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Review

What's New with the Old Ones: Updates on Analytical Methods for Fossil Research

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Abstract

Fossils are portals to the past, providing researchers with vital information about the evolution of life on Earth throughout the geological eras. The present study synthesizes the recent trends in fossil research, emphasizing the most common techniques found in the specialized literature over the past 20 years. The bibliographic survey revealed that destructive methods continue to play a significant role in scientific production related to this topic, particularly in studies on 3D morphologies, diagenesis, nutritional ecology, dating, elucidating dietary or habitat preferences, or understanding the physiology of extinct species. However, noninvasive tools, such as Raman spectroscopy, are rapidly rising, particularly when integrated with imaging techniques. As such, fossil research continues to advance even beyond the borders of our planet, exploring extraterrestrial samples in a quest to unlock the universal mystery of life. At the same time, the advent of advanced AI methods—particularly model chatbots that rival the capabilities of experienced scientists—has facilitated and enhanced data interpretation and classification. As fossil research evolves, upcoming technological advancements in spatial resolution, penetration depth, and detection sensitivity will integrate state-of-the-art spectroscopic tools. This will undoubtedly take fossil research to new heights, generating breakthroughs that optimize analysis while preserving invaluable specimens. Overall, the present study offers a holistic overview of analytical techniques through meta-analysis and bibliometric mapping, including a critical assessment of commonly used methods and offering a glimpse into the integration of machine learning and AI tools in fossil research.

Keywords: fossil research; bibliographic study; noninvasive techniques; spectroscopy

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1. Fossils in Heritage Sciences: Current Status

Given the precious, non-renewable, and sometimes unique character of heritage items, including archaeological findings, the current international trends in heritage research emphasize the need to utilize minimally invasive, preferably completely non-destructive methods for the characterization of such objects. A special category of heritage items comprises fossils, defined as any "remains, impression, or trace of an organism from past geological eras, which was kept in sediments". The investigation of fossils, as remnants of past times, enables researchers to gather information about life on Earth, how it has changed throughout the geological periods, food and migration patterns, and how plants, animals, or humans have adapted to environmental changes. To understand such patterns, it is useful to study large groups of objects and realize the proper connections and associations. However, fossils have unique character, with each one having its own history, which

considerably limits the analytical approaches that can be applied, making their study highly restrictive at times. Currently, some of the most precise tools for fossil analysis include destructive methods, which can require either sampling or processing steps in such a manner that the original sample can no longer be retrieved nor used for other types of investigations [1]. Thus, the need for noninvasive techniques arises, namely techniques that should preferably be non-destructive and keep the integrity of the fossils but, at the same time, offer pertinent scientific information about them.

2. Bibliographic Study

Taking these premises into consideration, the present study aimed to answer several questions that have emerged, such as what has been achieved in the analytical analysis of fossils over the last 20 years, how far technological advances have reached, and whether there is still a gap to be filled in this area. For this goal, without focusing on a specific fossil category but rather the broad domain of fossil analytical research, a bibliographic study was conducted using the VOSviewer software (v. 1.6.20) [2]. Data were selected from the Web of Science bibliographic database, using the search syntax "fossil" OR "fossils" NOT "fuel" NOT "fuels" to eliminate the misleading results generated by fossil fuels. A total of 68 journals were included, at the intersection of physics, chemistry, and biology, with geology, archaeology, anthropology, and plant and animal sciences. A co-occurrence analysis was performed based on the relativeness of all keywords within the papers (including both author keywords and AI-extracted keywords), generating 14,147 entries. For these, the minimum number of occurrences was set at 10 (meaning that a word would have to be encountered in at least 10 papers to be included in the visualization). Of all the entries, 361 words met the selected threshold and were used to generate the network visualization shown in Figure 1. The generated network visualization emphasizes the interconnectedness of concepts in paleontology and related areas by identifying frequently co-occurring terms, thus revealing the central themes of the scientific studies in the past 20 years, such as fossil origin, evolution, diversity, and preservation. The keywords were grouped into 5 main clusters, shown in different colors in the figure, which reflected the deep interdisciplinarity of this field. The first cluster (red) focused mainly on geochemistry and taphonomy. It was the largest cluster, including 41 of the total keywords, such as *taphonomy*, *diagenesis*, *sediments*, *geochemistry*, *preservation*, *temperature*, *bone*, *water*, *oxygen isotopes*, and *organic matter*. Studies included here focused on the post-mortem processes affecting fossil formation and preservation, highlighting how biological remains are chemically and physically altered. The second cluster (green) focused on evolution and phylogeny. It included 29 keywords such as *evolution*, *phylogeny*, *morphology*, *taxonomy*, *classification*, *anatomy*, *new species*, *biogeography*, and *behavior*, being related to species identification, evolutionary relationships, geographic distribution, speciation, and evolutionary timelines. The blue cluster (3), with 26 items, was formed around paleoclimatology and paleoecology. It included keywords like *Pleistocene*, *Holocene*, *climate change*, and *reconstruction*, highlighting the importance of studying ancient climates and their influence on the fossil record. The emphasis on the Pleistocene and Holocene suggests a focus on recent Quaternary periods. Cluster 4 (yellow) included 19 items focused on fossil formation, biostratigraphy, and preservation. With core keywords such as *fossil record*, *patterns*, *age*, *biostratigraphy*, *basin*, *origin*, and *extinction*, cluster 4 underlines the importance of fossilization processes, preservation quality, the distribution of fossils across geological strata in sedimentological contexts, and temporal distribution. The fifth cluster (purple) contained 16 items focused on the biodiversity and dynamics of fossils. The main keywords in this cluster were *diversity*, *diversification*, *extinction*, *radiation*, *fossil record*, *biodiversity*, and *early evolution*. These are associated with the core themes of macroevolutionary patterns, extinction patterns, and early-life diversification.

