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Trends on paleoart in the paleontology research and public education: A thematic review

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Abstract Paleoart, the artistic representation of prehistoric life based on scientific evidence, plays a crucial role in paleontological research and public education. It serves as a bridge between scientific discoveries and public understanding, making complex paleontological data accessible and engaging. Despite its importance, there has been limited comprehensive analysis of the trends and historical development of paleoart within academic research and educational contexts. This gap hinders a holistic understanding of how paleoart has contributed to and been influenced by advancements in paleontological research and public education.Utilizing a thematic review (TR) methodology, this study incorporates keywords such as paleoart, paleontology, and education from the SCOPUS, WoS and Mendeley databases, and a total of 30 papers published between 2013 and 2024 were reviewed. The thematic analysis reveals three key themes: scientific and aesthetic decision, Integration of digital technology, and outreach impact. The findings highlight how paleoartists balance scientific fidelity with creative interpretation, addressing the challenges of reconstructing extinct organisms from incomplete fossil records. The integration of advanced digital tools, such as 3D modeling, augmented reality (AR), and virtual reality (VR), has significantly enhanced the accuracy, accessibility, and educational value of paleoart. This review underscores the need for continued exploration of technological innovations and interdisciplinary collaborations to further strengthen paleoart's scientific precision and artistic appeal. The findings also pave the way for future research into the specific impacts of paleoart on public understanding and educational outcomes. By informing strategies to optimize the use of paleoart in scientific communication, this research provides valuable insights for educators, researchers, and policymakers. Future studies should prioritize the development of standardized frameworks and guidelines for paleoart creation, ensuring its sustained evolution as a compelling medium for paleontological visualization and education.

Keywords: paleoart, paleoartist, paleontology, public education

1. Introduction

"Paleoart" (European spelling "paleoart") refers to any original artistic effort to reconstruct prehistoric life on the basis of current scientific evidence (Ansón et al., 2015). It has become a popular synonym for paleontological sculptures and paintings (Ansón et al., 2015). This art genre depicts paleontological subjects, either realistically or artistically, by reconstructing extinct biota and their habitats on the basis of scientific data (Wings et al., 2023). Paleoart is deeply connected to paleontological science, aiming at purely scientific reconstruction (Manucci & Romano, 2023). It serves as an important medium for communicating scientific understanding of prehistoric life to both the public and researchers (Davis et al., 2022). (Manucci & Romano, 2023) trace the evolution of paleoart over four centuries, exploring its historical and contemporary significance. Figure 1 illustrates one of the most renowned paleoart works in history, showing the first "fully realized" paleoart scene.

Paleontology is inherently multidisciplinary. Initially, the roles of scientist and artist were unified in a single individual until the emergence of the paleoartist, a professional dedicated to naturalistic representations who skillfully integrates both aesthetic and scientific knowledge (Manucci & Romano, 2023). According to Marco Ansón and Manuel Hernández Fernández (2015), two types of paleoartists can be distinguished on the basis of their approach to representing extinct organisms: the researching reconstructors and the creative ones. Researching reconstructors meticulously reconstructs animals through various phases, beginning with in-depth fossil research. In contrast, creative paleoartists use previously accurate reconstructions as references.

The term "paleoimagery" is closely related to "paleoart" and encompasses all artistic productions inspired by paleontology, including those in popular cultures such as cinema and fiction, which have distinct purposes (Manucci & Romano, 2023). It is crucial to clearly distinguish academic paleoart from nonacademic paleoimagery (Ansón et al., 2015). For example, Figure 2 showcases artwork with paleontology as its main theme, depicting scenes of prehistoric creatures coexisting with human beings. These works fall under the category of paleoimagery. Ghilardi (2010) argues that the term "paleodesign" is preferable to "paleoart," as the latter could refer to items such as mugs, ceramics, and clothing featuring dinosaurs for

paleontologists. Paleodesign is thus a branch of art applied to paleontology. Throughout the review, numerous related expressions have been proposed. However, it is essential to clarify the meanings of the terms within this field.

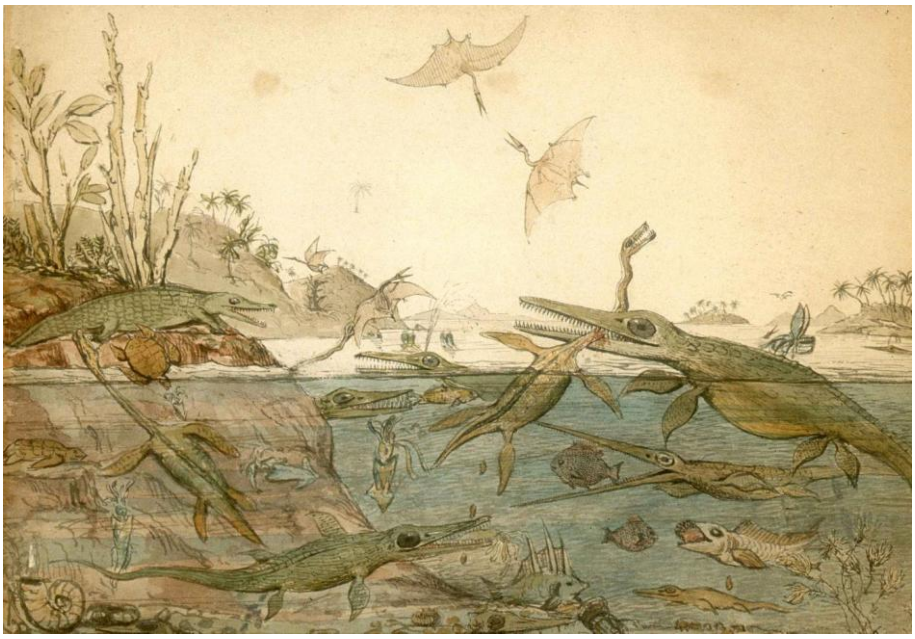

Figure 1 Geologist Henry De la Beche's 1830 watercolor painting Duria Antiquior - A more Ancient Dorset, based on fossils found by Mary Anning.

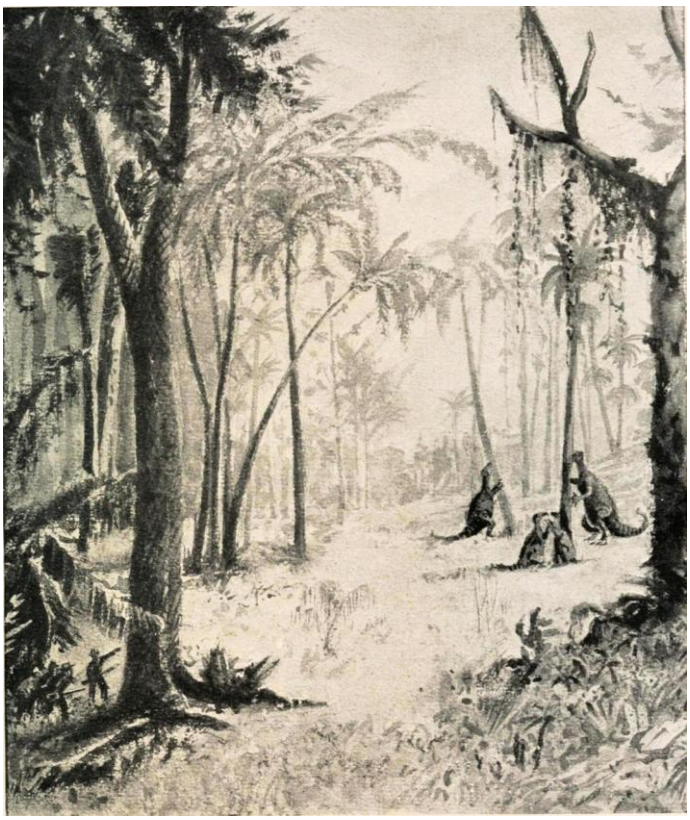

Figure 2 An illustration from The Lost World by Arthur Conan Doyle (1859–1930), The internet Archive.

