A submerged body will only resurface when gas accumulation exceeds its density, an event whose timing is strongly dependent on water temperature [40–43].

The formation of adipocere, a saponified transformation of adipose tissue promoted by anaerobic and humid conditions, also follows a predictable kinetic pathway, typically initiating after several weeks and stabilizing over months, thereby providing a temporal window for medium- to long-term PMSI estimation. However, the mechanical action of currents, waves, and friction against the substrate can accelerate skeletonization through abrasive processes, confounding estimates based solely on biological decomposition. The principal challenge lies in the enormous environmental variability: a body in a cold, deep alpine lake may exhibit minimal signs of decomposition after months, whereas the same body in a shallow tropical river could skeletonize within weeks. Consequently, a

reliable PMSI estimate requires an integrated taphonomic model that accounts for the local biocenosis, hydrological data (currents, tides), and the physicochemical conditions of the water. This approach transforms each discovery into a complex natural experiment, the chronology of which must be deciphered [44–46].

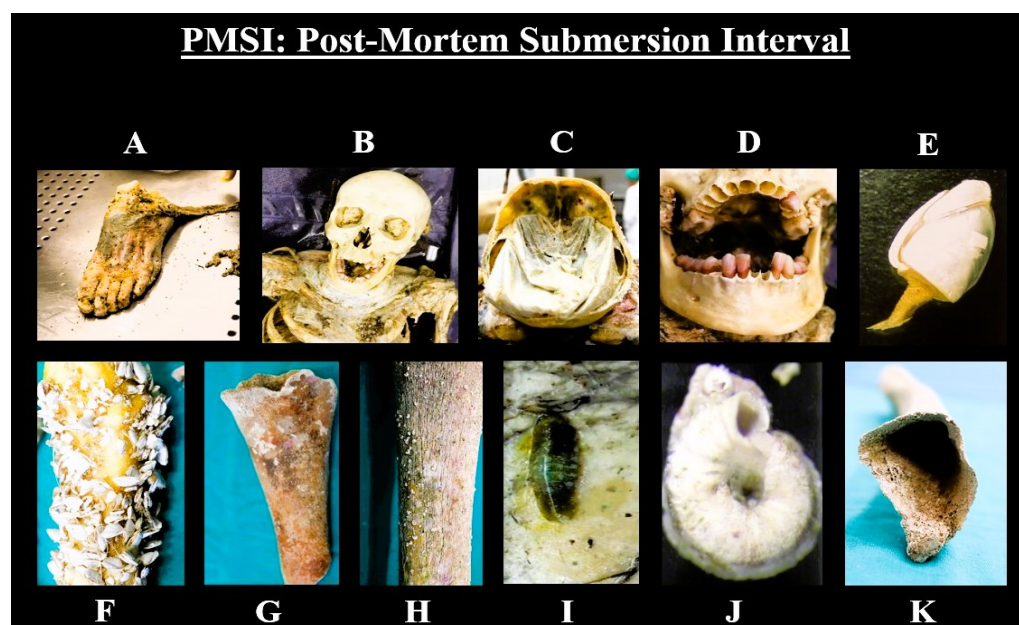


Figure 3. Examples of taphonomy in a marine environment: (A), saponification and disarticulation of a foot recovered from a marine environment; (B), skeletonisation of a missing person found at sea; (C), brain decomposition in a marine environment; (D), the “pink teeth phenomenon”, a documented but uncommon finding, indicative of drowning; (E), enlargement of marine barnacles; (F), distal epiphysis covered with marine barnacles; (G), alteration of cortical pigmentation in a marine environment; (H), femoral oxycortical filled with calcified shells of *Serpula spirobis*; (I), *Talitrus saltator* is a marine crustacean of the order Amphipoda; (J), Close-up view of *Serpula spirobis*; (K), Abrasive action of marine sediments and sand transported by wave motion or currents in a coastal marine environment.

