Article

Digital Archaeology Underwater: Ethical, Epistemic, and Climate Challenges for a Collaborative Future

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Abstract

This article explores the converging challenges and opportunities at the intersection of underwater cultural heritage, digital archaeology, and participatory science. In an era of accelerated climate change, data fragmentation, and rapid technological advancement, underwater archaeology is being reshaped by the rise of generative artificial intelligence (GAI), FAIR (Findable, Accessible, Interoperable, and Reusable) data governance, and the growing role of public archaeology. We argue for an ethical and epistemologically inclusive framework that recognizes the importance of co-authorship, data transparency, and multisensory narratives in interpreting submerged sites. Drawing on case studies from Latin America and Europe, this article demonstrates how socio-technical networks, collaborative models, and culturally sensitive ontologies offer a pathway toward a decolonized, accessible, and sustainable archaeology. This paper concludes with recommendations for integrated public policy and citizen-driven heritage protection, highlighting digital archaeology's transformative potential in the Anthropocene.

Keywords: underwater archaeology; digital heritage; participatory science; climate change; generative AI; FAIR data; public archaeology; epistemic justice

1. Introduction

This paper will address a small but relevant number of issues concerning the social value of the cultural heritage and the role of archaeologists and computers in its protection, study, and fruition by a wide public at the intersection of underwater cultural heritage, digital archaeology, and participatory science. In an era of accelerated climate change, political turmoil, data fragmentation, loss of trust in the media, and rapid technological advancement, underwater archaeology is being reshaped by the rise of generative artificial intelligence (GAI), FAIR (Findable, Accessible, Interoperable, and Reusable) data governance, and the growing role of public archaeology.

This article proposes a conceptual model for the consolidation of a critical digital archaeology, focused on submerged heritage and anchored on five interdependent axes: (1) the impacts of generative AI on modeling and interpretive reconstruction; (2) the necessity for public policies guided by FAIR principles; (3) the predictive role of archaeology in the face of climate emergency; (4) the centrality of public archaeology, collective intelligence, and participatory science; and (5) the valorization of plural epistemologies from an epistemic justice perspective. It is argued that the opening of sites to the public—both

physical and digital—and the broad availability of archaeological data are indispensable conditions for ensuring the right to memory, scientific transparency, and the co-production of knowledge in democratic contexts.

Several authors have addressed the topics mentioned above, which call for a more transparent, public, and inclusive archaeology that should be more present in the lives of the citizens.

Critically understanding one's own culture constitutes the structural foundation for pluralistic and historically conscious societies. As Geertz [1] emphasized, culture is a system of shared meanings that provides interpretive frameworks for social life, while Hall [2,3] and Bourdieu [4] demonstrated how cultural practices shape identities, tastes, and social hierarchies. More recently, Smith [5], Harrison [6], and Assmann [7] have reinforced that heritage is not a static legacy but a socially embedded process through which communities negotiate memory, belonging, and identity. This awareness, grounded in cultural critique, is therefore central to the development of historically reflective and inclusive societies.

At the same time, the adoption of digital technologies in the field of underwater archaeology—such as three-dimensional modeling, geographic information systems (GISs), and, more recently, generative artificial intelligence (AI)—has redefined the boundaries between archaeological practice, technical mediation, and public participation. Dallas [8] and Huggett [9] argue that digital infrastructures are not neutral tools but epistemic frameworks that actively shape how archaeological knowledge is curated, legitimized, and communicated. Jeffrey [10] similarly highlights how digital visualization can democratize heritage engagement while simultaneously raising questions about authenticity and authority. Richards [11] and Niccolucci and Richards [12] demonstrate how curated repositories and interoperable infrastructures, such as the ARIADNE project, provide long-term access and sustainability for archaeological data. Complementing these perspectives, Lercari [13] shows how immersive 3D environments can enable reflexive and embodied experiences of the past, while recent studies have begun to explore the potential of generative adversarial networks (GANs) for reconstructing incomplete archaeological objects [14,15]. Together, these developments illustrate that digital archaeology is not only transforming technical practice but also reshaping the epistemological and political conditions under which submerged heritage is interpreted, shared, and contested.

The Greeks once affirmed that an unexamined life is not worth living. Building on this Socratic maxim, it is possible to argue that the construction of a meaningful existence involves a critical understanding of one's own culture. Identity, values, and convictions do not arise spontaneously; rather, they result from a trajectory of shared social experiences rooted in practices, symbols, and cultural narratives [1,2]. As Hall [2] argued, identities are discursively constructed within specific cultural and historical contexts, while Bourdieu [4] emphasized how dispositions and judgments are internalized through processes of socialization and habitus. Similarly, Taylor [16] (1989) and Appadurai [17] underscore that modern subjectivities emerge from complex interactions between collective imaginaries, globalization, and cultural flows. Even unconsciously, individuals internalize schemes of perception and judgment that are structured by the historical and social conditions in which they are embedded [4].

Recognizing culture as a system of shared meanings—which shapes not only what we think but also how we think—is therefore fundamental to understanding the formation of the modern "self" [16]. In a globalized context, where flows of information and cultural imaginaries intersect and intertwine, this awareness contributes significantly to the development of critical and pluralistic identities [17].

Films, literature, oral narratives, folkloric practices, educational systems, and social interactions are central elements in shaping the ways individuals perceive and interpret the

contemporary world [18]. These cultural mechanisms organize worldviews and influence attitudes, values, and decision-making processes [3,19]. Religions provide a paradigmatic example: often transmitted along geographical and communal lines, they can foster cohesion but can also become sources of exclusion, prejudice, and conflict. In this regard, archaeology and historical awareness play a crucial role in helping individuals navigate their convictions with tolerance and critical reflection, counterbalancing tendencies toward exclusivism and cultural essentialism.

In this regard, history and archaeology play a central role in helping us understand reality as a continuous process of cultural transformation, enabling the recognition of diversity as a structuring element of human experience [20]. As Elias [21] highlights, the evolution of institutions, such as penal systems, is directly related to the increasing complexity of social sensitivities and the internalization of self-regulation norms. The study and interpretation of material remains from the past can function as marks of this historical transformation and influence human thought in multifaceted and often unintended ways [22].

2. Social Value of Archaeology

Archaeology, as it is known in contemporary Western societies, was consolidated as a scientific discipline based on the rationalist assumptions of the European Enlightenment. In this context, historical knowledge came to be structured through empirical criticism and systematic observation, replacing theological paradigms of creation with narratives based on material evidence and relative chronologies [18]. From the nineteenth century onward, archaeological remains acquired significant epistemic and symbolic value, contributing to the construction of national identities and to the formation of the first cultural heritage protection laws [23]. Several countries established public policies aimed at safeguarding historical libraries, monuments, cultural landscapes, and archaeological sites, many of which were incorporated into museological practices through processes of in situ and virtual musealization [5].

