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When from Technology Comes Beauty: A Glass-Gem Case Study to Promote Inclusive and High-Quality Learning Paths in Heritage Science

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Abstract: The glass-gem collection at the National Archeological Museum of Aquileia (Italy) was recently studied by in-depth archaeometric investigation campaigns, which are still running. Some objects in this very rich collection were characterized by performing a completely non-destructive analysis. In order to enhance our knowledge of Heritage Science, specific educational paths were designed, which, in one case, were already tested in a summer school involving Italian middle-school students. This article will characterize a single glass-gem (as a case study), highlighting how ancient craftsmen combined technical skill and product beauty expertly. A multidisciplinary approach yielded valuable details about morphology, composition, and production technique, demonstrating additional information beyond that gleaned from typological and iconographic studies. At the same time, educational pathways based on this research study are valuable, inclusive, and high-quality examples in the so-called STEM field that develop better knowledge, conservation methods, and techniques for the enhancement of cultural heritage collections.

Keywords: glass gem; non-destructive analysis; STEM and heritage science educational paths; multidisciplinary approach

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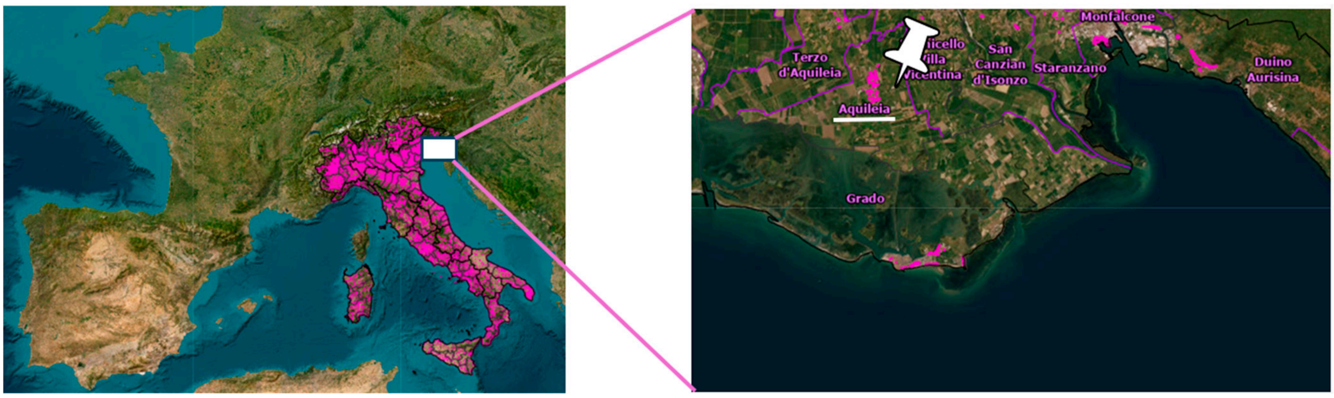
1. Introduction

Artistic glassmaking has ancient origins: glassmakers of different historical periods and places used different raw materials and manufacturing techniques. Since ancient times, glass has been produced for a variety of uses, and some peculiar objects are, for example, exhibited at the British Museum [1]. Generally, glass classification is based on its elemental composition, namely its major (i.e., silica), minor (for example, soda, ashes, or potash), and trace components (i.e., B, F, Ti, and Fe but also Sb, Sn, and Pb elements). Glass was produced for imitation purposes too, for example, in gemology [2]. In fact, ancient glassmakers were constantly looking for new recipes to mimic natural gems and stones used in jewelry; opaque glasses could be obtained (and tuned) by means of the careful insertion of some elements, likely forming microcrystalline phases (such as calcium or lead antimoniate), while the coloration of glass is the result of complex interactions between structural and chemical effects. In particular, the presence and the relative concentration of transition metals play a fundamental role, acting as chromophores in the glass base matrix [3]. The whole composition of the specimens thus reflects the progress achieved by the manufacturers' workshop, and it can be used as an archeological marker of the time of production and the geographical area of provenance. Roman glassmakers skillfully achieved control over color, mixing colorizers and decolorizers [4–6]. Some beautiful examples are in the National Archeological Museum of Aquileia's (Italy) collection [7,8], which consists of more than 1300 glass gems dating from the 2nd century BCE to the 3rd century CE. Such a rich collection, however, has not yet been analyzed in-depth from a scientific point of view; in fact, the finding site is known (Aquileia itself), but most of its masterpieces are objects of many concerns.

Aquileia (see the location in the map below) is one of the most important Roman sites in northern Italy, which was declared a World Heritage Site (UNESCO) in 1998. The city was founded in 181 BCE in a strategic area, connecting the west to the east, namely the Mediterranean to the northern and eastern regions of ancient Europe. In the Roman period, Aquileia was a thriving trading center and a cosmopolitan place made up of different people, languages, and cultures. In this context, manufacturing activities developed; excellence was achieved in regard to the manufacturing of gems and cameos, as well as extremely refined artifacts made of amber and glass. In such productions, the workshops in Aquileia played a leading role [9]. The Archeological Museum was built in 1882 to preserve and promote the archeological heritage that has been brought to light since the 18th century by findings and excavations, which have made it possible to reconstruct the history of the city, its monuments, and its urban development. The glass gems in the National Archeological Museum of Aquileia are an optimal set of samples for research purposes because they all come from the ancient city; post-antique specimens are residual.



Map adapted from ISTAT webpage, https://gisportal.istat.it/portal/apps/MapSeries/index.html?appid=e8601c3731ea44ffb12f848d6d5f004f, accessed on 20 December 2024, with the areas characterized by tourist interest highlighted in pink.

Aquileia City is outlined in white (the ISTAT documentation is freely available under a CC license by Creative Commons 4.0: https://creativecommons.org/licenses/by/4.0/).

To deepen our knowledge about the conservation and valorization of the glass-gem collection in the National Archeological Museum of Aquileia, a specific project was designed called the "Glass-Gems Exploration Using Multidisciplinary Methods, Analyses, and Experiments" (GEMMAE) [10–13]. During several in situ campaigns, it was possible to deepen the results of previous campaigns by selecting peculiar specimens and performing in-depth optical microscopy analysis, colorimetry measurements, and recording further vibrational spectra.

Scientific techniques were all chosen considering their non-destructiveness since this was a mandatory requirement for the GEMMAE project. We understand that some information could be lost, but we wanted to preserve the studied cultural heritage samples. Moreover, the chosen analyses do not involve any contact with or any pre-treatment of the specimens. The only requirement (when the measurements were not performed in situ) was the shipping of the samples to the laboratory.

This paper will focus on a single case study, where ancient craftsmen combined technical skill and product beauty excellently. A single glass gem was selected for the dual purpose of characterizing it (determining its properties for study and conservation purposes) and valorizing it (using it as a case study in educational projects as well). In particular, a multidisciplinary approach allowed us to derive valuable details concerning morphology, composition, and production technique. Major, minor, and trace elements have been detected, being very useful indicators for dating, provenance, and manufacturing issues. Though specific elements could account for provenance studies [6], we focused our attention on crystalline phases, too. This study testifies to the feasibility of a non-destructive approach for glass composition determination, and it proves to be relevant for museum glass-gem collections. Characterization studies were accompanied by the design of educational activities to be offered in Italian schools, based on the study of the glass gem selected and on the adopted protocol: educational pathways, in addition to being a good example of collection enhancement, are a useful tool to raise awareness and increase the attractiveness of STEM (Science, Technology, Engineering, and Mathematics).

In the following, we will present a first intervention during an Italian summer camp. The choice of the Italian context was motivated not only by the nationality of the GEMMAE project but also by the results collected by national surveys (such as INVALSI [14]) and international surveys (such as PISA and TIMSS [15,16]) on the average knowledge levels of male and female students in Italy in the area of mathematics and science. We know that Italian male and female high-school students have skills in line with the average of OECD countries, but their scores are still much lower than those of other European and non-European (especially Asian) countries. So, STEM education still deserves great attention.

