heritage

Article

Once upon a Glass–Cycles, Recycles and Reuses of a Never-Ending Material

Tania Chinni [1,*], Alberta Silvestri [2], Sara Fiorentino [1] and Mariangela Vandini [1]

[1] Department of Cultural Heritage, University of Bologna, Via Degli Ariani 1, 48121 Ravenna, Italy
[2] Department of Geosciences, University of Padua, Via G. Gradenigo 6, 35131 Padua, Italy
* Correspondence: tania.chinni2@unibo.it

Abstract: Glass can be considered a locus of meaning, a material which has been the repository of traditional knowledge and technological expertise for at least three millennia. The history of glass speaks of know-how, technological transitions, and contaminations of recipes for its manufacture, which have changed across the world over the centuries. As the amount of recovered glass from archaeological contexts is much lower compared to ceramic and metal finds, research has often considered glass as a rare material. Furthermore, glass production, in ancient times as in the present day, requires the use of selected raw materials and noticeable amounts of fuel, making reuse and recycling practices necessary to foster sustainability, from both an economical and an environmental perspective. Latin authors, such as Juvenal and Martial, reported buyers of broken glass in Imperial Rome, presumably destined for recycling. Archaeometry has also provided data that allow, today, to clarify different aspects related to production cycles, uses and reuses of a material that, starting from the Roman age, became as common as modern plastics. From beakers and goblets reused with different purposes to mosaic tesserae detached for making new mosaics or to be refused and employed as "pigments" for colouring glass, this paper aims to provide an overview of reuse and recycling practices of ancient glass through a discussion of selected case studies from Roman to Middle Ages, showing how the cycle of this material can be framed as an actual example of sustainable circular economy in the past.

Keywords: glass recycling and reuse; ancient glass; archaeological studies; archaeometry

Citation: Chinni, T.; Silvestri, A.; Fiorentino, S.; Vandini, M. Once upon a Glass–Cycles, Recycles and Reuses of a Never-Ending Material. *Heritage* **2023**, *6*, 662–671. https://doi.org/10.3390/heritage6010035

Academic Editors: Chiara Coletti, Luigi Germinario, Claudio Mazzoli, Rebecca Piovesan and Elena Tesser

Received: 28 November 2022
Revised: 11 January 2023
Accepted: 13 January 2023
Published: 14 January 2023

1. Introduction

Following decades of public awareness and information campaigns, glass is now considered a highly reusable and recyclable material: it does not emit potentially harmful substances to humans and the environment, it does not absorb odours and it does not alter the flavour of its contents. But when did it all start? The sustainability of glass dates back a long time before the birth of the ecological awareness that today guides our decisions in terms of recycling and reuse. The reasons behind these practices have mainly been related to practical issues, linked to the immediate availability and greater cost-effectiveness of the material to be re-fused. The process of recycling, however, can have been impacted by a variety of economic and/or social factors in the past. Because modern recycling is largely based on economic concepts of value, global trade and energy expenditure, these concepts are frequently applied incorrectly to the past.

Despite the recent increase in papers dealing with recycling in the past [1–5], there is little discussion of the motivating factors for and the implications of recycling [6]. As Sainsbury and colleagues pointed out, the recycling process should be viewed more appropriately as a contribution of meaning to objects and materials, involving four important parameters in the analysis: time, form, function and property [7]. With its modern baggage, the word "recycling" frequently causes misunderstandings in the ancient interpretation, as recycling is quite often conceived as a task related solely to economic and environmental

concerns. Given these considerations, it may be more appropriate to refer to "mutability" when talking about recycling in the past, a concept which has recently been introduced by Sainsbury and colleagues to describe "a more useful umbrella term for a wide range of activities involving changes to both form and substance" [7]. In line with the definitions proposed by Sainsbury and co-workers, this paper will use the term "recycling" when the original object has been completely remade through a melting step, and none of the original form remains. The term "reuse" will be employed to highlight a change in the purpose or cultural significance of the object.