The development of digital technology has profoundly impacted paleoarts by increasing the accuracy, accessibility, and educational value of paleontological reconstructions. Advanced tools such as 3D scanning, photogrammetry, and virtual reality have allowed for more precise and detailed depictions of extinct organisms and their environments (Cunningham et al., 2014). These technologies enable paleoartists to create lifelike models that can be easily shared and viewed in digital formats, expanding the reach of paleontological education beyond traditional museum settings (Feldman, 2016). Additionally, digital paleoart facilitates interdisciplinary collaboration, allowing scientists and artists to work together more efficiently to produce

scientifically accurate and visually compelling representations. Web communities dedicated to paleoart are rapidly expanding and actively participating in events and debates worldwide (Manucci & Romano, 2023). This technological advancement not only enhances public engagement with paleontology but also aids in the preservation and dissemination of paleontological knowledge.

Since the late nineteenth century, popular media and museums have been inundated with increasingly sophisticated visual representations of ancient life. These depictions aim to transcend mere artistic fantasies by relying on archaeological findings and scientific reasoning, thereby creating a powerful connection between academia and the public (Hochadel, 2022). Geological education is essential, yet earth sciences lack adequate public presence, and scientific literacy in geology remains low (Seghedi et al., 2017). Berta (2021) emphasized the importance of media attention, noting that many researchers engaged in basic research need their findings and trademarks to be seen, heard, and utilized in public education and outreach. Additionally, while entertainment and education are often viewed as separate experiences, heritage sites frequently aim to combine both (Khatwa Ford, 2019). In addition to the intrinsic connection between paleontology and art, paleoart plays a crucial role in visually communicating science and evolution to the public, as seen in museum exhibitions and other venues (Berta, 2021).

Despite the broad influence of the paleoart, the scientific and aesthetic decisions involved in its creation are seldom discussed in the formal academic literature or subjected to peer review (Davis et al., 2022). The field lacks a substantial number of specialized artists, and no academic institutions offer degrees in paleoart (Hochadel, 2022). Furthermore, poor-quality paleoart can effectively perpetuate misconceptions(Ross et al., 2013), which are then propagated through popular media(Davis et al., 2022). Additionally, while significant scholarship has focused on the depiction of vertebrates in paleoarts, invertebrates have received much less attention(Allmon, 2017).

Therefore, this thematic review aims to address existing gaps in the field of paleoart by providing a comprehensive analysis of the scientific and aesthetic decisions involved in its creation. Additionally, it emphasizes the importance of these decisions and the application of 3D digital technologies in producing accurate and educational representations of prehistoric life. This paper conducts a thematic assessment of discussions on paleoart in paleontology research and public education published between 2013 and 2024, framed by the following research question:

RQ: What are the current trends in paleontology research and public education in the literature from 2013--2024?

2. Materials and Methods

The term thematic review (TR) uses ATLAS.ti as the tool and was introduced by Dr. Zairul (Zairul, 2020; Zairul et al., 2023). This method has also been protected by copyright under the registration number CRLY2023W02032. Thematic Review FlowZ (TreZ) is utilized because the methodology of this study involves applying a thematic analysis procedure when a literature review is conducted (Figure 3). Braun and Clarke (2013) define thematic analysis as a process of identifying the pattern and constructing themes through thorough reading of the subject.

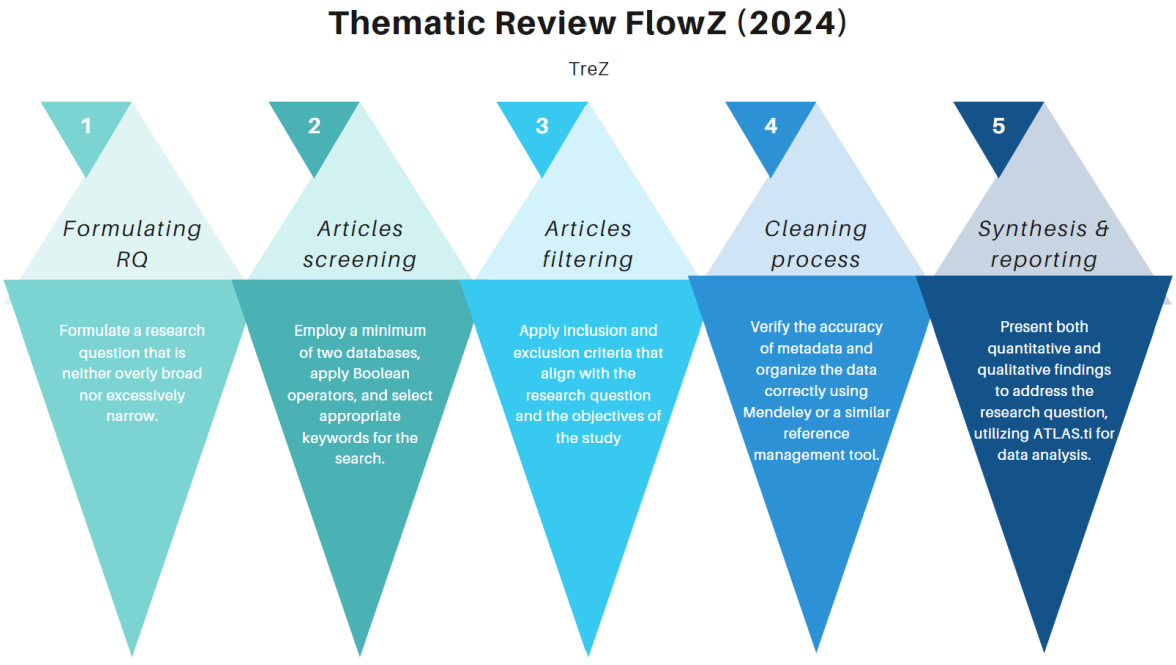

Figure 3 Thematic Review FlowZ (TreZ).

Initially, the process begins with formulating the research question (see the previous section), which serves as a roadmap for the subsequent stages of the review, establishing the focus and scope. Next, the article screening step (Table 1) involves identifying and preliminarily selecting studies on the basis of their relevance to the research question. This is followed by the article filtering stage (Figure 4), where inclusion and exclusion criteria are applied to refine the selection of studies, ensuring that only the most pertinent articles are retained for further analysis. The fourth step, cleaning (Figure 3), involves a thorough double-checking of the metadata of the articles to ensure the accuracy and completeness of the data collected. The final step in the process is data extraction, where a thematic analysis is conducted via tools such as ATLAS.ti to develop themes on the basis of extensive reading of the subject matter in the selected articles. This structured approach enhances the reliability and depth of the review, ensuring a comprehensive analysis of the literature.

Table 1 Search strings from scopus, WoS and mendeley.