In addition, we cannot forget how the same studies have shown a negative record for Italy: referring to 15-year-olds, the PISA2022 study [15]) showed that Italy has the worst gender gap in math achievement with 21 points of score difference between boys (482) and girls (461). The gender gap is a problem of global significance, not only from an educational point of view but also economically. The Global Gender Gap Report 2023 [17] (commissioned by the World Economic Forum) points out that Diversity, Equity, and Inclusion (DEI) programs should always be taken into account: a sector that has invested the least in DEI goals is precisely education and training (13%). Moreover, the same report highlights that the current Gender Gap Index (GGI) for Italy in 2023 is 0.705, ranking in the 79th position (worsening its previous ranking—55th in 2020). We therefore designed our intervention taking into account role-model issues too (see for example [18]). The summer camp will be described in the Materials and Method section, also addressing the urgency of summer learning loss, i.e., a phenomenon now recognized in educational research, where, by assessing the skills and knowledge of students at the end of one school year and the beginning of the next, learning losses are often recorded [19].

All the project was inspired by the United Nations 2030 Agenda [20], to provide high-quality, inclusive, and sustainability-focused actions. To cite a few, we tried to meet the following targets: 11.4—Strengthen efforts to protect and safeguard the world's cultural and natural heritage, 4.1—Ensure that all girls and boys complete free, equitable, and quality primary and secondary education leading to relevant and effective learning outcomes, and 4.3—Ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education, including university.

In the following, we will describe materials and methods, both for the scientific analysis and the teaching and learning methods used, the educational pathways offered, and the results achieved. We stress that this multidisciplinary study is an excellent example of how scientific disciplines can collaborate with the humanities: first, art and science, gathering different expertise from archeology and glyptic to scientific disciplines, but also scientific experiments designed through innovative STEM education methodologies. Moreover, a similar protocol could be considered a best practice example and easily applicable to similar collections, supporting the sector of Heritage Science.

2. Materials and Methods

The GEMMAE project initially selected a set of about 100 glass-gems to be studied, with different colors and transparencies, which at first could be divided into two main macro-groups, represented by:

- Single-color glass-gems;
- Multilayered glass-gems (with layers of different colors).

The set was carefully chosen by a selection of typological and glyptic features during a preliminary study carried out in situ at the National Archeological Museum of Aquileia and selected for a PIXE/PIGE analysis campaign, but many other complementary techniques were used, also in subsequent campaigns [10–13]. Most of the analyzed glass-gems are dated to the Roman period (2nd century BCE–3rd century CE), and the specimens had not been characterized before by any scientific analyses.

2.1. Inlaid Glass-Gem

Different glass-gem sub-families can be defined within the glass-gem collection since single-color glass gems could show images in negative or in relief, and multilayered gems could present two or more layers, with inlays of different materials too. We have chosen one single sample that could well represent when from technology comes beauty: the case study is an inlaid glass from the National Archeological Museum of Aquileia, in-depth characterized using a non-destructive suite of analytical techniques.

Figure 1 displays a picture of the selected inlaid blue glass gem with a vine leaf in green. Similar iconographical and gemological details were present in other inlaid glasses. Moreover, other museum collections display similar objects. One beautiful example comes from the British Museum Collection: a blue glass oval inlaid with a vine leaf in green enamel and gold, set in a modern finger ring [21].

Figure 1. Obverse of the analyzed glass gem (with size 1.3 × 1 × 0.3 cm) (credit: E. Gagetti).

2.2. Scientific Techniques Used for Cultural Heritage Characterization

The optical microscopy (OM) observations were performed using a Leica S6E stereo-optics microscope that has a zoom range of 0.63×–4.0× (total magnification of 10–64 with 16× eyepieces), coupled with Motic GM171 dark field gemological stage. The OM images were obtained using a digital stereomicroscope Dinolite Digital Pro™, with a polaroid option and a 5 MP camera.

The colorimeter parameters on the glass gems have been collected by a Konica Minolta CM-2600d spectrophotometer using a 6 mm diameter window and focusing the instrument's spot on the different colors previously observed on the gemstone. For each spot of analysis, three acquisitions were performed by the D65 light source in the spectroscopic range between 350 and 750 nm, and the average was considered representative of the color parameters. The data acquired has been elaborated using Color Data Software CM-S100w SpectraMagic™ NX—ver. 3.4, and the CIEL*a*b spatial color space have been considered [BIBLIO UNI EN ISO/CIE 11664-6:2023]:

- L* = 100 white, 0 black;
- a* = +red − green;
- b* = +yellow − blue.

Both Specular Component Included and Excluded (SCI-SCE) have been compared, considering the effects of surface texture on the color appearance.

Micro-Raman analyses were performed on-site using a Renishaw Virsa™, a fiber-optic-coupled Raman spectroscopy system equipped with 785 and 532 nm laser sources with 1500 L/mm and 2400 L/mm gratings, respectively, and a thermo-electric cooled detector. The utilized spectrometer was coupled with an SB200 motorized (x, y, z) base, setting 4×, 20×, 50×, and 100× objectives to focus the source in confocal operation mode. Before each measurement session, a calibration procedure was performed using a silicon reference sample to check the relative Raman band at 520.6 ± 0.1 cm^{-1}. The spectra were acquired and elaborated using Renishaw's Windows®-based Raman Environment (WiRE™) software https://www.renishaw.com/softwarelicensing/en/connect/WiRE.

Due to the heterogeneity of the investigated materials, the acquisition parameters were optimized to increase the signal-to-noise ratio as much as possible (typically, 50 accumulations of 10 s each). The analyses were focused on the different glass colors and glass texture/matrix peculiarities previously identified by OM. The Raman features were interpreted by matching the acquired Raman spectrum with spectra in reference publications. Collected spectra were finally elaborated with OriginPro 2020 software (OriginLabs).

Ion beam PIXE/PIGE analyses were carried out at the NewAGLAE facility (Centre de Recherche et Restauration des Musées de France—C2RMF, Equipex ANR-10-EQPX-22), based in the Palais du Louvre in Paris (France). A 3 MeV proton beam, extracted through a 0.1 μm thick Si_3N_4 window (surface 1 mm^2), hits the samples with a beam spot about 50 μm wide. For PIXE analysis, four 50 mm^2 Silicon Drift Detectors (SDD) were used with a 50 μm aluminum filter to enhance the detection of high energy X-rays, while one SDD with a smaller solid angle was used in a helium atmosphere to enhance the response to low energy X-rays. In this configuration, it is possible to identify the elements with $Z > 11$ and to measure their concentrations with a lower limit of detection for higher atomic numbers and depending on irradiation conditions. An ultrapure germanium detector was used to detect in parallel the γ-rays from 60 keV to 2 MeV for PIGE analysis, fundamental for the measurement of sodium concentration. PIXE data analysis was performed following the procedures described in [22] by PIGE normalization [23]. Precise quantitative measurements of element concentrations were obtained and controlled by regularly using a set of calibration references, in particular, standard glasses like BRILL A, B, and D. Errors can be estimated as in [24], with values ranging from 1 to 10%, depending on the concentrations.

2.3. Teaching and Learning Methods

To enhance knowledge of Heritage Science, after the multidisciplinary study carried out, we designed specific teaching activities following a laboratory-based approach based on Inquiry (see [25–28] and references therein): this methodology involves moments of brainstorming, experimentation, hypothesis formulation, model building, discussion and comparison with peers. The importance of experimentation relies on the learning-by-doing approach, which in turn refers to the assumption that people learn best when they are personally involved—active involvement (see for example [29,30]). This theory overturns the teaching paradigm that traditionally describes students as passive actors in school.

Activities were chosen within the so-called STEM field, which refers to scientific and technological disciplines and their fields of study. Again, methodological references for teaching STEM disciplines combine integrated and interdisciplinary approaches with the use of laboratory teaching strategies and digital technologies.

Based on our previous experiences [31], we focused our attention on the topic of light and colors, and we designed a learning path called "Where do the colors come from?". After the first introductory part on light and its interactions with materials, a focus on the inlaid glass-gem case study was carried out. First, it was presented the museum glass-gem collection and the GEMMAE project (also through a virtual visit to the museum, showing movies and pictures from the experimental campaign). Then, the selected glass gem was considered. Our case study was indeed a very good example of how transparency and opacity can result in different colors and hues. Moreover, the use of different colored layers and materials can better emphasize specific iconographic details and highlight how skillful techniques can create very beautiful objects.

