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Virtual Mineralogical Museums and Mineral Websites as Learning Agents: Analysis of How Minerals Are Represented

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Abstract: Virtual mineralogical museums can help visitors construct and enhance their personal scientific mineral models through the information they incorporate. For this to be possible, they must contain a series of key aspects related to minerals' properties (chemical and physical), use and origin, and the relationships between them. In this study, 38 sites are analyzed, their main characteristics identified, and their educational value assessed, to verify whether all the key aspects considered for the construction of an appropriate and complete mineral model are present. Photographs and mineral files predominate over 3D models and 3D tours. In many of the sites aimed at university students or geoscience experts, there are abundant data about mineral properties, but not in those aimed at a broad public audience. Data about the uses and relationship between uses, extraction, and mineral properties are seldom included. Even if connectivity is very high in all the sites, there are no elements that can be used to test if there has been a knowledge gain after visiting them. The results show that there is still a lot of information missing for this type of resources to be truly helpful for the general population and, specifically, for educational uses.

Keywords: virtual museums; science education; online education; mineral model; ICT tools

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1. Introduction

Museums are one of the most valuable resources to help achieve scientific knowledge for the general population. They are places where knowledge can be constructed and acquired and they can offer significant experiences to visitors through exhibitions (Figure 1) [1,2]. During the 19th century, they started to be considered as an educational tool, both for adults and children, and this currently remains one of museums' primary goals [3]. Today, museums have the potential to be used as didactic resources and go beyond being mere exhibitions [4]. They can help in closing the gap between formal and informal science learning [5,6], providing concrete experiences to understand better scientific ideas [7]. Additionally, interactivity and immersive environments are linked to increased motivation and learning, helping visitors to refresh and use their personal scientific models regardless of their age [8,9].

In 1947, Andre Malraux introduced the concept of virtual museums, which consist of an imaginary place with no walls that any person interested in the subject can access [10,11]. In contrast to traditional museums, virtual museums can be accessed regardless of time and location, at a lower cost, they can include simulations and recreations, and transform the learning process [12].

Virtual science museums mainly consist of compilations of digital photographs of elements such as animals, scientific instruments, fossils, and rocks, among others. They can incorporate items that are both in public and private collections, increasing user exposure to physically unavailable displays. Others also incorporate sound files, videos, diagrams, or external links to other documents that it could be impossible to have access to in conventional museums [13].

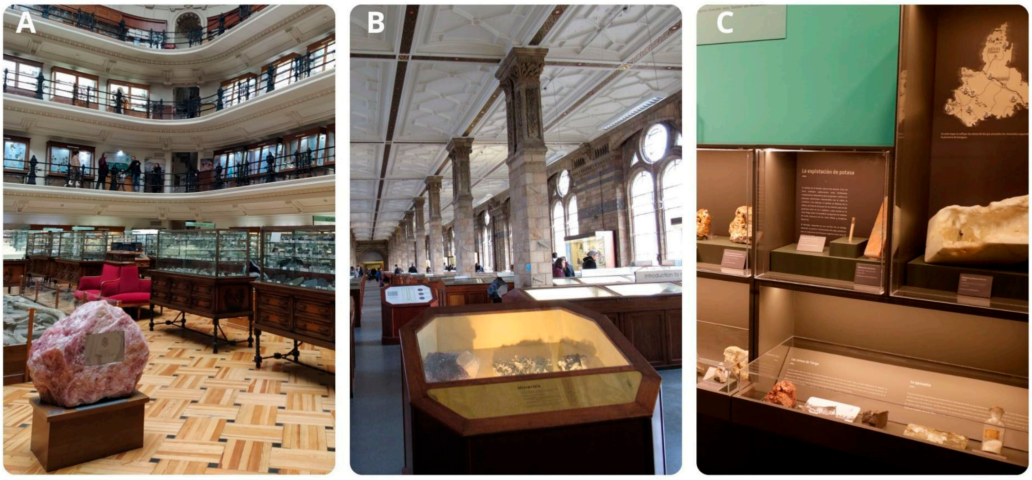

Figure 1. Physical museums with mineral collections. (**A**): Museo Geominero (Madrid, Spain); (**B**): Natural History Museum (London, UK); (**C**): Museum of Natural Sciences of the University of Zaragoza (Zaragoza, Spain).

Virtual museums transcend the potential of traditional ones as they can be used in different ways, with one of the most relevant being the possibility of comparing the object in question to other similar objects or displays or increasing the correlations between them. In other words, they can be used to put in contact items that it would be impossible to have together in a face-to-face context [14]. To be precise, this lack of context when visiting a conventional museum can be easily overcome in its virtual counterparts [4]. Students can navigate these virtual museums anytime they need and teachers can use them as an educational resource, as long as they have content that is representative enough and can be adapted to the curriculum [15]. In addition, contrary to physical museums, their space is not limited [16]. Also, as virtual museums are available to anyone with internet access, they can become valuable assets in non-formal learning environments.