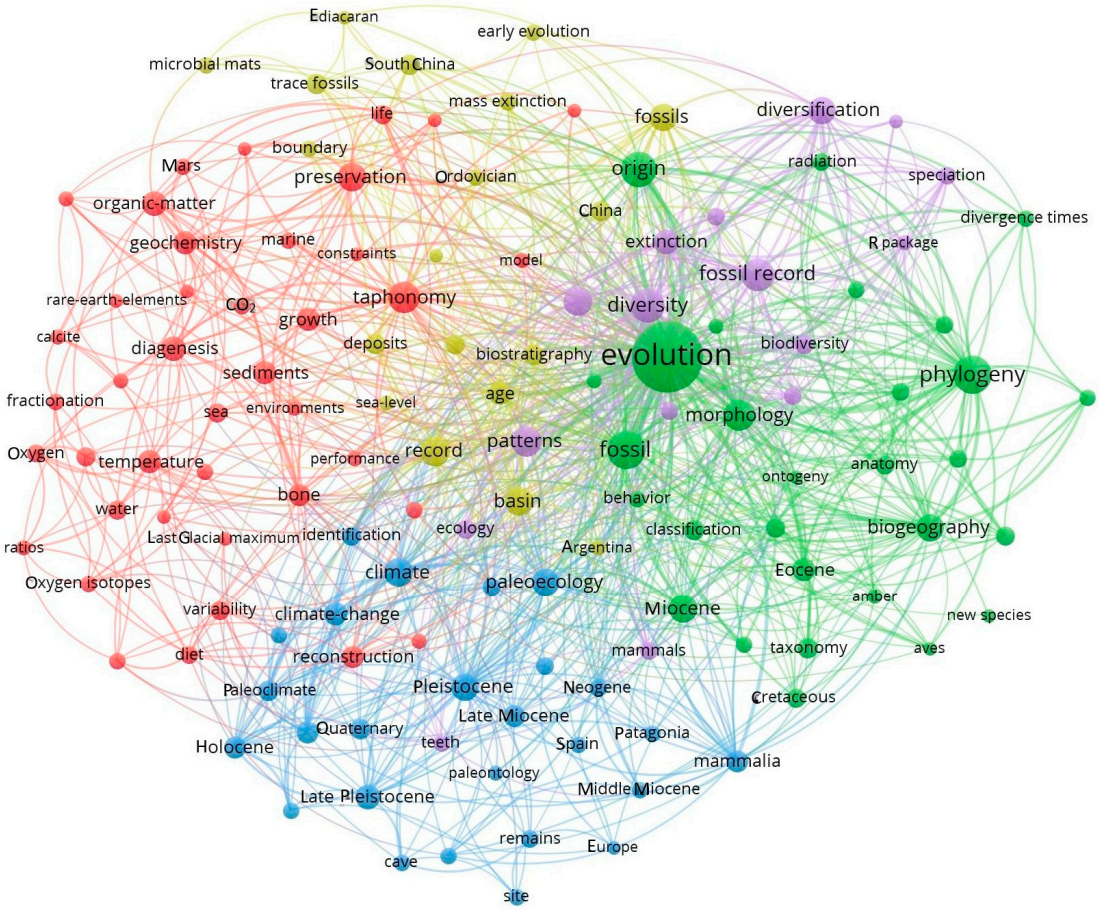


Figure 1. Network visualization of keywords in cluster 1 (red), cluster 2 (green), cluster 3 (blue), cluster 4 (yellow), and cluster 5 (purple).

These five clusters are interconnected. For example, the sedimentation and preservation processes (cluster 1) act as a foundation for the fossil record (cluster 3), which in turn is the dataset for identifying the biodiversity patterns (cluster 5). These patterns (cluster 5), however, need to be interpreted in a phylogenetic context (cluster 2), taking into account the evolutionary relationships, which can explain how species have adapted to ancient climates (cluster 4). Moreover, the reconstruction of paleoenvironments (cluster 4) is based on the geochemical proxies included in cluster 1.

Overall, an emphasis has been put on the origin and evolution of life on Earth [3,4] through the study of the diversity and classification of the fossil record [5–7]. Studies have tackled the development of life throughout the geological eras, starting with the appearance of complex multicellular life in the Ediacaran period [8–12], through the Cambrian Explosion, which brought about the rapid diversification of most animal groups [13–16], and the Ordovician, when marine life flourished [17,18], up to the most recent geological period, the Quaternary Period, when human civilization started to thrive [19,20].

By analyzing the same dataset based on the co-occurrence of the authors' originating country, a co-authorship map was generated. Figure 2 presents the density visualization of the countries generated following the selection of a minimum number of 5 countries per document, thus including 63 countries. The color code correlates with the scientific activity spanning each country, ranging from blue, which denotes low activity, to an intense red, signifying high activity.

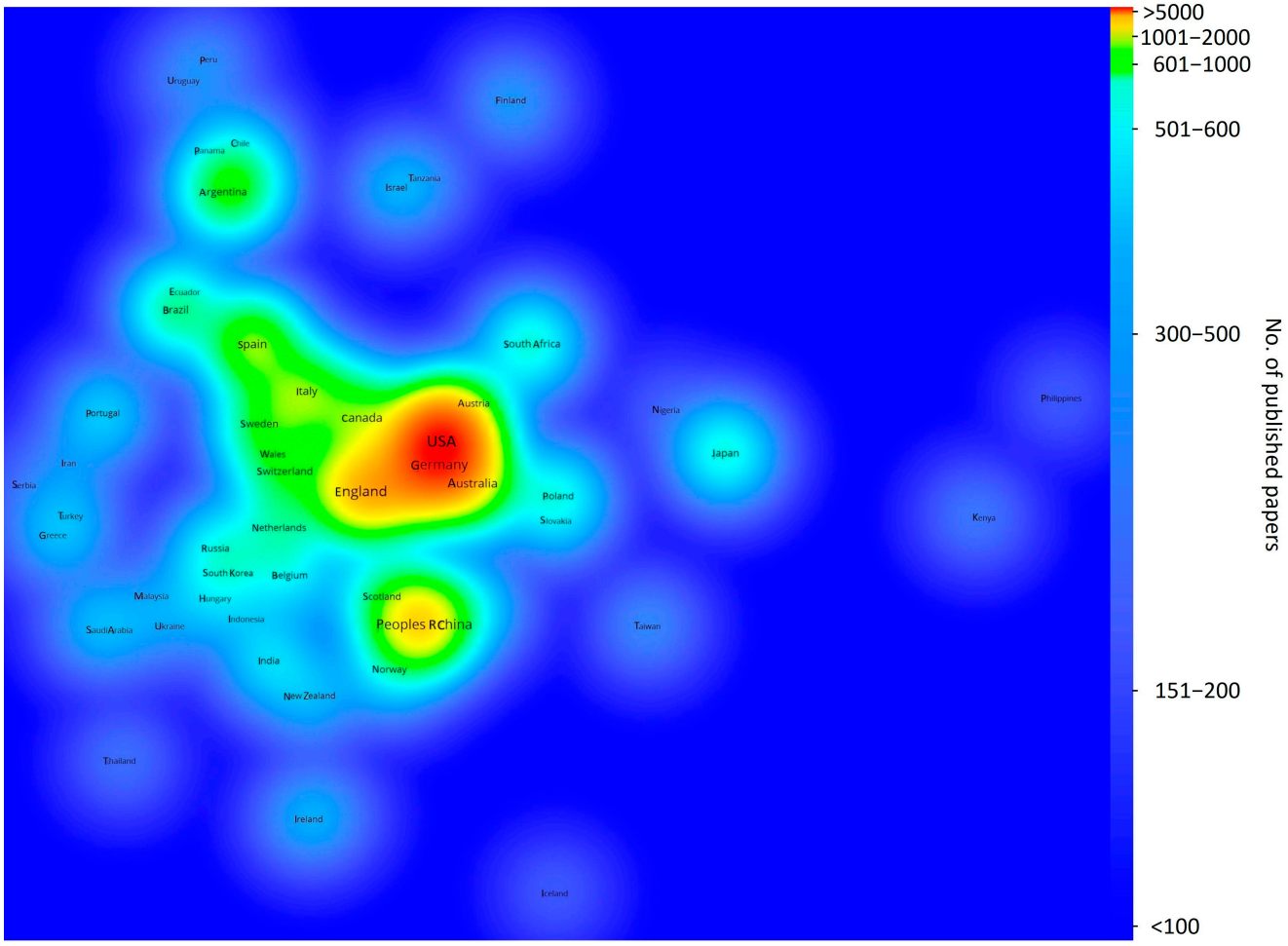


Figure 2. Co-authorship map of origin countries.

The figure highlights the main countries from which analytical fossil research stems, such as the U.S.A., followed by some European countries: Great Britain, France, and Germany. Another important cluster forms around the People's Republic of China. The reason behind the wealthier scientific production is a combination of several factors. First of all, these are countries in which a large percentage (>2%) of the gross domestic product (GDP) is allocated to the R&D sector [21]. They also benefit from the existence of historical, renowned institutions and have greater accessibility to international collaborations and scientific publishing. Another key aspect is that they have sites that are rich in fossils, such as the western states in the U.S.A. or the Liaoning, Yunnan, and Sichuan provinces in China, where well-preserved dinosaurs have been found, or the Solnhofen limestone, where several Archaeopteryx fossils have been uncovered. Meanwhile, countries like Argentina, Romania, South Africa, Scotland, and Spain showed varying levels of involvement. While some of these, such as Argentina or Romania, might also have a large fossil record, limited and unstable funding, along with fewer publishing opportunities, make them less competitive in this field.