This first educational project was designed for an Italian summer school, with 12 middle-school students (aged 11–14 years old, 2 female and 10 male students), for a three-hour activity. The number of female and male students was not the result of any selection, but it was only connected to the participants of previous after-school interventions (at the Luisa Berardi Association). The project was shared and discussed with the summer school educators before the beginning of the path in order to adjust the activities to the average level of the group of students and figure out the most effective tools/actions. The interactions between the university team and the summer school educators were supported by a dedicated tutor, who also contributed to the educational path design. A detailed description of this first teaching project is available in Appendix A.

The summer camp was hosted by the Luisa Berardi Association, which has been operating since 1995 in a semi-peripheral area of the city of Milan (Italy), characterized by high social fragmentation (conditions of socio-economic–educational fragility). The children living in these contexts often have schooling difficulties, also due to the causes mentioned above, low schooling or knowledge of the Italian language of their parents, in the case of children with migrant backgrounds. During the summer months, at the closure of schools (an indispensable didactic, educational, and socialization presidium), there is a long parenthesis of the absence of recreational and educational proposals. The Association usually offers free interventions that are constantly updated by careful readings of emerging needs to respond concretely to the difficulties of the children, the young people, and the families in the area for better integration of all the social components of the territory. Summer loss learning is a well-known issue [19], and the loss of this learning is hardly made up over the school year, creating a gap that continues to widen and with which the school can hardly cope. Therefore, the summer period becomes a risk factor for educational poverty, contributing to increasing inequalities, mostly for students coming from less advantageous economic conditions families, and this was an important motivation for our educational intervention.

The selection of summer camp children was linked to the after-school program that already takes place during the year for middle-school students. The Association's web page is constantly updated on the various activities carried out [32].

Considering the gender gap issue, the activities were carried out by female scientists, with the aim of providing children with an opportunity to have direct contact with female figures involved in science on a professional and personal level, acting as "role models" (see for example [18]). Personal contact with women working in STEM leads to a general improvement in female students' attitudes toward STEM, strengthening self-efficacy and self-concept and broadening professional aspirations in this area. An important factor is the frequent and continuous presentation of counter-stereotypical role models [33].

Other general educational paths in the field of Heritage Science are being designed, too, mainly focused on the GEMMAE project, our multidisciplinary characterization campaign, and exploiting well-established resources in virtual laboratories. One of them is the PhET lab (interactive simulations for Science and Mathematics at the University of Colorado, Boulder, CO, USA) [34], but many virtual visits can also be offered in international infrastructures where scientific experiments are carried out. At Milano-Bicocca University, we have been offering PCTO (Italian acronym for "pathways for soft skills and orientation") paths designed for high-school students, and more interventions are being designed with the museum collaboration, too. All the details related to educational paths will be available on the GEMMAE website in a special education section [35], acting as a carrier of enhancement of knowledge in Heritage Science.

3. Results and Discussion

3.1. Scientific Investigations Results and Discussion

Cultural heritage studies require multidisciplinary approaches to answer the interdisciplinary nature of the problems that must be solved, partly due to the high heterogeneity of the studied materials [36]. Thus, considering this variety as well as the limitations of the on-site diagnostic activities (especially concerning the time duration: usually, each analysis campaign is concentrated in a few days), the multi-technique diagnostic protocol requires a step-by-step approach.

In the present case, the protocol consists of a workflow starting from the deep OM observations by the stereo microscope in order to detect the detailed differences in transparencies, colors, surfy alteration, cracking, presence of inclusions and/or opacifiers, bubbles aspect, and so on. Moreover, the OM information represents a helpful map to guide the selection of the spots for further analysis, especially for the micro-Raman acquisition.

For what our study case concerns, inv. no. Aq 27491 sample is an oval tablet gemstone made of artificial glass (Figure 1); the measurements are 13.0 × 10.0 × 3.0 mm. The gem's color consists of vivid violetish blue (vB), while a yellowish-green (yG) vine leaf is inlaid into the obverse. In Figure 2, the images acquired by digital microscope are reported; particularly, a difference in transparency is clearly visible: semi-transparent (STP) the vB portion and semitranslucent (STL) the yG leaf (Figure 2a), where also the glass pits are larger and more concentrated [37]. Moreover, the yG appears as a different glass layer overlapped on the tablet's obverse (Figure 2b). Thanks to the reflected light, the surface features can be observed; indeed, the spotty aspect well visible in the tablet's reverse (Figure 2c) is commonly observable on the whole gem's surface. Finally, the girdle, although characterized by cavities, cracks, and small glass pits, too, shows a polished aspect without remains of the process (Figure 2d).

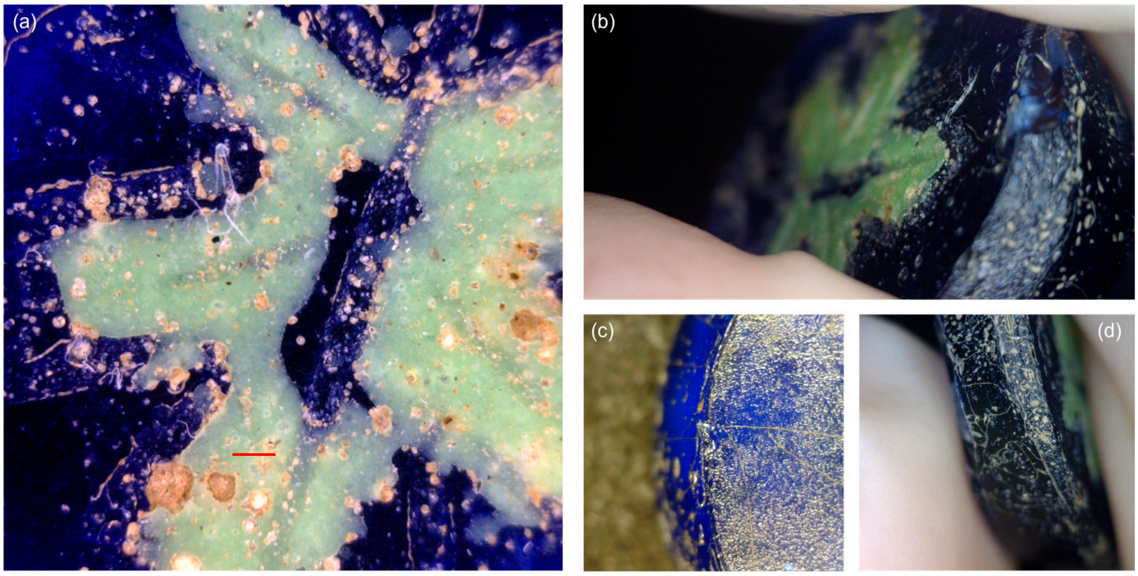
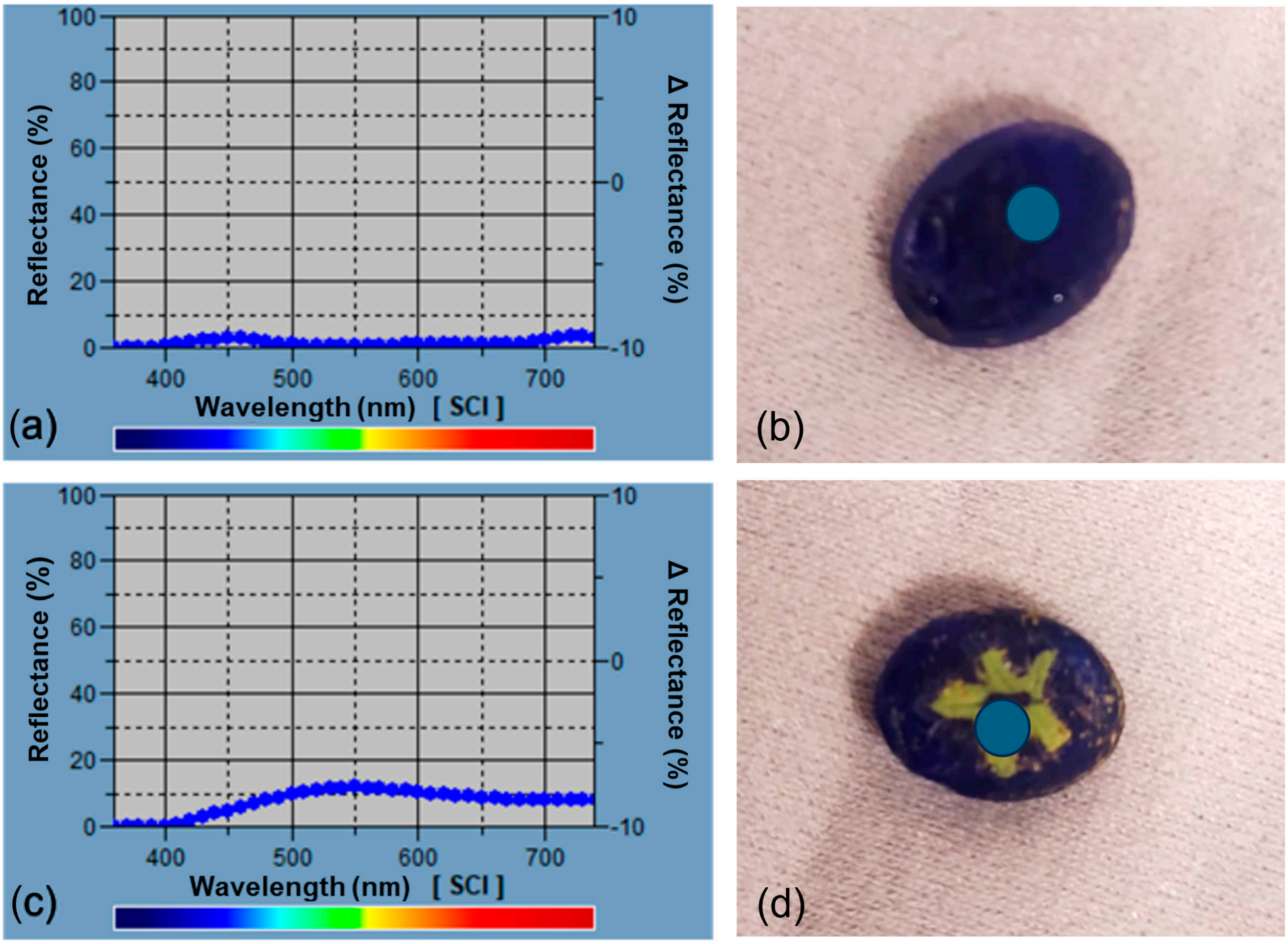