Being separated by themes or included in other more general virtual science museums, virtual exhibitions that deal with rocks or mineral resources are valuable for pure scientific knowledge, from an aesthetic point of view, and for their connection with different elements in everyday life [4,17,18]. Since prehistoric times, the use of minerals has expanded due to the implementation of new or better technologies and increased scientific knowledge. For instance, in a mobile phone, we can find more than thirty chemical elements, and almost all of them come from the extraction and processing of different minerals [19]. The same is true for many other elements, from televisions to wind turbines and solar panels, on which we are so dependent today. In fact, the energy transition, and the exponential growth in the extraction of mineral resources, could trigger supply problems in the future [20,21]. For this reason, being aware of the importance of these natural resources, how they are extracted, and what they are used for, can be used as a starting point to consider the associated environmental impacts and how to address these issues from a responsible consumption perspective. In turn, this can be easily connected to broader themes such as sustainability, climate change, or the circular economy, among others [19]. It can help improve citizen participation in decision-making processes, a key aspect of scientific literacy that is often overlooked or superficially treated [22,23].

Being fully available to all, the potential use of virtual mineralogical museums has increased far beyond the primary purposes for which they were created, enlarging the information and communication technologies (ICT) resources available for mineral identification. Nonetheless, this does not imply that their contents are always presented in such a way that they can help visitors to improve their knowledge and understanding of minerals. The current paper is focused on analyzing the main contents of each museum and each mineral file, in order to establish a series of recommendations to improve present and future virtual mineralogical museums. As such, one of the main goals is to classify the information they display and to identify the mineral model that visitors can infer from them. To this end, the following research questions (RQs) will be addressed in this paper:

- RQ1: What are the main characteristics of virtual mineralogical museums?
- RQ2: What is their educational value?
- RQ3: Which is the mineral model expressed in virtual mineralogical museums?

2. Site Selection

When talking about virtual museums, there are at least two categories when considering their digitalization [24,25]. First, there are physical museums that have a virtual counterpart. These can be divided into the following two types: those with basic website information (visiting hours, location, events...) and those that display their collections, partially or totally, online. In the second category are those museums that only exist online, with no physical counterpart. The latter are particularly valuable for education as they offer context-oriented information that can be used as a complementary resource during the learning process.

The site's selection was carried out using an internet search engine, which displays the results from the most to least relevant site, considering impact and number of visitors. Different terms were used in the search engine in several languages (*virtual mineral museums, virtual mineralogical museum, museo virtual de minerales, musée virtuel de minéraux*, etc.) to find the most frequently visited or popular virtual mineral museums.

In addition, the selected sites had to fulfil several requirements, as follows: (a) they had to be accessible, that is, they must be free of charge, not being mandatory to register on any platform to access them; (b) they had to be created before 2020 (before the COVID-19 pandemic); and (c) they could, or could not, have a physical counterpart. The main website language was not considered an exclusion criterion as there are many tools that can be used for immediate translation. Additionally, other factors such as geographic location in those cases that had a physical counterpart, cultural, or educational factors (i.e., the level at which they were aimed, if any) were not considered as exclusion criterion. Websites that only include basic information about an existing museum (location, visiting hours, etc.) or sites not related to minerals (i.e., focused on the history of mineralogy or mining) were excluded. After this preliminary selection, their main characteristics (related to RQ1), their educational value (RQ2), and their main content (related to RQ3, specifically considering the presence or absence of different elements related to the mineral model) were analyzed. A total of 38 online virtual mineral museums and mineral databases were included in this study (see list in Appendix A).

3. Comparative Analysis

Once the virtual museums and websites were selected, and their main contents listed, it was possible to provide an answer to the research questions.

3.1. RQ1: What Are the Main Characteristics of Virtual Mineralogical Museums?

Figure 2 summarizes the main characteristics of the 38 sites analyzed. Noteworthy is that 15 of them have a physical counterpart. For instance, the Mineralogy and Petrography Museum, "Grigore Cobălcescu", has an extensive collection of online 3D models of mineral specimens that were recently incorporated, but the physical museum can also be visited in Iasi (Romania) [26].

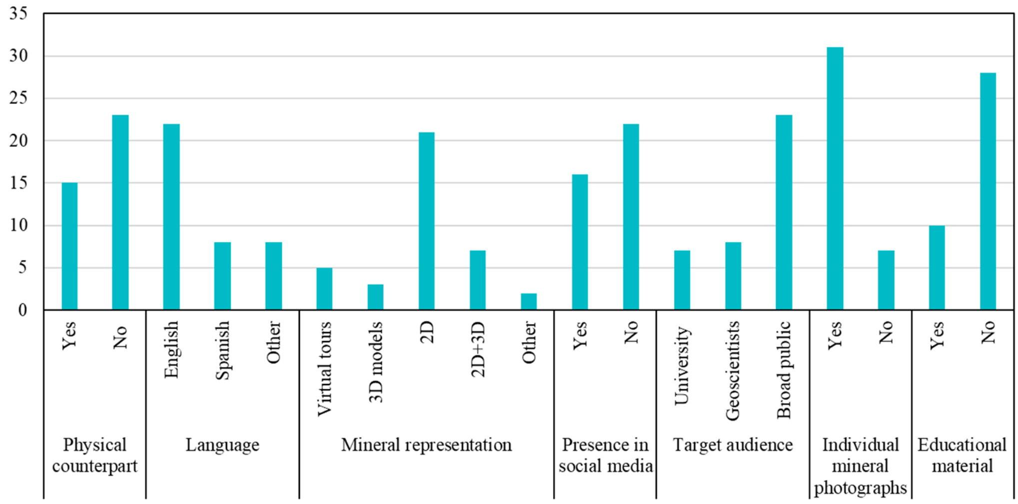

Figure 2. Main characteristics of the 38 virtual mineralogical museums analyzed.