The international relevance attributed to material heritage extends beyond the scientific and educational fields and encompasses the economic sector. Cultural tourism—an activity that involves visiting historical sites, archaeological sites, and museums—currently represents about 6% of the global Gross Domestic Product (GDP), according to estimates from the World Tourism Organization [24], and in 2023, tourism, much of it cultural, represented over 12% of the Portuguese GDP [25]. This economic significance underscores the need for integrated heritage management policies that combine preservation, sustainability, and public accessibility.

The impact of tourism on cultural heritage is widely studied and presents both beneficial and harmful implications, depending on the socioeconomic context and the degree of planning behind public policies [26,27]. In general, however, cultural tourism can foster the appreciation of the past and stimulate the economic development of local communities, even though it can sometimes generate pressures on heritage sites, including loss of authenticity, restricted access, and environmental stress [28].

With the intensification of globalization and the expansion of global literacy, the construction and dissemination of cultural narratives by social groups historically marginalized is expanding, especially those without a tradition of written records [6]. The emergence of digital technologies, social media, and participatory platforms has broadened the scope of memory production, fostering the pluralization of heritage discourses on a planetary scale [29].

In this cosmopolitan context, cultural heritage assumes a strategic importance not only as a repository of cultural diversity but also as an instrument for promoting intercultural

empathy and the recognition of otherness. The concept of "global collective memory" is becoming a key interpretative tool for understanding how humanity deals with its heritages and differences from an ethical and planetary perspective [7].

Archaeological sites function as symbolic mediators between past and present, anchoring individual experiences in a materialized collective memory. As historical subjects, our identities are shaped by an accumulation of experiences that, consciously or not, influence the ways we interpret archaeological remains, and physical remains of the past inform and illustrate our history and influence the constitution of subjective narratives [30].

Unlike family albums, which evoke specific personal memories, archaeological cultural goods operate on a social and intergenerational scale, constituting vectors of belonging, symbolic agency, and meaningful production. Culture, in this context, transcends familial influence by providing the structural frameworks that configure our understanding of the world, our beliefs, and the ways we position ourselves within stratified social or ethnic structures [4,22].

The presence of the past—whether tangible or latent, visible or hidden—is a constant feature of contemporary cultural dynamics. Whether ignored or celebrated, the past shapes identities, memory policies, and ways of inhabiting the present. As Lowenthal [22] argues, "the past is a constant presence, structuring our decisions, fears, and aspirations, even when we do not consciously recognize it".

Cultural heritage plays a significant role in mediating the relationship between individuals, society, and the environment by reaffirming bonds of belonging and historical continuity. By reminding us of our roots and our integration in broader cultural systems, it contributes to the construction of our identity, reinforces collective self-esteem, provides a sense of stability in times of rapid transformation, and creates a sense of cosmopolitan belonging in an increasingly diverse world [5,6].

Heritage is not merely a legacy of the past; it is also an active symbolic resource that explains why we become emotionally mobilized by events or objects that, in many cases, do not directly affect our lives. Such cultural effects derive from processes of socialization and internalization of historical narratives that shape perceptions of threats, duties, and solidarities [31].

Thus, understanding the contemporary world is a direct consequence of the relationships established with a multiplicity of agents—from material objects and living beings to systems of ideas, oral traditions, collective memories, and even cognitive distortions of the past [7,32]. In a global context characterized by increasing mobility, diversity, and uncertainty, cultural heritage becomes a tool for social cohesion and symbolic resistance against historical discontinuity. In sum, maritime archaeology can be an incredible tool for our wellbeing, and its fruition can be enhanced by computers and social media.

3. Perceiving the Past: Cultural Heritage, Identity, and Social Meaning

Cultural heritage can manifest itself in tangible or intangible forms, visible or invisible. It is often buried, submerged, or subtly incorporated into natural and urban landscapes, becoming almost imperceptible to everyday observation. However, once perceived and cognitively processed, it exerts a profound influence on ways of life, attributing meaning, historical continuity, and collective identity to individuals and social groups [33]. The role of archaeologists is to share their discoveries, and computers are a powerful tool to that end.

As mentioned above, heritage operates as a system of meanings that transcends the materiality of remains, as it provides interpretive frameworks for memory, morality, and social action. When recognized and valued, the past ceases to be merely a repository of ruins and becomes an active source of wisdom and inspiration, capable of expanding

historical awareness and revealing the plurality of possible paths for the present and the future [6,34].

The experience of one of the authors, who lived as an immigrant in the state of Texas for over two decades, highlighted how engagement with local cultural heritage can serve as an essential mediator in the process of intercultural integration. Studying the material and symbolic culture of the region allowed him to gain a deeper understanding not only of the values and convictions that structured local social practices but also of the expectations projected onto foreign individuals integrated in that context. Although until recently American universities were characterized by their cosmopolitan orientation and by the emphasis on academic merit as an organizing principle, this meritocratic logic was often modulated by traditions, regional imaginaries, and inherited cultural systems [4,35].

Visits to archaeological sites and historical museums proved particularly revealing in this process, functioning as pedagogical and affective devices that convey narratives of belonging, identity, and collective memory. These musealized spaces act as interpretive arenas where the past is performed and re-signified, offering visitors an opportunity to decode the symbolic elements that underpin local cultural cohesion [36].

As Ginzburg [37] stated, history can be defined as the study of what is presumed to have happened based on divergent accounts from different historical subjects, whereas archaeology seeks to understand what actually occurred through the analysis of surviving material remains of human action. In this sense, archaeology not only complements historical narratives but also challenges and complicates them, allowing access to experiences and narratives that were historically silenced or excluded from written records.

A deeper understanding of the world we inhabit—in its historical, cultural, and structural dimensions—can significantly enrich the quality of our lives. Culture, as a form of symbolic capital, is integrated into our human capital [4], informing the cognitive and affective dispositions that shape our social perceptions. In this sense, archaeology plays a strategic role by revealing, through materiality, the dynamics of social differentiation that characterize contemporary Western societies, which are today notoriously marked by systems of stratification and inequality [38]. In doing so, archaeology contributes to a critical reading of the present in light of the long-term processes that structure social, economic, and identity relations.

The major problem with archaeology is that most archaeological sites are inaccessible to the general public, and even those open to visitation often present significant interpretive challenges. For non-specialist audiences, reading and cognitively reconstructing cultural landscapes from fragmented remains is not always intuitive. The absence of interpretive resources—such as digital reconstructions, models, contextualized signage, or specialized guides—compromises the visitor experience, rendering ruins visually opaque, monotonous, or even incomprehensible [8,39].

Historically, archaeology consolidated itself as a rather elitist field, practiced mostly by and for dominant social classes, which delayed the development of approaches focused on cultural mediation, heritage education, and civic engagement [40]. This distance between archaeological knowledge production and its democratization is still evident in many contexts, where the perception of heritage as a collective good remains weak. Overcoming this problem requires not only new formats for public presentation of sites but also a structural change in science communication policies and social participation in archaeological heritage management.

