

## Knowledge about Molecular Paleontology among high school students in Southern Brazil

Conhecimento sobre Paleontologia Molecular entre estudantes do Ensino Médio do Sul do Brasil

Conocimiento sobre Paleontología Molecular entre estudiantes de secundaria en el sur de Brasil

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### Abstract

This work is the result of exploratory and descriptive research, with quantitative nature of data, which aimed to investigate the knowledge of high school students in southern Brazil about aspects related to Paleontology in general and, more specifically, to the basic concepts of Molecular Paleontology. The sample group consisted of 52 high school students of 2<sup>nd</sup> grade from two private schools located in the municipalities of Araucária (PR) and Palhoça (SC), southern Brazil. Data were obtained through a structured online questionnaire, prepared via the *Google Forms* platform, consisting of 21 objective multiple-choice questions. The analysis of the questions was performed using descriptive statistics to examine the frequency of responses distributed in the three categories of analysis: 1) *socioeconomic characteristics*, 2) *general knowledge about Paleontology* and 3) *specific knowledge about Molecular Paleontology*. The results demonstrate that the students' answers on basic concepts of Molecular Paleontology are consistent with the data available in the scientific literature, which demonstrates that high school students are able to acquire and apply complex contents related to molecular biology, fossils, and evolution in a school environment. Since there are few studies that sought to investigate the understanding of basic education students about Paleogenomics and Paleoproteomics subjects, it is clear that the data presented here may fill a gap in the existing knowledge in our country.

**Keywords:** Teaching paleontology; Basic education; Exceptional preservation; Nonmineralized biomaterials; Soft tissue; Fossil biomolecules; Ancient DNA.

### Resumo

Este trabalho é fruto de uma pesquisa exploratória e descritiva, de natureza quantitativa de dados, que teve por objetivo investigar o conhecimento de estudantes do Ensino Médio do sul do Brasil sobre aspectos relacionados à Paleontologia em geral e, mais especificamente, aos conceitos básicos da Paleontologia Molecular. O grupo amostral foi composto por 52 estudantes da 2ª série do Ensino Médio, de duas escolas privadas, localizadas nos municípios de Araucária (PR) e Palhoça (SC), região sul do Brasil. Os dados foram obtidos através de questionário estruturado on-line, elaborado via plataforma *Google Forms*, composto de 21 questões objetivas de múltipla escolha. A análise dos questionamentos foi feita utilizando-se de estatística descritiva para exame da frequência de respostas distribuídas nas três categorias de análise: 1) *características socioeconômicas*, 2) *conhecimentos gerais sobre Paleontologia* e 3) *conhecimentos específicos sobre Paleontologia Molecular*. Os resultados demonstram que as respostas dos estudantes sobre conceitos básicos da Paleontologia Molecular encontram-se coerentes com os dados disponíveis na literatura científica, o que demonstra que os alunos do Ensino Médio são capazes de adquirir e aplicar conteúdos complexos vinculados à biologia molecular, fósseis e evolução, em ambiente escolar. Uma vez que são raros os estudos que buscaram investigar a compreensão de alunos da educação básica a respeito de assuntos da Paleogenômica e

Paleoproteômica, percebe-se que os dados aqui apresentados poderão suprir uma lacuna do conhecimento existente em nosso país.

**Palavras-chave:** Ensino de paleontologia; Educação básica; Preservação excepcional; Biomateriais não mineralizados; Tecidos moles; Biomoléculas fósseis; DNA antigo.

### Resumen

Este trabajo es el resultado de una investigación exploratoria y descriptiva, con una naturaleza cuantitativa de datos, que tuvo como objetivo investigar el conocimiento de estudiantes de secundaria en el sur de Brasil sobre aspectos relacionados con la Paleontología en general y, más específicamente, con los conceptos básicos de la Paleontología Molecular. La muestra estuvo compuesta por 52 estudiantes de 2º grado de secundaria de dos escuelas privadas ubicadas en las ciudades de Araucária (PR) y Palhoça (SC), sur de Brasil. Los datos se obtuvieron a través de un cuestionario online estructurado, elaborado por medio de la plataforma Google Forms, compuesto por 21 preguntas objetivas de opción múltiple. El análisis de las preguntas se realizó mediante estadística descriptiva para examinar la frecuencia de respuestas distribuidas en las tres categorías de análisis: 1) características socioeconómicas, 2) conocimientos generales sobre Paleontología y 3) conocimientos específicos sobre Paleontología Molecular. Los resultados demuestran que las respuestas de los estudiantes sobre conceptos básicos de Paleontología Molecular son consistentes con los datos disponibles en la literatura científica, lo que demuestra que los estudiantes de secundaria son capaces de adquirir y aplicar contenidos complejos relacionados con biología molecular, fósiles y evolución en un ambiente escolar. Dado que son pocos los estudios que buscaron investigar la comprensión de los estudiantes de educación básica sobre temas de Paleogenómica y Paleoproteómica, se nota que los datos aquí presentados pueden llenar un vacío en el conocimiento existente en nuestro país.

**Palabras clave:** Enseñanza de paleontología; Educación básica; Preservación excepcional; Biomateriales no mineralizados; Tejido blando; Biomoléculas fósiles; ADN antiguo.

## 1. Introduction

Information regarding the most recent scientific discoveries in the field of Biology, Paleontology, Chemistry and related areas of geosciences is widely disseminated from the academic environment to the general public through the media and pop culture (Jones, 2019), the latter understood here as experiences and products that become popular from the media logic, being linked to the culture and cyberculture industries (Soares, 2014).

It is known that the approach of biogeoscientific concepts in the school environment is much more influenced by images broadcast by cinema and the media than by scientific publications, which are mostly restricted to the academic community (Schwanke & Silva, 2010). The teaching of genetics and molecular biology, for example, has stood out, when associated with Paleontology, due to the increase in biotechnological information disseminated by the film industry (Machado & Meirelles, 2018; Jones, 2019).

In this context, science fiction films such as those in the franchise *Jurassic Park* and *Jurassic World* continue to be an inspiration for many future scientists (Jones, 2019). Despite the presence of certain inconsistencies (Haupt & Traer, 2017), the trilogies have served as excellent didactic resources for the appropriation and resignification of complex scientific concepts, since they provide essential paleobiological information related to structuring educational content such as “Biological Mechanisms” and “Genetic Manipulation”, present in State Curriculum Guidelines (Lazzarin, Christofoletti & Scheifele, 2020), in addition to, mainly, promoting Specific Competencies 2 and 3 in the area of Nature Sciences and Their Technologies (CNT), guided by the National Common Curriculum Base (BNCC) (Alves, Gomes & Machado, 2021; Brasil, 2018).

Take, for example, the first film in the *Jurassic Park* franchise, released in 1993, based on the book of the same name by Michael Crichton. In a classic scene, it is demonstrated, almost as in a scientific prediction, the possibility of finding preserved DNA molecules from dinosaurs. In the film, these molecules, collected in a prehistoric mosquito trapped by a plant resin (fossilized as amber), are used to reconstruct the dinosaur genome and bring these animals back to life (Crichton, 1990; Gomes-Maluf & Souza, 2008).

However, this prediction was not random; on the contrary, it was based on evidence already available in the 1980s concerning findings of organic molecules found in mammalian fossils (Higuchi et al., 1984) and on independent speculations

in professional contexts and in the media (Pellegrino, 1985), well before the release, in 1990, of the now famous book *Jurassic Park*, which came to life in theaters from 1993 onwards. Therefore, subsequent films in the *Jurassic Park* and *Jurassic World* trilogies were and still are based on concepts from *Molecular Paleontology* (Alves, 2022), and, by the way, helped to develop the science and technology behind ancient DNA research (Jones, 2019; Chimes & Vieira, 2021).

*Molecular Paleontology*, an emerging interdisciplinary field of study, related to the area of *Taphonomy*, aims at the recovery, identification, and characterization of traces of organic molecules found in the fossil record, with the aid of distinct advanced molecular techniques of ultrastructural detection (Alves, 2022; Buckley, 2018; Boskovic et al., 2021). This area of research can be worked from two possible approaches to investigation at the molecular level: *Paleogenomics*, which studies ancient DNA (aDNA), and *Paleoproteomics*, which studies ancient proteins (Alves, 2022). In this way, it contributes, for example, to the understanding of the biology of past fauna and flora, to the identification of species, and to the analysis of the evolutionary relationships of groups of extinct beings.