Other museums, such as the Smithsonian Natural History Museum, the Natural History Museum of Utah or the Mineralogy & Petrology Museum Tour (University of Alberta), can be visited both in person and through a 3D virtual tour (Figure 3). however, in many of the sites, their virtuality resides in the fact that they contain digital galleries with photographs and/or 3D minerals or crystal models, rather than being fictional museums created in a hyper-environment. The 3D elements can be viewed using certain applications, such as Jsmol, Sketchfab, and Smorf, the latter being used in different sites to represent 3D crystal models which can be manipulated.

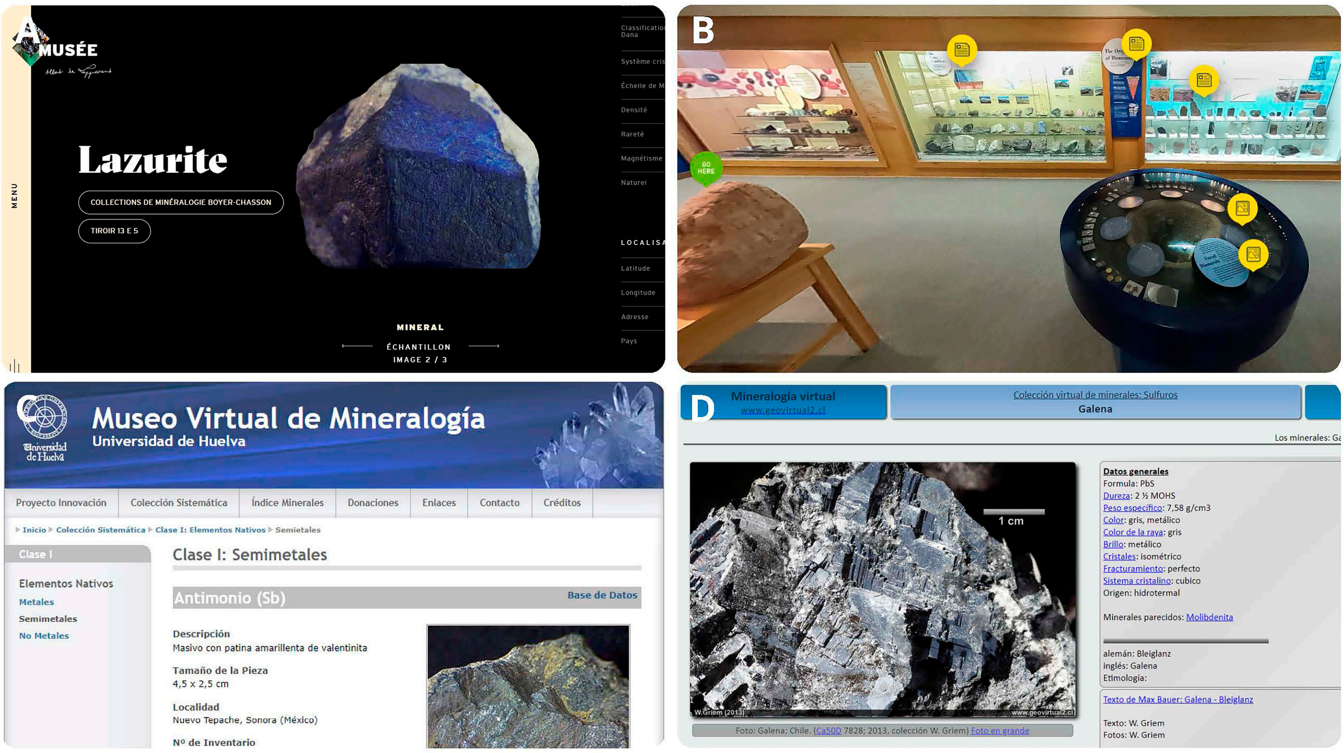

Figure 3. Screenshots of different virtual mineralogical museums. (**A**): Musée Virtuel Albert de Lapparent; (**B**): Mineralogy & Petrology Museum Tour (University of Alberta); (**C**): Museo Virtual de Mineralogía (Universidad de Huelva); (**D**): Museo Virtual de la Región de Atacama, Chile.

Regarding the target audience, seven of these virtual mineralogical museums were specifically created for university students from different territories but with the same goal. As such, the Virtual Museum of Minerals and Molecules was first intended as lecture materials for students of the University of Wisconsin-Madison and the University of Minnesota (United States) [27]. However, these 3D molecular models of more than 150 substances present in soils can be used by many others to understand their internal properties and chemical composition. Many virtual mineralogical museums whose main language is Spanish were created as a teaching complementary tool for geology undergraduate students, such as the Virtual Museum of the Geological Collection of the University of León or the "Minerales De Visu" museum [18,28].

Besides the pure virtual mineralogical museums, there are several mineral databases that frequently appear on the search engines. One example is Athena, an online mineral database created in 1986 that was made available online almost a decade later. Nevertheless, these mineral databases usually target geoscientists, as they contain data that could only be used by specialized persons (mineral structure index, x-ray power diffraction, Raman spectrum, infrared spectrum, etc.). Some examples are Mindat, Webmineral, and RRUFF [29].