Figure 2. Digital microscopy images of the study sample; (**a**,**b**) inlaid vine leaf detail, polarized light; (**c**,**d**) surface texture details, reflected light. Red line in (**a**) is 0.5 mm, while in (**b**–**d**), the border of the glass gem, with size of 3 mm, is visible.

Thus, the study sample is made of two glasses, which are obviously different in color but also the other properties highlighted by OM: transparency and surface appearance. The two different glasses have been investigated by other techniques: colorimeter and micro-Raman Spectroscopy.

The colorimeter test results are reported in Figure 3. Unfortunately, due to the transparency of the violetish blue glass and the consequent high light source dispersion during the test, the reflectance spectrum for the gem's body color shows a shallow signal-to-noise ratio (Figure 3a), making any discussion about characteristic chromophores almost impossible. On the other hand, the reflectance spectrum corresponding to the leaf shows a better quality (Figure 3c), where the absorption of blue wavelengths with a reflectance of green and yellow ones are clearly visible, as expected for the gY color identified. Observing the parameters L*a*b reported in the table (Figure 3d), the effect of the surface texture in the colorimeter test is not significant, but the leaf's L parameters are higher than the ones for the vBlue. Moreover, negative parameters of a* (Figure 3d-Leaf) and b* (Figure 3d-vBlue) are in line with green and blue hues, respectively [38]. A significant positive value for the b* parameter in the leaf is correlated with the high yellow component of the modifying hue.



Analysis spot	L*(D65)	a*(D65)	b*(D65)	
vBlue	8.34	7.57	−13.76	SCI
vBlue	5.73	8.29	−15.61	SCE
Leaf	38.64	−8.28	20.26	SCI
Leaf	38.88	−8.21	20.02	SCE

(e)

Figure 3. Colorimeter analysis: (**a**,**c**) show the reflectance spectra, while the sample's images where the two colorimeter test spots are reported in (**b**,**d**) for the vB and the yG, respectively. Finally, the L*a*b parameters for the SCI and SCE analyses of the leaf and the vB glasses are shown in (**e**).

Concerning the colorimeter, the difference between the vB and the yG glasses was also investigated by micro-Raman spectroscopy (Figure 4a,b). In particular, the Raman spectra acquired by focusing the 532 nm laser source on the glass gem and the inlaid leaf are reported in Figure 4a (blue and green lines, respectively), and the corresponding analysis spot areas at 50× magnification are shown in Figure 4c,d, where the altered surfaces are extremely well visible on both areas. It must be noted that this type of surface's alterations can be correlated with the weathering of the glass, mainly due to water interactions [37,39].

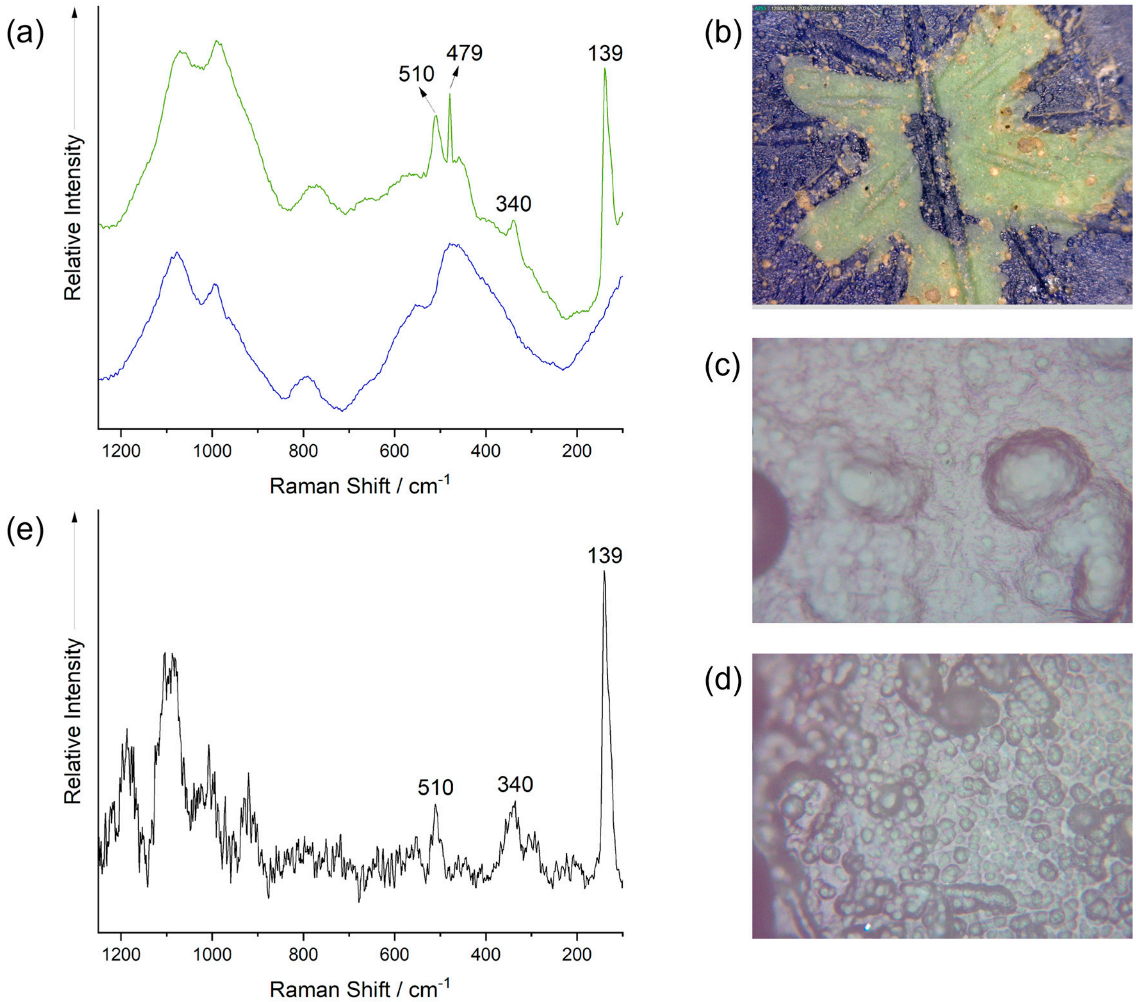


Figure 4. micro-Raman spectroscopy results: (**a**) the spectrum acquired in the range between 100 and 1250 cm^{-1} focusing the 532 nm laser source on the vB glass, constituting the glass of the gem (blue line), overlapped to the one acquired in the same condition on the yG glass constituting the leaf (green line); (**b**) a panorama view at low magnification of the area considered for the Raman analysis; (**c**,**d**) optical microscopy images corresponding to the areas where the Raman source was focused to acquire the spectra reported in (**a**) blue and green lines, respectively (50× objective, reflected light); (**e**) Raman spectrum acquired on the same focusing area of (**a**) green line and (**d**) images, using the 785 nm source, baseline subtracted.

