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Bone maceration: a systematic review of techniques, efficiency and structural outcomes

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ADMINISTRATIVE INFORMATION

Support - None.

Review Stage at time of this submission - Completed but not published.

Conflicts of interest - None declared.

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Amendments - This protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) on 8 May 2026 and was last updated on 8 May 2026.

INTRODUCTION

Review question / Objective The aim of this systematic literature review was to synthesize current evidence on bone maceration techniques and provide a detailed overview of the most commonly used methods, including their strengths, limitations, and suitability for different applications. The review sought to answer the question: Which maceration method is most appropriate for specific purposes? In particular, it examined the effectiveness of each technique, the contexts in which certain methods may be less appropriate, and how factors such as processing time, cost, equipment requirements, and the preservation of anatomical and molecular structures influence methodological selection. Through the systematic analysis and comparison of findings across studies, this review aimed to develop a comprehensive reference framework for identifying the most suitable maceration approach according to specific research or practical objectives. Which maceration methodology is best suited for which application?

Condition being studied Bone maceration is the process of removing soft tissues from skeletal remains in order to obtain clean bones for further examination, preservation, or display. It is a fundamental procedure employed across a wide range of disciplines, including anatomical education, archaeological and anthropological research, forensic investigations, veterinary and medical sciences, and museum curation. The resulting skeletal specimens are used for purposes such as teaching anatomy, studying pathological or evolutionary changes, conducting forensic identification, and preparing exhibit-quality materials for public display.

A variety of maceration techniques have been developed, ranging from traditional manual and natural decomposition methods to chemical, thermal, and enzymatic approaches. The selection of an appropriate technique is highly dependent on the intended application, as each method differs in terms of efficiency, cost, processing time, equipment requirements, and impact on skeletal integrity. Importantly, the chosen maceration procedure can substantially influence the quality

and preservation of the specimen. Certain techniques may alter bone colour, damage surface morphology, weaken structural integrity, or compromise the preservation of biomolecules such as DNA and proteins. Consequently, careful consideration of the advantages and limitations of each method is essential to ensure that the resulting skeletal material remains suitable for its intended scientific, educational, or forensic purpose. Bone maceration refers to the process of removing soft tissue in order to obtain skeletal elements free of soft tissue. It is a widely used technique, which produces specimens for many different types of applications such as education, scientific research, forensics and museum exhibitions. The choice of maceration technique used needs to be tailored to each specific application as it can critically influence outcomes, such as DNA preservation and bone surface structure among many others.

METHODS

Participant or population Bone specimens subjected to different maceration techniques compared to each other for forensic, morphological or teaching purposes.

Intervention The interventions investigated in this systematic review comprised a broad range of bone maceration techniques that have been developed and refined over time to facilitate the removal of soft tissue from skeletal remains. These methods differ substantially in their underlying mechanisms, procedural complexity, duration, and impact on the preservation and quality of skeletal material.

The interventions include mechanical dissection techniques, in which soft tissues are manually removed using surgical or dissection instruments, either as a standalone procedure or in combination with additional cleaning methods. Water-based maceration methods are also investigated and encompassed cold-water, warm-water, and hot-water maceration approaches, each relying on varying temperatures to accelerate tissue decomposition and separation from bone. Natural decomposition methods, including outdoor or open-air decomposition, are examined as low-intervention techniques that depend on environmental conditions and microbial activity for gradual tissue removal.

Biological and biochemical interventions include enzymatic maceration and the use of insects such as dermestid beetles. Enzymatic methods employ proteolytic enzymes to selectively digest soft tissues while aiming to preserve delicate skeletal structures, whereas insect-assisted maceration

utilized the natural feeding behaviour of dermestid colonies to achieve highly detailed skeletal preparation. Chemical maceration techniques are additionally assessed and include the use of detergents, alkaline solutions, hydrogen peroxide, and other chemical agents intended to accelerate tissue dissolution and bone cleaning.