Underwater archaeological sites are, by definition, invisible. This characteristic makes them exemplary of a subfield historically marked by low public visibility, limited accessibility, and professional practices that are often non-transparent. In many regions, underwater archaeology still operates in a hermetic manner, frequently traversed by internal dynamics

of academic rivalry, institutional isolation, and resistance to interdisciplinary collaboration and open data [41,42].

In his introduction to the *Oxford Handbook of Maritime Archaeology*, George Bass [43] highlighted an alarming fact: it is estimated that only about 25% of excavated archaeological sites are effectively published, implying a critical rate of heritage destruction under the justification of scientific research. This observation is based on several studies, according to which more than 70% of excavations conducted in the Near East remain unpublished [44,45], while approximately 80% of archaeological materials from Italian sites have not been formally published [46,47].

This scenario of publication deficit, combined with the inherent invisibility of submerged sites, underscores the urgent need for open science strategies, digital curation, and institutional accountability in contemporary underwater archaeology. There is no evidence that the maritime subfield shows significantly better publication rates than terrestrial excavations mentioned above—on the contrary, the very difficulty of physical and technological access seems to contribute to lower transparency and dissemination.

However, when submerged sites are documented and made accessible through photographic records, videos, or three-dimensional modeling, they rarely fail to elicit admiration and fascination—not merely due to the myth of treasure hunting but because of the concrete possibility of accessing materialized fragments of human experience. Preserved in anoxic environments, often sealed under sediments, submerged artifacts—such as wood, leather, textiles, seeds, and food remains—can be preserved with remarkably greater stability than those recovered in terrestrial sites [48,49].

This conservation advantage often makes shipwrecks archaeological time capsules: they preserve a nearly frozen historical moment, offering tangible evidence of the routines and daily lives of individuals who often left no written records. Humble artifacts, often discarded after wear, acquire new interpretive value in these contexts. Unlike funerary goods or ceremonial objects frequently recovered in terrestrial excavations, underwater materials reveal the ordinary and economic practices of marginalized social layers, expanding the possibility of constructing a more plural and less elite-centered history [50,51]. Submerged sites, therefore, have a high pedagogical value and their capacity to promote epistemic justice by enabling the inclusion of historically silenced voices that have been overlooked by traditional archaeology centered on monuments and major civilizations.

Making underwater archaeological sites accessible to the public—whether through controlled physical visits or immersive virtual experiences—without compromising their integrity constitutes, arguably, one of the highest ethical and scientific responsibilities of contemporary archaeology. This practice is fully aligned with the spirit of Article 27 of the Universal Declaration of Human Rights [52], which affirms the right of every individual "to freely participate in the cultural life of the community, to enjoy the arts and to share in scientific advancement and its benefits" [28].

Access to submerged heritage should not be understood merely as a privilege but as a cultural right that fosters belonging, encourages heritage education, and promotes the democratization of knowledge. Virtual musealization, digital twins of archaeological sites, and interactive 3D reconstructions represent viable pathways for this mediation, allowing even fragile or physically inaccessible contexts to be experienced and understood by diverse audiences, and replicas of fragile and rare artifacts to be printed in schools around the world [12,53,54].

Digital archaeology applied to submerged heritage has the potential to integrate conservation, inclusion, and accessibility, fulfilling technical, social, and political functions. The most critical factor in any effective policy for site accessibility—particularly in the underwater context—lies in the availability and dissemination of scientifically grounded

publications. Such materials must clearly and accurately address the historical and heritage significance of the sites, their vulnerability, visitation protocols, and conduct guidelines to prevent both physical and symbolic damage to archaeological contexts [28,55].

This information constitutes instruments for heritage education and cultural citizenship, encouraging critical public engagement and responsible appropriation of heritage. It is recommended that such materials also promote participatory documentary practices, such as photography, audiovisual recording, and collaborative research initiatives, which can expand both knowledge and site safeguarding efforts [29].

Public policies that integrate scientific communication, free access to information, and active civil society participation have greater potential to promote community belonging and to transform visitors into allies in the protection of submerged cultural heritage [56].

4. Vulnerable Underwater Sites: Ethics, Risk, and Preventive Documentation

The diversity of sites associated with maritime cultural heritage is broad and encompasses both submerged and terrestrial contexts. Underwater archaeological sites, in particular, can be classified into two main categories: stable and vulnerable. The stability of a site depends on multiple factors, including depth, sediment type, currents, the presence of biological organisms, and the degree of human intervention [55].

Organic materials, such as wood and leather, and ferrous metals, such as wrought iron and steel, tend to undergo accelerated degradation when exposed to environments with high oxygenation and intense biological activity. For this reason, specialized literature recommends that submerged sites be recorded with maximum accuracy and resolution using techniques such as 3D scanning, photogrammetry, and georeferencing before being reburied with sediments or covered with geotextile fabrics to simulate anoxic environments [57,58].

Ideally, these sites should remain in situ, in accordance with the 2001 UNESCO Convention, and be periodically monitored through environmental sensors or scientific diving campaigns. This approach is ethical, sustainable, and consistent with the principles of preventive conservation, which prioritize the integrity of the archaeological context and its transmission to future generations.

There is consensus among archaeologists and heritage management specialists that vulnerable underwater sites—especially shipwrecks and ruins exposed to accelerated degradation processes—should be properly documented, recorded with technical rigor, and, whenever possible, protected or reburied with materials that slow their deterioration [28,55].

This approach seeks to balance the right of access to heritage with the need to guarantee its integrity for future research and for the benefit of future generations. It constitutes a conservationist strategy broadly accepted by the scientific community and subject to minimal controversy among underwater archaeology professionals [59].

Arguments in "defense" of treasure hunting will not be addressed in this article, as they represent an extractivist and populist perspective that promotes the systematic destruction of natural and cultural resources for the sake of immediate economic gain of a few, and increasingly, as schemes to raise or launder money from investors. Historically, treasure hunting originated as an informal practice among recreational divers who discovered shipwrecks with valuable cargoes in shallow waters, particularly in Florida. Over time, this activity evolved into an industrialized sector, where real profit became linked to investment schemes, often involving speculation in the stock market [60,61].

Today, treasure hunting is a discreet and difficult-to-monitor practice whose impact on underwater cultural heritage is devastating [62]. Recent studies show that the international trade in antiquities has increasingly become part of global illicit networks linked to the

financing of terrorism, money laundering, and the illegal trade in narcotics, arms, and human beings [63,64]. This reality imposes an urgent challenge to heritage protection policies and demands a clear stance from the archaeological community and international cultural preservation organizations.