5. The Role of Imaging in Taphonomic Analysis and PMI Estimation of Human Remains Recovered from Terrestrial Environments

Taphonomic analysis of remains recovered from terrestrial contexts is significantly enhanced by non-invasive imaging techniques, particularly computed tomography (CT) and three-dimensional reconstructions (photogrammetry/3D modelling). These tools enable the high-resolution documentation of decomposition and skeletonization progression, facilitating objective measurements of residual soft tissue volume, the presence and distribution of endocavitary gases, the localization of microfractures, and the mapping of areas of tissue loss [47–52]. Such digital metrics improve comparability across cases and enable the construction of datasets for PMI estimation models.

Imaging further aids in distinguishing antemortem or perimortem traumatic injuries from post-mortem alterations induced by scavengers or environmental agents. Bite patterns, bone erosion margins, perforations, and gnawing marks exhibit recurring morphological characteristics that CT and 3D reconstructions can catalogue without altering the remains, thereby promoting a more accurate interpretation of lesion causation and dynamics. The systematic study of damage produced by vertebrates and invertebrates provides important discriminative elements for taphonomic reconstruction [53–56]. The interaction between the cadaver and the soil represents another key factor: imaging documents sediment penetration into anatomical cavities, the formation of mineral concretions, superficial

mummification effects, or the presence of roots causing disarticulation. Experimental studies have demonstrated that soil properties (grain composition, pH, organic content) influence the rate of degradation and the likelihood of preservation product formation, such as adipocere, elements which must be integrated into PMI models. Regarding semi-quantitative indicators useful for PMI estimation, the literature proposes various parameters obtainable from CT and 3D scans, as also indicated in Table 1: (1) residual soft tissue volume; (2) radiological density and variation in adipose tissue density (potentially correlated with saponification/adipocere phases); (3) quantity and distribution of endocavitary gas; (4) degree of skeletal disarticulation and fragmentation. Integrating these indicators with environmental data (temperature, humidity, solar exposure, and local scavenger activity) increases the robustness of predictive PMI models, particularly when supported by regional databases and statistical or machine learning approaches.

Finally, CT and 3D documentation enable longitudinal study (repeated scans on the same specimen within experimental settings) and facilitate comparison with forensic casework. This approach promotes the validation of decomposition timelines and the standardization of acquisition protocols. It is particularly valuable in archaeological excavations or recovery operations in rural or urban contexts, where physical manipulation of remains may compromise taphonomic evidence. The development of georeferenced datasets and integrated models combining imaging, microbiome analysis, and environmental parameters represents the most promising direction for achieving more reliable and reproducible PMI estimations [57–62].

Table 1. CT/3D Indicators, Taphonomic Interpretation, and Utility for Terrestrial Environment PMI.

Indicator (CT/3D/Photogrammetry)	Technical Description	Taphonomic Interpretation	Use for PMI
Gas accumulation in body cavities (PMCT)	Gas in cavities and soft tissues [51]	Bacterial proliferation, active stage of decomposition [49,51]	Quantitative marker for early PMI stages [51,57]
Residual soft tissue volume (3D CT)	Volumetric segmentation of tissues [47,50]	Progressive autolysis and putrefaction [47,50]	Placement in intermediate-advanced PMI [50,57]
Radiological density of fat/saponification	Typical attenuation of adipocere [48]	Formation of adipocere in humid/anaerobic environments [48]	Indicates medium-long PMI and specific soil conditions [48]
Pattern of skin/tissue loss (3D)	Detail of areas of tissue removal [47,59]	Necrophagous activity: insects, rodents, carnivores [47,53]	Chronology of necrophagous activity, useful for relative PMI [53,57]
Non-traumatic post-mortem fractures (HR CT)	Fracture surfaces from desiccation or pressure [47,50]	Advanced desiccation or soil compression [47,56]	Indicator of long PMI [47,50]
Sediment infiltration in cavities (CT)	Presence of soil in sinuses, orbits, cavities [47,56]	Soil interactions; displacement, burial [47,56]	Helps reconstruct context and duration of deposition [56]
Roots traversing or adhering to remains (macro 3D)	Precise identification of root perforations [47,56]	Prolonged presence in vegetated substrates [47,56]	Strong marker for very prolonged PMI [47,56]
Articular disarticulation (skeletal CT)	Observation of joint connections [47,50]	Canonical progression of decomposition, predation [47,53]	Useful for late PMI in temperate climates [47,50]