In a way, the importance of this topic of study contrasts with the difficulties faced in its assimilation by pre-university students. At the same time that the teaching of general concepts of *Molecular Paleontology* to students at the most basic levels (Elementary and High School) is encouraged and welcomed by researchers in the area (Alves, 2021a, 2021b), others point out that the absorption of concepts related to fossilization, such as biogeochemical processes and time scales, can be challenging, especially if students are not familiar with aspects of physiology and ecology of organisms, in addition to the concept of geological time (Kortz & Murray, 2009; Martindale & Weiss, 2020). Therefore, in order for methods of approaching the subject to be developed and applied satisfactorily, a prior understanding of the level of knowledge that students have in relation to these topics is essential.

In this sense, it is observed that there are few available studies that prioritized the investigation of the level of knowledge of Basic Education students about *Molecular Paleontology* subjects. This is a problem that deserves attention, since these data allow us to know the profile of the student and their interests and to establish guidelines for teachers through a basic content that explains what *Molecular Paleontology* is and what is its importance for the understanding of evolution and /or diversification of life throughout the history of the planet (Alves, Gomes & Machado, 2021). From this, it becomes possible to mediate a significant learning process for students with a view to building skills and abilities that should compose the knowledge baggage of future university students.

That said, the objective of this study was to investigate the knowledge of high school students in southern Brazil about aspects related to *Paleontology* in general and, more specifically, to the basic concepts of *Molecular Paleontology*.

## **2. Materials and Methods**

An exploratory and descriptive study with quantitative nature of data was carried out. According to Gil (2010), exploratory research aims to provide greater familiarity with the problem, in order to make it more explicit or to build hypotheses, including searching for information through bibliographic survey and data collection instruments.

The descriptive character of the study, in turn, has as its main objective the description of the characteristics of a certain population or phenomenon (Gil, 2010). To this end, in this case, the procedures include systematic collection of information, following steps of recording, describing, analyzing, and interpreting complex phenomena from a social perspective, without, however, interfering with the facts (Moreira, 2011; Ramírez-Montoya et al., 2021).

The ethical principles disciplined by Resolution 466/2012 of the National Council of Ethics in Research (CONEP) (Brasil, 2012) were complied with, as the research participants were clarified about the objectives of the study, being assured confidentiality, anonymity, willingness to participate or not in the study, and permissions to use the information for academic purposes.

## 2.1 Data collection instruments and procedures

The collection of information took place through a structured online questionnaire, prepared via the Google Forms platform. The electronic form link was shared with students on June 20 and 23.

The instrument was composed of 21 objective multiple-choice questions that explored three units of analysis: (1) socioeconomic characteristics of the participants, (2) general knowledge about Paleontology, and (3) specific knowledge about Molecular Paleontology.

The collected data were stored in a database in the Microsoft Excel program for further analysis.

## 2.2 Participants

The target population consisted of 2<sup>nd</sup> grade high school students from two private schools located in central areas of the municipalities of Araucária-PR (n=22) and Palhoça-SC (n=30). The inclusion criteria adopted in this study were as follows: (1) students should have an active e-mail account, and (2) be regularly enrolled in the second grade of the last stage of Basic Education. The latter is justified because, in the last decade, textbook authors have been inserting some elements of Molecular Paleontology associated with evolution and biotechnology contents (Paleoproteomics and Paleogenomics) in Biology textbooks for the final years (2<sup>nd</sup> and 3<sup>rd</sup> grades) of High School (Linhares, Gewandsznajder & Pacca, 2016; Lopes & Rosso, 2016).

Furthermore, it is understood that students who are in this stage of study have previously seen fundamental contents of the subjects of Chemistry of Life, Cell Biology, Evolution, Genetics, and Molecular Biology (Alves, Gomes & Machado, 2021). The knowledge from these disciplines is essential for understanding basic paleomolecular concepts and the composition, structure, and function of the objects of study in this area, since, roughly speaking, "Molecular Paleontology is just the identification of Molecular Biology of ancient materials, with some modifications suffered in the process of formation of the rocks" (Ibid., p. 124).

## 2.3 Data analysis

For the evaluation of the questions, a standard template of what was expected as an answer was used. Descriptive statistics were used to examine the frequency of responses to research questions distributed across the three categories of analysis. The analysis of the examined items was described in graphs, using simple percentages.

## 3. Results and Discussion

The frequency of student body responses for the categories selected in the survey is described below.

### 3.1 Socioeconomic aspects

Of the 52 participants involved in the study, 30 (57.7%) identified themselves as female and 22 (42.3%) as male. It was observed that, of the total number of students, 84.6% of them do not have a job, while the rest (15.4%) work, although they still depend financially on their guardians. As for the intention to attend Higher Education, 73.1% of them say they want to attend an undergraduate degree, while 26.9% consider not knowing how to respond at the moment. Regarding reading habits on general subjects, 40.4% of students report reading occasionally, followed by those who read daily (28.8%), weekly (9.6%), and those who do not cultivate the habit of reading (21.2%).

### 3.2 General knowledge about Paleontology

#### 3.2.1 Previous contact with Paleontology contents

It was observed that 80.8% of the students declared having studied paleontological subjects at some school stage, followed by those who did not remember (13.5%) and those who declared not having studied paleontological themes at any school stage (5.7%).

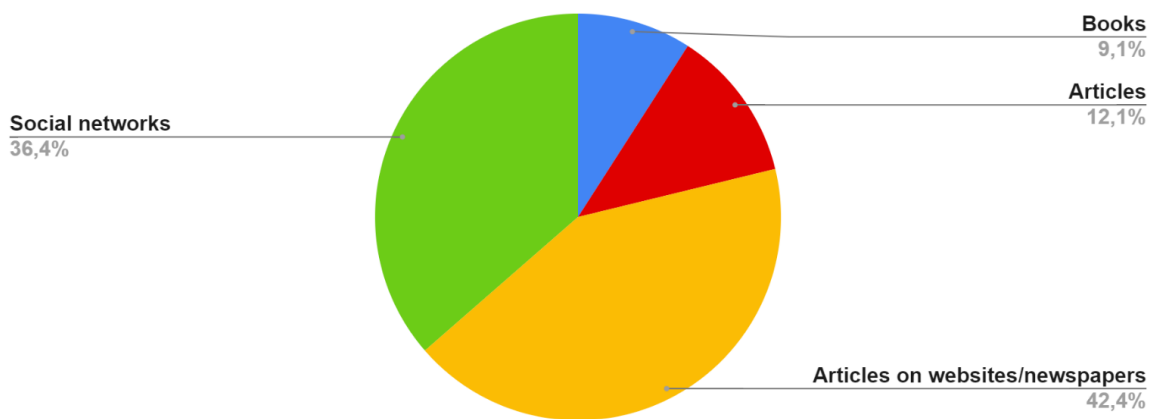
These results stand out when compared with data available in the scientific literature, which show that most high school students from public schools in other regions of the country have never heard of paleontology at school (Mendes, Nunes & Pires, 2015; Duarte et al., 2016; Santos, Moreira & Fernando, 2018).

A possible explanation for the fact that this study found such a high number when compared to previous studies is that it was carried out in private educational institutions, which could reflect the disparity that still exists today in the level of learning between the profiles of students in the public and private Brazilian education network (Brasil, 2021; França & Feijó, 2021), in addition to the possibility that the teachers of these schools had previously planned their classes in order to address bio-paleontological issues.

#### 3.2.2 Sources and reading habit on paleontological subjects

Students were also asked about their habit of reading information on paleontological subjects. The results show that, when asked directly about it, 78.8% of students answered that they do not usually read about Paleontology, while the remaining 21.2% are those who seek information on the subject. When answering about the preferred place for reading about Paleontology, 36.5% did not indicate any, while 63.5% of the students identified a preferred place for reading. Of this 63.5%, the majority (42.4%) reported finding information in articles on websites and/or newspapers, followed by social networks (36.4%), articles (12.1%), and books (9.1%) (Figure 1).

**Figure 1** - Distribution of high school students according to sources of knowledge acquisition on Paleontology (n=33).



Source: Authors (2022).