SCOPUS	(TITLE-ABS-KEY ("paleoart" OR "paleoartist" OR "artistic reconstruction" OR "sculpting") AND TITLE-ABS-KEY ("paleontology" OR "paleontological" OR "fossil" OR "dinosaur" OR "Paleobiology")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	25 results
WoS	"paleoart" OR "paleoart" OR "paleoartist" OR "artistic reconstruction" OR "paleontological art" OR "paleoimagers" OR "Artistic Restoration" OR "scientific illustrations" (All Fields) AND "paleontology" OR "paleontological" OR "fossil" OR "dinosaur" (All Fields) and English (Languages) and Article or Review Article (Document Types) and English (Languages)	53 results
Mendeley	TITLE: “paleoart” Year: 2013 TO 2024, Doc Type: 111, Access type: Open Access	15 results
Science Direct	("paleoart" OR "paleoartist" OR "artistic" OR "sculpting")AND("paleontology" OR "fossil" OR "dinosaur" AND ("education"OR "outreach") Year: 2013 TO 2024, Article type: Review articles AND Research articles	57 results

The next step involves identifying patterns and constructing categories to comprehend the trends related to the paleoart, as discussed in the literature from 2013--2024. This phase of the research aims to analyze and interpret the findings to formulate recommendations for future research on the paleoart within paleontology research and public education. This approach will be instrumental in clarifying the evolution of these trends over time and identifying which new directions or innovations could be crucial for future developments in this field. To ensure a comprehensive and relevant analysis, the selection of literature for this review was guided by specific criteria: 1) the publication date ranged from 2013--2024, ensuring that the research was current and significant; 2) the inclusion of key terms such as 'paleoart,' 'paleontology,' and 'education' in the literature to focus on studies that are directly relevant to the main themes of this research. This methodical selection process helps capture a broad spectrum of contemporary insights and developments in these fields.

The literature review was conducted by searching four major academic databases: SCOPUS, Web of Science, Mendeley and Science Direct. In SCOPUS, the search was defined with the keywords "paleoart," "paleoartist," "artistic reconstruction," "sculpting," "paleontology," "paleontological," "fossil," "dinosaur," and "paleobiology" in the title, and keywords (TITLE-ABS-KEY). The search was restricted to publications in English and was limited to article and review article document types (LIMIT-TO (DOCTYPE, "ar" OR "cp" OR "re")). This search strategy resulted in 30 articles. In Web of Science, the search uses a similar set of keywords across all fields without specific field restrictions, with a focus on English-language articles and review articles. This search resulted in 53 articles. In Mendeley, the search was defined with the title keyword "paleoart" for publications from 2013--2024 and restricted to open access document types. This search resulted in 15 articles. In ScienceDirect, the search combined the keywords "paleoart," "paleoartist," "artistic," "sculpting," "paleontology," "fossil," "dinosaur," "education," and "outreach" for publications from 2013--2024. The search was limited to review articles and research articles, yielding 57 results. This diverse array of search strategies across different databases may reflect variations in their indexing depth, journal coverage, and search algorithm specifics, providing a comprehensive collection of articles for review. This paper details the methodological steps undertaken here, ensuring a robust selection of studies that enhance the validity and reliability of the review findings (Table 1).

The search began with formulated queries tailored to the study's objectives. The initial search results were comprehensive, aiming to encompass a broad spectrum of relevant literature. Upon merging the search results from all the databases, we proceeded to identify and remove duplicate entries to maintain the uniqueness of each record in subsequent analyses. The consolidated list of records then underwent rigorous screening on the basis of predefined inclusion and exclusion criteria. These criteria were meticulously developed to align closely with the research questions and objectives of the review. The inclusion criteria mandated that each study addressed paleoart, paleontology, or public education as central themes and was published in a peer-reviewed journal. Exclusion criteria ruled out articles that did not directly focus on the themes of

paleoart or paleontology or were outside the defined publication period. Studies not meeting these criteria were excluded, ensuring that only the most pertinent studies were retained. This rigorous selection process resulted in the inclusion of 30 studies for the thematic review, as depicted in Figure 4. These studies collectively met all specified eligibility requirements and are expected to provide substantial insights pertinent to the research question. This selection process not only ensures the inclusion of relevant data but also minimizes biases, contributing significantly to the reliability of the review's conclusions.

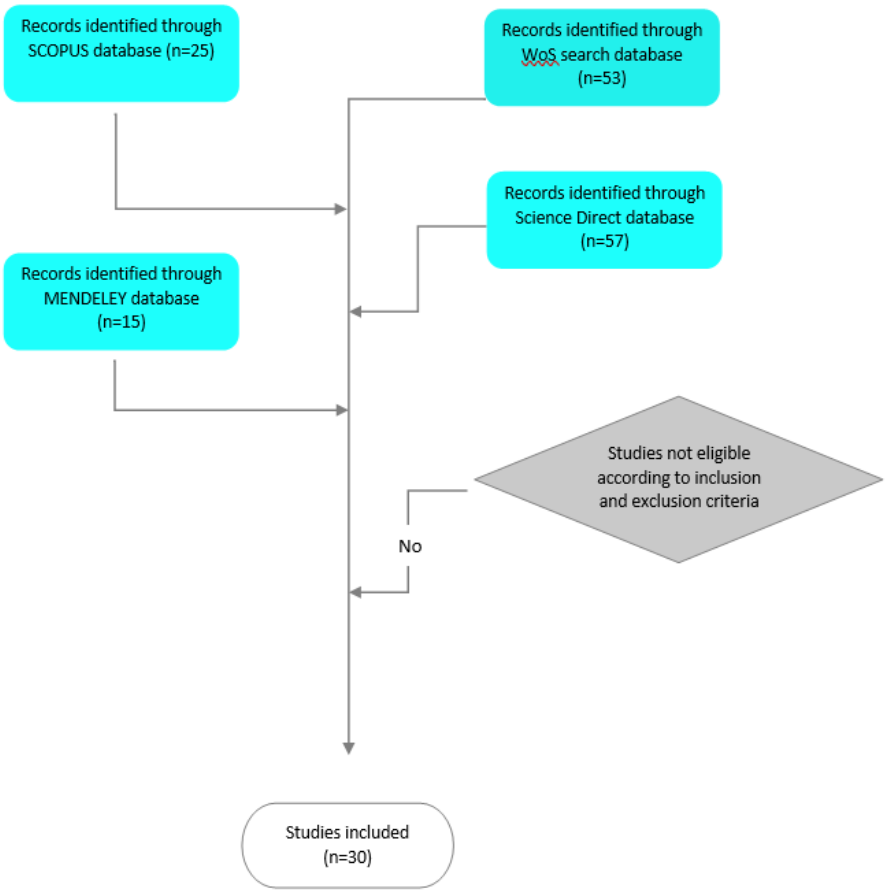

Figure 4 Inclusion and exclusion criteria in the thematic review.

3. Results

This section aims to detail the main findings of the thematic review. This study reviews the trends of paleoart in paleontology research and public education; the results are divided into quantitative and qualitative sections. The quantitative section begins with a word cloud generated from the analysis of the 30 documents. This is followed by an analysis of publication status by year, the number of articles published per periodical, and the geographical distribution by country of publication. In the qualitative analysis, three significant themes were ultimately found among the trends: scientific and aesthetic decisions, the integration of digital technology, and the impact of outreach. The theme of scientific and aesthetic decisions explores how paleoartists balance scientific accuracy with artistic creativity, assessing criteria such as fidelity to paleontological evidence, the influence of contemporary art styles, and the need to create visually engaging representations. The integration of digital technology examines the adoption of advanced tools and techniques in paleoarts, evaluating criteria such as the use of 3D modeling, digital painting, and virtual reality to increase the precision and realism of prehistoric reconstructions. Finally, the outreach impact theme considers the role of the paleoart in public education and engagement, focusing on criteria such as the effectiveness of visual storytelling in museums, educational materials, and media, as well as the ability of the paleoart to foster a deeper understanding and appreciation of paleontological research among diverse audiences. These themes collectively highlight the multifaceted contributions of the paleoart to both scientific inquiry and public education.