Table 1. *Cont.*

Indicator (CT/3D/Photogrammetry)	Technical Description	Taphonomic Interpretation	Use for PMI
Distribution of mummified tissue masses (CT/photogrammetry)	Identification of desiccated tissues [47,50]	Arid and ventilated environment; slowed decomposition [47,50]	Indicates medium-long PMI and dry microclimate [50,57]
Bone microstructural modifications (HR CT)	Cortical erosion, vacuolization [47,53]	Roots, osteophagous insects, acidic soil [47,53,56]	Marker for very advanced PMI [47,53]

6. The Role of Imaging in Taphonomic Analysis and PMSI Estimation of Human Remains Recovered from Aquatic Environments

The application of imaging, specifically post-mortem computed tomography (PMCT), along with micro-CT, photogrammetry, and 3D reconstructions, provides essential non-invasive tools for analysing the taphonomic processes of remains recovered from aquatic environments and for refining the estimation of the PMI/PMSI. PMCT enables the detection and quantification of phenomena distinctive to aquatic decomposition, such as skin slippage (“washer-woman changes”), the presence and distribution of adipocere/saponification in adipose tissues, the localization of endocavitary gases, and the identification of sediments trapped within body cavities. These elements help reconstruct the temporal sequence of decomposition and the conditions of submersion. As summarized in Table 2, radiological imaging is particularly useful for discriminating between post-mortem damage caused by aquatic fauna (erosions, irregular perforations, tissue loss) and antemortem traumatic lesions.

It also facilitates the assessment of the depth and morphology of bone alterations resulting from predation or sediment abrasion, information that is critical for avoiding interpretative errors in PMI estimates [63–66]. The evaluation of adipocere formation through radiological and forensic chemical analysis (e.g., GC-MS on selected samples) provides markers of tissue preservation that can indicate periods of prolonged submersion and anaerobic or cold environmental conditions favourable to saponification. However, the temporal variability in adipocere formation necessitates integration with contextual data on salinity, temperature, depth, and the protective effects of clothing.

The integration of imaging, environmental data, and anthropological information is further strengthened by the development of statistical and computational models, including artificial intelligence-based systems, capable of correlating decomposition patterns with variables such as water type, temperature, salinity, depth, currents, body mass, clothing, and the presence of alterations [67–73]. This multidisciplinary approach currently represents the most effective strategy for improving the precision and reliability of PMI/PMSI estimation for remains recovered from water. Despite this progress, significant challenges persist. The considerable environmental variability, including diverse water compositions, thermal fluctuations, hydrodynamic dynamics, sediment characteristics, and aquatic fauna activity, hinders the development of generalizable taphonomic models. A lack of controlled long-term experimental studies on submerged human cadavers, particularly in deep-water environments, limits the ability to calibrate reliable temporal intervals.

Table 2. Semi-quantitative imaging indicators (PMCT/3D) for remains recovered from aquatic environments.