3. Emerging Analytical Chemistry Principles for Fossil Research

Since this paper is focused on the analytical methods involved in the study of fossils, a more in-depth understanding was pursued, following the indications of the bibliographic analysis. Thus, 642 author keywords within the papers included in this study were processed with the help of the word cloud online tool [22]. The generated word cloud (Figure 3) highlights the analytical tools used most often, with emphasis on spectroscopic

and imagistic techniques. Spectroscopic tools are great for analyzing the interaction between electromagnetic radiation and matter, as well as identifying its composition and properties. Moreover, the combination of spectroscopy tools and imaging methods provides information on both the composition and spatial distribution, thus enhancing material characterization. Thus, Raman spectroscopy, microscopy, and fluorescence appear to be encountered often alongside other elemental and structural characterization methods, such as XRD, XRF, SEM, and imaging methods, such as hyperspectral analysis. Although several invasive methods stand out in the word cloud, meaning that they still have an important contribution in this area, the prominence of noninvasive spectroscopic methods in the word cloud indicates an increased interest in preserving fossil integrity.

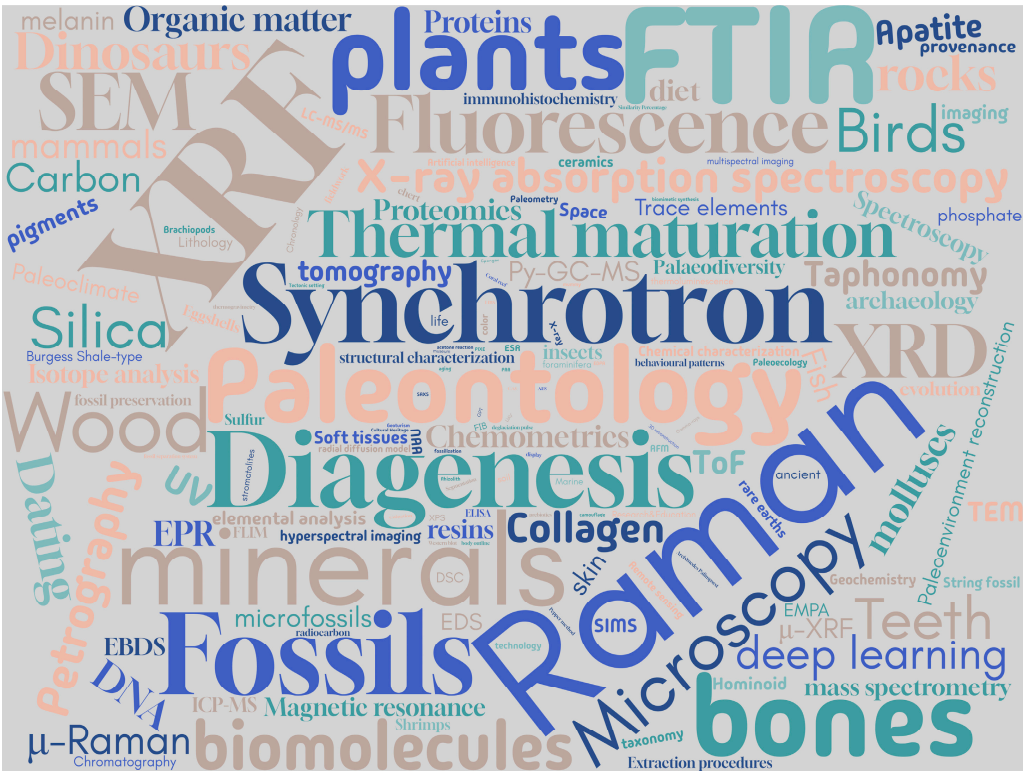


Figure 3. Word cloud generated based on techniques and subject.

A non-exhaustive list of analytical methods is given in Table 1, grouped according to their level of invasiveness and as either noninvasive or invasive or destructive or non-destructive. Methods that do not require sampling or direct contact with the object are considered to be noninvasive, while invasive ones do require either contact or sampling. On the other hand, non-destructive methods may require contact with the surface but inflict no harm upon the investigated object, whereas destructive methods interact with the object in such a manner that a smaller or greater portion of it cannot be recovered or is irremediably altered within the process of analysis.

Based on the gained expertise, several key directions have emerged in the field of fossil analysis, such as non-destructiveness, increased operability, downscaling equipment size, and AI integration.

Table 1. Synthesis of techniques used most often for the study of fossils.

Type	Analytical Method	Aim	Pros (↑) and Cons (↓)	Type of Fossil	Selective References
NON-INVASIVE, NON-DESTRUCTIVE	(μ-)XRF	Elemental analysis	↑ Suitable for elemental mapping of fossils ↑ Minimal or no sample preparation ↑ Highly portable ↑ Easily accessible ↑ High sensitivity for heavy elements, great for detection of REEs ↓ Limited to the detection of inorganic elements ↓ Can be affected by matrix effects	Bones Teeth Shells Fish Crustaceans Feathers Wood	[23–28]
	(μ-)XAS, SAXS		↑ Suitable for elemental mapping of fossils ↑ Can detect trace elements ↓ Micro-techniques require synchrotron-radiation	Bones Teeth Soft tissues Amber Kerogens Microfossils	[29–31]
	(μ-)/(n-)CT, XRM		↑ Suitable for visualization of dense fossils ↑ Allows 3D morphology ↓ Limited accuracy for low-contrast samples	Bones Shells Embryos Amber	[23,32–34]
	Fluorescence, UV-Vis spectroscopy	Fossilization processes Morphological differentiation Preliminary screening of fossils	↑ Suitable for screening of fossils ↑ Useful for understanding fossilization processes ↑ Suitable for differentiating organic and mineral phases ↑ Preliminary determination of morphological structure ↑Identification of the oxidation state ↑ Reconstruction of fossil paravian body ↑ Identification of unseen structures in fossil feathers ↑ Understanding nesting behavior ↓ Hard to discern overlapping signals ↓ May be affected by spectral interference	Amber Soft tissues Proteins	[35–44]
	Multi- or hyperspectral imaging	Surface mapping	↑ Highly suitable for highlighting diagenetic transformations in fossils ↑ Fossil detection and screening ↑ Mapping surface textures and compositional variations ↑ Evaluation of collagen level in fossil bones ↓ Limited resolution	Wood Bones Amber Shells Soft tissues	[7,45–49]
	Raman spectroscopy	Molecular composition Taxonomic identification	↑ Useful for the identification of compositional patterns ↑ Suitable for evaluating biogenicity ↑ Identification of biologically synthesized compounds ↑ Elucidating fossil preservation mechanisms ↑ Useful in palaeothermometry ↑ Characterization of diverse biosignatures ↑ Best suited for carbonaceous materials ↓ May be affected by fluorescence signal	Proteins Lipids Minerals	[36,50–59]