3.1. Quantitative reporting

In the preliminary analysis, the largest words appearing in the word cloud indicate a high frequency in the documents; they are "paleoart" and "dinosaur(s)". In Figure 5, the word cloud from the 30 papers captures high-frequency words, including "dinosaur(s)" (used 1000 times), "paleoart" (mentioned 423 times) and "fossil(s)" (mentioned 730 times).

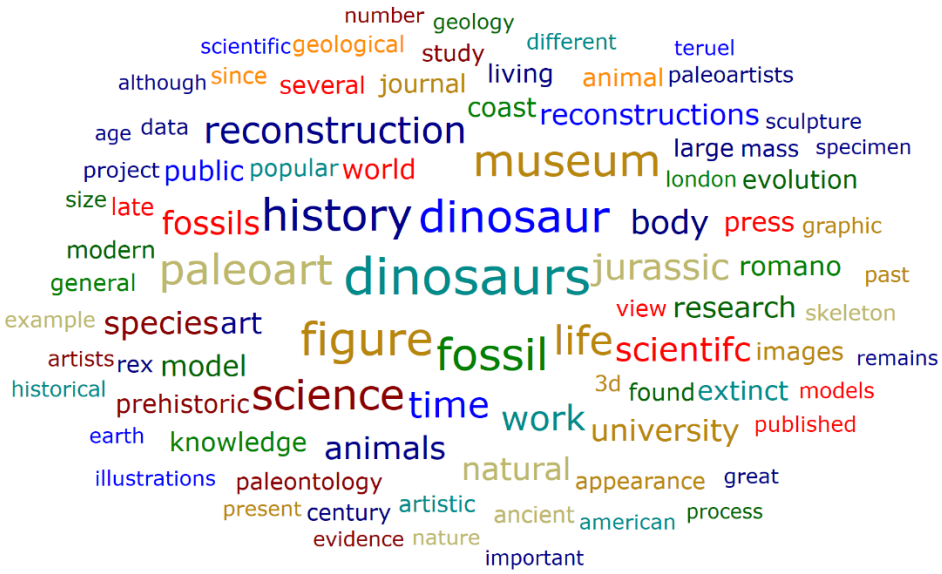

Figure 5 Word cloud generated from 30 articles.

Table 2 categorizes various studies on paleoarts into three themes: scientific and aesthetic decisions, the integration of digital technology, and outreach impacts. A total of 30 studies were reviewed, with 13 addressing scientific and aesthetic decisions, 8 focusing on the integration of digital technology, and 9 highlighting the impact of outreach. Key contributors to the scientific and aesthetic decision theme include Allmon (2017), Anson & Hernández Fernández (2020), and Witton (2017), among others. The predominance of articles on scientific accuracy and aesthetic value in paleoart reflects the critical importance of this issue in the creation of paleoart. Studies such as those of De Sousa Oliveira et al. (2023) and Romano et al. (2016, 2021, 2022) emphasize the integration of digital technology. The impact of outreach is highlighted in studies such as Wings et al. (2023), Berta (2021), and Ross et al. (2013). This distribution indicates a balanced interest across the three themes, reflecting the multifaceted nature of paleoart research and its relevance to both scientific inquiry and public education.

This study provides a comprehensive analysis of trends in paleoart publications over the past decade. The data reveal a growing scholarly interest in paleoart, particularly since 2021. Italy, the United Kingdom, and the United States emerge as leading contributors, whereas countries such as Norway, Russia, Switzerland, and the Czech Republic show potential areas for development. These findings highlight significant temporal trends and country-specific disparities, emphasizing the need for broader academic engagement and international collaboration. Addressing gaps, such as the underrepresentation of certain countries and the lack of formal academic programs in paleoart, could enhance the field's impact on both scientific research and public education. Future research should encourage academic institutions to develop specialized paleoart programs, promote international collaboration, and establish standards to ensure the quality and accuracy of paleoart representations. The results indicate that the paleoart remains a crucial aspect of paleontological research and public education across various countries. While Italy and the United States are at the forefront, there is broad international interest spanning Europe and North America, as shown in Figure 7.

3.2. Qualitative reporting

The research question (RQ) of this thematic review focuses on identifying the current trends in paleoart within paleontology research and public education, as evidenced in the literature from 2013--2024. The study is organized around three primary themes: (1) scientific and aesthetic decisions, which examine the interplay between scientific accuracy and artistic interpretation in the creation of paleoart; (2) the integration of digital technology, which explores how digital tools and methods are utilized to enhance the realism and accessibility of the paleoart; and (3) outreach impact, which assesses the effectiveness of the paleoart in engaging the public and disseminating paleontological knowledge. This thematic structure provides a comprehensive overview of the evolving landscape of paleoart and its role in both scientific research and educational outreach, as shown in Figure 7.

3.2.1. Theme 1: Scientific and aesthetic decisions

Paleoart, the artistic representation of prehistoric life, uniquely intersects science and art by visually reconstructing extinct organisms and their environments on the basis of the best available scientific evidence. A paleoartist must effectively merge aesthetic and scientific knowledge (Manucci & Romano, 2023). However, the creation of paleoart is not merely a technical exercise in accuracy; it involves complex scientific and aesthetic decisions. Paleoartists assert that while their

reconstructions are "reasonable approximations," it is impossible to determine their exact accuracy, as any reconstruction inherently involves subjectivity (Hochadel, 2022; Vujaković, 2019). Manucci and Romano (2023) emphasized that the reconstruction process relies on both aesthetic and scientific knowledge, ensuring the fidelity and educational value of the paleoart. These decisions are critical in bridging the gap between paleontological data and public understanding, making science accessible and engaging. This theme explores how paleoartists navigate the intricate balance between scientific fidelity and artistic interpretation.

Table 2 Author vs. Theme.

	Theme 1: Scientific and aesthetic decision	Theme 2: Integration of digital technology	Theme 3: Outreach impact
(Wings et al., 2023)	0	0	1
(Allmon, 2017)	1	0	0
(Ansón & Hernández Fernández, 2020)	1	0	0
(Eriksson, 2014)	0	0	1
(Brinkman, 2018)	1	0	0
(Currie, 2023)	1	0	0
(Davis et al., 2022)	0	1	0
(De Francesco & Marra, 2021)	0	0	1
(De Sousa Oliveira et al., 2023)	0	1	0
(Feldman, 2016)	0	1	0
(Hochadel, 2022)	0	1	0
(Manucci & Romano, 2023)	1	0	0
(Ansón et al., 2015)	1	0	0
(Miller, 2021)	1	0	0
(Monnin, 2023)	1	0	0
(Půtová, 2021)	0	0	1
(Romano et al., 2016)	0	1	0
(Romano et al., 2021)	0	1	0
(Romano et al., 2022a)	0	1	0
(Romano & Sardella, 2020)	0	0	1
(Ross et al., 2013)	0	0	1
(SEGHEDI et al., 2017)	0	0	1
(Szanajda & Jie Li, 2023)	1	0	0
(Witton, 2017)	1	0	0
(Vujaković, 2019)	1	0	0
(Eriksson & Horn, 2017)	1	0	0
(Eriksson et al., 2022)	1	0	0
(Bennett et al., 2022)	0	1	0
(Khatwa Ford, 2019)	0	0	1
(Alcalá, 2018)	0	0	1
Totals	13	8	9

Hochadel (2022) emphasized that scientific accuracy is paramount in paleoart, and the hierarchy between science and art has never been questioned. When a paleoart loses its level of accuracy, the scientific content it supports also diminishes in quality (Ansón et al., 2015). However, little attention has been given to the interaction between art and science and the development of a rigorous paleoart methodology (Witton, 2017). Life reconstructions of extinct organisms are inherently flawed due to fossil incompleteness and the misconceptions or preconceived ideas of scientists and paleoartists. Unfortunately, paleoartists rarely have the opportunity to explain their published life reconstructions (De Sousa Oliveira et al., 2023). Today, we are confronted with a saturation of images created by various artists that often fail to accurately represent the organisms they depict (Ansón et al., 2015).