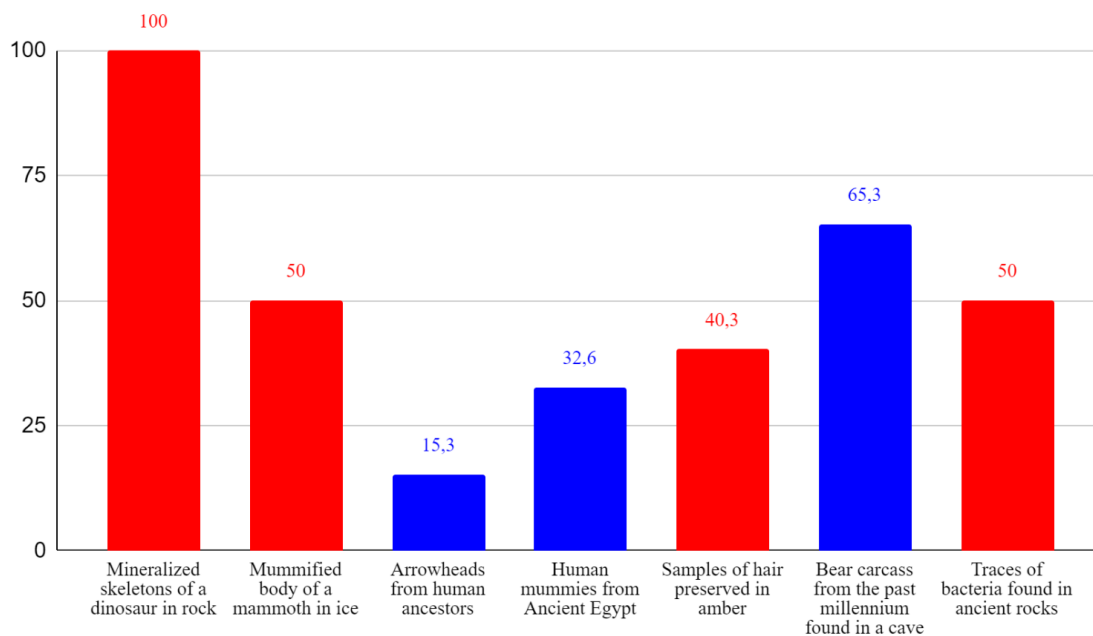
Previous studies carried out with high school students from the northeast region of Brazil showed that most participants from this region of the country obtain information about paleontology from documentaries and films (Santos, Moreira & Fernando, 2018; Araújo & Siqueira, 2020), leaving as secondary the habit of reading. The explanation for the difference found with the data of this study could be the socioeconomic disparity since the studies were carried out with students from public schools in small municipalities in which the encouragement of reading may not be prioritized.

### 3.2.3 Ability to identify a fossil

When the students were asked if they know the meaning of the term *fossil*, the vast majority (98.1%) answered that they were able to distinguish what is or is not a fossil, while only 1.9% declared not knowing the term.

Students were also asked to select, among predetermined topics, the elements that they consider to be a fossil, with the possibility of indicating more than one option per answer. The results showed that, for students, the fossils can be represented by mineralized skeletons of a dinosaur in rock (100%), followed by those who understand the fossils as a bear carcass from the past millennium found in a cave (65.3%), a mummified body of a mammoth in ice (50%), traces of bacteria found in ancient rocks (50%), samples of hair preserved in amber (40.3%), human mummies from Ancient Egypt (32.6%) and arrowheads from human ancestors (15.3%) (Figure 2).

**Figure 2** - Relative distribution of high school students according to perception of the fossil concept (n=52). Legend: columns in red: fossils, columns in blue: non-fossils; Y axis in percentage.



Source: Authors (2022).

In general, divergence can be seen in the students' answers regarding their previous concepts acquired about the fossils, because at the same time that half (50%) of them indicated the preserved body of a mammoth in the ice as being a fossil, another 65.3% associated it with a bear carcass from the last millennium found in a cave and 32.6% also considered human mummies from Ancient Egypt. This reveals what some authors (Novais, 2018; Borsonelli & Rodrigues, 2019; Duarte et al., 2019) have already mentioned, the fact that archaeological and paleontological concepts end up being confused in the minds of high school students and even among teachers.

Among these results, some conceptions stand out, as in the case of dinosaurs in rock, in which 100% of them correctly associate this option with a type of fossil. The reason for this can be explained by the focus given to the biological element associated with the rock, that is, dinosaurs, as they are animals that are already part of popular culture due to their wide media representation (Gomes-Maluf & Souza, 2008; Schwanke & Silva, 2010; Lucena, 2013; Borsonelli & Rodrigues, 2019).

This influence that the media exerts on the process of cultural appropriation of scientific concepts is important for the mediation of student learning (Gomes-Maluf & Souza, 2008), although the concepts portrayed in the media are not always presented with scientific accuracy (Schwanke & Silva, 2010). For example, a problem involved in the representation of



dinosaurs in animations is the coexistence between non-avian and human dinosaurs in the same time and space, which generates doubts and conceptual confusion about the correlation between fossils and deep time (Rosa, Oliveira & Rocha, 2018; Borsonelli & Rodrigues, 2019).

As a result, the learning of paleontological concepts by high school students ends up becoming fragmented (Santos, Moreira & Fernando, 2018). In this study, it is observed, for example, that students make conceptual errors when associating fossils with elements of Archeology study, such as the bear carcass from the millennium spent in a cave, human mummies from Ancient Egypt, and arrowheads of human ancestors.

Therefore, in view of these results, it is understood that it is essential that teachers develop teaching strategies that seek to incorporate media resources into everyday pedagogical practices in classroom environments (Schwanke & Silva, 2010), with rigor and scientific and critical analysis in the selection of the contents (Schwanke & Silva, 2010; Lucena, 2013), and work on the topic from an interdisciplinary approach (Calheiros & Maia, 2022), in order to achieve significant learning about the concepts of fossils.

### 3.2.4 The experience with the trilogy *Jurassic Park*

As for the experience of having watched films from the *Jurassic Park* franchise, 82.7% of the students responded that they had the opportunity to see at least one of the films, while only 17.3% responded that they had not yet watched any of them.

It is observed that, even though it was a trilogy released in the early 1990s, it still influences current generations, including the *generation Z* (Gen Z) analyzed in this work. This generation is characterized by individuals born between 1996 and 2012 (Fernández-Cruz & Fernández-Díaz, 2016). Students of this generation are known to be digital natives, their main characteristics being: 1) experts in the understanding of technology; 2) multitasking; 3) socially open from digital platforms and social networks; 4) like instant answers and solutions; 5) are interactive.

That is why it is not always easy to understand the position that the school should adopt in the teaching and learning process of these young people (Fernández-Cruz & Fernández-Díaz, 2016). However, studies that aim to investigate the levels of knowledge of Gen Z about scientific conceptions linked to pop culture become useful to outline learning strategies, with the purpose of transporting this culture to the classrooms (Añez, 2017; Rodrigues, 2020).

In the case of this study, it is clear that *Jurassic Park*, as an element of pop culture, continues to be a relevant source of information to be used by Brazilian teachers in classroom environments as a strategy for discussing and improving innovative concepts of Paleontology (Borsonelli & Rodrigues, 2019).

## 3.3 Knowledge about Molecular Paleontology

### 3.3.1 Familiarity with the terms *Molecular Paleontology* and *Soft tissues*

When asked if they had heard about Molecular Paleontology, the majority (61.5%) of the student body declared that they were not familiar with this term, while the rest (38.5%) indicated they knew it. On the other hand, when asked if they have read or heard about the findings of “soft tissues”, that is traces of tissues, blood vessels, cells, proteins, and/or DNA, among other original biomolecules, in fossils of extinct animals, the majority (67.3%) of the students answered in the affirmative, while the rest (32.7%) had never read or heard about it.

The expression *soft tissues* is a generalized informal term that was incorporated into public language due to the influence of the media in its application in articles and *releases* (Alves, 2022). The equivalent technical term that has been used in scientific communications in the field of Molecular Paleontology is *nonmineralized biomaterials* (Thomas & Taylor, 2019; Alves & Machado, 2021a, 2021b, 2021c; Gomes, Machado & Alves, 2022).

The *nonmineralized biomaterials* can be defined as

a set of biological materials that include soft tissues, cells, organic molecules, and/or their degradation products, at the level of functional groups useful for tracking the original molecule, which are not originally biomineralized tissues (e.g., bones and teeth) and, somehow, were not replaced by minerals during fossilization (Alves & Machado, 2021a, p. 2).

However, for this investigation, we chose to use the expression *soft tissues* because it is a concept that fell into popular taste under the influence of the media, to verify if the students actually knew the objects of study of Molecular Paleontology, that is, the traces of endogenous and original organic materials, however, from a common name closer to their realities.

This is because, currently, it is known that the media not only plays the role of disseminating information but also that forming opinions and concepts (Schwanke & Silva, 2010). In the case of education, students' conceptions are predominantly marked by what they read in information vehicles and by cinematographic images.

In this context, the students' answers allowed us to understand that the strategy established here worked, since most of them demonstrated to know the popular term *soft tissues*, contrary to what happened when they were asked about the technical term *Molecular Paleontology*, the name of the scientific field that they, for the most part, have never heard or read about.