Table 1. *Cont.*

Type	Analytical Method	Aim	Pros (↑) and Cons (↓)	Type of Fossil	Selective References
	PIXE	Elemental analysis	↑ High sensitivity to elements in trace amounts ↓ Requires thin sections	Bones Teeth Soft tissues	[35]
INVASIVE, NON-DESTRUCTIVE	SEM(-EDS)	Surface analysis	↑ Provides high-resolution images ↑Can offer information about the state of fossils ↑ Useful for the identification of melanosomes ↓ Can require sample coating for conductivity	Bone Teeth Scales	[59–62]
	EBSD	Crystalline structure	↑ Suitable for examining fine-grain structures ↑ Evaluation of sedimentary processes ↑ Evaluation of diagenetic processes on foraminiferous fossils ↑ Allows the quantitative analysis of crystalline microstructures ↓ Requires sample preparation	Minerals	[54,63–65]
	(μ-)FTIR	Molecular composition	↑ Suitable for analysis of functional groups ↑ Information about the molecular composition ↑ Taxonomic identification ↑ Evaluating biogenicity ↑ Identification of biologically synthesized compounds ↑ Identifying the effects of diagenetic processes ↑ Elucidating fossil preservation mechanisms ↓ May require crushing of the sample	Bones Amber	[1,47,50,66–70]
	EPR	Chemical composition	↑ Information about chemical composition ↑ Molecular interactions ↑ Useful for detecting paramagnetic centers ↑ Effective for dating ↓ Requires specific sample preparation	Teeth Shell	[66,71–73]
	NAA	Chemical composition	↑ Effective for dating ↑ Suitable for trace element analysis ↑ Determining chemical elements ↑ Useful in studies concerning the preservation of bone tissues ↓ Requires access to nuclear reactor or generator ↓ Limited elemental detection ↓ High operational costs	Bones Teeth Coprolites Shells Sediments	[72,74]
	(μ-)XRD	Mineralogical characteriza-tion	↑ Current standard for identifying the crystalline structure of fossils ↓ Requires specific sample preparation	Minerals	[48]

Table 1. *Cont.*

Type	Analytical Method	Aim	Pros (↑) and Cons (↓)	Type of Fossil	Selective References
	Thermoluminescence	Dating	↑ Effective for dating ↓ Results may be affected by exposure of luminous centers to light after unearthing	Bones Minerals	[72,73]
INVASIVE, DESTRUCTIVE	Dendrochronology	Dating Species identification	↑ Effective for dating ↑ Useful for the identification of wood species ↓ Requires core drilling or sawing	Wood	[73,75]
	TGA	Chemical fingerprinting	↑ Suitable for determination of resin fossils' origins ↑ Effective for dating ↑ Useful for understanding diagenetic processes ↓ Irreversible damage to the sample	Bones Coprolites	[70]
	FIB-SEM-EDS	Chemical and structural composition	↑ Great for nano-scale chemical imaging ↓ Damages sample surface	Embryos Soft tissues Microbialmats Biofilms Amber	[32,53,61,76]
	TEM	Crystallographic structure Morphology	↑ Can offer information about the size and shape of bioapatite crystals ↓ Requires thin sections	Proteins Biominerals	[53,60,69,71,77]
	Isotope analysis	Nutritional ecology Feeding and migration patterns	↑ Useful for evaluating the ecological impact of certain species ↑ Effective for dating ↑ Useful in paleoenvironmental studies ↓ Frequently affected by external sample contamination	Teeth Bones Shells	[71,78–82]
	DNA analysis	Evolutionary studies Species identification	↑ Highly suitable for elucidating evolutionary links ↑ Identifying extinct species ↓ Requires well-preserved organic material	Bones Teeth Hair	[1,5,83]
	Py-GC-MS	Organic composition	↑ Information about chemical composition ↑ Identification of fossilized organic pigments ↑ Identification and classification of fossilized resins ↓ Sample destruction is unavoidable	Coprolites Resins Soft tissues	[38,66,84,85]
	(Tof-)/(NANO)SIMS	Molecular, elemental, and isotopic composition	↑ suitable for isotopic mapping ↑ High spatial resolution ↑ Depth profiling ↑ Minimal sample preparation ↓ Expensive equipment ↓ Long acquisition time	Tissues Organelles	[33,86–90]
	DSC	Chemical fingerprinting	↑ Investigating resin age ↓ Requires sample heating, altering its original properties	Collagen Resins	[70]
	LIBS	Surface and stratigraphical elemental analysis	↑ Useful for fossil identification ↑ Allows controlled in-depth analysis ↑ Individual fingerprinting and fossil sampling ↓ Micro-destructive	Bones Teeth Sediments	[91,92]

3.1. Non-Destructiveness

Prioritizing sustainability and sensitivity, recent trends in analytical chemistry related to the study of fossils involve more and more noninvasive and non-destructive methods. Such methods aim to preserve the fossils while still offering pertinent information. They in-

clude elemental analysis methods, such as those based on the interaction of X-rays with the matter, along with other spectroscopic tools, such as fluorescence spectroscopy or Raman spectroscopy, or imaging tools, such as multi- or hyperspectral imaging. These methods are useful for fossil identification, understanding the elemental, molecular, or structural composition of fossils and their transformation over time, and also for palaeothermometry studies without compromising sample integrity. However, noninvasive approaches can sometimes lack the precision and sensitivity of minimally invasive techniques. Methods requiring direct contact with the surface and, in some cases, even sample extraction can be regarded as non-destructive if neither the contact surface nor the sample is harmed in any way. Such is the case for XRD, for example, which does require a sample to be taken from the original object, but the analysis itself leaves the sample unharmed. Other non-destructive methods which do need samples are methods used for dating, such as electron paramagnetic resonance or neutron activation analysis. Other dating methods, such as thermogravimetric analysis (TGA) or thermoluminescence, are destructive, as they alter the original properties of the sample irrevocably. Methods such as isotopic or DNA analysis, along with various types of mass spectrometry, or differential scanning calorimetry are also regarded as destructive methods. Laser-induced breakdown spectroscopy (LIBS), although it inflicts damage on the surface of the objects, can be considered micro-destructive, as the level of damage inflicted upon the object is considered, in many cases, to be negligible.

On the other hand, for some of the techniques, the classification as non-destructive, micro-destructive, or destructive can vary from case to case. For instance, conventional dendrochronology requires core drilling or sawing to be able to measure all tree rings, but when coupled with CT scanning, it becomes a safe and more accurate alternative to wood dating [93]. Similarly, Fourier transform infrared spectroscopy (FTIR), which can also be used as a method for dating wood [94], often requires sampling, and most of the time, the sample is crushed due to the necessary force that has to be applied to obtain noise-free spectra. But FTIR can also be performed in some specific cases with the help of a laser fiber, and it can be applied directly onto the studied surface without harming it in any way.

The fact that XRD is often used in fossil analysis is probably because, aside from it being an invasive and destructive technique, it is one of the most reliable ones for the analysis of crystalline structures. XRD diffractograms can shed light on the origin of the samples [54], the mineralogical composition of fossils [95] and identification of their crystalline structure [96], indirect dating through the parallel comparison of sedimentary matrices in which fossils are embedded [97]. Moreover, some studies have used XRD not only for the identification of both natural and additional minerals, coming from the environment, but also for the identification of collagen residues [95]. The intake of minerals from the sedimentary matrix is identifiable through a series of molecular and elemental analysis techniques [98,99], and is the consequence of a dual exchange between the fossil and the burial environment, as some elements are selectively replacing the ones from the bones, while others are leaching out into the sedimentary matrix [95].

Generally, X-ray-based methods have been utilized for over a century in various forms, ranging from complex, large-scale facilities, such as synchrotrons, to benchtop equipment and even small, battery-operated, portable equipment, such as pXRF. The detection limit of such methods varies from tens to a few hundred ppm in portable equipment, up to a few mm in benchtop equipment and to about 1 μm in synchrotron facilities. Furthermore, the possibility of acquiring elemental distribution maps significantly enhances the classical X-ray-based methods. However, in the case of medium to large objects, the acquisition time for such distribution images is quite lengthy. Bergmann and his co-workers [23] have made a synthesis of X-ray techniques used for fossil studies, highlighting not just the plethora of methods, but also their relevance to the field. Although the fundamental

principle is the same, based on the interaction of X-rays with the atoms, which generates specific emissions, a wide variety of methods have emerged, which, used either alone or in combination, allow users to obtain an equally large palette of information. Thus, X-ray-based methods can provide data about the elemental composition and the spatial distribution of the chemical elements for surfaces of up to a few centimeters, generating 3D images and spatial and morphological data with micro/nano-resolution, even for low-contrast objects, differentiating between various chemical species (even for light elements), structural determination and highlighting of the objects' texture [23]. The detection of low-energy elements, like P, K, S, Cl, or Ca, can play an important role in the understanding of biosynthetic processes and endogenous compounds [23,100]. Additionally, a great amount of information can be obtained from trace elements. XRF can indicate the mineralogical features of the environment [16,95], or its oxidative nature, through the detection of rare-earth elements, such as Ce or Eu in fossils, or that REE ions can substitute calcium ions, altering the natural mineralogy of fossil samples [24,101].