Imaging Indicator (CT/3D)	Taphonomic Description in Aquatic Environment	Potential Relationship with PMI/PMSI	Limitations and Need for Integration
Skin slippage and maceration (“washer-woman changes”)	PMCT visualization of epidermal detachment, fluid accumulation between skin layers, and tissue distension [63,64].	May indicate submersion from days to weeks, with timing highly variable based on water temperature [65,66].	High variability: cold temperatures, wave action, depth, and clothing alter the timeline [74,75].
Adipocere quantification and radiodensity	PMCT enables the identification of lipid saponification zones and analysis of Hounsfield Unit (HU) density in adipose tissue [66,67,71].	Increased adipocere presence suggests prolonged submersion (weeks–months) under anaerobic/cold conditions [68,72].	Adipocere formation is irregular; requires confirmation via forensic chemical analysis (e.g., GC-MS) [73,76].
Distribution and volume of endocavitary gas	Three-dimensional identification and volumetric segmentation of gas in the thorax, abdomen, and soft tissues [68,69].	In cold water, gas production may be delayed, useful for environment-specific temporal models [70,72].	Gas can escape early through wounds, scavenger activity, or aquatic fauna, risking underestimation [63,74,77].
Sediment and aquatic material in cavities	PMCT highlights sand, silt, debris, and microlife trapped in airways, sinuses, and body cavities [65,66,75].	Can suggest body dynamics (flotation, dragging, deep submersion), aiding event chronology reconstruction rather than providing a direct PMI [69,71].	Limited standalone temporal value; useful only in combination with other indicators [70,72,73].
Degree of soft tissue loss and alterations from aquatic fauna	Imaging aids in distinguishing post-mortem erosion from aquatic scavenging/predation from vital trauma [63,67].	Predation patterns (fish, crustaceans) follow relatively known sequences, usable for coarse estimates (days–weeks) [66,72].	High variability based on species, depth, and season necessitates local ecological analysis [71,74,75].
Skeletal fragmentation and disarticulation	3D reconstructions allow assessment of the degree of skeletal disarticulation and bone abrasion [64,65].	Greater disarticulation may correlate with prolonged submersion and/or high hydrodynamic energy [67,68].	Process is heavily dependent on currents and fauna; a non-linear indicator of PMI [73,76,77].
Integrated morphometric models (soft tissue volume, adipose density, gas, fragmentation)	Combined 3D CT datasets with machine learning for multivariate correlations [70,72,74].	Enable more robust PMI estimates than single indicators; particularly useful in cold-water contexts [66,71,75].	Require regional databases and detailed environmental parameters (temperature, salinity, currents) [67,69,76].

The simultaneous overlapping of phenomena such as adipocere formation, predation, abrasion, body movement, and substrate interactions complicates the chronological reconstruction of post-mortem processes. Finally, the rapid degradation of DNA and soft tissues in aquatic environments can compromise genetic analyses and hinder identification efforts. In light of these complexities, it is essential that investigations follow standardized and shared protocols, systematically integrating anthropological, radiological, taphonomic, ecological, and environmental data. Each case must be considered in its specificity to allow imaging to fully realize its potential in the forensic context.

These multimodal approaches enhance the robustness of estimations compared to traditional methods relying solely on macroscopic observation [74–80]. Finally, imaging enables permanent digital documentation, which is fundamental for inter-laboratory comparisons, the validation of taphonomic scales, and judicial proceedings. It also supports the necessity for standardized protocols for the recovery, acquisition, and interpretation of submerged remains, especially in complex scenarios such as shipwrecks, maritime migration incidents, or deep-water recoveries.

7. AI and ML–Methodological Evolution for Determining Reliable PMI or PMSI

The introduction of AI and ML into forensic practice represents a significant methodological evolution for forensic anthropology and taphonomy, as it enables the systematic, objective, and reproducible management and analysis of large datasets derived from imaging (CT, micro-CT, 3D scans, photogrammetry).

These algorithmic tools automate the extraction of complex parameters, such as tissue density, residual soft matter volume, gas or sediment distribution, and the degree of skeletal disarticulation, thereby reducing operator subjectivity and minimizing errors associated with manual or visual estimation [81,82].