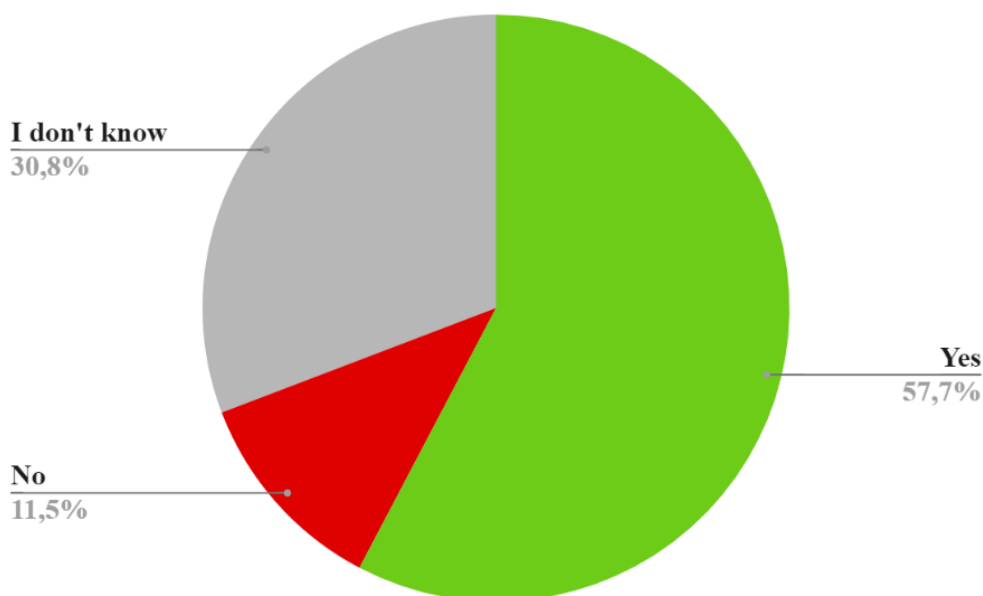
Throughout the remainder of this work, we will use the terms “soft tissues”, “original biomaterials”, and “nonmineralized biomaterials” interchangeably to refer to the exceptionally preserved findings of different types of trace organic materials (tissues, cells, and molecules) endogenous and original.

### **3.3.2 Possibility of recovering organic material in fossils**

Students were also asked whether they believe it is possible to recover traces of “soft tissues” from exceptionally well-preserved fossils. The majority (57.7%) of the students say that it is possible to find evidence of these organic materials inside fossilized remains, followed by those who did not know how to respond (30.8%) and those who really do not believe in this possibility (11.5%) (Figure 3).



**Figure 3** - Distribution of high school students according to the perception of the possibility of recovering traces of endogenous biomaterials in fossils (n=52).



Source: Authors (2022).

Although almost 60% of students understand that it is possible to find “soft tissues” in well-preserved fossils, it is known that Molecular Paleontology subjects are still not part of the daily life of students in a school environment.

When interviewed, experts in the field suggest some simple but effective ideas to be used by teachers in the classroom during biology classes, in the absence of addressing this content in textbooks. For example, the Polish molecular taphonomer, Dawid Surmik, assistant professor and member of the Research Group on Paleoecology and Taphonomy, Institute of Earth Sciences, Faculty of Natural Sciences, University of Silesia, proposes that

The disciplines of [...] Biology [...] must bring elements that allow the student to understand that the fossil record, sometimes, preserves more than hard tissues - bones and teeth. This will certainly make the curriculum more attractive! Young people are eager to learn and, of course, everyone would like to find dinosaur DNA (Alves, 2021a, p. 3-4).

For Colombian molecular paleontologist Edwin Cadena, associate professor of the Postgraduate Program in Earth System Sciences and member of the Research Group on Traditional and Molecular Neotropical Paleontology at the Universidad del Rosario (Bogotá),

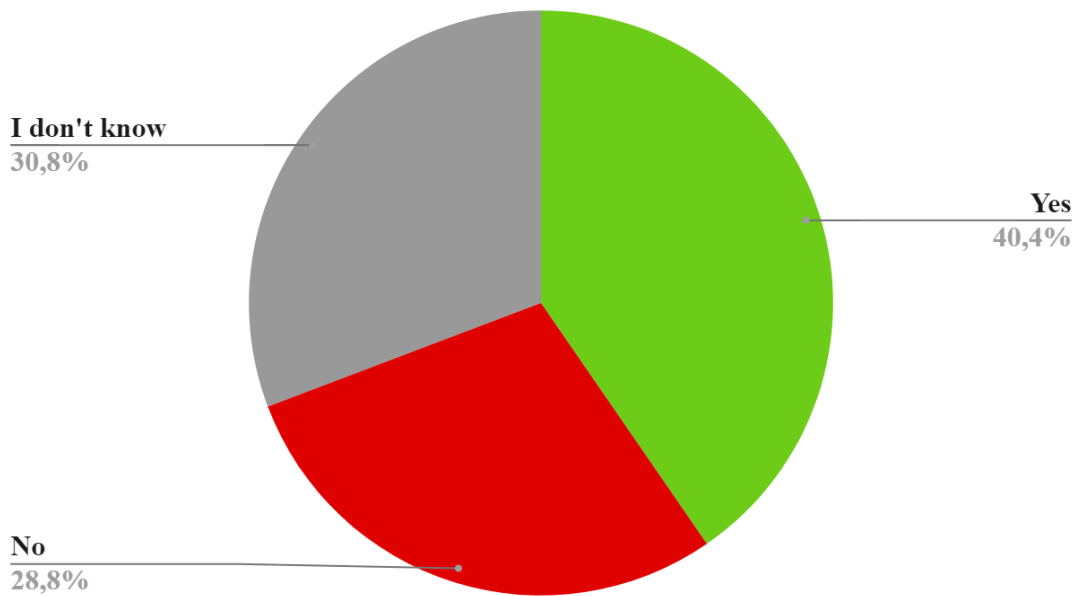
the findings of Molecular Paleontology are part of the information that was preserved in the fossils and, therefore, it is part of its essence, just as we study its morphological variability, diversity, and size, among others, we must also teach children and adolescents that, in some cases, past-life preservation can reach a previously unthinkable scale. [...] The idea that we are molecules could be worked with them! Our body, our brain, everything works thanks to cells and organic components, and we can play football because our bones are an intelligent machine in a way, and all of this can be preserved in some cases in the fossil record. This could be an idea of how to connect Molecular Paleontology with something from the students' daily lives (Alves, 2021b, p. 33, 34).

In view of this, we understand that, if the theme about the possibility of recovering paleomolecular traces is worked on in the classroom, in order to use analogies and examples closer to the student's reality, the subject may become instigating, and significant for your learning, from this innovative content, which will compose your baggage of knowledge.

### 3.3.3 Possibility of DNA recovery of non-avian dinosaurs

Another even more specific question presented to the students concerns the possibility that scientists, in real life, compared to the fiction in the movie *Jurassic Park*, have already recovered traces of DNA in fossils of non-avian dinosaurs. For 40.4% of the apprentices, this feat has already been accomplished and the scientists have already stored this molecule in the laboratory, while 28.8% of them said they did not believe in this hypothesis, and 30.8% did not know how to answer (Figure 4).

**Figure 4** - Distribution of high school students according to the perception of the possibility of having already recovered traces of DNA in fossils of non-avian dinosaurs (n=52).



Source: Authors (2022).

When the responses are added together, it is observed that the majority (59.6%) of the students are positioned as those who either do not believe or do not yet have a defined position on the subject. These answers are within what is expected for the set of knowledge of high school students on the subject (Añez, 2017; Rodrigues, 2020).

Because it is a common question that arouses the attention of students, it is important to clarify these questions. Therefore, initially it is essential to establish a time comparison for the different points addressed. It should be considered that the evidence points out that non-avian dinosaurs became extinct about 66 million years ago (Alvarez et al., 1980; Chiarenza et al., 2020). In turn, available data show that aDNA molecules could survive an average time limit of 1 million years (Allentoft et al., 2012).

For example, aDNA sequences have been found in an equid dated between 560-780 thousand years (Orlando et al., 2013), in forest remnants of southern Greenland in 700-thousand-year-old ice cores (Willerslev et al., 2007), and in mammoths dating back more than 1 million years (van der Valk et al., 2021).

It is a fact that, over the last few decades, some claims about the recovery and sequencing of DNA segments from dinosaur fossils turned out to be contaminants of other organisms (Li, Na & Zhu, 1995; Wang, Yan & Jin, 1997; Woodward, Weyand & Bunnell, 1994; Young, Huyen & Allard, 1995). However, although it has not been possible, so far, to extract, amplify, or sequence stretches of DNA from dinosaurs, this does not mean that chemical markers of original ancient DNAs

have not been identified in fossils of these animals (Alves, 2022). Chemical markers are understood to be chemical residues of the structure (skeleton) of an organic molecule.