Therefore, effective collaboration and communication between paleontologists and paleoartists are essential for creating accurate paleontological representations. According to Marco Ansón and Manuel Hernández Fernández (2015), paleoart creation is a process of synthesizing all the latest knowledge and suggesting the latest hypotheses and scientific trends in a visual way. Therefore, it must be accurate for effectively representing ancient organisms, which requires scientific support. Extending this discussion on collaboration, Currie (2023) delves into the collaborative efforts among paleontologists,

preparators, and volunteers, suggesting that this triad is essential for producing high-quality paleoart. Furthermore, scientific results can inspire artists, and art can inspire scientists (Szanajda & Jie Li, 2023). The relationship between scientists and paleoartists fosters constructive interaction, where the questions posed by artists drive scientific advancement (Manucci & Romano, 2023). However, (Monnin, 2023) noted that verbal communication often fails because of differences in technical vocabulary. Miller (2021) highlights the aesthetic and semantic unity in paleoart, which reinforces its scientific credibility and its potential to convey complex paleontological concepts effectively.

In this context, the role of aesthetics and imagination in paleontological reasoning is a crucial area of exploration (Monnin, 2023). Great modern paleoart should be rich in romance and creativity while maintaining scientific credibility (Witton, 2017). Vujaković (2019) contend that all representations of ancient life, whether verbal or graphic, involve some degree of concealment, describing paleoart as an extended metaphor that synthesizes scientific knowledge into engaging visual narratives. Anson and Hernández Fernández (2020) advocate for the multidisciplinary nature of paleoart, arguing that it serves as a crucial tool for portraying extinct animals, thereby merging scientific accuracy with artistic expression. This perspective underscores the importance of paleoart in enhancing our understanding of extinct life forms through accurate and aesthetically pleasing reconstructions. Similarly, Brinkman (2018) highlighted the indispensable role of illustrators in vertebrate paleontology, reinforcing the idea that visual representation is vital for scientific communication.

For example, Allmon (2017) draws parallels between ammonite restoration and other extinct vertebrates, emphasizing the intertwined relationship between paleontological science and paleoart. He also emphasized basic questions of both paleontological science and paleoart, including the pervasive occurrence of uncritical copying and the lack of clear explanation for why particular models are chosen over others. Eriksson and Horn (2017) discuss the challenges and advancements in depicting organisms with limited fossil records, emphasizing the importance of novel analytical techniques and artistic creativity in overcoming these obstacles.

In the future, Monnin (2023) identifies emerging critical tasks for the future, such as historical studies and the development of productive collaboration models between paleoartists and paleontologists, underscoring the need for continuous evolution in this field. Similarly, Szanajda and Jie Li (2023) highlight the transformation of collaboration. Witton (2017) emphasized the necessity of a rigorous methodology in the paleoart, cautioning against uncritical copying and advocating for a robust framework to create scientifically accurate representations. The composite nature of life reconstruction in paleoart, which combines scientific interpretation and artistic vision, necessitates a clear distinction between these components. Like separating results and interpretations in scientific studies, distinguishing between science-based interpretation and artistic vision enhances reproducibility and minimizes incorrect conclusions. Therefore, future works should include a section that explicitly states the study-based information and the reasoning behind artistic choices. This approach will not only add scientific value to the reconstructions but also clarify their adaptability for related studies (De Sousa Oliveira et al., 2023). Advocating for a multidisciplinary approach that integrates scientific accuracy with artistic creativity ensures that the paleoart not only informs but also inspires and educates a broad audience. This thematic review highlights the evolving nature of paleoart and the ongoing efforts to enhance its methodological rigor and collaborative foundations, reflecting its growing importance in the field of paleontology.

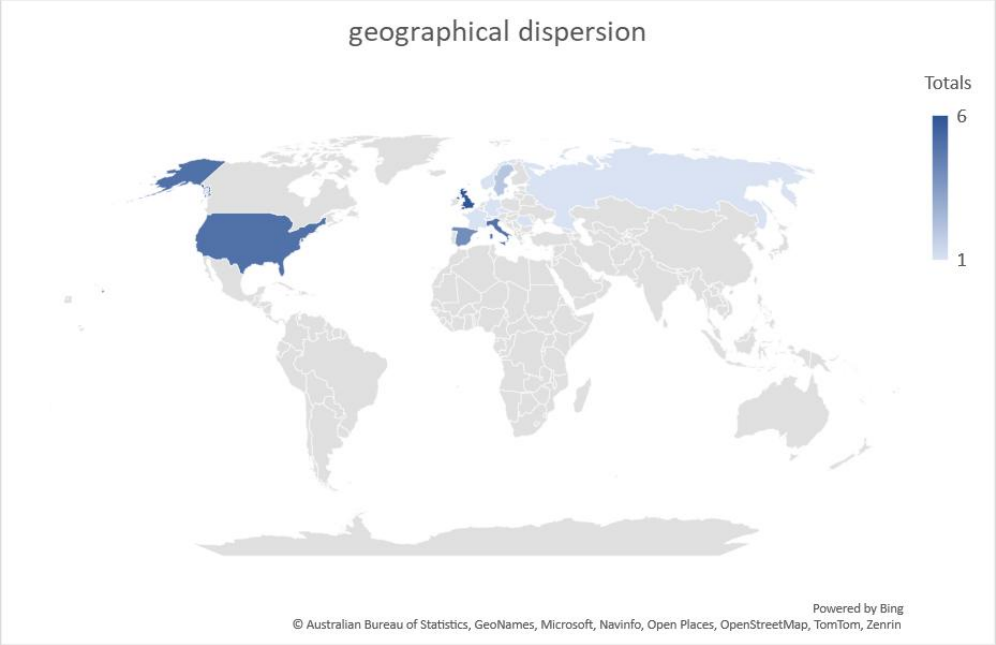

Figure 6 Paper breakdown according to the year of publication.