Furthermore, leveraging structured databases that integrate environmental characteristics (soil or water type, temperature, humidity, salinity, currents, fauna, preservation state) with radiological and morphometric data, ML models can correlate decomposition patterns and taphonomic transformations with the time elapsed since death. This offers more robust and quantifiable PMI/PMSI estimates with a measurable degree of confidence [83–88]. This multidisciplinary, data-driven approach, illustrated in Table 3, also presents significant practical advantages: the creation of permanent, shareable digital archives among forensic centres, the ability to re-evaluate cases over time using new algorithms, enhanced inter-laboratory comparison, and a high degree of procedural standardization.

Table 3. Comparative overview: Imaging, taphonomic parameters, and the contribution of AI/ML in terrestrial versus aquatic environments.

Category	Terrestrial Environment	Aquatic Environment	Utility of Imaging	Advantages of AI/ML	AI/ML and Methodological Limitations
Primary Imaging Techniques	CT, micro-CT, digital X-ray, photogrammetry, laser scanning [89–94]	CT, micro-CT, underwater photogrammetry, 3D sonar, acoustic imaging [94–97]	Non-invasive documentation, internal decomposition assessment, volumetric measurements [89–91]	Automated segmentation, feature extraction, pattern recognition, PMI/PMSI prediction [98–101]	Limited datasets, environmental variability, imaging artifacts, opacity of complex models [100–103]
Analyzable Taphonomic Parameters	Gas volume, desiccation, insect activity, mineralization, exposure fractures [91,104]	Intracavitary sediments, aquatic fauna, bioerosion, disarticulation, tissue loss [94,105–107]	Objective quantification of taphonomic parameters, standardized measurements [89,92]	Temporal analysis, correlation with environmental data, automatic recognition of decomposition stages [99–101]	Requirement for complete environmental metadata, difficulty in generalizing cross-habitat models [103,108]
Key Environmental Differences	Decomposition influenced by temperature, humidity, insects; potential mummification [104,109]	Initially accelerated, then slowed decomposition; strong influence of currents and salinity; greater disarticulation [105–107,110]	Highlights distinctive environmental patterns and facilitates the differentiation of taphonomic processes [90,92]	Models adaptable to specific habitats, automatic correction for environmental variables [98,100]	Risk of overfitting, lack of diverse longitudinal datasets [108,111]
Utility for PMI/PMSI	Residual tissue density, endocavitary gas, putrefaction levels, entomological data [104,109]	Sediment analysis, aquatic fauna, tissue loss, degree of disarticulation, adipocere residues [105,106,110]	Improves estimation precision and inter-laboratory comparability [81–89]	Multimodal PMI/PMSI models (imaging + environment + morphometrics); enhanced reproducibility [98–101]	Need for legal validation, sensitivity to local conditions (fresh/salt water, varied terrain) [102,103,111]

Furthermore, the use of ML/AI in PMI estimation enables the integration of variables that extend beyond simple macroscopic observation, for instance by combining demographic, biomechanical, environmental, and taphonomic data. This renders the interpretation more nuanced and adaptable to real-world contexts, such as specific terrain, water types, climate, and fauna.

However, significant limitations and challenges persist. Firstly, the efficacy of ML models is highly dependent on the quality, quantity, and representativeness of the input data: datasets that are too small, selectively sampled, or unrepresentative risk producing overfitted models with poor generalizability. Additionally, the “black box” nature of certain models, particularly neural networks, referring to the difficulty in transparently

interpreting the reasoning behind their decisions, can pose a substantial obstacle if not accompanied by robust validation standards, interpretability measures, and critical review.

Finally, the significant variability across environmental factors (e.g., climate, salinity, fauna, terrestrial or aquatic conditions) necessitates a case-specific analysis; generic models risk overestimating the universality of certain correlations [112–116].

In conclusion, the adoption of AI and ML for the collection and analysis of data from human remains, when coupled with advanced imaging techniques and an integrated forensic approach, represents one of the most promising pathways toward achieving more accurate, objective, and standardized PMI/PMSI estimations. Nevertheless, this advancement requires robust datasets, shared protocols, and a conscientious management of its inherent methodological limitations.