Some methods of identifying aDNA sequences, such as *Microscopy*, *Histochemistry*, *High-Performance Liquid Chromatography*, *Immunological Techniques [Antibodies]*, and *Mass Spectrometry*, have already been successfully applied to fossil samples of the Dinosauria clade in the search for this important preserved molecule, and the results confirmed the presence of chemical markers of nucleic acids in a dinosaur *Tarbosaurus bataar* (Pawlicki, 1995), in *Tyrannosaurus rex* (Schweitzer et al., 1997a), in *Brachylophosaurus canadensis* and *Tyrannosaurus rex* (Schweitzer et al., 2013), in a duck beak dinosaur of the species *Hypacrosaurus stebingeri* (Bailleul et al., 2020) and in *Caudipteryx* (Bailleul, 2021).

But these identified chemical markers only demonstrate that there are traces there of what was once an intact DNA molecule. If there are remaining sequences of this molecule in fossils dating back millions of years, they would probably be in small fragments, chemically altered today, making any amplification and sequencing technique impossible, for the purpose of in-depth analysis and attempted DNA reconstruction of non-avian dinosaurs (Alves, 2022).

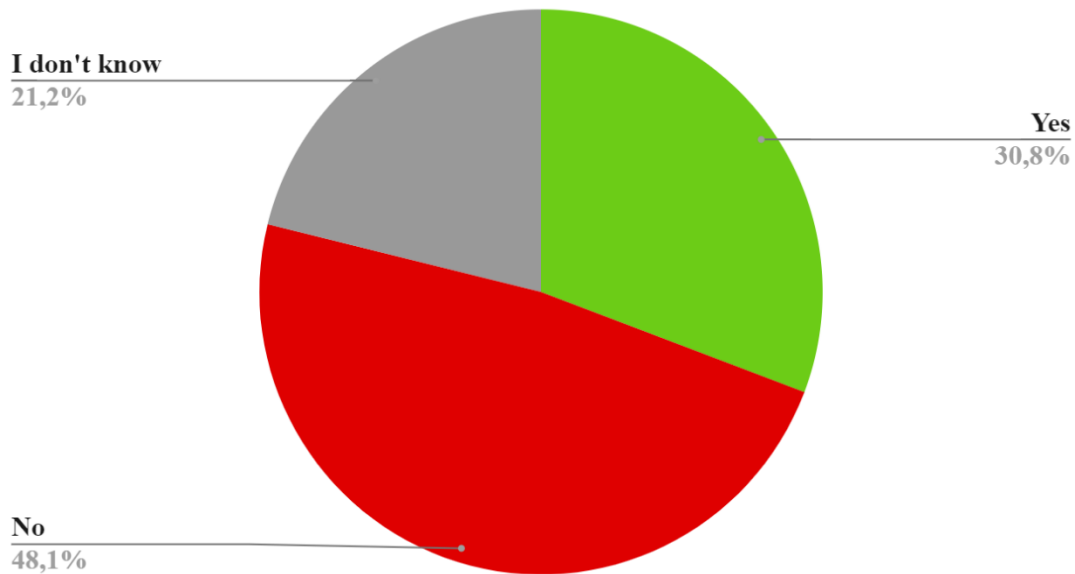
However, in fossils considered more recent, that is, tens of thousands of years, the chances of finding original DNA sequences increase (Prüfer et al., 2014). For example, recently, paleogenomics research applied to Paleoanthropology, that is, the field of study of human evolution at the interface between Archaeology and Paleontology, gained prominence in the media with the Nobel Prize in Physiology and Medicine being awarded to Svante Pääbo, a pioneer in the study of ancient DNA (Nobel Prize, 2022).

Therefore, we understand that researchers who study aDNA and ancient proteins have an increasing social responsibility to work with educational institutions, such as schools and museums, to communicate the meaning of their research to this type of public, in order to clarify doubts, and promote the approximation, interest, and popularization of innovative biogeoscientific knowledge (Brandt et al., 2022).

### **3.3.4 Possibility of species de-extinction**

When asked whether the recovery of aDNA in fossils could make it possible to de-extinct species, 48.1% of the students answered no, followed by those who believe it is possible to recreate extinct animals (30.8%) and those who did not know how to answer (21.2%) (Figure 5).

**Figure 5** - Distribution of high school students according to the perception of the possibility of de-extinction of species from the recovery of ancient DNA (n=52).



Source: Authors (2022).

The term *de-extinction* refers to the process of recreating an organism that is a member or resembles a member of an extinct species through retro-creation, cloning, genetic engineering or reverse genetic engineering (Soja & Huerta, 2001; Jones, 2014; Shapiro, 2017; Novak, 2018; Jones, 2019).

When we talk about *de-extinction*, the fictional story told in the first film of the trilogy *Jurassic Park* comes to mind, in which scientists from the fictional company Ingen managed to extract DNA of non-avian dinosaurs, which was stored inside a mosquito trapped in fossilized resin (amber). However, as the genetic material had been found in small quantities, synthetic biologists used genetic engineering techniques to fill in gaps in the dinosaurs' DNA. With that, they completed the missing sequences with DNA from some living species, such as frogs and a type of sepia – related to squid. This gave them the ability to change sex (first film) and the ability to camouflage themselves and control their body temperature (*Jurassic World* trilogy).

The question that arises is: if life imitates art, is it possible that real-life scientists have already tried to use state-of-the-art molecular biology techniques in the quest to recover genetic material from insects trapped in amber? The answer is yes.

Media appeal and pop culture are so influential that researchers respond, positively or negatively, to this attention by reinventing the way they work (Jones, 2019). Recent research, for example, has sought to determine whether aDNA is present in insects preserved in copal, a sub-fossilized resin precursor to amber (Penney et al., 2013; Modi et al., 2021). However, the results obtained showed the presence of insignificant short sequences, little concentrated, and extremely degraded, which indicate that aDNA is not preserved in good conditions in this type of material.

Insects trapped in amber are *hollow* on the inside, even in the case of those that are instantly enveloped in resin, because “bacteria and enzymes continue to work in the intestine, rotting the insect from the inside” (Ross, 1998, p. 33). According to Susannah Maidment, a British paleontologist at the Natural History Museum in London, when amber preserves insects, it tends to preserve the outer exoskeleton, not the inner soft tissues. Therefore, blood is not preserved inside mosquitoes in amber (Ross, 1998).

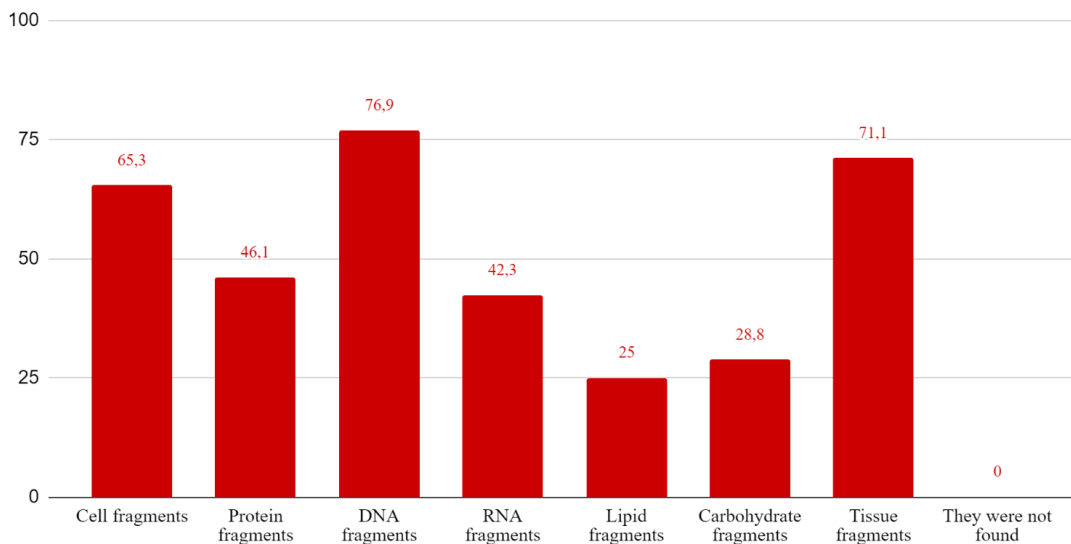
On the other hand, species that have recently become extinct in geological time, that is, on a scale of a few thousand years, which have already had a large amount of aDNA recovered (above 300 base pairs) and sequenced, may be among the candidates for *de-extinction* (Novak, 2018). For the project to succeed, it is also necessary the existence of a living species

phenotypically related to the extinct, which will be used as a “surrogate belly”, as is the case of the extinct woolly mammoth, which has high genetic proximity to the extinct. the current Asian elephants (*Elephas maximus*) (Shapiro, 2017).