More recently developed interventions, such as microwave-assisted maceration, are also identified. These approaches aim to reduce processing time and improve procedural efficiency through the application of controlled heat energy. Across the included studies, the effectiveness of each intervention is evaluated according to outcomes such as processing duration, completeness of soft tissue removal, preservation of bone morphology and surface integrity, retention of molecular material such as DNA, cost-effectiveness, safety considerations, and overall suitability for specific applications.

Comparator No restrictions are applied.

Study designs to be included All studies applying at least two different maceration techniques or investigating the effect of the respective maceration technique on bone are included.

Eligibility criteria Studies investigating the preparation of skeletal specimens for forensic, educational, or research purposes, as well as studies examining the effects of maceration procedures on bone samples, were considered eligible for inclusion in this review. Eligible studies included those assessing the effectiveness, outcomes, or preservation characteristics associated with different maceration techniques. Studies primarily focused on historical, archaeological, or anthropological practices unrelated to contemporary specimen preparation—such as cultural or ritual defleshing practices associated with burial customs—were excluded. Publications written in languages other than English or German, as well as studies for which the full text could not be accessed, were also excluded from the review.

Additional exclusion criteria comprised conference abstracts and proceedings, case reports, expert opinions, personal observations, and technical notes that did not include a comparative evaluation of maceration methods. Furthermore, publications deemed unrelated to the review topic, along with books, book chapters, doctoral or master's theses, technical guidelines, and review articles, were excluded to ensure the inclusion of primary research studies only.

Information sources Studies are identified by searching the databases PubMed (MEDLINE), SCOPUS and EMBASE. Titles and abstracts of identified records were initially screened to determine their potential relevance to the review topic. Following the screening process, duplicate entries were identified and removed. The remaining full-text articles were subsequently assessed for eligibility according to the predefined inclusion and exclusion criteria.

To ensure comprehensive coverage of the literature, the reference lists of all included studies were manually reviewed, and additional relevant publications addressing bone maceration were identified and included where appropriate. Data extraction and study selection were conducted by the two authors independently. Any disagreements arising during the screening or eligibility assessment process were resolved through discussion, and where consensus could not be reached, consultation with a third reviewer was undertaken to achieve final agreement.

Main outcome(s) The collected data is categorised into two groups. The first group includes articles that tested maceration methods either generally, for particular specimen types (e.g. skulls or delicate bones), or for specific intended fields of application such as forensic cases, or processing embalmed or frozen specimens, or whether human or animal specimens were used. The second group consists of articles that analysed maceration methods in relation to their effects on specific bone properties (e.g. DNA preservation or microscopic bone structure).

Quality assessment / Risk of bias analysis The methodological quality and risk of bias of the included studies will be independently assessed by two reviewers using appraisal tools appropriate to the study design. The McGill University Mixed Methods Appraisal Tool (MMAT) will be used to evaluate the methodological quality of studies across domains such as study design appropriateness, data collection, participant selection, and interpretation of findings. Studies will additionally be assessed using the Newcastle–Ottawa Scale (NOS), which evaluates selection of participants, comparability of study groups, and ascertainment of outcomes or exposures. Any disagreements between reviewers will be resolved through discussion or consultation with a third reviewer. The results of the quality assessment will be presented in tabular form and incorporated into the interpretation of findings to inform the overall strength and reliability of the evidence.

Strategy of data synthesis This systematic review will follow the PRISMA guidelines for the synthesis and reporting of evidence.

Data extracted from eligible studies will be entered into a standardized data extraction table. Extracted information will include study characteristics (authors, year, country, and study design), specimen characteristics, details on the maceration processes compared and key findings. Extracted data will be checked for completeness and consistency prior to synthesis.

A narrative synthesis will be conducted for all included studies. Studies will be grouped according to similarities in maceration method, bone alterations observed and intended application. The synthesis will summarize and compare study findings, highlighting patterns, consistencies, and discrepancies across studies. Summary tables and figures will be used to present study characteristics and findings in a structured manner.

Subgroup analysis Not applicable.

Sensitivity analysis Not applicable.

Language restriction Yes, only studies in English or German will be included.

Country(ies) involved Austria.

Keywords bone; maceration; skeleton; cleaning; soft tissue.

Contributions of each author

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