Only 10 sites include some type of educational materials, half of them having a physical counterpart. These materials are very varied in terms of content but are almost always informative or explanatory. There is a predominance of downloadable materials such as mineral identification charts, infographics about properties or uses of minerals, brochures, field guides, etc. In those sites that have a physical counterpart, one can frequently find files with information that is related to educational activities that can be carried out on-site, some even include online and downloadable teaching guides and worksheets.

3.2. RQ2: What Is Their Educational Value?

According to [16], to evaluate the educational value of a virtual museum up to eight criteria can be assessed, as follows: (1) the possibility of organizing group activities; (2) the presence of additional information in audio or (3) in written form; (4) connectivity with other relevant information; (5) the presence of knowledge tests or (6) gamification elements; (7) challenging elements that encourage the user to find out more about the topic; and (8) features that capture the focus of attention of the visitors (interactive artifacts that allow zoom, movement, tours, etc.). This approach was initially used to analyze museums which incorporate mixed reality or virtual reality experiences but, as the items used to assess educational value are not strictly technology-dependent, they can be applied in a broader context. In this case, they can be used to analyze the educational value of the virtual mineralogical museums selected. Each criterion is assessed through three evaluative aspects with values ranging from 1 (the lowest level) to 3 (highest level). For instance, in the case of the "knowledge test" category, 1 is assigned to those sites where there is no possibility to test the knowledge included, 2 for those where there is a possibility to do so, but it is only on a few aspects of the material, and 3 for those in which it is possible to test knowledge included in different parts of the material and about different aspects of the information provided. For the rest of the descriptions of each criterion, they can be found in Appendix A included in [16]. Each of the 38 museums analyzed was assigned a score from one to three in the eight aforementioned categories (Table 1). The mean values for each individual category, considering the results obtained for the 38 sites, were calculated separately.

As also seen in [16], in the sites analyzed, there are none that are specifically designed to carry out group activities, as all the museums obtained a score of 1 (it is not possible to organize any group activities while interacting with the museum). All the virtual museums analyzed were created for individual use, and none of them included specific information or any recommendations about how to use it in groups. In a teaching context, this is something that would necessarily fall on the teachers, adapting its use to their specific needs.

Table 1. The educational value of the 38 virtual mineralogical museums analyzed in this study.

Criteria	Mean	Criteria	Mean
Group activities	1.00	Knowledge tests	1.03
Additional audial information	1.16	Gamification elements	1.03
Additional written information	2.45	Challenging elements	1.97
Connectivity	2.29	Focus of attention	1.95

The museums created for university students specifically have more written content than other sites. There are sections with abundant written information, for instance, descriptions about the properties of minerals with different examples included, as well as links to other mineral-related sites and to reference materials. Many of the sites have smooth connectivity with other sections, related to minerals or not, depending on the specific site. For instance, the Museo Virtual de la Región de Atacama, Chile or the American Southwest Virtual Museum also include non-mineral-related content (general history, culture, artifacts, landscapes, mining history, flora, fauna, etc.), providing an overview of the specific area of focus from different perspectives, enriching the learning process.

As for gamification elements, the virtual museum of the University of Sevilla has some matching games where the visitor has to match, among other options, the mineral name with the mineral picture, which could also be considered a certain type of knowledge test. Nonetheless, this type of content is absent in the vast majority of the sites.

Several sites have 3D mineral models that can be manipulated by visitors (i.e., the Mineralogy and Petrography Museum "Grigore Cobălcescu", the Mineralogical & Geological Museum—Harvard), which can motivate them to find more about the different mineral properties that can be observed in the samples. Others include virtual tours to the physical museum galleries that encourage the visitor to walk through them, keeping their attention.

3.3. RQ3: Which Is the Mineral Model Expressed in Virtual Mineralogical Museums?

The Encyclopedia Britannica defines a *mineral* as a "naturally occurring homogeneous solid with a definite chemical composition and a highly ordered atomic arrangement; it is usually formed by inorganic processes" [30]. In this short but concise sentence, several aspects are highlighted. First, a mineral has a definite chemical composition, represented by a specific chemical formula (which can vary within certain limits) and structure. The definition also makes a general reference to its origin—natural and inorganic—but leaves out many other fundamental properties. Specifically, physical characteristics (external), which include color, luster, streak, hardness, specific gravity, etc. that are intrinsic, and sometimes unique, to each mineral species. All these characteristics form part of the scientific model of the mineral.

To help learners, any educative resource about minerals should consider the following different key aspects to scaffold the construction of a more complete model [31]:

- Properties: These can be used to identify/describe a mineral, they can be divided into external or macro-characteristics (such as color, luster, streak, hardness) and internal or micro-characteristics (chemical formula, internal structure). The interaction between both is going to determine the general appearance of the mineral.
- Uses: Each mineral can have one or more uses, which are going to be strongly related to their macro- and microcharacteristics. This can be directly related with consumption, which is in turn linked to extraction.
- Origin/occurrence: Minerals are linked to a specific geological context and occurrence, which will determine their properties and also the impacts (social, environmental, economic) that their extraction can have in the specific place where they occur, the mineral association, among others.