When aiming to reveal the surface topography of a sample, SEM allows the user to observe materials at very high resolutions, generating images of the object's surface and offering information about the topography and composition of the surface, while TEM, which is based on the transmission of an electron beam through the sample, offers information about the internal structure of the analyzed object. An important progress has been made by Moisan [102], who has used a redefined version of the silicone cast techniques for SEM, which allows the user to visualize fossil plant structures, offering important biological information. While both SEM, TEM, and other derived methods are considered to be invasive, because they either require extraction procedures or thin sections, they do not all have the same destructiveness level. For instance, SEM and SEM-EDS are non-destructive, while TEM or FIB-SEM require additional processing steps that change the properties of the sample, thus being considered destructive methods.

Another analysis technique that can additionally offer in-depth information through stratigraphical analysis is LIBS (laser-induced breakdown spectroscopy), based on atomic emission spectroscopy. LIBS is emerging as a useful tool for revealing the chemical composition of fossils, as well as for highlighting the exchanges between fossils and the environmental matrix [91]. Likewise, it has proven useful for fossil identification [92]. Aiming to use LIBS as a rapid screening tool in fossil field studies, Roberts et al [103] have strived to identify suitable spectral lines which are specific to fossils, and which could be used to differentiate them from the surrounding rocks, a recurring theme in the study of fossils: Schilling and co-workers [104], have used CT scanning to separate fossilized bone from its surrounding sediment matrix, while Kaye et al [41] have created the first automated de-vice for sorting of micro-fossils, based on laser-stimulated fluorescence.

LIBS offers distinct advantages in terms of portability and rapid analysis. Modern LIBS systems achieve lateral spatial resolutions in the range of 10–100 µm, with detection limits typically between 1–100 ppm, depending on the matrix and element. While less sensitive than XRF for some heavier elements, LIBS excels in detecting light elements such as Li, Be, B, C, N, and O, which are difficult to quantify using conventional XRF. Furthermore, its capacity for depth profiling—enabled by sequential laser ablation—allows semi-quantitative stratigraphic analysis, which is valuable for assessing fossil diagenesis or mineral accretion layers. LIBS sensitivity is further enhanced through time-resolved detection (gated detection), with temporal resolutions on the order of nanoseconds, optimizing signal-to-noise ratios in complex fossil matrices.

Previous studies have found that LIBS coupled with machine learning models, such as neural networks, can be useful for the classification of animal bones and discrimination between individuals [92]. Thus, LIBS can emerge as an alternative tool for DNA analy-

sis studies, which, along with stable isotope studies, make up another large percentage of the surveyed literature. Although they have undeniable advantages, they also have certain limitations and disadvantages. For instance, it is of utmost importance that the analyzed sample contains viable, uncontaminated material, which does not happen often. Additionally, such methods can require the use of complementary techniques, such as chromatographic ones, for the purification of the samples [71]. They often need large volumes to process, for multiple runs, to eliminate or reduce the possibility of erroneous results. Wasting of financial and time resources for analysis that are not guaranteed to yield correct and coherent information can be avoided by inserting a supplementary step before the extraction procedure, which could highlight the existence of other types of materials, such as proteins or bioapatite, as indirect indicators of viable DNA. Proteins and DNA are highly susceptible to degradation processes, and their content can be considerably reduced with time [46]. However, proteins tend to be more resistant than DNA, especially when mineral binding occurs. This has been demonstrated through molecular dynamics simulations, which proved that intramineral proteins from *Struthio camelus* eggshells can induce biomineralization, leading to the selective preservation of those proteins [105]. Moreover, although regarded with skepticism by many researchers, who believe that the presence of exogenous contamination could lead to false positive results regarding the presence of proteins and collagen, previous studies have demonstrated that, under proper conditions, the conservation of proteins in very old samples is indeed possible [106], even in small-size skeletal parts [107]. Thus, despite the natural degradation processes that happen over long periods, scientific studies have revealed that there is rarely viable DNA within a fossil sample, even for very old ones [105,108], without it also containing viable protein material [109–111]. Another useful marker is the presence of minerals, such as bioapatite ($Ca_{10}(PO_4)_6(OH)_2$), which, along with fluorapatite ($Ca_5(PO_4)_3F$), are hydroxyapatite variations containing carbonate and fluoride, respectively. Fluorapatite is more stable than bioapatite, and they can both be found in hard tissues of vertebrates, such as bones and teeth [67,112,113], along with secondary minerals, such as chamosite, barite, goethite, calcite, and its less stable polymorph—aragonite, in various proportions [114]. Another common mineral in fossils is quartz, usually encountered in sponges and diatoms, but also in silicified wood [115,116].

Although more resistant than organic material, minerals can also be affected by natural degradation processes, though to a lesser extent. Similarly, for proteins, the bioapatite content in fossil bones can be reduced to half of the normal values encountered in fresh bones as a result of the mineral exchange between bones and the burial environment [69], which can be enough for qualitative studies. To obtain information about the organic and mineral content of fossils, some of the most common approaches include FTIR and Raman spectroscopy. These are useful tools for studying the molecular structure of complex biological systems, which can offer real-time data on the molecular bonds and structure of the analyzed samples [117] as they do not alter the nature of the samples. Both of them offer low detection limits (~μM in the case of Raman spectroscopy or from ng to μg in the case of FTIR) as well as good spectral and spatial resolution (~1–2 cm^{-1}/~1 μm for Raman spectroscopy and 1–4 cm^{-1}/3–10 μm for FTIR).

Although expensive and destructive, stable isotope analysis has been used in multiple studies to highlight the feeding patterns of extinct species, highlight unexpected features, and evaluate the ecological impact or migration patterns of certain species. With extremely low detection limits (down to tens of picograms) and extremely good precision for the δ value measurements (~0.05‰ $\delta^{13}C$, 0.08‰ $\delta^{18}O$) [118,119], the use of such a technique is highly suitable for identifying specific geochemical features imprinted on each animal by its living environment and its habits. This fingerprint is reflected in the bones, teeth, and

other tissues [71,81], but the post-mortem diagenetic processes have to be accounted for, processes which can alter the trace elements content or the bioapatite structure. Some of the most frequently investigated ones are carbon ($\delta^{13}C$), hydrogen (δD), nitrogen ($\delta^{15}N$), oxygen ($\delta^{18}O$), and sulfur ($\delta^{34}S$) isotopes, which are mainly extracted from bones or teeth. For instance, the work of Clementz is a great advancement in the field, offering information about diet and how isotopic analysis can help distinguish between the source of water intake, either from surface water bodies or from the ingestion of plants [81]. New insight on the reconstruction of Hominin diets through amino acid stable isotope ratios was recently gained through a study by Larsen et al. [120]. Based on isotopic analysis, conclusions about the impact of environmental instability on animals or about the geographical area of a location can be drawn.