5. Virtual Access Through Computer Graphics and Procedural Modeling

Controlled access to vulnerable underwater sites, particularly shipwrecks, can be facilitated through the use of advanced computational models. Virtual reality (VR) and augmented reality (AR) technologies are emerging as promising tools in this field, especially when combined with procedural computational modeling techniques. This combination enables the creation of high-resolution immersive three-dimensional models that can be explored by users through accessible devices, such as VR headsets or interactive digital platforms. Computer-assisted modeling allows archaeologists to develop digital reconstructions of the past with varying degrees of fidelity and to iteratively modify them in order to test hypotheses about submerged archaeological contexts, evaluating their plausibility based on technical and scientific criteria [65].

These computational models also allow for the visualization of data collected at archaeological sites with different levels of metric and semantic precision, enabling a deeper understanding of the structural integrity and spatial arrangement of recorded elements. For archaeologists, this offers the opportunity to observe shipwreck remains in a virtual environment, overcoming limitations such as low underwater visibility, poor lighting, and the inherent constraints of the stratigraphic excavation method. The controlled nature of underwater excavations imposes significant restrictions on external observation: efforts are made to minimize continuous exposure of hull parts and artifacts, making comprehensive visualization during the excavation process unlikely.

Thus, even if tourists or visitors accompany an excavation, it is unlikely that they will have full visual access to the complete context or to the interpretive phases. Generally, excavated objects are carefully cleaned, identified, recorded, and subsequently removed for analysis or reburied for conservation, thereby limiting continuous visual enjoyment and immediate understanding of the site [66].

Through the use of computer modeling, archaeologists can create a complete 3D visualization of a vessel's hull remains, preserved cargo as found, detailed construction features, and internal space reconstructions. Furthermore, procedural modeling techniques allow for the proposal of different reconstruction hypotheses and even invite lay audiences to engage in their own interpretive experiences, promoting more dynamic and educational interactions.

This approach has been successfully applied in projects that combine underwater archaeology and digital reconstructions, as demonstrated by Dell'Unto, Landeschi, and Leander Touati [66], who emphasize the potential of immersive visual narratives to communicate complex archaeological contexts. According to the authors, such reconstructions not only enrich scientific documentation but also promote public engagement by making invisible elements of submerged material culture visible.

6. Relatively Stable Sites: Management, Hazards, and Community Engagement

Relatively stable, less vulnerable sites are more numerous and, perhaps, less archaeologically significant. This group includes clusters of iron cannons and concreted anchors on rocky seabeds, or metal ships sunk within the past century, for which construction plans, photographs, and films are still available. Metal vessels are more abundant than older sites and are often used for fishing or recreational diving. Artifact collection is illegal but difficult

to control unless there is a strong relationship between governments and local communities. As noted by Maarleveld [55], the involvement of coastal communities in the management of contemporary shipwrecks can be decisive for the protection of these heritage assets, especially when integrated into participatory monitoring and heritage education strategies.

A relevant issue associated with metal ships is the recurring presence of ghost nets—fishing gear lost or abandoned—which remain entangled in submerged structures. These elements pose significant risks both to marine fauna and to divers and underwater visitors. Each shipwreck constitutes a specific case study, making it difficult to formulate a single, universal policy to address the problem. In some contexts, these nets are highly dangerous and represent a serious form of marine pollution. In others, however, they integrate into the artificial reef formed around the vessel, becoming part of a new ecosystem and presenting minimal risks [67].

Another recurring problem in metal shipwrecks is the presence of potentially polluting elements, such as fuels, heavy metals, or even unexploded munitions—material legacies of armed conflicts or naval accidents. Such environmental and safety risks require careful technical assessment and specific interventions, considering that each sunken vessel represents a unique case study whose documentation and publication are fundamental for guiding management and mitigation strategies [68].

Additionally, a subset of relatively stable sites includes ballast piles and accumulations of amphorae, often protected by polypropylene meshes or containment structures made of mesh boxes. These solutions aim to mitigate anthropogenic impacts, such as the illegal collection of artifacts or physical disturbances caused by divers and tourist vessels.

Human actions have historically represented the greatest threat to submerged cultural heritage—not always motivated by greed but often by ignorance or lack of heritage awareness. A popular tale from Croatia recounts the story of an old sponge diver who reportedly took pleasure in walking over mounds of amphorae, hearing the sound of the pieces breaking under his lead boots.

With the advent of autonomous diving, this behavior became even more frequent, resulting in severe impacts on these sites, particularly through the predatory collection of intact amphorae, objects highly valued on the antiquities market. The absence of effective heritage education policies and collaborative monitoring has contributed to the irreversible degradation of many of these archaeological contexts.

Another important type of submerged archaeological site is constituted by submerged ruins, generally located in shallow areas due to processes associated with low-magnitude tectonic subsidence or coastal erosion. These contexts tend to exhibit greater structural stability compared to shipwrecks or organic deposits and are therefore often considered suitable for underwater visitation activities, such as recreational scuba diving or snorkeling. Their accessibility, combined with visibility and lower fragility, makes these ruins important assets for the development of public archaeology strategies and sustainable tourism [69].

All these underwater archaeological sites—from the most vulnerable to the structurally stable—can be made accessible to the public through different scientific dissemination strategies, with specialized publications being one of the most effective and enduring means. In this context, public participation in archaeological projects is generally structured in two complementary phases. The first corresponds to the prospecting and excavation phase, during which community involvement can occur through initiatives such as citizen archaeology, heritage education, and volunteer programs. The second phase concerns site management, involving the curation, maintenance, and continuous monitoring of submerged cultural assets—tasks that can and should be shared with local collectives, educational institutions, and diving groups, reinforcing the principle of shared responsibility for heritage [41].

7. Participatory Fieldwork: Public Engagement in Underwater Excavations

There have been experimental initiatives to open underwater excavations to observation by non-specialist visitors, with promising results in terms of public engagement. In 2001, for example, tourists were guided to the excavation site of the Arade 1 shipwreck—a late 16th-century French vessel that sank off the Portuguese coast. Despite the limitations imposed by low underwater visibility, the experience was reported as highly positive, generating enthusiasm and direct visitor involvement in the archaeological process.

Such practices reveal the pedagogical and affective potential of public underwater archaeology, provided they are conducted with appropriate safety and preservation protocols [41,70]. Other experiences of public participation in underwater archaeology have also demonstrated remarkable results. A notable example occurred during the excavation of the Pepper Wreck in the mid-1990s, when amateur diving clubs were integrated as avocational collaborators in the documentation process. The performance of these teams showed a high degree of technical precision, particularly in measurements and recording, validating the potential of citizen science applied to underwater archaeology. These experiences reinforce the idea that, under appropriate supervision, non-specialist groups can significantly contribute to the production of reliable scientific data and to the strengthening of public archaeology [71,72].