### 3.3.5 Types of original biomaterials recovered from fossils

Students were also asked to respond, among the predetermined options to be marked, and with the possibility of indicating more than one option per answer, about what type of remaining organic material they believe has already been found in exceptionally well-preserved fossils. Responses included DNA fragments (76.9%), tissue fragments (71.2%), cell fragments (65.4%), protein fragments (46.2%), RNA fragments (42.3 %), carbohydrate fragments (28.8%), lipid fragments (25%) (Figure 6).

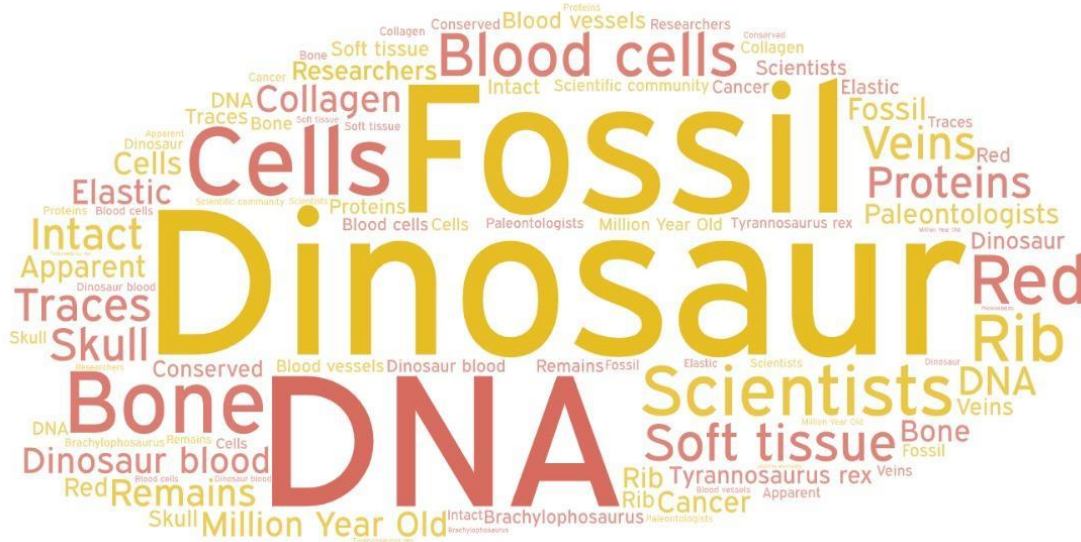
**Figure 6** - Distribution of high school students according to the perception of types of remaining organic material already found in exceptionally well-preserved fossils (n=52). Legend: y-axis shows values in percentage.



Source: Authors (2022).

The highest frequencies of responses were concentrated in the options regarding fragments of *DNA*, *tissues*, and *cells*. We noticed that these types of structures mentioned by high school students are the same examples of biomaterials that can be found on the internet, more specifically in the titles of articles on popular dissemination sites (Figure 7, Table 1), which convey news about the organic finds exceptionally preserved inside fossils.

**Figure 7** - Cloud of words used in news headlines about traces of original biomaterials recovered from fossils. *Note:* the headings of the news articles were inserted in the Wordart.com program. In order for each cloud to present a more informative result, prepositions, articles, adverbs, and interjections were removed. The size of the word is related to its frequency of occurrence, that is, the larger the word, the more often it is used.



Source: Authors (2022).

**Table 1** - Description of journalistic news related to traces of original biomaterials recovered from fossils. *Note:* A simple Google search was performed. As inclusion criteria, articles published in Portuguese were selected whose theme was the findings of organic materials preserved in fossils, explicit in the title, and which contained the variables to be presented in the list.

| Nº | DATE       | WEBSITE                    | ARTICLE TITLE   |
|----|------------|----------------------------|---|
| 1  | 03/24/2005 | Estadão                    | Paleontologists discover soft tissue from dinosaur bone                         |
| 2  | 03/25/2005 | Publico.pt                 | Dinosaur soft tissues, veins and cells discovered                               |
| 3  | 03/25/2005 | Folha de São Paulo         | Group finds cells in <i>Tyrannosaurus</i>                                       |
| 4  | 05/02/2009 | Ikessauro                  | Proteins are found in <i>Brachylophosaurus</i> bones                            |
| 5  | 05/04/2009 | Terra                      | Scientists identify blood vessels and collagen in fossil                        |
| 6  | 06/10/2015 | Exame.com                  | Blood cells found in 75-million-year-old dinosaur fossils                       |
| 7  | 06/10/2015 | Hypescience                | Scientists find 75-million-year-old dinosaur blood                              |
| 8  | 06/10/2015 | UOL                        | 75-million-year-old blood cells found in dinosaur fossil                        |
| 9  | 06/10/2015 | Gazeta do Povo             | Dinosaur fossils preserve apparent red blood cells and collagen                 |
| 10 | 06/11/2015 | Canal Tech                 | Scientists discover intact blood cells in dinosaur fossils                      |
| 11 | 06/21/2015 | Piauí Hoje                 | Scientists Find Remains of Dinosaur Blood                                       |
| 12 | 07/22/2015 | History UOL                | Researchers find fossils with dinosaur blood                                    |
| 13 | 01/31/2017 | UOL                        | Dinosaur rib holds oldest soft tissue remains ever found                        |
| 14 | 03/05/2020 | Terra Rara                 | Dinosaur DNA and Proteins Found in Fossils Say Paleontologists                  |
| 15 | 03/10/2020 | National Geographic Brasil | Traces of Fossil DNA Found in Dinosaur Skull                                    |
| 16 | 03/09/2021 | Paleontologia Hoje         | Discovery of soft and elastic tissues in a <i>Tyrannosaurus rex</i> fossil      |
| 17 | 06/15/2021 | Profissão Biotec           | Possible traces of fossil DNA and cancer found in dinosaur bones                |
| 18 | 09/28/2021 | SoCientifica               | Highly conserved dinosaur cells may contain DNA                                 |
| 19 | 10/01/2021 | UOL                        | Possible fossilized dinosaur DNA divides opinion among the scientific community |
| 20 | 10/02/2021 | Aventuras na História      | Scientists find 125-million-year-old dinosaur cells that may still contain DNA  |

Source: Authors (2022).

From this, it is possible to establish a logical relationship between the knowledge produced by paleontological research groups and the dissemination of this knowledge to the population through the media and its role in information and opinion formation. And, more specifically, to infer, from this search (Table 1), that the knowledge acquired by students about

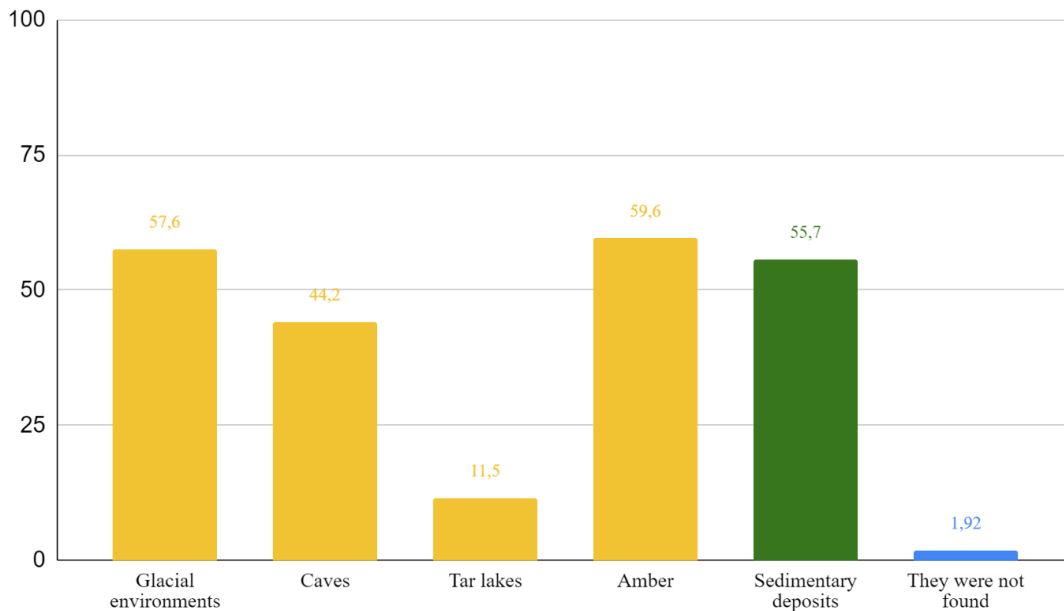


the types of remaining organic materials found in fossils could be somehow associated with what they read on the internet on the subject.

### 3.3.6 Types of paleoenvironments where exceptional preservation occurs

When asked in which type of paleoenvironment, that is, fossil formation environment, the students thought that traces of “soft tissues” had already been found, they replied, with the possibility of indicating more than one option per answer, the microenvironments of amber (59.6%), followed by glacial environments (57.7%), sedimentary deposits (55.8%), caves (44.2%), tar lakes (11.5%) and there were still those who believe that were not found (1.9%) (Figure 8).