Another important achievement can be attributed to Naito et al. [121], who analyzed the isotopic values of amino acids extracted from collagen, proving that carnivorous species such as cave bears (*U. spelaeus*) from Romania (in Eastern Europe) had a plant-based diet during cold periods. The $\delta^{15}N$ values of glutamate (which included the contributions of both glutamic acid and glutamine) and phenylalanine translated into high $\delta^{15}N$ levels for bulk collagen, a feature not seen in cave bears from other European areas, which could be accounted for through either a plant-based diet, a diet including plants with high $\delta^{15}N$ values, or a combination of both.

For isotope analysis to be relevant, it is necessary to first ensure the existence of viable biological material and, even more so, ensure that the original isotopic information has not been altered through post-mortem processes, such as the precipitation of secondary minerals or the adsorption of free ions from the burial environment [81]. The comparison of archaeological and modern bovine bones has allowed researchers to understand how the burial environment induces disorganization of collagen's secondary structure [122]. While fresh bones contain about 22 wt% collagen, fossils usually contain only about 1 wt% and have a ratio of atomic carbon and nitrogen ($C:N_{atomic}$) between 2.9 and 3.6. Generally, if the collagen level is below 1 wt%, and the carbon content is below 30 wt%, then the sample is considered to be deteriorated. On the other hand, if the carbon level is much greater than 35 wt%, then the sample is considered to be contaminated from the burial environment. Either way, it is agreed upon that no viable information can be retrieved from the sample. Current procedures to check for the existence of viable collagen are based on determining indices such as the total collagen yield, concentrations, and carbon-to-nitrogen ratios and amino acid analysis [81].

There are also some alternative methods to study the composition of fossils, including EPR, Py-GC-MS, or FTIR. Vibrational spectroscopy, either FTIR or Raman, is a very useful tool for the field of geosciences. Although they have the same functioning principle, the two methods do not exclude, but rather complement each other, given the fact that certain molecular vibrations can be permitted in Raman but forbidden in FTIR, and the other way around [123–126]. The vibrational modes of certain functional groups, such as C-O, C=O, C-N, N-H, O-H, are weak Raman scatterers, but have strong IR absorption, while other functional groups, such as C-H, S-H, C=S, C-C, C=C, are strong Raman scatterers. Thus, Raman spectroscopy is well-suited for studying the molecular frame, while FTIR is better suited for studying functional groups associated with organic macromolecules [50]. Although at times regarded with doubt [127], Raman spectroscopy is becoming a tool more and more encountered in scientific studies, due to its ease of use and versatile nature. Although infrared spectroscopy is not a new thing, it took more than a century from the discovery of the IR portion of the electromagnetic spectrum [128] to the first steps of what is now known as infrared spectroscopy, with the experiments performed at the beginning of the 20th century by W.W. Coblentz [129]. Soon after, commercial spectrometers followed

and have greatly improved since. The 1970s brought about the first commercial FTIR with a dedicated computer, considered the precursor of modern FTIR instruments [130], and the first commercial Raman microscope in 1977 [131], which has revolutionized the world of geology and materials science by enabling micro-scale molecular measurements [132]. However, one crucial aspect to be mentioned is the fact that correct spectral identification relies on access to good-quality spectral libraries [126].

Just like any other technique, infrared spectroscopy can have limitations, including the difficulty of differentiating between absorptions from inorganic matter of biological origin and those from permeabilization processes [67]. In certain cases, especially when samples have suffered diagenetic alterations, signals can overlap, making the correct spectral identification difficult or even impossible [133].

Similar to FTIR, Raman spectroscopy can be coupled with microscopy techniques, allowing the mapping of the surface of the investigated samples. Such combinations have the advantage that they do not require any sample preparation steps. On the other hand, the Raman signal, coming from the scattered radiation, is much weaker and harder to detect than in the case of IR spectroscopy, and it can often be influenced by other features of the sample (especially in the case of samples having strong fluorescence properties). Thus, Raman spectroscopy requires longer exposure time than FTIR spectroscopy, and also a stronger irradiation, preferably at multiple wavelengths. However, caution must be taken when selecting the laser parameters to not damaging the sample. Overall, although it can prove to be very useful for fossil analysis, Raman spectroscopy results generally still need to be validated or correlated with other techniques, and RS is rarely used as a stand-alone method in fossil studies.

Raman spectroscopy can be used as an alternate tool for isotopic analysis in paleotemperature estimation, as indicated by the study of Choi and co-workers [54], which have analyzed four different types of fossil amniotic eggshells using a complex protocol, including Raman spectroscopy, XRD, XRF, FTIR, and EBSD. Their study showed that Raman imaging can evidence the presence of carbonaceous material, through the graphite (G) and disordered carbon (D) bands, which can, in turn, be used to infer the maximum paleotemperature that the carbonaceous material has been subjected to [54]. Thermal maturation studies have lately caught the attention of researchers, who have exploited the relation between the maximum temperature that fossils have experienced during their history and their thermal maturity and color. Color analysis proves to be an easy and fast approach to understanding thermal maturation in fossils, as fossils' color darkens after exposure to high temperatures [54,134].

As recently proven by Rossi, Unitt, and McNamara [59], which have used multivariate statistical analysis to discriminate between tissues of different compositions, following their thermal maturation, Raman spectroscopy can be useful in identifying the biosignatures of fossils. Their study yielded good results, especially for melanin-rich tissues, as degraded melanin still retains a characteristic Raman band, which allows their differentiation from other types of tissues. Moreover, even slight shifts in the location and shape of the D and G bands can be linked to differences in the melanin-metal associations in various types of tissues.

A specific category is given by dating studies, for which several techniques have been used so far, including radiocarbon dating, luminescence techniques, dendrochronology, magnetic resonance, or nuclear techniques, such as NAA. Generally, these methods have certain limitations, either the need to sample a greater volume, the need for costly reagents, or the need to avoid erroneous results induced by contaminated samples or by manipulation procedures. Luminescence-based techniques, such as thermoluminescence, on the other hand, have proven great potential in this area of research, with radiation detection limits

as low as mGy, and even μGy, under certain conditions [135]. The comparison with standard techniques indicates a high precision, as long as the luminous centers have not been affected by light exposure post-excavation [72]. Dating studies can refer not only to geochronological dating but also thermal dating, a concept that refers to estimating the thermal age equivalent of a fossil sample, by normalization to a 10 °C constant temperature standard [105]. The notion of thermal age is based on the fact that temperature, and especially high-temperature variations, play a major role in the degradation of materials. Thus, it can be useful in understanding the preservation state of fossils.

Another type of spectroscopic method encountered in studies of fossilized materials is light-induced fluorescence spectroscopy. Although not used as much as other types of spectroscopic methods, it has proven useful for the level of oxidation in amber samples, for example, by using long-wave UV radiation (365 nm) and comparing the exhibited fluorescence with known samples. By using emission spectra and 3D excitation-emission maps, Li and co-workers [38] have established that the presence of carbonyl groups can be responsible for the high fluorescence but also for the quenching of the fluorescence emission, when it is linked to atoms having unpaired electrons, its concentration being inversely proportional to the intensity of the fluorescence signal.

3.2. Operability

Regarding the operability of equipment, in terms of functionality, reliability, and versatility, an important recent feature is the transition from single to multiple lines of investigation. Individual techniques have great merit in the study of fossils, especially in the case of clear, targeted, very specific inquiries. In such cases, single techniques can yield the necessary information. But this is not always the case, as many times, the research questions are either more complex, or ambiguous, or they can change as a function of the results. In instances like this, a multiple-techniques investigation protocol can be employed. This can be done by either using several techniques, one at a time, or by taking advantage of the technological breakthroughs of the past decades, which have led to the combination of 2 or 3 methods into a single equipment [46,136].