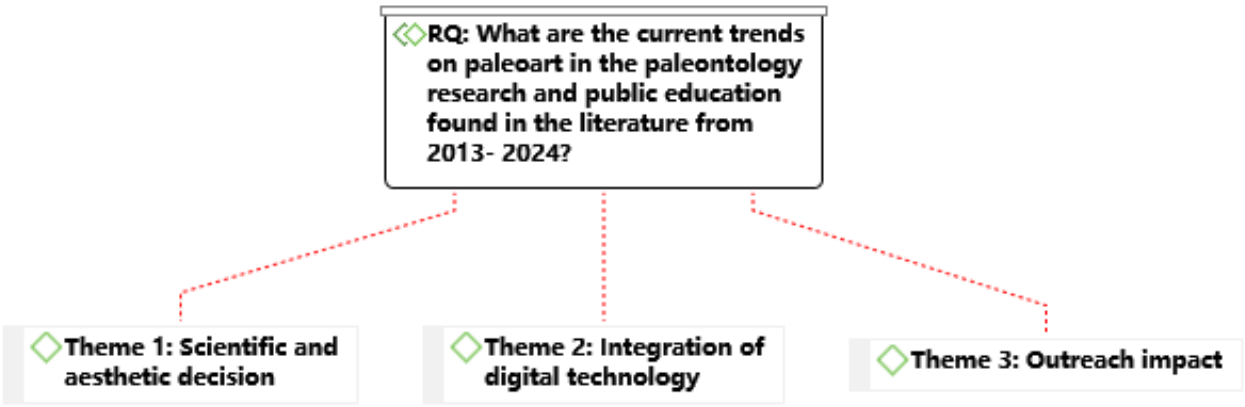

Figure 7 The themes used to answer RQ.

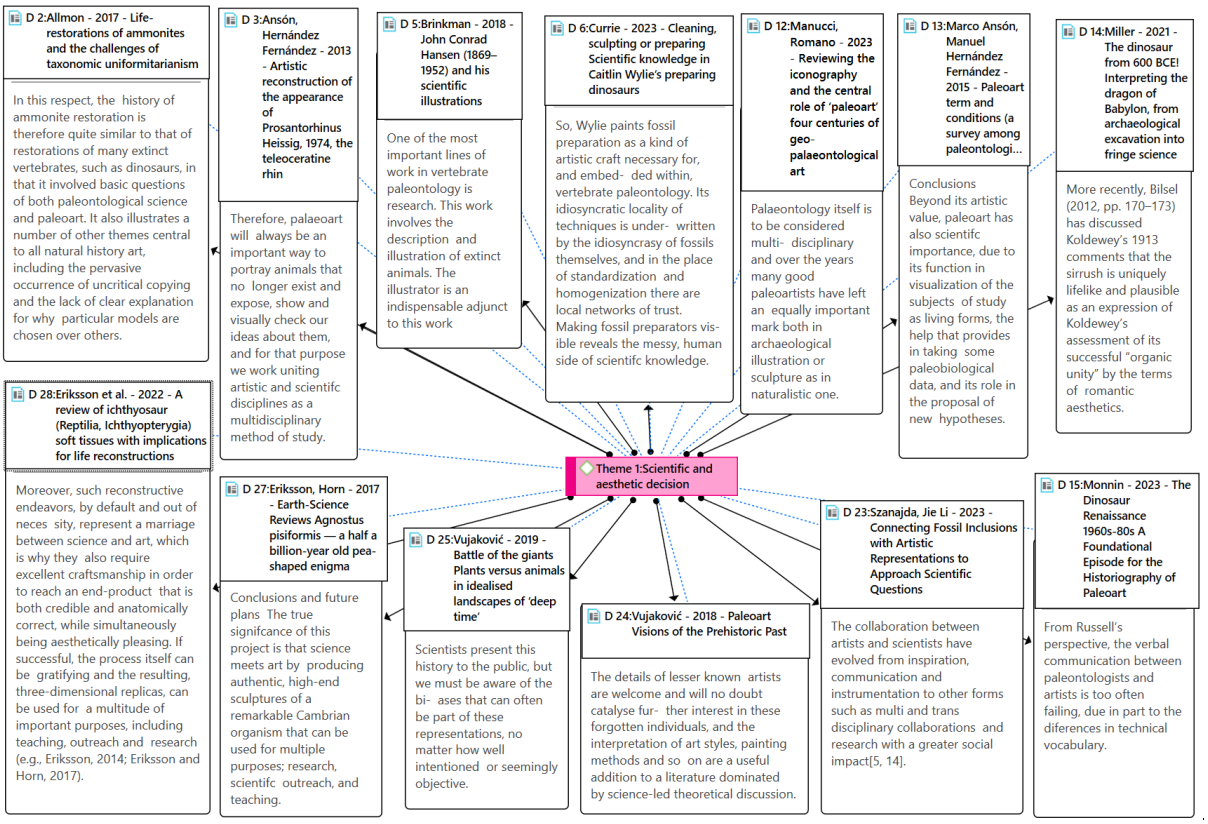

Figure 8 Theme 1 (scientific and aesthetic decision).

3.2.2. Theme 2: Integration of Digital Technology

The application of advanced virtual tools has sparked a profound revolution in paleoart, heralding a second renaissance in the field. The adaptability of 3D graphics has made them widely applicable in academic studies(Hochadel, 2022; Manucci & Romano, 2023). Moreover, the incorporation of augmented reality (AR), virtual reality (VR), and 3D modeling in creating paleoart signifies a significant trend. These technologies enhance the accuracy and engagement of paleontological reconstructions, making them more interactive and accessible to the public. The integration of digital technology into paleoart represents a significant thematic trend in the literature, showcasing how advancements in digital methodologies are reshaping the field. The collaboration between virtual paleontology and paleoart, through digital reconstructions, can effectively communicate ancient life to a wide range of audiences (Hochadel, 2022). The rapid development of novel analytical techniques and artistic outlets has exponentially increased our understanding of ancient life, making reconstructive prospects significantly brighter (Eriksson et al., 2022). Digitalization has fundamentally changed paleoart.

Augmented reality (AR) holds immense potential, particularly in the field of paleontology, where it can revive extinct animals (Bennett et al., 2022). Davis et al., (2022) introduce a stylized low polygon aesthetic for augmented reality (AR) applications at the La Brea Tar Pits, illustrating the potential of digital models to enhance educational experiences while

optimizing for mobile platforms. Feldman (2016) address the challenges in accurately representing dinosaurs in media, emphasizing the significance of cinematic virtual reality (CVR) in creating immersive and educational experiences. This initiative merges digital paleoart reconstruction, prototype VR pipeline development, and the refinement of narrative structural principles for immersive media. The reconstruction process uses cutting-edge digital art methods such as 3D laser scanning, photogrammetry, digital sculpting, realistic shading, and softbody muscle simulation. By leveraging the immersive capabilities of virtual reality along with these digital techniques, the project strives to bring Dreadnoughtus back to life with remarkable precision. Feldman (2016) believe that as CVRs become more accessible, digital paleoartists are increasingly motivated to embrace this innovative medium.

De Sousa Oliveira et al., (2023) demonstrated the importance of 3D reconstruction techniques through their work on a Late Jurassic metrihorychid skull. The disarticulated bones were individually scanned with an Artec Space Spider structured light surface scanner (Artec Group, Inc.) and then virtually reassembled via Artec Studio 13 software (Artec Group, Inc.). This process facilitated both the morphological description and the scientific illustration of the sample, revealing how these methods enable detailed morphological studies of complex fossils. Similarly, Romano et al. (2022) and their various contributions underline the utility of advanced photogrammetry and 3D modeling techniques for both the restoration and body mass estimation of prehistoric creatures, leading to more precise and comprehensive digital reconstructions. The above quotations are shown in Figure 5.

The adoption of digital tools such as augmented or virtual reality offers remarkable opportunities but also presents challenges in paleoart creation and promotion (Bennett et al., 2022). AR undeniably has the power to excite and engage both children and adults; however, its novelty may decline over time. The maintenance of new technology, particularly apps available only through designated app stores, is challenging, and download barriers also exist (Bennett et al., 2022).