Several considerations can be carried out by comparing the two Raman spectra. Both spectra show the typical bands associated with the silica glass vibrational modes [40,41], but the bands in the higher spectral region appear different in relative intensity. The silica glasses are rich in Non-Bridging Oxygens (NBOs) and show relatively strong intensities of the bands in 990 cm^{-1} and 1070 cm^{-1} spectral regions, where the Q^2 (silicate species with two NBOs) vibrational modes are assigned [41–45]. This information is useful due to its implication regarding the stability of the glass. It is known that a higher presence of NBOs corresponds to a higher sensibility of the glass to alterations because the NBOs enhance the cation's mobility as a primary consequence of the depolymerization of the silica structure [42,46]. For this reason, the surface alterations observed by OM in the present study case, with intense pitting in the green glass and inlaid areas, can be correlated with a relatively high presence of NBOs in the glass structure. Conversely, Robinet (et al., 2006 [42]) indicated the same doublet bands as characteristic of calcium-rich glass and assigned a

988 cm^{-1} sharp band to the copper-rich glass. Consequently, a prudence limit in the glass chemistry hypothesis was considered due to the overlap of possible assignments.

In the lower spectral region, the green Raman spectrum shows well-defined bands at 139, 340, and 510 cm^{-1} consistent with the lead antimoniate [38,47–49], plus an extremely sharp peak at 479 cm^{-1}, which are both absent in the blue ones. This represents the huge difference between the two spectra. Regarding Roman glass, the lead antimoniate was a well-known yellow pigment, and it was quite common in yellow and green archeological glasses [38,50,51]. Therefore, the leaf owes the yellow component of its yellowish-green hue to the presence of this pigment.

Regarding the sharp peak at 479 cm^{-1}, in order to exclude the possibility of a luminescence artifact, a second acquisition was carried out, changing the laser source and applying a 785 nm source to the same spot area previously analyzed by a 532 nm source (Figure 4d). The collected Raman spectrum is reported in Figure 4e. No bands at 479 cm^{-1} were detected in this second case, while the lead antimoniate characteristic peaks were still well visible. The same test was repeated on different areas of the green leaf, and the same results were obtained by switching between the two sources. Moreover, the Full Width at Half Magnitude (FWHM) of the 479 cm^{-1} was calculated, resulting in only 5.3 cm^{-1}. Based on these considerations, it is possible to hypothesize a luminescence artifact (equal to 545.9 nm emission if converted in wavelength). It must be noted that studies in the literature on modern materials report luminescence emission in the green visible range of the electromagnetic spectrum for Sb-based artificial glass [52,53].

No other phases, including calcium-antimoniate, were detected.

Considering the complexity and overlapping of the glass vibrational modes assignments and the broadening of the Raman bands, chemical information was combined with results obtained by the PIXE/PIGE technique.

PIXE/PIGE data were collected at different points of different colors. In Figure 5, details of one of the spots analyzed by PIXE/PIGE are shown, where the yG layer was present. PIXE results for glass composition were derived after PIGE normalization: elemental composition was first obtained by PIXE, and the oxide concentration could then be derived by PIGE (following the procedure described in Section 2.1). Table 1 reports the overall results obtained in the vB and yG regions. For what concerns the glass matrix, both areas show a composition comparable with the natron-based Roman glass [54], Na-rich and K in traces. Moreover, calcium is present in higher concentrations in yG areas (8.4 wt.% vs. 6.4 wt.% in vB), confirming the interpretation of the bands of the higher Raman spectral region. In line with this consideration, the relatively elevated concentration CaO levels indicate the use of the stabilizer within the glass formula.

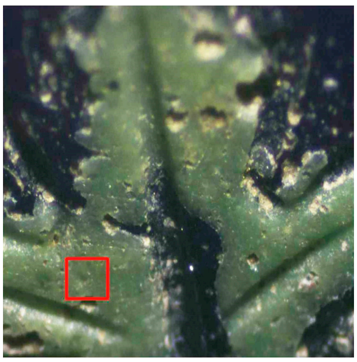


Figure 5. Detail of a PIXE/PIGE measurement: particularly of the front of inv. no. Aq 27491 sample. The red square, with size of 500 × 500 µm^2, indicates the exact position of the PIXE/PIGE measurement.

Table 1. PIXE/PIGE results for the vB and yG regions of the analyzed specimen: all contents are in wt.% (dl: below detection limit).

Regions	Na_2O Gamma	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	CoO	NiO	CuO	ZnO	SrO	Ag_2O	SnO_2	Sb_2O_5	BaO(Lβ)	PbO(Lα)
vB	7.93	0.47	2.53	77.95	0.07	0.31	1.31	0.64	6.42	0.11	0.03	0.11	0.01	0.14	0.00	0.06	0.01	0.02	0.52	0.01	0.35
yG	10.85	0.59	2.51	51.67	0.11	dl	0.76	0.55	8.37	0.16	0.03	0.01	0.01	1.96	0.01	0.05	0.05	0.18	1.04	0.03	19.30

It must also be noted that no other opacifiers or precipitated phases were detected by micro-Raman spectroscopy, confirming that the calcium belongs only to the glass matrix and the STL transparency of the leaf is due only to the lead antimoniate, which is an opaque yellow pigment. Crossing the Raman and the PIXE/PIGE results, a structural hypothesis concerning this phase could be discussed:

- PIXE e PIGE analysis confirms the presence of lead and antimonium in the yG area;
- The Raman spectrum (Figure 4a green) shows strong 139 cm^{-1} coupled with well visible 510 cm^{-1}, as expected for cubic lead antimoniate ($Pb_2Sb_2O_7$);
- The Raman spectrum (Figure 4a green) also shows 340 cm^{-1}, as predicted for lead antimoniate [38,47–49] in ternary structure, typically Pb–Sb–Sn oxide, allowing the entrance of Sn^{5+};
- The Sn has been detected only as a trace concentration (0.18 wt.%);
- PIXE e PIGE analysis shows 1.7 wt.% of iron and 2.0 wt.% of copper in the yG area, while in the vB, the concentrations are lower.

Therefore, the yG leaf owes its color (and its STL transparency) to a dominant presence of cubic lead antimoniate opaque yellow pigment; it could be combined with ternary lead-tin antimoniate, or in consideration of the low Sn concentration, to another cation (i.e., the iron) [55]. More data must be acquired to increase the statistic and confirm this last hypothesis. In any case, the Cu^{2+} chromophore in the glass matrix is essential in generating the green hue [28]. Similarly, the blue hue of the oval tablet is due to Co^{2+} detected by PIXE e PIGE analysis, combined with Cu^{2+} in the glass matrix. It must be noted that cobalt had a powerful chromophore effect despite its low concentration.

We should also highlight that no gold was detected, though focusing PIXE/PIGE analysis on the engraved parts. Our hypothesis is that the golden parts were lost over time, leaving just excavated signs.

3.2. Learning Path Results and Discussion

The STEM learning path designed for this study and entitled "Where do the colors come from?" was offered during an Italian summer school (as explained in the methodology section) and was focused, at first, on the topic of light and colors. The starting point of the laboratory was a brainstorming done with the aim of collecting students' ideas and pre-knowledge about the main topic of colors. The tutors who carried out the laboratory asked the children some questions to stimulate their answers, for example: "What is color?"; "What does the color of objects depend on?" and "Have you ever seen a rainbow?".

During the whole laboratory, the students were divided into different groups; one child for each group had to collect and document the group's observations, questions, and discoveries on a paper to help the discussion and sharing at the end of the activities. Three small groups were formed, allowing one or more tutors to follow 4 students.