8. Discussion

The estimation of the Post-Mortem Interval (PMI) and, in aquatic contexts, the Post-Mortem Submersion Interval (PMSI), remains one of the most complex and debated challenges in anthropology and forensic sciences. This is because the taphonomic processes influencing decomposition are highly dynamic, depending on a multiplicity of interacting biotic and abiotic factors that produce significant variability across different recovery scenarios. In both terrestrial and aquatic environments, human decomposition follows non-linear pathways, comprising combinations of physiological, chemical, physical-mechanical, and ecological events that complicate the creation of universally applicable temporal models [117–119].

Within this framework of complexity, imaging has assumed a crucial role in improving the understanding of taphonomic processes and providing more robust, quantitative indicators for PMI/PMSI estimation.

Techniques such as PMCT, micro-CT, photogrammetry, and 3D modeling enable the objective, non-invasive, and reproducible observation and measurement of internal and superficial alterations. For remains recovered from terrestrial environments, imaging allows for the documentation of internal decomposition progression, the distribution of putrefactive gases, soft tissue loss, joint integrity, and skeletal modifications due to desiccation, solar radiation, entomological activity, and soil interaction. In aquatic environments, imaging permits the identification and quantification of phenomena peculiar to underwater decomposition, such as skin slippage, bioerosion, sediment abrasion, saponification processes, aquatic fauna predation, and the presence of intracavitary sediment. All these elements provide information on the dynamics of submersion, the duration of time in water, and the nature of the recovery environment [120–125].

A particularly innovative aspect offered by imaging is its capacity to generate quantitative datasets—including tissue volumes, adipose tissue radiodensity, three-dimensional gas mapping, skeletal morphometric analyses, and associated sediment mapping. These datasets can be compared over time and across different cases, facilitating the construction of more robust and standardized taphonomic scales. This approach marks a significant shift from traditional macroscopic observations, which are often subjective and difficult to compare between different experts or laboratories [126–129].

Furthermore, the use of imaging is integrated within a broader context of multidisciplinary collaboration, where radiological information is combined with environmental data (temperature, humidity, salinity, depth, currents, solar exposure, necrophagous fauna), anthropometric measurements, forensic chemistry, and genetic analyses. This integration is reshaping investigative methodology, moving away from static, point-in-time assessments toward a dynamic and complex model that accounts for the interaction between the body and its environment over time [130,131].

The growing number of variables involved, however, often surpasses the interpretive capacity of traditional methods. It is within this scenario that artificial intelligence (AI) and machine learning (ML) are emerging as pivotal tools (Figure 4). Deep learning algorithms applied to radiological images enable the automatic segmentation of tissues, quantification of residual soft tissue volume, identification of gas or adipocere patterns, recognition of microscopic bone surface alterations, and the classification of taphonomic phenomena with greater precision and consistency than human-only analysis. Simultaneously, multivariate predictive models allow for the extraction of correlations between imaging-derived parameters and environmental conditions, generating more adaptive PMI/PMSI estimates that are less susceptible to the subjective variability of forensic interpretation [132–138].