Depth always plays an important role in the accessibility of underwater sites. For sites of moderate depth and beyond, it is difficult to bring tourists safely. The use of cameras and real-time transmissions has been attempted at deepwater sites, with varying degrees of success. Robert Ballard and other researchers have conducted live broadcasts of deep-sea research and excavations with great success, involving, for example, large groups of students who could interact with researchers. These experiences highlight the educational potential of remote and immersive mediation technologies [8,73].

Moreover, virtual reconstruction and augmented reality techniques are increasingly being incorporated into archaeological practice to expand public access even to sites that are physically difficult to reach [74,75]. Three-dimensional modeling, accompanied by paradata documentation, has been recommended as a way to ensure transparency, auditability, and community involvement in the reconstruction of the past [76–78]. These digital tools, combined with ontological curation and context-sensitive data management, allow remote experiences to be both enriching and ethically responsible [8,75]. The most interesting and perhaps successful project is perhaps that of Timmy Gambin's Xlendi shipwreck excavation in Malta, in which Pierre Drap's team created a virtual reality site that could be visited on the internet [79].

International guidelines, such as the 2001 UNESCO Convention, emphasize that making submerged heritage accessible—virtually or physically—without putting it at risk is a cultural and legal obligation for states and institutions, in accordance with the right of all individuals to participate in cultural life and benefit from scientific advancement [28]. These approaches, based on open science, socio-technical networks, and collective intelligence, represent the most promising path to democratize access to underwater archaeological knowledge without compromising the integrity of the sites.

In any case, public participation should be the most important component of any underwater archaeology project. Archaeology is too important to be left solely in the hands of archaeologists and must be conceived and conducted with the involvement of education professionals, cultural mediators, and participatory management specialists [76,80]. Heritage sustainability is an ethical imperative [81].

Public and collaborative archaeology enhances the legitimacy of projects by fostering social belonging, educational engagement, and shared responsibility for site preserva-

tion [29]. Community archaeology initiatives that directly involve local populations in the identification, interpretation, and management of archaeological heritage have proven effective in promoting civic engagement and the social appropriation of the past [81,82]. Likewise, educational archaeology, implemented in partnership with schools and educational institutions, contributes to the creation of interactive learning environments, where students are encouraged to develop a critical and pluralistic understanding of archaeological sites and their multiple meanings [83,84].

These approaches align with UNESCO's guidelines on heritage education and strengthen the articulation between technical knowledge and local knowledge, while promoting project sustainability through the cultivation of belonging and the co-authorship of collective memory [28]. The diversity of perspectives that emerges in these collaborative contexts expands the interpretive scope of archaeology while promoting cognitive justice and epistemic inclusion in the field of heritage.

8. Collaborative Management of Underwater Cultural Heritage

Developed democracies have implemented policies that decentralize management and foster citizen co-responsibility. A notable example is the United Kingdom's *Adopt-a-Wreck* program, created in 2000 with funding from the Heritage Lottery Fund and administered by the Nautical Archaeology Society (NAS). The initiative allows diving clubs and local groups to formally "adopt" a submerged archaeological site, taking responsibility for its documentation, monitoring, and dissemination [41,85].

Each year, the NAS awards the *Adopt-a-Wreck Award* to the individual or group that has made the most significant contribution to research, protection, and dissemination of knowledge about submerged sites through this initiative [85]. This approach strengthens heritage citizenship, transforms recreational diving into a structured amateur archaeological practice, and expands the social reach of the discipline.

It constitutes an innovative public policy operating at the intersection of citizen science, public archaeology, and participatory conservation, and may serve as a reference for countries seeking collaborative models for managing submerged cultural heritage [41]. By recognizing and institutionalizing the role of local communities, the program contributes to the social sustainability of sites, preventing abandonment and promoting heritage education in a horizontal manner.

The constant presence of divers and the awareness of coastal communities about the existence of archaeological sites constitute the most effective strategies for protecting shipwrecks from degradation and destruction. Conversely, abandonment is widely recognized as the greatest enemy of cultural heritage—both on land and submerged sites. Specialized literature highlights that community and participatory initiatives tend to be more successful than exclusively state-led programs, particularly when they foster a sense of belonging, local capacity-building, and continuous monitoring [5,86].

In countries with higher levels of education and heritage awareness, such as those in Western Europe, there is a broader internalization of the symbolic and historical value of cultural assets. In more rural contexts or regions marked by structural inequalities, such as parts of Latin America, for example, relationships between the state and citizens are often distant or conflictual, compromising the sustainability of grassroots policies [87,88]. Institutional distrust, combined with a lack of effective communication, often undermines collaborative actions and fuels feelings of exclusion or indifference toward the fate of cultural assets.

Thus, it is essential that public archaeological preservation policies recognize these differences and adopt adaptive strategies, respecting local dynamics and promoting spaces for listening, dialogue, and shared responsibility. Public archaeology, by articulating science

and social engagement, emerges as a promising alternative to break with the top-down logic of heritage management and to build networks of collective care.

Portugal provides a striking example of a state whose cultural heritage policy has been characterized by a history of institutional secrecy and systematic distrust toward active citizenship. This posture has resulted in a severe communication gap between the state and civil society, leading to widespread public unawareness of both the discoveries and the losses of heritage assets within its territory [42]. This detachment compromises not only the transparency of management actions but also public engagement, which is recognized as an essential element for the sustainability of heritage policies [5,86].

In this context, the government's role should be proactive and democratic: to formulate and communicate a clear strategic vision for the study, protection, and dissemination of cultural heritage and to articulate this vision with various stakeholders—including universities, civil society organizations, local communities, and municipal authorities. The creation of participatory mechanisms, public consultation channels, and open data policies is a fundamental instrument for enabling such articulation [8].

Informing the public about trends, goals, programs, and institutional guidelines is not only a government duty but also an effective way to promote cultural citizenship, enhance the sense of belonging, and stimulate community involvement in determining the fate of heritage assets. As Waterton [89] argues, heritage management should not be purely technical; it must also be political, communicational, and deeply rooted in the recognition of the epistemic diversity of the social actors involved.

9. Democratizing Knowledge: Public Archaeology and Cultural Citizenship

Healthy societies are those that cultivate an active awareness of their past, recognizing the structuring role of collective memory in the formation of identity and social cohesion. In developed democracies, the valorization of cultural heritage occurs through consensus achieved via continuous dialogical processes among government, academia, and civil society [5,6]. Scientific publications, interactive exhibitions, and media dissemination of archaeological discoveries are fundamental tools to foster citizen participation and encourage the development of local or regional heritage awareness.

In this context, maritime cultural heritage assumes strategic importance, as it relates to ways of life, cultural practices, and cosmologies that shaped historical relationships between human communities and aquatic environments. As previously discussed, heritage not only represents our roots and identity but also constitutes the symbolic framework of our social values. Fears, convictions, and even notions such as truth and reality are largely historical products, influenced by dominant narratives and social construction processes of knowledge [22,90].