Some of these key aspects represent direct and explicit information that can be provided in the form of text and images. Still, other aspects have to be and imply a more complex comprehension level. Learning resources or activities that take into account all these different aspects related to minerals can be used and help to improve and deepen the understanding of what a mineral is [32].

As another goal was to analyze the implicit mineral model on the online resources contemplated in this study, the different characteristics that appear on each individual mineral file were considered, starting from those mentioned above that are part of the mineral model.

In order to have a better comprehension of what a mineral is, it is necessary that these types of sites contain, at least, photographs that allow visitors to observe some of its main external physical characteristics, such as color, luster, or crystal habit. For this reason, virtual museums that did not have individual mineral pictures (n = 7) were not included in the analysis. Of the remaining 31 museums, one had to be discarded as the website was not available at the time of this study.

Figure 4 summarizes the key aspects that are included in each virtual museum, both in those that have a physical counterpart (n = 10) and in those that do not have a physical counterpart (n = 20), expressed in terms of percentage of the total number of museums analyzed on each category. In some cases, not all the different elements were present in all the mineral files, descriptions, or documents present in these sites, this is the reason for the distinction between those in which it is always present and those in which it is sometimes present.

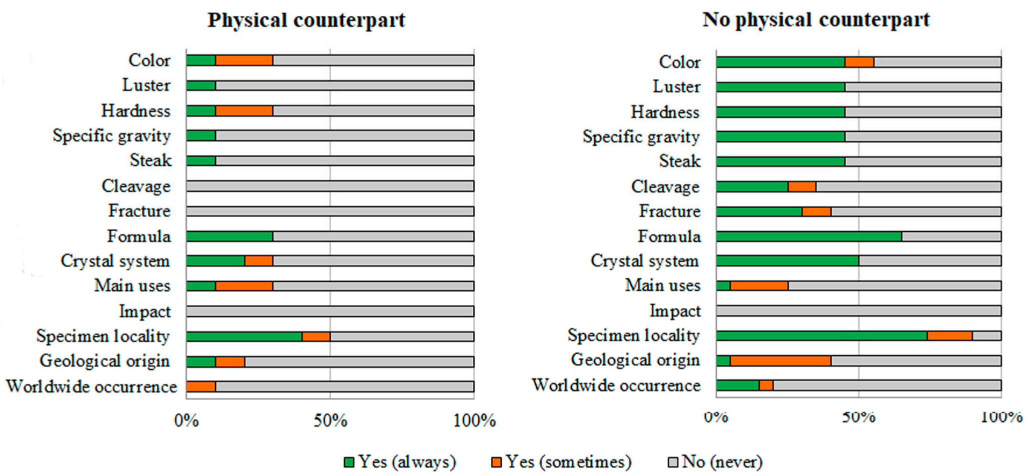

Figure 4. Presence of the different elements that are needed for a holistic understanding of minerals in virtual mineralogical museums and mineral databases in those that have physical counterpart (n = 10) and those that do not have a physical counterpart (n = 20). Data expressed in terms of percentage of the total number of museums analyzed on each category.

A substantial difference can be seen between the museums with physical and no physical counterpart. On average, all key aspects are better represented in virtual museums that do not have a physical counterpart. Photographs alone can help determine and better understand certain external and even internal characteristics. However, they cannot be solely used as the only content that helps the visitor to acquire a complete mineral model [33].

In those without a physical counterpart, it is more frequent to find descriptions of the mineral specimens including color, crystal system, chemical formula, size, and specimen locality. This last item is very important as it provides relevant information about the location of the mineral deposits in the world. Still, this relationship between locality and geological origin of the mineral or worldwide occurrence is not always made explicit.

In addition, the relationship between mineral properties and uses is fundamental to have a more complete understanding of what a mineral is [31]. However, as no explicit data are included regarding these aspects, it can be complicated for the visitors to infer the relationships between them. As stated before, our society is dependent on many minerals today and it is striking that there is no concrete explanation of their uses, at least in the case of minerals that have a distinct use, and how these uses relate to their properties. Some of these minerals are also very scarce or their extraction is concentrated in a limited number of countries. None of the museums analyzed consider the impact that their extraction has from an environmental perspective or from a social one, factors that could help broadening the understanding of certain mining-related conflicts [34].

There is also a notable difference when analyzing the presence of elements related to the mineral model in virtual museums in terms of their target audience, specifically in the case of the museums that do not have a physical counterpart (Figure 5).