**Figure 8** - Distribution of high school students according to the perception of types of taphonomic environments in which traces of “soft tissues” have already been found (n=52).



Source: Authors (2022).

It is observed that the highest frequencies of responses are concentrated in taphonomic environments related to amber and glaciers, as well as sedimentary deposits, which is interesting because these findings are supported by the data available in the scientific literature.

Both amber and permafrost environments (glaciers) provide a type of fossilization called *mummification*, in which partial or total preservation of an original living being occurs through freezing (cryopreservation), dehydration, or solidification through impermeable substances (amber) (Alves, 2022).

As for the sedimentary environments, there are different geological configurations formed from sediments (*e.g.*, fluvial deposits, sandstones, karst deposits, claystone, and marine deposits). However, research has shown that, at least for the recovery of nonmineralized biomaterials (*e.g.*, blood vessels, matrix tissues), rapid burial in a fluvial or sandstone depositional environment seems preferable over to other environments (Schweitzer et al., 2007, 2009, 2019).

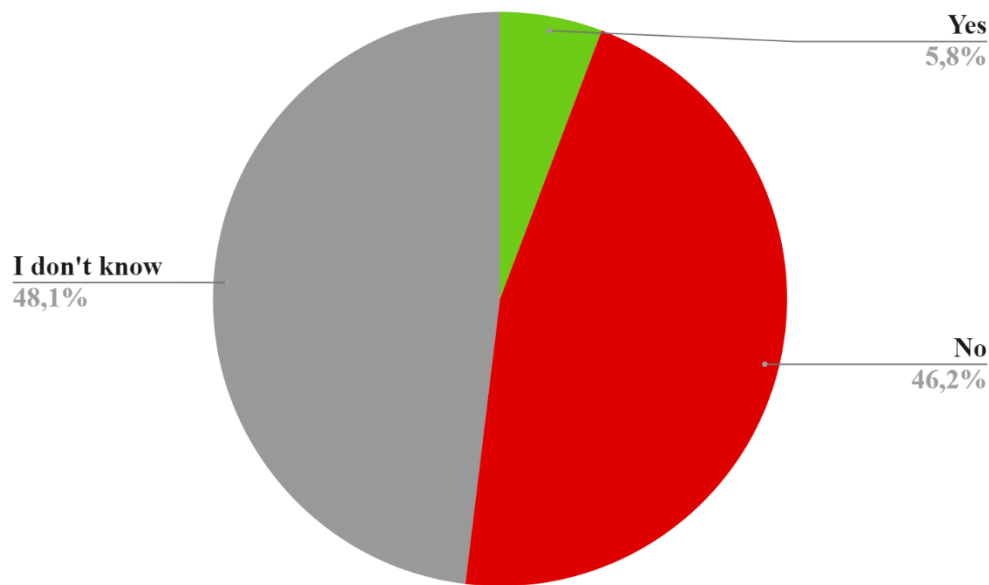
As Timothy P. Cleland, a molecular paleobiologist, at the Smithsonian Museum Conservation Institute, states, “Fossils found in sandstone appear to have a better preservation than those that come from shale or clay” (Morton, 2017, p. 40, 42). The hypothesis raised is that the phenomenon is due to the porous nature of the sand, which would allow suppurating

fluids, rich in microorganisms and loaded with enzymes, to disperse more quickly, providing a drier environment and thus delaying the decomposition of materials (Schweitzer et al., 2007).

### 3.3.7 Current status of explanations on exceptional preservation

Another question investigated relates to the students' view of the possibility that the preservation of traces of original “soft tissues” has already been fully explained by scientists. Approximately half (46.2%) of the students understand that the mechanisms have not yet been well explained, while there are those who think that everything is already well resolved (5.8%) and those who did not know how to give an opinion about it (48.1%) (Figure 9).

**Figure 9** -Distribution of high school students according to the perception of the possibility that the preservation of traces of original “soft tissues” has already been fully explained by scientists (n=52).



Source: Authors (2022).

Again, it is curious that approximately half of the students' answers meet the reality presented by the scientific literature. The data show that, although much effort has been made to develop different fossilization models in recent decades in order to explain the different types of molecular fossil preservation found, even today such proposed mechanisms are poorly understood (Parry et al., 2018; Fabbri et al., 2020). This is because, as stated by Schweitzer et al., “few of these preservation devices have been experimentally tested” (2014, p.1). Therefore, currently, there are still few studies regarding rigorous and testable mechanisms to reasonably explain the potential transformation and stabilization of organic matter through diagenesis over deep time (Boatman et al., 2019).

Intuitively, it is easy to understand that some extinct vertebrates, such as mammoths and other mammals from the last glacial period, can more easily preserve organic materials since these are often reported by the media as having been found in glacial deposits favorable to exceptional preservation (Borges, 2006). However, what about finds that have been found in sedimentary deposits from formerly warmer environments and from even deeper geological ages? (Thomas & Taylor, 2019; Alves & Machado, 2020, 2021b, 2021c; Gomes, Machado & Alves, 2022).

In view of this, it was noticed that high school students, in general, have the ability to understand the degree of complexity involved in exceptional preservation, including the difficulties in explaining this phenomenon, especially when

they use, in set, logic and intellectual intuition (Meneghetti, 2009). Furthermore, as Matthew Collins, professor of Biomolecular Archeology and specialist in paleoproteomics at the University of Copenhagen, says, because Molecular Paleontology is an area of controversy, “it helps to make students think about how science works and the fact that not everything is understood, but we are using different methods and approaches to try to understand” (Personal communication, November 10, 2022).

### 3.3.8 Original biomaterials found in Brazilian fossils?

When asked if they believe it is possible that traces of original “soft tissues” have already been found in fossils recovered in Brazilian territory, most (69.2%) of them understand this option as a reality, while the rest (30.8%) thinks that these nonmineralized biomaterials have not yet been found in Brazil.

As with previous questions, the response of most students to this question under analysis is also supported by the scientific literature. As for the Brazilian paleontological heritage, studies show that high school students from some regions of the country recognize that Brazil has fossiliferous records, mainly related to dinosaurs (Izaguirry et al., 2013; Borsonelli & Rodrigues, 2019).

With regard to “soft tissues”, in turn, it is known that Brazil has great potential in the exploration of nonmineralized biomaterials preserved in fossils, since it has one of the largest *Konservät-Lagerstätten* in the world, containing different fossilized specimens and presenting with exceptional preservation of their structures (Kellner, 2015; Kellner; Soares, 2019). In fact, traces of original organic molecules in plant fossils have already been found on national soil (Pereira, Carvalho & Azevedo, 2006, Pereira et al., 2009a, 2009b, 2011a, 2011b, 2020; Silva et al., 2018) and in fossils of vertebrate animals, as in the case of endogenous organic pigments in pterosaurs (Pineiro et al., 2019).

The traces of pigments found in the fossil record around the world, including in Brazil, can provide relevant information to understand the color pattern of extinct animals (Ghilardi, 2019). This question has facilitated the answer to the following question from students: What color were dinosaurs? The answer is provided by Molecular Paleontology. Molecular studies have recovered different pigments from the fossil record, such as melanins, porphyrins, and/or carotenoids, which combine to form different colors (Alves & Machado, 2021b, 2021c). These findings have helped, in particular, the work of Paleoart in Brazil and around the world.

Paleoart, a field of study that unites art and science, with the aim of reconstructing the life aspects of fossil organisms and their associated ancient environments, is today an important tool for the popularization of Brazilian paleontology as it acts as a bridge of approximation between paleontological knowledge and society (Moro, Hohemberger & Paniz, 2021). Paleoart has even been used as one of the geoscientific learning strategies for high school students.