These perspectives collectively underscore the transformative impact of digital technologies on paleoart, making paleontological data more accessible, interactive and accurate. The thematic trend in the literature emphasizes not only technical advancements but also broader implications for public engagement and scientific communication. As digital tools become increasingly sophisticated and widespread, their application in paleoart promises to continue revolutionizing how we understand and visualize ancient life, making it an indispensable part of both research and public education. The convergence of digital technology and paleoart, therefore, represents a critical area of ongoing innovation and interdisciplinary collaboration, reflecting a dynamic and evolving field.

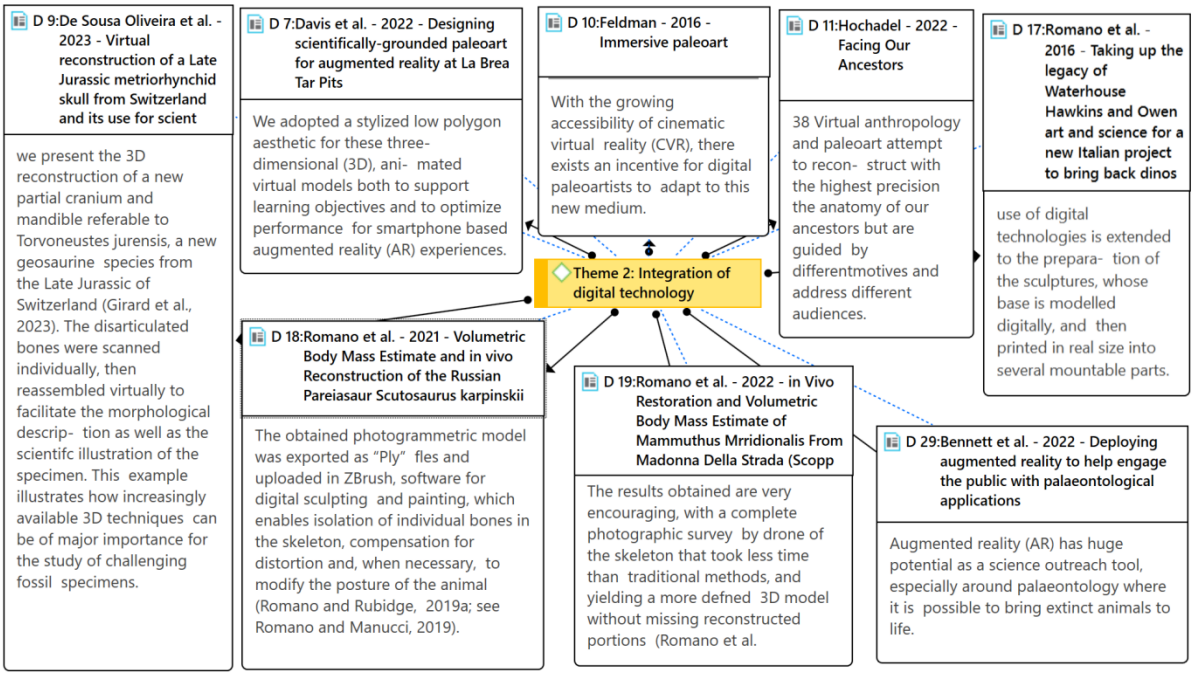

Figure 9 Theme 2 (Integration of Digital Technology).

3.2.3 Theme 3: Outreach impact

Paleoart has become an increasingly important teaching tool in paleontology, enabling the immediate visualization of paleontological research results (De Francesco & Marra, 2021). It is now the most commonly used medium to communicate paleontological topics to the public. In addition to providing insights into past ecosystems, paleoart also plays a crucial role in sparking public interest in these ancient environments (Berta, 2021). Paleoart's role in education is a key theme, focusing on how visual representations of prehistoric life help in teaching and public outreach. The ability of paleoart to translate complex

scientific data into understandable and engaging visuals is emphasized. This includes the use of paleoart in museums, educational materials, and media to foster a deeper understanding of paleontological research among students and the general public. Paleoart connects two spheres, the scientific sphere and the public sphere. This shows that research on the one hand and science popularization on the other hand cannot be sharply delineated (Hochadel, 2022).

A series of studies collectively emphasize the significant impact of paleoart on public engagement and education. One effective method to engage the general public in paleontology is to "breathe life" into extinct and fossilized creatures by transforming fossils into works of art and sculptures. These artistic representations can be displayed in museums, providing visitors with an immediate and vivid impression of what these once-living organisms look like (Eriksson, 2014). Wings et al., (2023) underscore the potential of paleontology-themed comics and graphic novels as effective tools for scientific outreach. They emphasize the importance of creating accessible knowledge transfer pathways through a variety of aesthetic forms of presentation in museums and collections to engage the public. Eriksson (2014) advocates for the use of paleoart as a primary medium to communicate paleontological topics to the public, noting its dual role in providing insights into past ecosystems and stimulating broader interest in scientific activities. Romano and Sardella (2020) further support this view by highlighting the importance of life restoration and the evocative power of the term "prehistoric" in capturing the public's imagination and supporting educational efforts.

Geological education, historical reconstructions, and the integration of natural history with paleoart as the carrier into public outreach play significant roles in enhancing scientific literacy. SEGHEDI et al., (2017) emphasize the critical role of geological education and the educational value of historical reconstructions. They suggest that these tools can significantly enhance student learning by providing tangible connections to past life and geological processes. Alcalá (2018) builds on this by demonstrating the potential of geotourism through initiatives such as the Dinópolis project, which effectively combines educational and recreational experiences to promote scientific literacy and tourism. Expanding this discussion to a broader context, Khatwa Ford (2019) and Půtová (2021) extend the discussion to the broader role of World Heritage Sites and natural history objects. These sites and objects are pivotal in fostering educational engagement and enhancing scientific literacy among diverse audiences. By integrating educational programs and information dissemination, these heritage sites serve as vital resources for public education and appreciation of natural history. Collectively, these studies underscore the multifaceted approaches necessary to engage the public in geological and paleontological sciences, suggesting that combining educational tools, recreational activities, and heritage sites can create a comprehensive strategy for improving scientific literacy.

In summary, the collective views of these authors demonstrate a multifaceted approach to communicating paleontological knowledge. They advocate the use of innovative educational tools and strategies, such as digital technologies, paleoart, and geotourism, to engage diverse audiences and enhance public understanding and appreciation of paleontology. This thematic review paper underscores the importance of these approaches in making paleontological studies accessible, engaging, and educational for the broader public.