After this first introductory part, the tutors asked the children to go outside of the classroom and try to create their own rainbow with the help of the sunlight and the use of a sprinkler. For the next activity, the students were asked to reproduce the rainbow that they saw in the garden but inside the classroom. The students, divided into groups, had different materials at their disposal to be freely used for the experimentation: prisms, compact discs (CDs), mirrors, rulers, flashlights, and colored plastic foils. The goal of this activity was to help the students understand that the white light interacting with specific objects separates into its seven colors and creates the rainbow.

After that, the tutors asked the students to play with specific materials (flashlights; transparent and colored plastic sheets) with the goal of creating a "light cocktail", mixing the colors of the light made by the flashlights. This activity was projected with the aim of stimulating students to better understand the phenomenon of light through the game they could make with different combinations of colors. In this way, the students could understand that colors could also be displayed, starting from the white light and its interaction with different materials, and they can also observe what happens using different filters (like colored plastic foils of different transparencies).

After the first part of the laboratory, the tutors showed the students an interactive PowerPoint presentation entitled “Colors in Relation”. The idea was to deepen the relationship between color and glass gems, starting from some optical games with colors, shown both through works of art and physical objects. The interactive part of this activity was made by asking the students to identify the colors in the different slides of the presentation. After this little optical game, the second phase of this part concerned the analysis of the colors of the glass gem here studied through photographs acquired during the last measurement campaign (that took place at the beginning of 2024), as well as beautiful examples of the items on display at the National Archeological Museum in Aquileia. For example, the picture from an object on display at the British Museum [21] was shown, where the glass gem has the same beautiful design, i.e., a vine leaf in green enamel and gold, but it is set in a finger ring, also suggesting the use of the glass gem. Then, also colorants and opacifiers for the selected glass gem were considered, highlighting their importance for hues. Moreover, the tutors showed, through illustrations and animations, that the colors’ appearance can be perceived differently in relationship with other hues (being superimposed or on the contour of the gem itself).

At the end of all the activities, the tutors organized an evaluation moment in which the students were asked to answer individually on a Post-It™ some questions: “What did you learn today?”; “What did you enjoy the most?”; “What did you like least?”. This part of the laboratory was projected both with the aim to stimulate the students to systematize the new concepts and to help the tutors understand which ideas were still unclear and needed more in-depth study.

Finally, as a gift of the experience, the tutors gave the students an instruction kit to build Newton’s disk on their own to discover what happens if they mix all the colors of the rainbow.

The importance of working in a laboratory mode allowed students to be personally immersed in what they were learning and to keep their motivation and attention at a high level, as seen in the pictures below (Figure 6), which show active and engaged students.

Working as the scientists work allows students to construct their own knowledge and learning, not simply tack on knowledge.

Through laboratory activities, students have to enact cognitive processes other than simply remembering or applying; they learn to evaluate, hypothesize, interpret, argue, compare, and explain collected data, very complex cognitive processes, and they develop cross-disciplinary skills that are fundamental to preparing for the world outside of school.

As seen in the attached documentation (see pictures in Appendix B), after exploratory moments from investigative questions, the boys and girls were asked to write down what they were discovering about the phenomenon of light and its interaction with bodies.

Using the laboratory in the study of scientific concepts, taking advantage of the inductive method, i.e., making room for observation and experimentation with the support of the expert (in this case, the female researchers), allowed students to begin to find the words to say, to explain new concepts.

Figure 6. Some pictures taken during experiments carried out within the learning path (see text for details).

As can be seen from the collected documentation, in later intergroup moments (see Figure A3), the female researchers helped systematize the knowledge and formalize with specific scientific language the findings and observations about the observed phenomena.

Observing and exploring is not enough. It is through doing and reflecting on "things" that real learning is built as we read the notes of the children involved in the experience.

The boys and the girls, at the end of the course, were asked to reflect and evaluate the experience and to acknowledge what they had liked most or least and what they had learned. As can be read below, each student put different aspects of the experience in evidence: some students highlighted simple, meaningful words, others the procedures, still others the scientist's way of working, or the important knowledge aspects about light that were learned (see figure below and detailed answers in Figure A4)

Here are the comments made by the students using some Post-It^{TM} at the end of the experiment:

> "Color, experiment, the word rainbow";

> "Experiment with minerals. I have created a rainbow with a flashlight and a mineral."

> "I enjoyed using the tools and working with them."

> "I enjoyed the fact that depending on the perspective, the color emitted by the light changes. The thing that interested me the least was the activity with the CD, as I already knew how it worked. I learned that depending on the background or outline, it can make a color appear to be a different shade."

> "I enjoyed the whole test, and I also liked how we did it and the fact that they gave me a detailed explanation."

> "What I liked the most: pointing out that the white light isn't exactly white, but it's the combination of all colors of the rainbow."

A moment for reflecting on and evaluating the experience at the end of the activity is essential for both the students and the teachers/educators. In fact, students have the opportunity to go back over things, retracing their experience, dwelling on the aspects that really were significant for them and that they learned; conductors (in this case, the female scientists), on the other hand, were able, from the students' words, to evaluate the achievement of the objectives for each of them and, if necessary, to design and/or redesign subsequent activities [56].

Concerning gender roles, we can outline that girls (though only 2 female students were present over a total number of 12 students) were actively participating in all the activities. Moreover, one of them was elected as representative of the group and was continuously asking for details and more information. Since the limited number of students, we cannot derive any quantitative details, nor can we say whether the role model (the presence of female scientists) could have been a real inspiration. However, all the children were extremely interested and enthusiastic throughout this activity.

As far as STEM education is concerned, we are confident that we have offered an inclusive and high-quality learning path, as also demonstrated by the comments posted by the Luisa Berardi Association on their social media [57]. The comment is in Italian, but the translation is enclosed below for the benefit of the readers:

Within our summer camp, Fridays are dedicated to new educational experiences.

On July 12 [2024, translator's note], we hosted Daniela Di Martino, a researcher from the University of Milano-Bicocca, and her scholars, Claudia Rabaioli and Martina Veneriano.

The topic covered was "Where do colors come from?" Through hands-on activities, with a real scientist approach, the children were able to experience and discover what light is and analyze it.

As an Association, we strongly believe in expanding knowledge, especially in STEM disciplines. It is an opportunity for young people to observe the world around them, ask questions, and discover their own interests and talents.

Thank you for the time given to the kids and the passion conveyed for science!

4. Conclusions

In Roman times, pieces of jewelry and glyptic items could be manufactured starting with different materials. Apart from gemstones, glasses were also used, mainly with the aim of imitating them. The importance of the GEMMAE project lies in increasing the knowledge about the materials employed in antique glass production, which will help in reconstructing the techniques, the supply chain and commercial roads as well.

Concerning our case study, all the information collected about the materials involved in antique glass production can be useful in better understanding the possible alteration and weathering issues of the samples, giving crucial information for the archeologists and conservators to take care of this specimen in the best way. We stress that the glass gem chosen as a case study has been completely characterized by a multidisciplinary, non-invasive analytical protocol. Only by using a multi-technique approach and crossing the data acquired can cultural heritage identification and characterization problems be solved. The gem resulted from a combination of two different types of glass to create an inlaid object, probably with a gold strand as finishing; this complexity proves the extraordinary abilities of the antique glass makers to create beautiful objects. The glass matrix was made with natron (mineral flux), and there are no compositions referable to the use of sodium ash, while the contents of chromophore elements, as well as of the elements referable to opacifiers, are strongly correlated with the color and with the opacity/transparency of the glass, respectively. Yet, the leaf (the upper layer) shows different composition, color, opacity, and alterations.

The choice of AGLAE FIXLAB facility and in situ mobile equipment campaigns was three-fold: (i) non-destructive techniques were mandatory for the study of items from the collection preserved in the National Archeological Museum of Aquileia; (ii) a detailed quantitative composition was required, for the goal of our project, and AGLAE facility allows the combined detection of major, minor and trace elements; (iii) complementary techniques are needed to obtain in-depth details (combining elemental and mineralogical phases characterizations). All conditions were satisfied in this project, and this testifies to its feasibility.