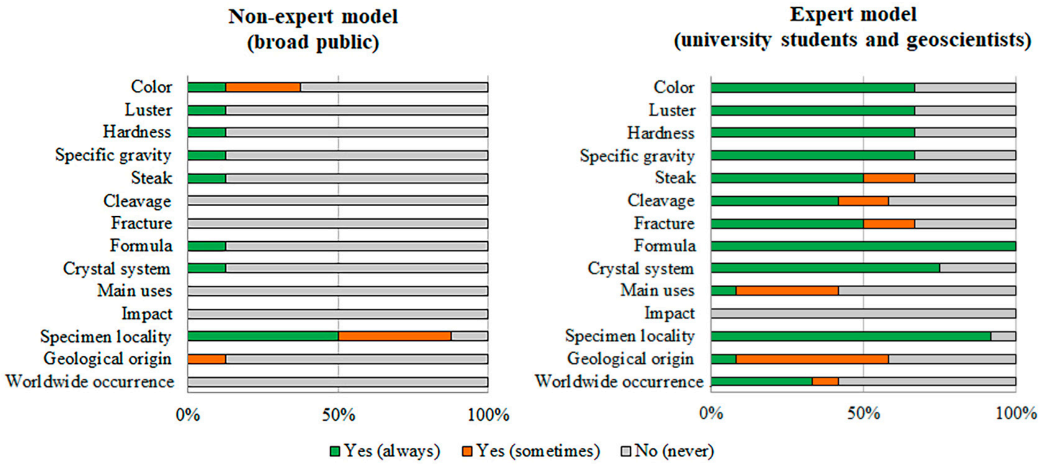

Figure 5. Presence of the different elements that are needed for a holistic understanding of minerals in virtual mineralogical museums and mineral databases that do not have a physical counterpart, as a function of the target audience: non-expert (n = 8) and expert (n = 12). Data expressed in terms of percentage of the total number of museums analyzed on each category.

Those that are exclusively virtual and that are aimed at university students and/or geoscientists (n = 12) include much more diverse information and details. As stated, of those analyzed, several sites were specifically created as a teaching tool for university students. As such, the creators purposively included more information about minerals than if they were aimed at the general public.

Essentially, virtual mineralogical museums promote the existence of two types of mineral models, the expert model, where different key aspects of minerals are frequently present, and the non-expert model, where little information is included. This only helps to widening the gap between the mineral model that the public has (related to informal science learning) from that of the experts (formal science learning).

4. Discussion

There exists a considerable quantity of virtual mineralogical museums in different languages, with or without physical counterpart, which helps to demonstrate that there is a clear interest in the subject. Still, these resources do not have sufficient nor representative content, as they provide an incomplete vision of what a mineral is, to serve as a complementary resource for teaching.

4.1. Implications for the Mineral Model

Minerals, their properties, uses, and the effects of extraction are frequently considered among the core ideas in several educational documents outlining what students should know by the end of their schooling. As such, according to the National Research Council, students in middle school should be aware of how mineral resources are formed, how they are distributed on Earth, the impact of their consumption, and the implications between their composition and their chemical structure [35]. In addition, all these concepts are included in the national curriculum of many countries, at different levels of depth, even including aspects related to resource depletion and sustainability. Such is the case in Australia, France, Spain, or Portugal. For this reason, it is striking that there is such a wide gap between what students should know and the type of resources, in this case, virtual mineralogical museums, that teachers can find at their disposal to use as reference materials or encourage their use among students in any science-learning activity. This can cause visitors, or people using them as a reference to learn about minerals, to end up with an incomplete mineral model.

Generally speaking, scientific models are simplified representations of natural elements and phenomena [36–38]. Models are always related to a target, they always have a purpose; they can be used to describe its main entities, explaining, establishing causes and effects, and making predictions of a phenomenon's behavior or target [33,39,40]. They work as a bridge between scientific theory and the perceived reality [41]. Since most of the scientific knowledge is abstract or imperceptible or both, models also constitute a way to express, disseminate, and submit scientific ideas to evaluation and to acceptance (science as a process) [42]. As such, they cannot be understood as entities isolated from science and its working methods and tools as they are an integral part of the structure and evolution of science and scientific theories [43]. For this reason, models play a crucial role in communication. Each person can have a mental model of a target, which can be expressed when discussing it with others until reaching an agreement, and that can differ depending on the purpose and context [33]. Because of this, models and modelling competence are considered an essential part of scientific literacy [44].

Some models constitute idealizations to make visible microscopic or abstract elements of reality. In the case of minerals, this can correspond to the arrangement of elements and/or molecules in the crystalline network, features that can be hard to imagine or even consider in the case of non-experts. Other models are constructed to describe and simplify complex phenomena, such as the mineral's chemical formula, which can be used to predict its main uses or properties, among others. However, models are seldom seen in science classrooms as shared mental representations elaborated to predict or explain natural phenomena and elements and made with an objective and bearing some limitations. In the opposite to that, they are often considered by students as simplified "copies" of reality [45,46]. Thus, the role of students with respect to science models should switch from "consuming" concrete expressions of scientific models to construct, express, use, evaluate and revising personal scientific models in order to find the best explanations for simple natural facts [47]. At least four steps are needed during the construction of a model of a phenomenon or item [48]. The first one is to acknowledge the need for a model, making systematic observations of the item under study. This can be achieved through direct, indirect, qualitative, or quantitative experiences [40]. The second is to construct and express the model based on those experiences. Next, evaluate the model (testing it) and revise and apply it in different situations. Some authors even group these four generic steps into two broader phases, including the first two steps in the so-called model formulation phase and the remaining in the model development phase [49].

It is not always feasible or possible to consider all these items at once in the classroom. Nevertheless, in the case of virtual museums, the inclusion of all these characteristics can be more easily conducted to show the interrelationships between them. For instance, they can be of use during the model formulation phase. As such, these resources can be used by visitors to collect evidence from the data presented (photographs, sections about properties, origins of minerals, mineral deposits, etc.), identify which are the key features of a mineral, and how they interact between them to synthesize their version of the mineral model.