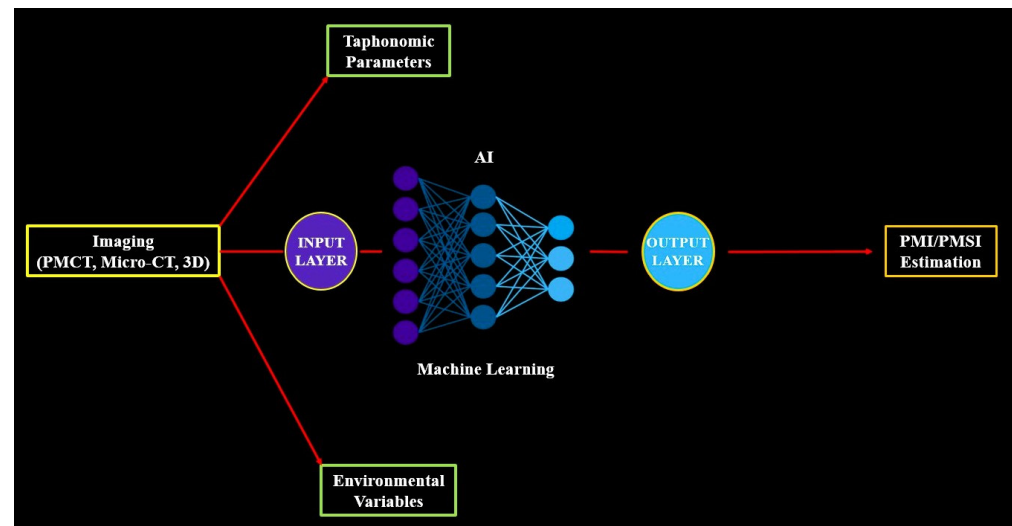


Figure 4. Conceptual framework illustrating the integrated role of post-mortem imaging, taphonomic parameters and environmental variables analyzed through artificial intelligence and machine learning models for improving PMI/PMSI estimation in terrestrial and aquatic contexts.

The construction of digital databases containing thousands of post-mortem scans, associated with environmental metadata and documented taphonomic information, forms the foundation for increasingly accurate AI models capable of generalizing and recognizing patterns even under complex environmental conditions. Despite this, significant limitations remain to be addressed: the scarcity of large, representative datasets, especially for submerged cases; the absence of uniform data collection standards; the difficulty in ensuring the transparency and reliability of AI models used in judicial contexts; the need for large-scale experimental validation; and the potential introduction of systematic biases in computational modeling [139–142].

In both terrestrial and aquatic environments, imaging and AI do not replace anthropological, taphonomic, and ecological analysis but rather augment it. Expert knowledge remains indispensable for correctly interpreting the data, contextualizing it within the framework of the specific case, and assessing potential environmental or anthropogenic interferences. The adoption of shared protocols for image acquisition, environmental condition recording, specimen analysis, and database management will be fundamental to ensuring comparability and scientific robustness. Overall, the future landscape of PMI/PMSI estimation is oriented toward an integrated approach where technology does not supplant expertise but rather enhances and supports it. Advanced imaging, combined with the computational analysis of data, represents one of the most promising directions for making the reconstruction of post-mortem processes more accurate, less subjective, and more adaptable to the specificities of the recovery context. However, the reliability of these tools will depend on the scientific community's capacity to build shared, validated, and

transparent models, and to continue exploring the complexity of human decomposition through experimental studies and interdisciplinary applications [143–145].

9. Conclusions

In conclusion, the estimation of the Post-Mortem Interval (PMI) and Post-Mortem Submersion Interval (PMSI) is now significantly advanced by a growing synergy between taphonomic observation, advanced imaging techniques, and computational tools powered by artificial intelligence and machine learning (AI/ML). This interdisciplinary integration represents the most promising avenue for overcoming the limitations inherent in traditional methods, offering the potential for more objective, reproducible, and contextually calibrated assessments. To ensure scientific reliability and robustness, however, key challenges must be addressed. Progress depends on the continued development of shared protocols, investment in large-scale, multimodal databases, rigorous validation of models across diverse ecological scenarios, and the preservation of a central role for human expertise in data interpretation and model guidance. Ultimately, only through a rigorous, multidisciplinary, and standardized approach can technological innovation decisively improve the reconstruction of post-mortem processes and the determination of the time since death in both terrestrial and aquatic environments.

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Abbreviations

The following abbreviations are used in this manuscript:

PMI	Post-Mortem Interval
PMSI	Post-Mortem Submersion Interval
CT	Computed Tomography
PMCT	Postmortem Computed Tomography
AI	Artificial Intelligence
ML	Machine Learning

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