A first learning path was designed and carried out to enhance knowledge of Heritage Science, using our case study as the starting point for educational activities. The results obtained were positive, and the attention and curiosity of the students were testified also by their active participation in the experiments and by their questions. Further interventions will be designed, also in closer connection to glass technology, the glassmaking process, and glass-gem color issues. Concerning gender gap issues, we could add that similar role-model activities should be more frequent to increase efficacy [33], as well as to counteract the so-called summer loss learning: in this regard, we have already planned new summer learning interventions with the Association Berardi in July 2025. A possible additional action to consider for sharing Heritage Science knowledge would be the visit to the National Archeological Museum in Aquileia, with the possibility of a closer look at the studied glass gem. In order to further enhance our project, a website [35] was created to gather data collected from the measurements, disseminate the results, highlight the collection, and publicize related events or activities (including those for educational purposes).

Our study is an excellent example of best practice that can be exported to the study of other museum collections to learn about, conserve, and valorize cultural heritage from a truly interdisciplinary Heritage Science perspective.

Following this case study, other specific specimens and glass-gem families will be further studied. Finally, we highlight that most members of the user group were women working at different levels in different fields, and during our educative activities, they acted as role models, motivating female students and researchers to perform novel behaviors and inspiring them to set ambitious goals (embracing UN 2030 Agenda Goal 5—Gender equality) [20].

Author Contributions: D.D.M., E.G. and M.P.R. conceived the project; M.M. designed the spectroscopic analysis protocol and performed spectroscopic investigations with the help of G.Z.; Q.L., M.P.R., G.M., E.G., M.N. and D.D.M. performed PIXE/PIGE experiments; Q.L. carried out the PIXE/PIGE raw data analysis. M.M., G.Z. and L.C. performed spectroscopic data analysis. D.D.M., M.Z., C.R., M.V. and D.D.M. conceived and conducted the learning paths. All authors gave contributions to gathering data and literature comparisons, also discussing the results. D.D.M. and M.M. wrote the manuscript in consultation with all authors. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The raw data required to reproduce these findings are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

WHERE DO COLORS COME FROM?

Brainstorming on rainbow/color:

Have you ever seen a rainbow?

What is color?

What does the color of objects depend on?

Collect their questions/observations on the board or on a poster board.

1—Let's make a rainbow (GARDEN WORK).

Just imagine what happens during a summer thunderstorm: rain falls intensely on the heads of unfortunate passersby who had forgotten their umbrellas at home, while the sky is ripped open by bright flashes of lightning, and powerful thunder can be heard in the distance. How scary! Now, fortunately, the storm has passed, it is no longer raining, and among the clouds, the sun is peeping out again. However, the air is still laden with tiny water droplets that make the air very humid. What can we observe in the sky?

Try to create your own rainbow!

One member of each group is responsible for collecting the findings with observations and drawings.

2—Can rainbows be made in the classroom? (inside group work)

Let's break down light: the seven colors of the spectrum.

With the materials you have available on the table, experiment freely! Try to reproduce the rainbow you saw outside, even inside the room. What happens if you expose objects to light?

Materials needed: prism, CDs, chandelier diamonds, rulers, mirrors, water, pens, white paper, sunlight.

[Any further instructions, if needed].

-Position the prism so that it is hit by sunlight;

-Rotate the prism to visualize the spectrum of colors on the desired surface (possibly helping with the white paper to better observe the colors in the spectrum)

3—What are the ingredients for making a rainbow? The cocktail of light

Figure out whether to amalgamate the material provided for this activity with that proposed for the previous activity to have the children experiment with it freely and directly.

Who hasn't happened at least once in their life to have a palette of colored tempera and enjoy mixing them with brushes and playing with colors? But have you ever tried doing it with lights? Play with the materials you have on hand, imagining that you are barmen and barmaids intent on making light cocktails! What happens? What do you observe?

Materials needed: flashlights (3), colored transparent plastic sheets (red, green, blue/blue), rubber bands, scissors;

Place: a dark room with a white vertical surface.

[Any further instructions, if needed:]

-Cut a small piece from each plastic sheet and secure it with a rubber band in front of each flashlight;

-Within the dark room, keep each flashlight lit and directed toward different points on the white wall;

-Move the light of the flashlights so that they converge and observe what happens by mixing the colors of the lights;

-Play with the shadows of objects or your hands.

4—To be left to them as a gift of the experience, an instruction kit to build Newton's disk on their own: the reverse experiment: we get white!

Newton's disk is named after its inventor, Isaac Newton, who conducted experiments on the refraction of light between 1671 and 1672. Newton passed a beam of light through a crystal prism, and the beam broke down into the seven colors of the solar spectrum, what we know as the colors of the rainbow. The English physicist then proved that the light we see as white is actually composed of the seven colors of the solar spectrum: red, orange, yellow, green, blue, violet, and indigo. In fact, the rainbow phenomenon is based on the same principle: sunlight passes through water droplets that remain suspended in the air after a thunderstorm and breaks down into the seven colors of the spectrum.

Light is a form of energy generated by a light source (sun, lightbulb, or fire). It is transmitted in waves of different lengths in a straight line. When these waves hit an object, some rays are absorbed by the object; others bounce back and reach our eyes, which perceive colors. Therefore, the color we see is that which is repelled by the object: the lemon is yellow because it absorbs all waves except one, so it absorbs all colors except yellow, which is reflected.

What about black and white? The object that reflects all light waves will appear white to us, like snow. White is the sum of all colors. In contrast, the object that absorbs all colors without returning light waves to our eyes will be black, like a blackboard.

With the experiment conducted by Newton, we discovered that white light, upon entering a prism, separates into its seven colors. Will the reverse also be true? If we try to bring all seven colors together, will we get white? To mix the colors, the scientist devised a colored disc, spinning it quickly mixes the light reflected from the different colors on the disc, sending back to our eyes a light that appears white to us.

Materials needed: white cardboard or cardboard, a sheet of white paper, a compass, a protractor and ruler, a pencil, crayons, scissors and glue, and string.

[Any further instructions, if needed].

5—Deepening: colors in relation.

Interactive activity entitled: "Colors in Relation", regarding both works of art that study colors and physical objects, such as glass gems from the Roman period, analyzed by the Applied Physics in Cultural Heritage lab at the Aquileia Museum. Works from Josef Albers' "Interaction of Color" are shown to the children, inviting them to identify the colors shown and their possible equality with other areas of the work, then reveal the resolution through animations and stratagems of the artist. Also shown are some works regarding the "Bezold Effect", where the relationship of colors is more about brightness instead of hue, as shown in previous works. The second phase, on the other hand, concerns the analysis of the colors of the glass gem here studied through photographs acquired during the last measurement campaign that took place in early 2024. It will be shown, through illustrations and animations, how the colors that appear are not the real ones but depend on the relationship with other hues, even in the case of matter and not only in abstract works of art, also introducing the concept of transparency.

6—Evaluation/restitution activity

Through Post-It™
What did you learn today?
What did you enjoy the most?
What did you like least?
What would you have liked to learn more about?

Appendix B

Documentation of the learning path

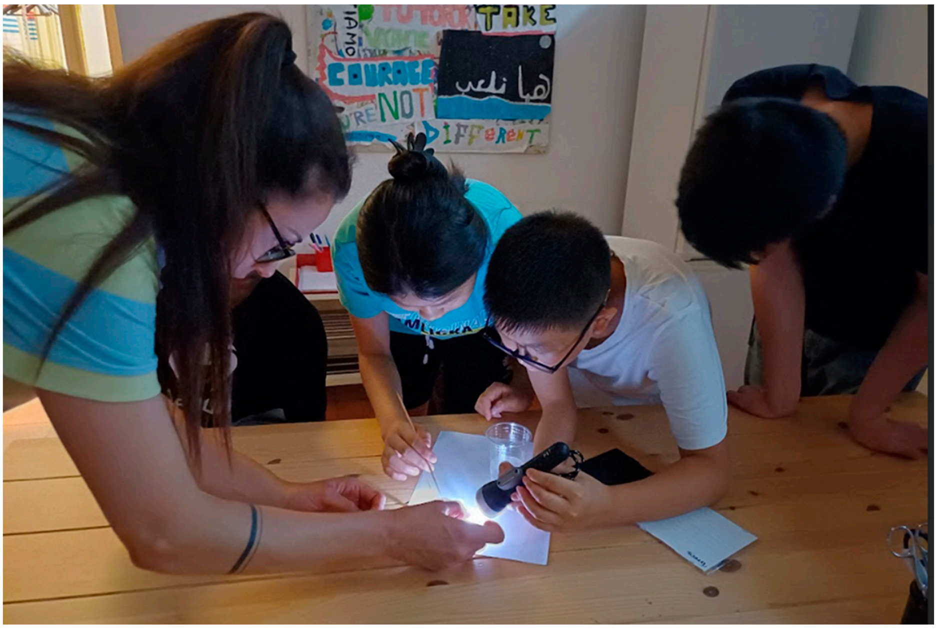

Figure A1. Detail of the laboratory experiments in working groups: set-up and experimentation.