Howard Zinn, the American historian committed to public education and civil rights, once stated that "if we don't know our history, we have to rely on our politicians." Although said ironically, the phrase expresses a sharp critique of historical alienation and essentially proposes a society of critical citizens, aware of their place in history, rather than passive subjects. Access to historical knowledge is therefore an ethical and democratic imperative, as it underpins society's capacity to question, propose, and build alternatives to the status quo [91].

The survival of democratic institutions—and of civilization as a whole—is largely tied to the preservation of collective memory. In times of accelerated globalization and mass migration, local memories—anchored in material and intangible cultural heritage—become even more valuable. They act as reservoirs of diverse ways of life, territorial relationships, worldviews, and social practices that are under threat of disappearance [7,92].

In this regard, archaeology contributes both to the reconstruction of the past and to resistance against forgetting. Strengthening participatory heritage policies that recognize the value of local memories is essential to ensure that these reserves of cultural diversity are not lost under the pressures of contemporary cultural homogenization [5].

Virtual or physical visits to underwater archaeological sites constitute a fundamental aspect of every citizen's cultural rights, as enshrined in Article 27 of the 1948 Universal Declaration of Human Rights, which guarantees free participation in the cultural life of the community. Such experiences not only promote access to knowledge but also strengthen the sense of belonging and the appreciation of local, regional, and national heritage.

As discussed earlier, the publication of archaeological data is an essential tool for democratizing access to heritage, especially in the underwater context, where physical access is often restricted by technical, environmental, or safety issues. Specialized literature reinforces that interpretative mediation—through texts, 3D visualizations, digital reconstructions, or interactive exhibitions—is vital for transforming archaeological remains into accessible and meaningful narratives for diverse audiences [8,74].

Although reading a scientific or outreach publication does not replace the sensory experience of an in situ visit, the production and dissemination of materials targeted at specific audiences—such as students, educators, tourists, or coastal communities—has the potential to considerably enrich the understanding and enjoyment of eventual site visits. In this context, virtualization becomes not merely a viable alternative but a complementary practice that expands the social and educational reach of underwater archaeology [93].

During a brief period at the Portuguese state agency for nautical archaeology, one of the authors participated in the excavation of the India nau *Nossa Senhora dos Mártires*, lost at the Tagus river bar near Lisbon in 1606. This shipwreck was the central theme of the Portuguese Pavilion at the 1998 World Expo in Lisbon [94,95].

The excavation was conducted by a team of archaeologists still in training—since, at the time, there were no specialized underwater archaeology courses in Portugal—with technical support from amateur divers. Registration procedures widely consolidated in international practice were adopted: horizontal plans, longitudinal and cross sections, photographic documentation, manual sketches, direct measurements, and triangulation with tapes and fixed points anchored to nearby rock formations.

From this work, the raw data generated were made public—targeting various audiences: from children and high school students to model makers, enthusiasts, and, naturally, our peers in the academic community. The active dissemination of the material later enabled the development of navigable 3D models and virtual visit experiences, especially with the advent of accessible graphic engines adapted from video game environments.

The complete openness of the data was the key to the viability of these experiences. The best images of the site were captured by Guilherme Garcia, a professional photographer who approached the team spontaneously after hearing about the project and requested permission to document the site.

This case exemplifies how transparency, open access, and multidisciplinary collaboration are crucial not only for scientific production but also for the social appropriation of archaeological knowledge [8,93]. In a field often constrained by closed institutional structures, effective data sharing can transform local projects into global references.

The ultimate goal of archaeology is the production of shareable, critical, and situated knowledge, capable of expanding humanity's self-understanding over time. The archaeological training received by one of the authors in the United States reflected a disciplinary tradition where archaeology is conceived as a subfield of anthropology, anchored in a holistic approach to the human condition. In this context, archaeology is less a technique of excavation and more a reflective field that invites us to revisit the great philosophical

questions: Who are we? Where do we come from? Where are we going? What can we know? What should we do? [20,96].

Moreover, North American anthropological archaeology structures its investigations around four fundamental pillars: the recognition that we are part of the natural world and subject to its laws; the acknowledgment that we possess a unique capacity to adapt, modify, and construct environments; the existential unease in the face of meaning structures that escape empirical perception; and the appreciation of inner life as an essential, though often overlooked, dimension of human experience [23,97].

These foundations extend archaeology beyond a technical practice, positioning it as an ethical and epistemological field that contributes to understanding symbolic systems, ways of life, values, and narratives that constitute the cultural diversity of humanity. As Ian Hodder [23] proposes, archaeology should be understood as a continuous negotiation of meanings, where the past is interpreted in light of the urgencies and dilemmas of the present.

Returning to the Portuguese context—a country marked by a recent history of mass literacy and a complex trajectory of democratic consolidation and community organization—it is possible to affirm that promoting participatory archaeology, through programs inspired by successful initiatives, such as the UK's *Adopt-a-Wreck* program [85], would represent a significant step toward overcoming the current scenario. In Portugal, underwater archaeology has mostly been conducted by closed groups operating under a logic of institutional secrecy, where information—even when minimal or technically irrelevant—is treated as symbolic capital and a tool of power.

This model contradicts the fundamental principles of public archaeology and democratic access to heritage, resulting in the near-total erasure, both in governmental discourse and in the media, of Portugal's rich and diverse maritime history. Such unawareness undermines the valorization of coastal communities' historical experiences, their technological creativity, adaptive strategies, belief systems, nautical calendars, devotions, and traditions that constitute the nation's intangible and submerged heritage [29,39].

The absence of a policy of transparency, collaboration, and heritage education prevents the construction of a collective sense of belonging and responsibility for the archaeological legacy. Recognizing the right of citizens to participate in the management of submerged cultural heritage is not only an ethical imperative but a condition for Portuguese archaeology to fulfill its social role. In this sense, the state must abandon the paradigm of exclusionary tutelage and assume an active stance in building collaborative networks with divers, schools, local collectives, journalists, and coastal communities. Only then will it be possible to democratize access to archaeological knowledge and transform archaeology into a tool for empowerment, critical education, and epistemic justice.

Portugal's submerged cultural heritage must be conceived as a public good, accessible and shared with students, journalists, researchers, and the general public. The effective democratization of access to archaeological knowledge requires encouraging active civil society participation in the documentation, monitoring, and dissemination of heritage, following best practices of public and participatory archaeology [81,82].

The state agency responsible for this heritage must not only protect underwater sites but also inform, guide, and train local collectives, diving clubs, schools, fisher associations, hobbyists with metal detectors, and municipalities—promoting collaborative networks and inclusive governance practices. The availability of data, transparency in collection management, and the opening of dialogue channels with different stakeholders are fundamental measures for building a more equitable and sustainable model of submerged cultural heritage management [8,76].