4.2. Recommendations

Certain improvements and recommendations are proposed to help curators of virtual mineralogical museums include different content so visitors can have a holistic understanding of what a mineral is.

Even if mineral photographs are usually the main content of these types of museums, a section dedicated to the description of general properties of minerals is necessary, providing examples using representative mineral specimens where they can be clearly observed. It is not easy for a non-expert to establish connections between the macro- and microcharacteristics of minerals. A distinct link between these characteristics could be established, making explicit the connections through examples that are understandable at all levels.

Additionally, more data about uses could be included, as in many cases the relationship between minerals, properties, and uses can become unclear for visitors. As such, including data about how minerals' main characteristics determine their uses in our society could also be a priority. Specific examples should be provided as to why some minerals can be used for certain applications while others, with a similar chemical composition or external aspect, cannot. Contextualizing this content using examples that can be familiar to visitors can provide a better navigation experience and enhance the learning opportunities.

Aspects related to the occurrence of deposits as well as environmental and social impacts of the mining industry could be included. Photographs or deposit maps alone are a limited tool to help visitors to improve their knowledge about these factors. In addition, incorporating more than one or two photographs per mineral and including some showing the most common mineral associations could help to relate origin and occurrence. Introducing information on mining heritage and the history of selected mines that are no longer operating could help have a broader vision of the general relevance of this sector. It could also raise awareness about the importance of preserving historical and mining heritage [50], understand the effect that extraction has on the planet, and be more conscious of how scarce and geographically limited mineral resources are.

So that virtual mineralogical museums can be used as learning agents, more attention should be paid to the educational value of their contents [16]. There is an apparent lack of instruments that could allow users to evaluate their knowledge. Visitors can have intuitive ideas about certain characteristics of the mineral model but may not have access to the most appropriate resources to be able to test, modify, or improve it. As seen, this aspect has hardly been considered in the design and content of the web pages analyzed. In this context, different questionnaires, surveys, and self-assessment tools that can give them immediate feedback should be incorporated when possible. Other resources that could make virtual mineralogical museums valuable for teachers is including different digital or print-and-play games, as game-based learning has the potential to motivate students and reinforce learning of geology-related contents [51,52]. As such, with these considerations in mind, virtual mineralogical museums could be used not only in a science-learning activity related to minerals during the model formulation phase (collecting evidence and identify the key factors and the interaction between them) but also in the model development phase, allowing visitors to test the robustness of their models or use them to make predictions.

Nonetheless, even if these sites are a relevant resource that can be introduced and used in educational practices, it is important not to overlook the fact that, if we want students (and the future population) to have a holistic view of what minerals are, what they are used for, how they are extracted, what impacts they have, and what we can do to promote a sustainable and responsible use of these type of resources, it is necessary to combine its use with physical samples to allow direct interaction with them.

5. Conclusions

Virtual museums are becoming a truly relevant tool in the science learning process and classrooms, using information and communication technologies (ITC) at different educational levels (primary, secondary school, and university). Still, to be helpful, they must include specific mineral-related content that can help visitors reach a more complex and deeper understanding of the mineral model.

In this paper, the content of 38 virtual mineralogical museums was analyzed, of which 15 had a physical counterpart. Substantial differences can be seen between those two types of museums, with the latter having less specific mineral-related contents. It is more frequent to find more complete descriptions of mineral samples in those without a physical counterpart. Also, those virtual museums that are aimed at university students and/or geoscientists include much more diverse information and details. In the vast majority, the virtuality of these museums resides in the fact that they contain digital galleries with one or more photograph per mineral, being less abundant those that include 3D minerals or crystal models or 3D virtual tours. Only 10 sites include some type of educational materials but are almost always of informative or explanatory type (brochures, infographics, charts, etc.).

Regarding their educational value, museums have a high connectivity between sections and those created for university students specifically have more written content than those created for the general public. Gamification elements and knowledge tests are seldom present, so visitors cannot test if their knowledge about minerals has improved after visiting them.

To better reflect the model of mineral shared by experts, all these online resources should include information related to all the following key aspects of the minerals: 1) the properties (macro- and microcharacteristics, and how they relate between them); 2) uses and; 3) origin, considering also other interrelated factors such as the occurrence of mineral deposits, the impacts associated with the mining industry, and the sustainable use of natural resources. Unlike conventional museums, the availability of data and space is not a limiting factor. Therefore, the goal should be much broader, from design to commissioning. For this reason, the wide gap is striking that exists between what any person should know about minerals, according to the official documents that state what students should know by the end of their schooling, and the type of resources, in this case, virtual mineralogical museums, that teachers can find at their disposal.

As evidenced by this analysis, there are still many improvements that can be carried out in virtual mineralogical museums to improve their educational value and enhance their contents. All the suggested improvements refer to the sites' potential to increase a holistic understanding of minerals through different items. Another challenge should be to increase the interest in mineralogy in the public, highlighting the usefulness and dependence of our society on natural resources. Having a more complex mineral model could help modify how the general population values mineral resources, clarify the relevance that the mineral resource extraction sector has in our society, and link it with aspects related to resource efficiency, environment, climate change, and even the circular economy. Thus, improving the scientific literacy and decision-making processes of the population.