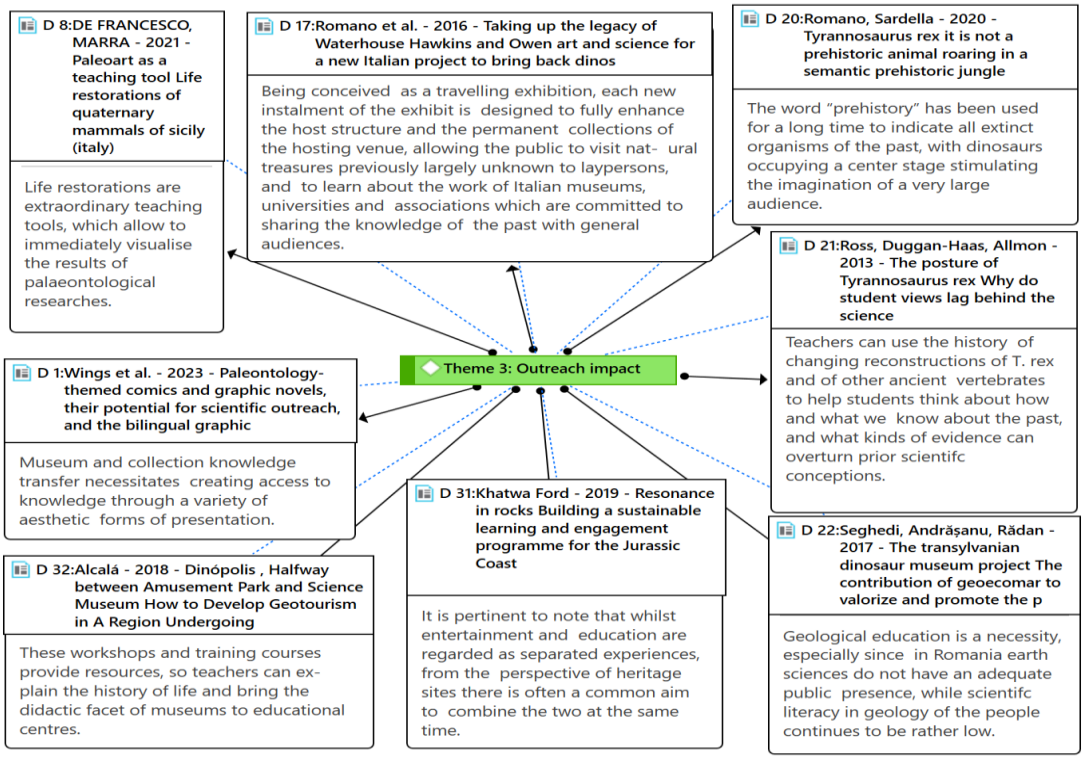

Figure 10 Theme 3 (Outreach Impact).

4. Discussion

Researcher-paleoartists, who are also creative practitioners, hold significant value within the paleoart community (Ansón et al., 2015). Anatomical knowledge is crucial for accurately depicting prehistoric creatures, requiring paleoartists to possess a substantial understanding of paleontology. Moreover, the role of paleontologists in guiding the creation of paleoart remains indispensable. According to Monnin (2023), two critical and interrelated tasks are emerging as essential: first, studying historical cases of the reciprocal relationship between paleoart and paleontology, and second, envisioning future collaborations between paleoartists and paleontologists.

From this background, two main points have emerged: the development of a framework for communication and cooperation among paleoartists, paleontologists, and curators (educational institutions or museums) in paleoart creation and the application of new technology in paleoart creation and display. These advancements aim to explore more possibilities for the expression of ancient art in the context of advancing science and technology, thereby playing a more significant role in public education.

4.1. Development of a framework for paleoart creation

The development of a structured framework for the creation of paleoart is essential to ensure scientific accuracy while fostering artistic creativity (Romano et al., 2016). The first step in this process involves establishing clear guidelines collaboratively developed by paleontologists and paleoartists, who play a crucial role within the paleoart community as both scientists and creative practitioners(Ansón & Hernández Fernández, 2020). These guidelines emphasize the use of well-documented fossil evidence, accurate depictions of anatomical features, and faithful representations of the paleoenvironment, including flora, fauna, and climatic conditions(Allmon, 2017).

Effective communication between paleoartists and paleontologists is crucial for the successful creation of paleoart (Manucci & Romano, 2023; Vujaković, 2019). This can be facilitated through regular collaborative workshops, interdisciplinary research teams, and standardized communication tools(Currie, 2023; De Sousa Oliveira et al., 2023; Romano et al., 2022b). Workshops and seminars allow both groups to discuss recent findings, share techniques, and work together on projects, whereas interdisciplinary teams can ensure consistency and clarity from inception to completion. Standardized tools and platforms for sharing data and visual references further enhance communication, ensuring that all parties are on the same page throughout the creative process.

Museums and other educational institutions play a vital role in disseminating paleontological knowledge to the public. To maximize the impact of paleoart in these settings, the framework should include strategies for effective engagement, such as collaborative exhibits, educational workshops, and interactive digital platforms. Collaborative exhibits designed by paleoartists, paleontologists, and museum curators can create accurate and compelling displays. Educational workshops can explain the creation process, enhancing public understanding and appreciation. Interactive digital platforms allow the public to explore paleoart in detail, understand the scientific basis of the reconstructions, and engage with the material in an immersive way. This holistic approach ensures that the paleoart continues to be a vital tool for scientific inquiry and public education.

4.2. Future trends and recommendations for paleoarts in public education

Paleoart is ultimately an artistic interpretation of science (Witton, 2017). On the one hand, the paleoart must show to the public the most accurate reconstruction of the appearance of organisms and environments of the past that are possible. On the other hand, owing to the progress of science and technology, paleoart should explore more forms of artistic expression. In this way, paleoart contemporary esthetics continue adapting in accordance with the contemporaneity of scientific knowledge and thought.

The integration of digital technologies and paleoart into paleontological research and public outreach presents numerous opportunities for enhancing scientific communication and education(Berta, 2021; Eriksson et al., 2022). Future studies should focus on expanding the accessibility and usability of these digital tools. This involves addressing technical challenges such as download barriers and the maintenance of apps, as highlighted by previous research. Additionally, there is a need to investigate the long-term educational impacts of these technologies. Longitudinal studies could assess how engagement with digital paleoart and VR experiences influences students' interest in ancient life and their understanding of scientific concepts over time.

Another area for future research is the development of interdisciplinary approaches that combine paleontology with other fields, such as computer science, education, and museology. This can lead to more sophisticated and immersive educational experiences. Collaborative efforts between scientists, educators, and technology developers will be essential in creating more effective and engaging tools for scientific outreach.

The future of paleoart in public education lies in its ability to integrate new technologies and artistic creativity to engage diverse audiences effectively. Museums and educational institutions should leverage the potential of paleoart and digital technologies to create interactive and immersive learning environments. As highlighted by Bennett et al. (2022), these

technologies can inspire and educate diverse audiences, though they also pose challenges such as app maintenance and technological barriers.

In summary, the development of a structured framework for paleoart creation and the integration of new technologies are essential steps for advancing the field. The collaborative efforts of paleoartists, paleontologists, and museum curators are crucial in ensuring the scientific accuracy and artistic integrity of paleoart. This interdisciplinary approach not only enhances the creation process but also maximizes the educational impact of the paleoart in public settings. By addressing technical challenges and exploring new forms of artistic expression, paleoart can continue to evolve and adapt, playing a significant role in both scientific research and public education. The holistic strategies discussed here underscore the importance of effective communication, collaboration, and the use of innovative tools to foster a deeper understanding and appreciation of ancient life among diverse audiences.

5. Conclusion

This thematic review explored the evolving trends in paleoart within paleontology research and public education from 2013--2024. By examining the interplay between scientific accuracy and artistic interpretation, the integration of digital technologies, and the impact of the paleoart on public engagement, this study highlights the multifaceted nature of the paleoart and its significance in both scientific and educational contexts. Paleoart continues to be a crucial aspect of paleontological research and public education, bridging the gap between scientific data and public understanding. Future research should focus on developing a specialized paleoart creation framework, promoting effective interdisciplinary collaboration and communication between artists and paleontologists, and establishing standards to ensure the quality and accuracy of paleoart representations. The contributions of integrating digital technologies and paleoart into paleontological research are manifold. These approaches significantly enhance public engagement by making complex scientific concepts more accessible and relatable. The incorporation of digital tools such as augmented and virtual reality holds promise for enhancing the educational and communicative value of paleoart, making it a powerful medium for public science.

Ethical Considerations

Not applicable.

Conflict of Interest

The author declares no conflicts of interest.

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