Archaeology, as a quintessentially public discipline, must be guided by principles of epistemic justice and social responsibility. Otherwise, it risks becoming a self-referential, technocratic endeavor disconnected from the real needs of communities and the challenges of the present. Put simply, archaeology must be public—or else it is inevitably a waste of money and time [98].

10. Digital Futures for Underwater Archaeology: Technologies, Justice, and Collaboration

In view of the arguments presented, it is important to reflect on the contemporary challenges that are redefining the fields of underwater and digital archaeology. The consolidation of the discipline in contexts marked by rapid technological transformations, climate emergency, and disputes over epistemic legitimacy demands a critical and integrated approach.

The following discussion is organized into five interrelated dimensions that have profoundly reshaped submerged archaeological practice: (1) the technological transformation driven by generative artificial intelligence; (2) the urgency of formulating open, integrated, and interoperable public policies; (3) the need for heritage strategies that are adaptive and sensitive to climate change; (4) the epistemic centrality of public engagement, collective intelligence, and participatory science; and (5) the ethical imperative of adopting plural and just epistemologies. Together, these axes outline a comprehensive framework for critically reassessing the methodological, infrastructural, and political-institutional foundations of underwater archaeology in the digital age.

11. Generative Artificial Intelligence and Archaeological Modeling

The rise of generative artificial intelligence (GAI), particularly through deep neural networks and probabilistic models, is reshaping traditional paradigms of archaeological reconstruction. Technologies, such as Generative Adversarial Networks (GANs), already enable the reconstitution of absent nautical structures from partial remains, the interpolation of volumetric gaps in submerged sites with a high degree of plausibility, and the simulation of hypothetical scenarios of navigation, occupation, or cultural collapse [53,59].

However, the application of GAI to underwater archaeology demands epistemic caution. Generative models operate based on historically situated datasets, often biased by colonial gaps, Eurocentrism, and documentary asymmetries. When used without critical mediation, these systems risk reproducing exclusionary epistemologies under the guise of "algorithmic neutrality" [99,100]. In peripheral or underrepresented archaeological contexts—such as the South Atlantic or the Caribbean—the risks of erasing local narratives and subordinated ancestries are significant.

Thus, it becomes imperative that archaeological computational modeling be informed by ontological frameworks that are sensitive to cultural context. Ontologies, such as the CIDOC Conceptual Reference Model (CRM) and the Basic Formal Ontology (BFO), offer robust foundations to ensure semantic interoperability, auditability, and transparency in the use of digital archaeological data [101,102]. Initiatives, such as the Heritage Digital Twin [91], demonstrate how it is possible to integrate technical precision, heritage preservation, and social responsibility in the construction of accessible and participatory three-dimensional models.

Finally, it is crucial that AI systems do not replace archaeological judgment but rather complement it. The articulation between archaeologists, computer scientists, and local communities must guide the design of technological tools, ensuring that the reconstruction of the past reflects epistemic plurality and scientific integrity.

12. FAIR Data Governance and Transnational Public Policies

The consolidation of "digital underwater archaeology" depends on a robust, transparent, and accessible data infrastructure. However, the field is still marked by significant structural challenges. Institutional fragmentation, the precariousness of digital infrastructures, and the lack of interoperability between databases hinder the systematic use of digital technologies in archaeological contexts, particularly in Latin America [103,104]. This gap compromises the scientific integrity of research, as well as public access and equitable governance of heritage information.

In this scenario, the FAIR principles—Findable, Accessible, Interoperable, and Reusable—emerge as fundamental guidelines to ensure the sustainability and openness of archaeological data [105]. Adopting these principles entails not only technical best practices but also a paradigmatic shift in heritage management policies toward building collaborative and auditable digital ecosystems.

The European experience with platforms such as ARIADNE (Advanced Research Infrastructure for Archaeological Dataset Networking in Europe) is exemplary in this regard. By connecting heterogeneous repositories through standardized ontologies like the CIDOC CRM, the ARIADNE project created a federated network of interoperable archaeological datasets, fostering scientific integration and democratizing access [12]. Similarly, Linked Open Data initiatives have demonstrated that the semantic structuring of archaeological datasets enables both their technical reuse and their public appropriation, facilitating the creation of interpretive narratives in educational and museum environments [106].

In Brazil, collaboration between public universities, heritage institutions such as IPHAN, the Brazilian Navy, and coastal communities could foster a national model of archaeological digital curation. This model should combine ontologies sensitive to Brazil's sociocultural context, public open-data infrastructure, and citizen participation tools. In addition to promoting transparency and social control, such a collaborative system could contribute to cognitive and epistemic justice by recognizing the multiple agents of heritage knowledge production.

The transnational governance of digital heritage further requires the formulation of integrated and intercultural public policies aimed at the long-term sustainability of archaeological information. This task demands multilateral agreements on interoperability, consistent funding for open platforms, and technical capacity-building strategies for researchers, managers, and local communities [8,9]. The absence of such policies exacerbates global digital asymmetries and threatens the conservation and democratic use of submerged archaeological heritage in times of climate crisis and geopolitical transformations.

13. Climate Crisis and Digital Preservation of Submerged Heritage

Submerged cultural heritage is among the most vulnerable to the effects of global climate change. Sea level rise, coastal erosion, ocean acidification, and the intensification of extreme weather events represent concrete threats to the physical integrity of coastal archaeological sites—from precolonial shell mounds to modern industrial vessels. These impacts manifest particularly severely in tropical and subtropical regions, where accelerated erosion and urban pressure on coastal zones compromise the stability of archaeological contexts [28,55].

In this scenario, underwater archaeology acquires a strategic role, not only in documentation but also in risk prediction and mitigation. The integration of technologies, such as remote sensing, underwater LiDAR, high-resolution bathymetry, and hydrodynamic modeling, has proven promising for the development of early warning systems and preventive digital conservation plans [57,107,108]. Furthermore, these tools allow the identification of vulnerability patterns and guide interventions for 3D scanning and the

creation of digital twins—digital replicas of endangered sites that serve both research and cultural dissemination purposes.

Predictive modeling, when associated with participatory approaches and local contextual data, becomes even more effective. A notable example is the study by Gómez-Barrero et al. [57] in the Mediterranean Sea, which combined geophysical analysis, multibeam bathymetry, and community involvement to prioritize sites based on their exposure to natural and anthropogenic risks. Such a transdisciplinary approach not only strengthens heritage resilience but also transforms digital models into pedagogical and deliberative tools for integrated public policies.

From an ethical and epistemological perspective, the preventive digitalization of submerged heritage should be understood not as a replacement for the original materiality but as a means of cultural continuity in times of climatic discontinuity. Moreover, digital archives must be accessible, auditable, and culturally contextualized, avoiding the risk that virtualization produces new forms of exclusion or algorithmic epistemicide [99,100,104].