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Appendix A

Table A1. List of virtual mineralogical museums and mineral databases analyzed (in alphabetical order).

Name of the Site	Link
American Southwest Virtual Museum	https://swvirtualmuseum.nau.edu/wp/index.php/artifacts/rocks-and-minerals/ (accessed on 6 July 2024)
Athena	https://athena.unige.ch/athena/ (accessed on 6 July 2024)
Clarence R. Smith Mineral Museum	https://minerals.ysu.edu/virtual-visit/ (accessed on 6 July 2024)
Collezione Pascarella	http://www.collezionepascarella.it/mineralogia (accessed on 6 July 2024)
CSM Virtual museum	https://projects.exeter.ac.uk/geomincentre/intro.htm (accessed on 6 July 2024)
Emile Amade virtual museum of mineralogy	http://amade.name/museum.html (accessed on 6 July 2024)
Gemmo	https://www.gemmo.eu/fr/ (accessed on 6 July 2024)
Mindat	https://mindat.org (accessed on 6 July 2024)
Minerales "De Visu"-UA	https://web.ua.es/es/lpa/minerales-visu/minerales-de-visu-ua.html (accessed on 6 July 2024)
Mineralienatlas	https://www.mineralienatlas.de (accessed on 6 July 2024)
Mineralogical & Geological Museum (Harvard)	https://mgmh.fas.harvard.edu/online-exhibits (accessed on 6 July 2024)
Mineralogy & Petrology Museum Tour	https://www.ualberta.ca/science/about-us/virtual-tours/mineralogy-petrology-museum.html (accessed on 6 July 2024)
Mineralogy and Petrography Museum "Grigore Cobălcescu"	http://geology.uaic.ro/muzee/mineralogie/ (accessed on 6 July 2024)
Musée de Minéralogie Paris	https://www.musee.minesparis.psl.eu/Collections/Collections/systematique/ (accessed on 6 July 2024)
Musée minéralogique de l'Abitibi-Témiscamingue	https://www.museemalartic.qc.ca/fr/index.cfm (accessed on 6 July 2024)
Musée Virtuel Albert de Lapparent	http://www.musee-delapparent.com/ (accessed on 6 July 2024)
Museo de geología—Universidad de Sevilla	http://direccioncitius.us.es/museo/minicio.php?id=5 (accessed on 6 July 2024)
Museo de Mienralogía Ingeniero Pablo Reyes Nuñez	https://nubeminera.cl/museo-de-mineralogia-virtual/ (accessed on 6 July 2024)
Museo Regionale di Scienze Naturali della Valle d'Aosta	https://digitalnature.regione.vda.it/ (accessed on 6 July 2024)
Museo Virtual de Geología	http://www.laboratorio.wesped.es (accessed on 6 July 2024)
Museo Virtual de Geología del SGM	https://www.sgm.gob.mx/Web/MuseoVirtual/ (accessed on 6 July 2024)
Museo Virtual de la Región de Atacama, Chile	https://www.geovirtual2.cl/geologiageneral/museo1.htm (accessed on 6 July 2024)
Museo Virtual de Mineralogía—Universidad de Huelva	https://www.uhu.es/museovirtualdemineralogia/ (accessed on 6 July 2024)
Natural History Museum of Utah	https://nhmu.utah.edu/museum/exhibits/gems-and-minerals (accessed on 6 July 2024)
Online Mineral Museum	http://www.johnbetts-fineminerals.com/museum.htm (accessed on 6 July 2024)
Rice Northwest Museum of Rocks & Minerals	https://ricenorthwestmuseum.org/virtual-tour-2/ (accessed on 6 July 2024)

Table A1. *Cont.*

Name of the Site	Link
RRUFF	https://rruff.info (accessed on 6 July 2024)
Smithsonian Natural History Museum	https://naturalhistory2.si.edu/vt3/NMNH/z_tour-022.html (accessed on 6 July 2024)
Smorf	https://smorf.nl (accessed on 6 July 2024)
The minerals & gemstone kindgom	https://www.minerals.net/ (accessed on 6 July 2024)
UMA Divulga—Museo Virtual	https://www.umadivulga.uma.es/museo-virtual/mineralogia/ (accessed on 6 July 2024)
Université Libre de Bruxelles—Musée Minéralogique	https://musemin.ulb.be/data/Presentation.html (accessed on 6 July 2024)
Virtual Museum of Chinese Minerals	https://www.cityu.edu.hk/chinese-minerals/ (accessed on 6 July 2024)
Virtual Museum of Geology	https://www.virtualmuseumofgeology.com (accessed on 6 July 2024)
Virtual Museum of Molecules and Minerals	https://virtual-museum.soils.wisc.edu (accessed on 6 July 2024)
Virtual museum of the Czech Geological Survey	http://muzeum.geology.cz/d.pl?item=6&l=e# (accessed on 6 July 2024)
Visite virtuelle du Musée de minéralogie et de paléontologie du Bugue	https://www.geopolis.fr/actualites/dernieres-actualites/501-visite-virtuelle-du-musee-de-mineralogie-et-de-paleontologie-du-bugue.html (accessed on 6 July 2024)
Webmineral	https://www.webmineral.com (accessed on 6 July 2024)

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