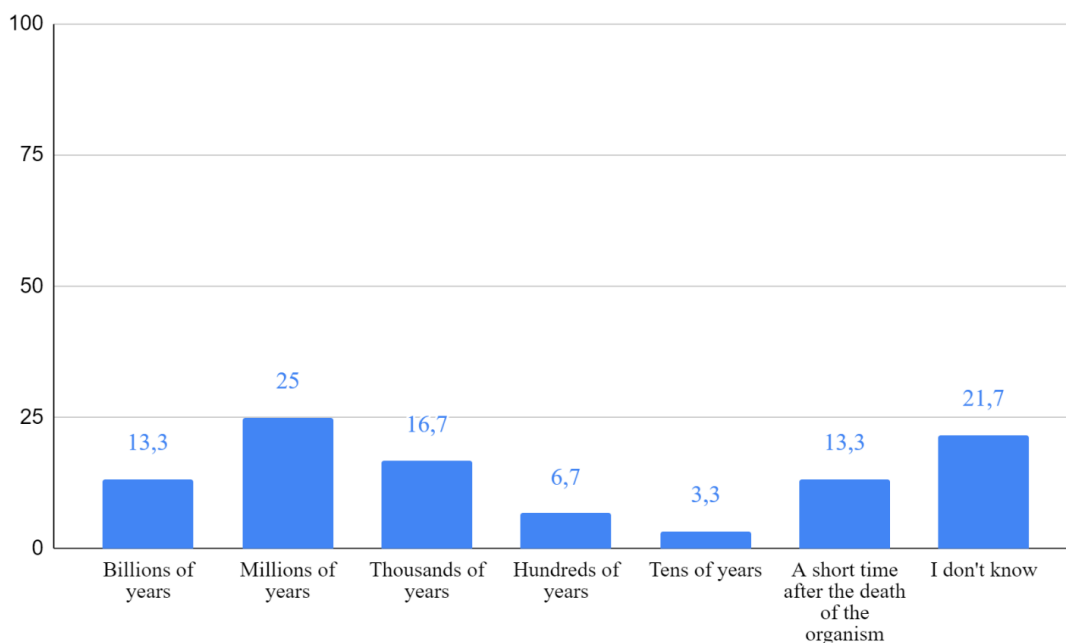
Therefore, it became evident that the knowledge about molecules related to the coloring of the past biota, when used in an interdisciplinary way with other areas of knowledge, in this case, Paleoart, can promote a greater interest in high school students in our country for the findings from Molecular Paleontology, especially those carried out in a context of Brazilian fossils. This could probably even explain the coherence found in most of the participants' answers to the question about the original biomaterials found in Brazilian fossils.

### 3.3.9 Survival time of biomolecules

Regarding the maximum period of time in which the remains of original “soft tissues” could be preserved inside fossils, the majority (25%) of the answers relate to an interval of millions of years, followed by those in which the preservation occurs for at most thousands of years (16.7%), billions of years (13.3%), a very short time after the death of the organism

(13.3%), hundreds of years (6.7%), tens of years (3.3%) and those who did not know how to give an opinion (21.7%) (Figure 10).

**Figure 10** - Distribution of high school students according to the perception of survival time of traces of original "soft tissues" inside fossils (n=52). Legend: y-axis shows values in percentage.



Source: Authors (2022).

It was noted that the students' answers are divided on this question. But, when considering the groups of answers of those students who understand that the traces of organic materials are preserved for at most thousands or millions of years, we arrive at an approximate total of 50% of the students whose answers are consistent with the scientific data available.

As partially presented in a previous topic (see topic 3. 3. 3), the discussion about the maximum time limit in which organic material can be preserved in the natural environment will depend on several factors. To become didactically understandable, it is important to separate organic materials into main groups of complex biomolecules that have been studied over time: protein and DNA.

The literature shows that data from theoretical kinetic tests and laboratory experiments on the decay of these biomolecules, which sought to identify the time limits of their survival in relation to environmental variables that simulate different conditions, such as humidity, temperature, oxygen, and pH, demonstrated, to date, that DNA molecules are preserved on average for 100,000 years (Schweitzer & Wittmeyer, 2006; Allentoft et al., 2012), reaching a maximum limit of up to 1 million years (Allentoft et al., 2012; van der Valk et al., 2021).

Proteins, in turn, because they are more resistant, have an average time limit of approximately 1 million years (Collins et al., 1995; Bada, Wang & Hamilton, 1999; Wadsworth & Buckley, 2014), and may reach a limit maximum survival of tens to hundreds of millions of years (Alves, 2022). For example, studies have identified different types of proteins in fossil specimens from the Mesozoic (Schweitzer et al., 1997a, 1997b, 1999a, 1999b) and Paleozoic (Thomas & Taylor, 2019) Eras.

Although this body of knowledge is very specific and current, it is not surprising that about half of the students answered as expected to this question, since the survival time of biomolecules is also a topic frequently addressed by the media (see topic 3. 3. 5). As for the other half, corresponding to students who think that traces of biomolecules could survive for a

short time in nature and those who did not know how to give an opinion, this situation also reflects the resistance still today on the part of some of the scientific community to accept that organic molecules could survive in deep time (Kaye, Gaugler & Sawlowicz, 2008; Bern, Phinney & Goldberg, 2009; Saitta et al., 2019; Korneisel et al., 2021; Saitta et al., 2021).

On the other hand, findings of original biomaterials accumulate and appear geologically extensive, geographically global, and taxonomically comprehensive, thus becoming increasingly difficult to explain by those who do not yet accept them (Schweitzer, 2011; Thomas & Taylor, 2019; Alves & Machado, 2020, 2021b, 2021c; Gomes, Machado & Alves, 2022).

### 3.3.10 Changing the scientific paradigm

When asked if the findings of "soft tissue" in fossils could change the previously consolidated thinking in science about the time limit in which this type of biological material can be preserved, the vast majority (98.1%) of students believe that they would, while only one (1.9%) responded that they did not believe in this possibility.

A *paradigm shift* is an expression used by Thomas Kuhn in his book *The Structure of Scientific Revolutions*, published in 1962, to represent a change in basic conceptions, or paradigms, within a certain dominant scientific theory (Alves & Valente, 2020).

It is observed that this has occurred with the emergence of *Molecular Taphonomy*. Molecular Taphonomy is a tool for studying the modification processes that occur in an organism, from the moment of death to laboratory analysis, focusing on the mechanisms that facilitate or prevent the preservation of endogenous biomolecules and/or their altered fragments (Alves, 2022).

This emerging field has led, in the last two decades, to a greater understanding of the nature of the fossil record, requiring paleontologists to rethink traditional notions about how fossilization occurs, mainly in the quest to characterize the decay and biomolecular stabilization pathways in diverse paleoenvironmental and diagenetic configurations (Ullmann, Ash & Scannella, 2022).

However, reflecting on a change in thinking that occurs from time to time in the scientific community, as a body of evidence accumulates in a given area and then begins to question certain previously accepted views, is not an easy process, however, it is a necessary exercise.

Faced with this, it is clear from the students' answers that they understand, probably intuitively, the process of change that is beginning in Paleontology, with the new discoveries of traces of "soft tissues" in exceptionally well-preserved fossils, and again are in line with what the most recent data show in this regard.

Finally, it is also worth emphasizing that, although more and more research is investigating the perception and/or level of knowledge of high school students about Genetics and Molecular Biology (Rotbain, Stavy & Marbach-Ad, 2008; Martins et al., 2020; Simão et al., 2022), there are few studies that sought to investigate students' understanding of paleogenomics and paleoproteomics. Therefore, a paradigm shift is also necessary regarding the insertion and valorization of aspects of teaching and learning associated with the current basic knowledge of Molecular Archeology, which aims, for example, to apply proteomic techniques for the identification and analysis of proteins in objects and /or ancient bones (Brandt et al., 2022), and Molecular Paleontology.

## 4. Conclusion

We consider that the previously established objectives have been achieved, as we identify and extract aspects of the knowledge of high school students related to Paleontology, in general, and more specifically to the basic concepts of Molecular Paleontology, making it possible to provide data that will come to fill a gap in existing knowledge in our country.

Regarding the specific questions of the category Knowledge about Molecular Paleontology, we observed that, in general, most of the students' answers are consistent with the data available in the scientific literature. The explanation for this phenomenon may lie in the fact that the research was carried out in private educational institutions, considered, in Brazil, as having a higher quality of education than the public ones, or because the teachers of these schools had previously planned their classes with the aim of address bio-paleontological issues.

Considering that the sample of this study presents, in general, an adequate level of knowledge regarding basic concepts of Molecular Paleontology, this suggests that high school students are able to acquire and apply complex contents related to molecular biology, fossils, and evolution in a school environment.

In view of this, a research question arises: Would Molecular Paleontology, or at least the fundamental questions associated with it, such as those discussed here, be intuitive? Suggestions for future studies include the deepening of this question, from the search for potential mechanisms involved in this phenomenon of learning, and others, related to the comparison of the level of knowledge of Molecular Paleontology among students from public and private schools and the insertion of other variables and essential topics for better coverage of the area.

As for the limitations of the study, we recognize that the sample is small and restricted to regional standards, so we suggest to future researchers the inclusion of a larger sample that can cover classes of the 2nd and 3rd grades of High School, in addition to expanding the study to other regions of the country.

On the other hand, the data presented here immediately provide a useful basis for establishing educational strategies, goals, and objectives to raise the quality of teaching in this interdisciplinary scientific field in basic education throughout the country, in addition to serving as a guide for new developments. research on paleomolecular teaching, still little explored in the scientific and educational literature.

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