Scanning electron microscopy is one of the techniques encountered in the study of fossils, either as a stand-alone technique or in combination with energy-dispersive X-ray spectroscopy (SEM-EDS), or with focalized ion beam systems (FIB-SEM-EDS). Although having lower imaging resolution (~5 nm for FIB-SEM-EDS, as compared to ~1 nm for conventional SEM-EDS), such combinations offer enriched data, including also depth information and layered mapping, on the order of nm [137,138]. Overall, such techniques allow the user to obtain valuable qualitative and quantitative information regarding the chemical structure of the fossils, helping to evaluate their conservation state, and, in certain cases, to identify fossil species [60].

Another example is infrared spectroscopy, which can have many variations of the classical technique, such as micro-FTIR, which couples the analytical power of infrared spectroscopy with microscopy, offering the possibility to chart molecules of interest. SR-FTIR is yet another variation of the classical FTIR, which uses synchrotron radiation with FTIR capabilities, employing a more powerful source, which also leads to a better resolution [133]. Although generally the spatial resolution of FTIR techniques is limited to about 50 μm, it can be improved in combination techniques, to approximately 5 μm, as is the case with SR-FTIR [33]. Synchrotron radiation can be employed not only for FTIR, but also a great number of other analytical techniques, enabling the rapid and accurate detection of elements, or identifying molecular bonds and chemical groups not only at the surface of the sample but also in-depth, with increased spatial resolution and detection limits [139]. Nowadays, such facilities, which allow a diverse range of

experiments, exist throughout the entire world [140] and most of them operate in the US, Japan, and Germany. Synchrotron radiation occurs when electrons are forced to assume a curved trajectory, and is characterized by a very bright beam of high-intensity photons, covering the low-IR up to hard-X-rays domain. In fact, for the study of fossils, some of the most common applications of synchrotron radiation are for elemental mapping through XRF and 3D morphological imaging through CT [23,34,139,141]. The range of materials suitable for synchrotron analysis is vast, from biological molecules to synthetic materials [139,140]. In terms of paleontology, synchrotron radiation has helped analyze preserved organic molecules, map minerals and fossils, and create elemental maps down to the nano-scale, identifying the crystalline structure of minerals and chemical elements down to trace concentrations, discriminating between fossilized tissues based on their elemental concentrations [142–144]. As such, by using different synchrotron radiation-based techniques, researchers have been able to tackle a wide range of scientific questions, identifying metallic residues coming from melanic pigments, creating 3D images of fossils, or even mapping organic tissue patterns [25,145–147]. A very important result was obtained by Boatman and co-workers, who have used synchrotron radiation to obtain the first comprehensive chemical and molecular characterization of vascular tissues recovered from a T. rex specimen in 2019 [148].

3.3. Downscaling

When it comes to size, large-scale facilities such as synchrotrons, which span over several tens of kilometers, represent the pinnacle of analytical possibilities, offering unmatched sensitivity and resolution. Compared to such facilities, benchtop equipment, hand-held devices, and even smartphones are considerably smaller, reaching down to a few tens of centimeters.

As technical improvement is a continuous endeavor for humanity, the rapid progress made in the past decades has allowed the creation of new types of sensors with special properties. Thus, increasingly compact components can be built and incorporated into lightweight, portable, and even handheld equipment. The development of micro/nanoelectromechanical systems (MEMS/NEMS), along with the advances in nanotechnology, and the integration of IoT and AI in the past decades, has paved the way for the development of miniaturized, ultra-small sensors [149–151]. As a consequence, modern compact, low-power sensors are commonly used in portable spectrometers, enabling manufacturers to reduce the size of equipment and, therefore, enhance their transportability. Moreover, one of the most impacted areas is probably the field of micropaleontology, which has greatly benefited from the introduction of miniaturized, high-precision technologies.

Typically, the advantage of portability entails a trade-off in spectral resolution, as portable instruments are constrained by the use of compact optics and miniaturized sensors, resulting in lower resolution compared to their benchtop counterparts. Benchtop systems, equipped with advanced optical components and more sophisticated detection architectures, achieve higher spectral fidelity and offer superior analytical control. Additionally, the penetration depth of portable devices is generally shallower, limiting their capacity for subsurface characterization. However, while benchtop instruments benefit from greater precision and often support more complex analytical workflows, they also require longer acquisition times due to higher data density, necessary sample preparation steps, and the use of high-resolution optics. In contrast, portable systems are optimized for rapid, in-situ screening, delivering results within seconds and typically requiring minimal to no sample preparation, making them particularly suited for preliminary assessments or field-based diagnostics. So, while large equipment offers higher resolution and sensitivity, portable devices deliver rapid and still reliable data. Although not directly helpful for

increasing sensor efficiency, detection limits, and signal-to-noise ratio [152], the miniaturization of sensors has helped revolutionize fieldwork across many disciplines, including paleontology and related fields, where lightweight analytical tools offer researchers reliable data on-site without compromising fossil integrity.

Advances have come so far that nowadays, even smartphones can be transformed into scientific equipment. For instance, smartphone-based colorimetry has been employed as a screening tool in the food safety industry [153,154] while smartphone-based imaging devices are being used in medical diagnosis, for the detection of various pathologies, and patient monitoring [155–158]. This also extends to various industry branches [159,160], demonstrating how the miniaturization of sensors reshapes analytical approaches. Moreover, the integration of smartphones into citizen science has been enhanced by the development of dedicated applications for the recognition of specific types of fossils [161,162]. Such applications are freely available now and can enhance the public's awareness of fossil recognition, preservation, and environmental concerns.

3.4. AI Integration

Driven by the difficulties of analyzing complex multispectral data, chemometric analysis has been developed [163–165], based on supervised or unsupervised methods, which, in turn, have evolved into deep-learning models [166]. Currently, deep learning methods enable artificial intelligence (AI) to perform complex tasks and are used in many scientific areas [167–169] and have proven to be valuable tools in the field of spectroscopic data. Deep learning relies on artificial neural networks (ANNs, NNs), which use mathematical equations, software, or electronic circuits and are designed to simulate the way the human brain works [170,171]. Such algorithms have multiple layers, allowing AI models to extract information, interpret large datasets, and find unseen patterns, reducing the time needed to process large datasets [172]. Even though accurate results require time and a strong database to train such algorithms, studies have shown that transfer learning and data augmentation can overcome this need [173].

With the new wave of generative models, including large multimodal models, image-generating models, code, and video-generating models [174–179], AI has become more intelligent and adaptable to a large diversity of applications. Furthermore, going into the realm of paleontology, a recent study has demonstrated the ability of a generative AI chatbot to analyze large geological datasets and recognize fossils, minerals, and rocks, matching the performance of trained scientists [180]. The GPT-based model developed by Baucon and de Carvalho [180] has successfully performed a multitude of science-related tasks, such as scientific writing of PhD-level abstracts, interpretation of scientific data, developing new research ideas, formulating research outlines, and academic coaching and teaching. AI and model chatbots can have multiple uses, from teaching to generating scientific ideas, and even completing missing links in the evolutionary timeline, all of which are as qualitative as the input dataset that has been used to train the AI [4,6,180]. To address concerns about training bias and dataset limitations, ongoing studies emphasize the importance of curating domain-specific datasets, incorporating expert feedback loops, and implementing explainability tools to ensure transparent and reproducible AI-driven classifications in paleontological contexts.

4. Conclusions and Future Perspectives

A growing trend in the past decades appears to be that of imaging techniques, which can be easier to understand and interpret, a trend in multiple areas, including paleontology. Thus, more and more techniques have been adapted to the visual requirements imposed by the users, allowing a more complex and more useful evaluation [32,57,181]. Especially

when dealing with non-homogeneous samples, such as fossils, imaging techniques can be useful for understanding the spatial distribution of components, at the micro or even nano-scale [26]. Nowadays, there is a quite large variety of imaging methods, some of which have already proven their efficiency for the study of fossils, and some which hold great potential to be applied in the near future, both destructive (such as LA-ICP-MS imaging or SIMS variations) and non-destructive techniques (FTIR/Raman/XRF/EDX imaging, EBSD, XANES).