Thus, in the face of the climate emergency, digital archaeology assumes a dual role: as an applied science for heritage risk management and as an instrument of climate justice, ensuring that historically vulnerable communities do not lose their archaeological heritage without documentation, public debate, and access to knowledge.

14. Public Archaeology and Sociotechnical Strategies for Collective Heritage Management

The consolidation of digital archaeology in the underwater field requires more than advances in computational techniques. It presupposes an ethical and epistemological repositioning that effectively incorporates the principles of public archaeology, citizen science, and collective intelligence. In a context marked by the increasing virtualization of data and institutional fragmentation, the legitimacy of archaeological practices depends directly on their capacity for social inclusion, accessible communication, and transdisciplinary dialogue.

Submerged archaeological sites are, by definition, invisible to most of the population. Overcoming this invisibility requires methodologies that connect material memory to social memory—strategies such as digital musealization, collaborative platforms, participatory 3D reconstructions, and accessible information systems are necessary tools in this process [13,29,39]. These technologies not only document sites at risk but also create digital ecosystems where diverse actors—coastal communities, fishermen, schools, researchers, and managers—interact on equal footing.

Collective intelligence emerges as an epistemic and political driver of this transformation. When mediated by well-structured sociotechnical networks, it allows the articulation of diverse knowledge systems—academic, traditional, ancestral, and everyday—thus expanding the horizons of interpretation, use, and protection of heritage. As Jenkins et al. [109] propose, it is not merely about opening data but about sharing agency: involving communities in the generation, curation, and validation of archaeological knowledge.

These practices point toward a model of post-disciplinary archaeology, anchored in concepts such as distributed curation, shared heritage governance, and epistemic participation [76,80]. This approach moves away from the historically hegemonic extractivist and unilateral paradigm toward an open, critical science committed to cognitive justice and the cultural sovereignty of territories.

In the field of underwater archaeology, international experiences like the Adopt a Wreck program, led by the Nautical Archaeology Society (United Kingdom), demonstrate that public engagement in the documentation and protection of sites can have concrete impacts on the preservation and symbolic appropriation of heritage [85]. In Brazil and other

Latin American countries, local experiences of community archaeology and participatory digitalization have evidenced the emancipatory potential of these practices, even in contexts of institutional precariousness and land conflicts [104,109].

In sum, twenty-first-century digital and underwater archaeology must abandon the vertical logic of the isolated specialist and adopt strategies of co-authorship, attentive listening, and redistribution of informational power. The future of the discipline depends, above all, on its openness to multiple epistemologies and its capacity to foster belonging, citizenship, and cultural continuity.

15. Plural Epistemologies and Digital Decolonization in Archaeology

The consolidation of digital archaeology requires that its technological innovations be grounded in broad and inclusive epistemological commitments. A truly transformative archaeology cannot be merely technocentric; it must question historical asymmetries in the production of knowledge and confront exclusionary mechanisms that marginalize Indigenous, Afro-descendant, and other non-hegemonic epistemologies. The plurality of narratives enriches the images we construct of the past under investigation. The notion of epistemicide—the systematic erasure of non-dominant knowledge forms—remains one of the main challenges for the decolonization of digital systems applied to cultural heritage.

In this sense, it is essential that digital archaeology be constructed based on principles of epistemological co-authorship, cognitive justice, and intercultural dialogue. Practices, such as distributed curation, the adoption of culturally sensitive ontologies [93,101], and the use of decentralized data platforms, are strategies that contribute to restoring the historical agency of communities historically silenced and whose heritage is still often instrumentalized by academic or state narratives.

The convergence between digital archaeology, infrastructure studies, and data anthropology has offered new possibilities for reconfiguring the field toward a more horizontal and participatory science. As Huggett [9] and Dallas [8] argue, the digital systems used in archaeology are not neutral: they embed values, political decisions, and knowledge hierarchies. Understanding the sociotechnical dimensions of digital infrastructure is thus essential for critically assessing mechanisms of representation and exclusion.

A data-centered archaeology must be co-designed with the social agents involved, creating space for multisensory narratives, collaborative metadata models, and strategies for the decolonial reappropriation of heritage collections. This implies incorporating local languages, subjective experiences, and non-Western cosmologies into documentation, modeling, and data dissemination processes.

Emerging models, such as the *Heritage Digital Twin* [93] and application profiles based on CIDOC CRM and BFO [105], demonstrate that it is technically feasible to integrate semantic precision with cultural responsibility. Additionally, experiences with vernacular ontologies, culturally contextualized linked data, and community-driven digital museum platforms reinforce the idea that technology and tradition are not opposing spheres but rather potential fields of collaboration.

Thus, twenty-first-century archaeology must move beyond mere collection management and embrace its role as a mediator of epistemological conflicts and facilitator of historical reparations, promoting a truly open, equitable, and plural digital archaeological ecosystem.

16. Final Remarks: Towards an Inclusive, Sustainable and Data-Driven Archaeology

Underwater and digital archaeology are currently undergoing profound methodological, epistemological, and political reconfigurations. The advancement of three-dimensional

modeling technologies, generative artificial intelligence, and geographic information systems, combined with the growing demand for epistemic inclusion and cognitive justice, imposes new challenges and responsibilities on the discipline. This article argues that the future of underwater archaeology rests not only on technical innovations but also on an ethical commitment to the plurality of knowledge systems, transparency in knowledge production processes, and the collective construction of narratives about the past.

Although promising, digital transformations are not neutral. They operate within sociotechnical ecosystems marked by historical asymmetries and ontological disputes. Thus, computational tools—such as digital twins, linked databases, and immersive visualizations—must be employed with critical awareness, cultural responsibility, and public oversight. Digital archaeology must not reproduce the vices of colonial science: it must act as an agent of democratization, accessibility, and the recognition of epistemic and cultural diversities.

Furthermore, the intensification of the climate crisis brings a new level of urgency to the digital preservation of submerged heritage. The preventive documentation of vulnerable sites, emergency scanning, and predictive modeling should be integral parts of public policies coordinated among universities, coastal communities, governments, and international institutions. Without this multilateral and interdisciplinary effort, not only valuable archaeological sites but also the histories and memories of the communities connected to them risk being lost.

Throughout this article, it has been argued that public archaeology, citizen science, and collective intelligence are essential pillars of twenty-first-century archaeology—a discipline that recognizes itself as a social practice and opens itself to co-authorship, participation, and intercultural dialogue. Initiatives such as virtual musealization, participatory mapping, and distributed curation should be understood not as complementary resources but as foundations for a socially relevant archaeology.

Finally, it is essential to recognize that archaeology, as a field of knowledge production, plays a central role in the construction of identities, memories, and possible futures. Archaeological knowledge does not belong solely to specialists but to all citizens who wish to understand who they are, where they come from, and how they can—collectively—envision a fairer, more sustainable, and more plural future.

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