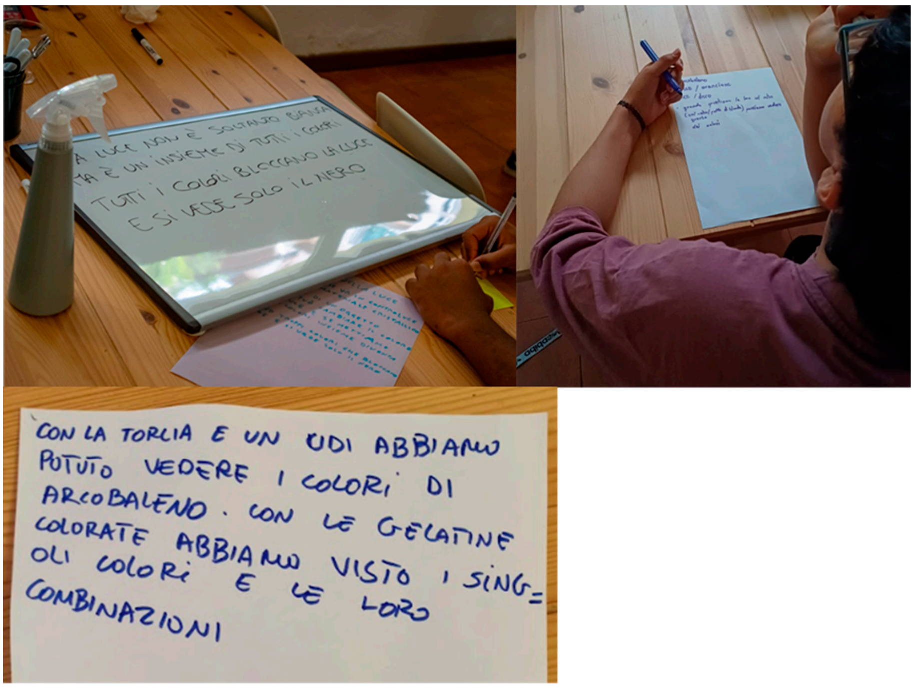

Figure A2. Moments of reflection (English translation: (1, top left) light is not white, but is the sum of all colors. All colors (the colored plastic foils) block the light, and only black is visible. (2. Bottom left) With the torchlight and a compact disc, we saw the rainbow. With the plastic colored foil, we saw single colors and their combinations).

Figure A3. Two pictures showing the deepening of the experimentation (in intergroup), to systemize, and to acquire the correct scientific literacy, with the example of colors in glass gems (also the one analyzed in this paper) "Anche nei materiali" (English translation: "Within materials too").

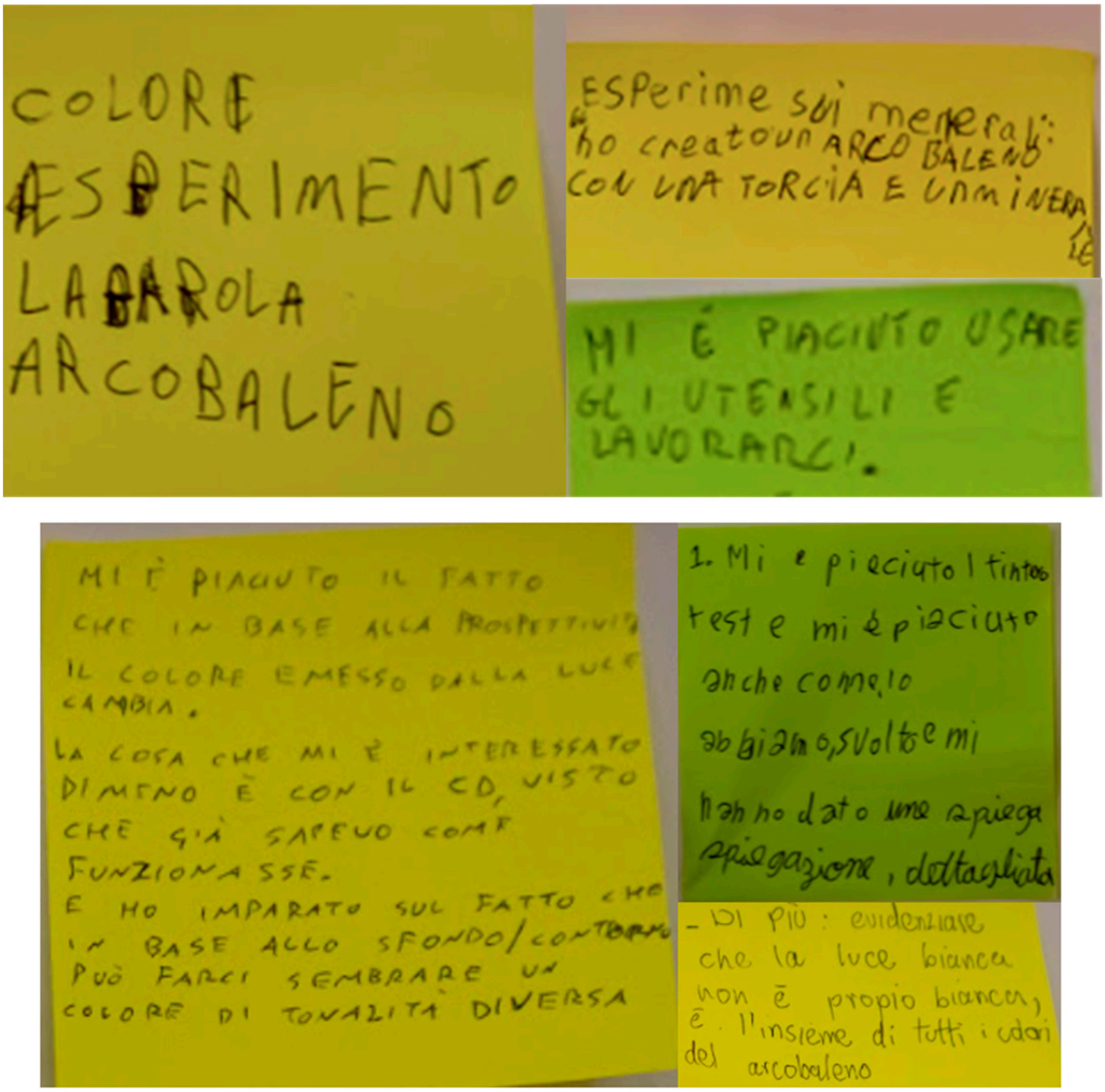

Figure A4. Some of the notes of girls and boys on the learning path experience. Italian text and the English translation (available in Section 3.2 of the manuscript) are reported below for the reader's convenience.

"Colori, esperimento, la parola arcobaleno" ["Color, experiment, the word rainbow"];

Esperimenti sui minerali, ho creato un arcobaleno con una torcia e un minerale" ["Experiments with minerals. I have created a rainbow with a flashlight and a mineral."]

Mi è piaciuto usare gli utensili e lavorarci" ["I enjoyed using the tools and working with them."]

"Mi è piaciuto il fatto che in base alla prospettiva, il colore emesso dalla luce cambia. La cosa che mi è interessata di meno è con il CD, visto che già sapevo come funzionasse. E ho imparato il fatto che in base allo sfondo/contorno può farci sembrare il colore di tonalità diverse". ["I enjoyed the fact that depending on the perspective, the color emitted by the light changes. The thing that interested me the least was the activity with the CD, as I already knew how it worked. I learned that depending on the background or outline, it can make a color appear to be a different shade."]

"Mi è piaciuto tutto il test e mi è piaciuto come lo abbiamo svolto e mi hanno dato una spiegazione dettagliata". ["I enjoyed the whole test and I also liked how we did it and the fact that they gave me a detailed explanation."]

"[mi è piaciuto] di più: evidenziare che la luce bianca non è proprio bianca, è l'insieme di tutti I colori dell'arcobaleno". ["What I liked the most: pointing out that the white light isn't exactly white, but it's the combination of all colors of the rainbow."]

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