Although destructive methods remain widely used, due to their proven sensitivity and reliability, the recent advancements in spectroscopic and imaging methods, along with the integration of AI-assisted data interpretation, reinforce the shift towards non-destructive, non-invasive approaches. This is an effort that the scientific community must achieve soon, to reverse the balance, by investing in developing new and more reliable non-destructive methods and by refining existing ones to replace the gold standard methods, which not only require sampling but also no longer allow the recovery of the sample after the analysis. Moreover, an increasingly recent trend brought upon by the improvement of miniaturized sensors and detectors is the use of smartphones, as either control units, through dedicated applications, or as actual analysis devices, at times coupled with AI tools for increased accuracy [156]. Of course, such tools cannot, at least at this moment, compete with standard equipment, which offers improved resolution and far more stability and precision. However, if future developments overcome the present smartphones' limitations in terms of imaging, magnification, resolution, detection limits, and computational power, it will probably be only a matter of time before smartphones can become viable tools for fossil evaluation, as well.

Given the non-renewable character of fossils, sustainable research practices are becoming mandatory. This generates a three-tiered roadmap (Figure 4), which frames the analytical tools in terms of preservation impact and technological evolution. Thus, a paradigm shift emerges from traditional methodologies—such as stable isotope analysis for paleoclimatic reconstruction, thin-section petrography for microstructural examination of fossilized tissues, or acid preparation for the extraction of fossils from calcareous matrices—which, while historically foundational, often entail irreversible physical or chemical alterations to the specimens. In contrast, contemporary fossil analysis increasingly emphasizes noninvasive, non-destructive, and portable approaches to maximize the preservation of fossil integrity. Techniques such as micro-computed tomography (micro-CT) and synchrotron radiation X-ray fluorescence (SR-XRF) now allow researchers to visualize internal structures and elemental distributions without compromising the specimen's integrity. Portable Raman spectroscopy and hyperspectral imaging are being deployed in the field for rapid, in situ characterization of mineralogical and organic components.

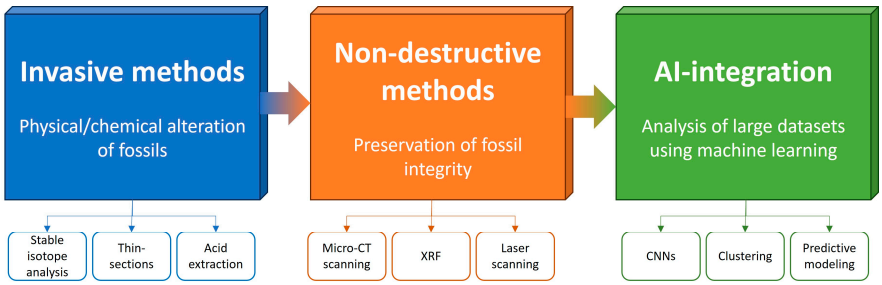


Figure 4. Visual roadmap and selected examples of fossil analytical research—past, present, and future—from invasive geochemical and physical methods to advanced, integrative digital approaches powered by non-destructive technologies and AI-assisted interpretation.

Moreover, the integration of artificial intelligence—particularly machine learning algorithms trained on digitized fossil databases—enables the automated classification of fossil morphologies, the detection of taphonomic signatures, and the prediction of paleoenvironmental conditions with increasing accuracy. Chatbot-based interfaces further support data curation, retrieval, and annotation, fostering more accessible, collaborative, and real-time engagement with large, multimodal paleontological datasets. These innovations mark a decisive transition toward a digitally augmented, conservation-oriented fossil science that aligns with open science principles and heritage preservation ethics (Figure 4).

As a general conclusion, it can be said that there is currently a great diversity of analytical techniques that have been employed for the study of fossil remains. Although current standards demand the use of complex, highly time- and cost-consuming methods, there are also many noninvasive or non-destructive, easy-to-use, more economical, and ecological alternative variants. The choice of the most appropriate method from this multitude of available techniques is not always a straightforward, easy process, and it must take into account several parameters. These include the aim of the study, the type of information that is being sought, the available resources, and the level of invasiveness that is agreed upon [46]. Overall, the last few decades, along with the diversification of techniques, have brought about a better understanding of the dynamic processes associated with the long-term storage of fossil remnants and the habitual traits of extinct organisms. Moreover, there is also the need for experts with trans-disciplinary skills able to understand and interpret such complex sets of data, especially given the advent of artificial chatbots, which have started to tackle the field of geosciences. This is still an area whose potential is yet to be fully explored, an area that will undoubtedly lift existing barriers and open new, unforeseen paths in the study of fossils while still maintaining strong ethical conduct and balancing the high economic costs and environmental impact associated with the use of AI.

Although much is yet to be discovered regarding Earth's fossils, another direction that is being exploited for more than a decade now, and will probably increase in the future targets the analysis of extraterrestrial fossils. For instance, the Perseverance and Curiosity rovers sent to Mars are equipped with a variety of analyzing instruments, including X-ray- and laser-based techniques for the analysis of chemical elements and mineralogical composition of Martian rocks, and the analysis of organic matter traces. Unlike Earth's fossil record, which is mainly made up of high-preservation potential fossils, due to the conditions on Mars and its geological history, it is highly improbable that such complex life remains will be found on Mars. More probably, the fossil record there will be reduced to anaerobic microbes [182]. Despite this fact, with the possibility of finding fossils on Mars hinted about three decades ago [183–185], and reinforced by recent discoveries [186,187], the analysis of Martian samples upon their retrieval from space will hopefully identify the presence of past life forms on Mars and find if there are any similarities between Earth fossils and extraterrestrial ones.

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Abbreviations

The following abbreviations are used in this manuscript:

CT	computed tomography
DNA	deoxyribonucleic acid
DSC	differential scanning calorimetry
EBSD	electron backscatter diffraction
EPR	electron paramagnetic resonance
FIB-SEM-EDS	focused ion beam-scanning electron microscopy coupled with electron backscatter spectroscopy
FTIR	Fourier transform infrared spectroscopy
LA-ICP-MS	laser ablation-inductively coupled plasma-mass spectrometry
NAA	neutron activation analysis
NANO-SIMS	nanoscale secondary ion mass spectrometry
nCT	nano-computed tomography
PCCT	phase-contrast computed tomography (photon-counting computed tomography)
PIXE	particle-induced X-ray emission
Py-GC-MS	pyrolysis-gas chromatography-mass spectrometry
REE	rare-earth element
RS	Raman spectroscopy
SAXS	small-angle X-ray scattering
SEM	scanning electron microscopy
SEM-EDS	scanning electron microscopy coupled with electron backscatter spectroscopy
SIMS	secondary ion mass spectrometry
SR-FTIR	synchrotron radiation-based Fourier transform infrared spectroscopy
TEM	transmission electron microscopy
TGA	thermogravimetry
TOF-SIMS	time-of-flight secondary ion mass spectrometry
XANES	X-ray absorption near edge structure
XAS	X-ray absorption spectroscopy
XEOL	X-ray excited optical luminescence
XRD	X-ray diffraction spectroscopy
XRF	X-ray fluorescence spectroscopy
XRF-μCT	X-ray fluorescence spectroscopy-micro-computed tomography
μCT	micro-computed tomography
(μ-)XRF	micro-X-ray fluorescence spectroscopy
XRS	X-ray-induced Raman spectroscopy

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