The suitability of glass for recycling was widely exploited in the past, and research has been conducted to attest to the various ways in which recycling can be detected in the archaeological record, with a focus on the first millennium AD [2]. It is widely recognised that the invention of blowing, between the 1st century BC and the 1st century AD, marked an epochal change in glass manufacturing and use. Glass changed from an aristocratic material used to make pieces not intended for widespread consumption into a material similar to plastics today, as costs and manufacturing time were reduced and glass objects became commonplace items [8]. Following the introduction of the glass-blowing technique, a decrease in the price of glass on the market occurred due to the faster and easier production of vessels [8–11]. Glass was mass-produced at a small number of specialised glassmaking sites, which supplied numerous secondary workshops where raw and broken glass was re-melted and shaped. The act of recycling was an integral part of the *chaîne opératoire* inside these workshops, to be carefully considered to fully understand the range of glass forms, colours and compositions found in archaeological records [2,5,12–16]. The re-introduction of glass waste and cullet into the production cycle is due to the material's unique properties, which allow it to remelt at lower temperatures than those required for the production of glass from raw materials. Therefore, even small kilns could be used to obtain new material to be reworked with significant time and cost savings compared to primary production. Furthermore, the recovery of objects reused with functions different from those for which they were created, as well as the ancient literary references to the practices of glass repair, demonstrate that the "life" of the product did not end when it was damaged or broken, but it continued afterwards as well. The concept is not extraneous to the archaeological field, where the notion of the biography of objects was discussed for the first time by Kopytoff [17]. Kopytoff suggested that, when studying objects, it is important to consider not only the original purpose for which an artefact was made, but also the various ways that it may have been used throughout its lifetime, and the various meanings that may have been attached to it culturally during this period. Further development of this idea is provided by [18], reflecting upon the need to apply the concept of use-life to objects from our material culture, for a more comprehensive understanding of the relationship between things and men. This concept has so far been studied especially in the field of ancient metallurgy [19,20].

This paper, based on a contribution presented at the 2022—AIAr (*Associazione Italiana di Archeometria*) Thematic Conference "Sustainability in Cultural Heritage" (29th June–1st July 2022, Padua, Italy), aims to highlight how the mutability of objects from the past can be discussed as a sustainability-related issue in the context of ancient productions, with a focus on glass between the Roman and Middle Ages.

2. Materials and Methods

No previously unpublished materials were studied or analysed for this paper. The article revisits data from glass assemblages that have already been studied and published, to frame them in the ongoing discussion about the sustainability of ancient productions. Therefore, all details on the selected materials for each case study covered in the article as well as for analytical protocol and the instrumental conditions can be found in the reference papers mentioned in the text.

3. Results and Discussion

Archaeological evidence and archaeometry have shown that, in the Roman age, the majority of raw glass was produced along the Levantine coast and in Northern Egypt [5,21–24]. As the cost of transport was significant, recycling and the secondary production of glass into smaller, localised workshops—where raw glass was eventually mixed with colourants/decolourants/opacifiers and then shaped into objects—was economically convenient. Broken glass had its own economic value in ancient times, as attested by written sources. Allusions to the trading of broken glass for sulphur to be used as an adhesive can be found, for instance, in Martial, Statius and Juvenal [25–27].

Archaeological evidence also supports the trade of raw glass in cullets. One of the most well-known cases is the merchant ship *Iulia Felix*, which went down off the coast of Grado in the first half of the third century AD: a wooden barrel was found in the ship's hold and contained about 140 kg of glass fragments from plates, cups and bottles [28,29]. The *Iulia Felix*'s cargo shows a peculiarity: glass is mostly colourless and naturally coloured, suggesting that even the choice of broken glass was very accurate and, presumably, intended to minimise issues with unwanted colouring during the re-fusion of the glass. Another intriguing fact is revealed by the archaeometric data collected on a variety of glass finds from the cargo [13,30]. Plots in Figure 1 highlight a clear distinction between the chemical compositions of the antimony-decoloured glass and the naturally coloured glass; antimony can be used to create colourless glass because it was a decolouring agent used exclusively in Roman times, so its concentration can be used to create a "recycling index" for glass [30]. Archaeometric data demonstrated that the *Iulia Felix*'s cargo contained recycled glass which was made with 54% antimony-decoloured glass, indicating that recycling has likely been practised for some time. Glass cullets to be recycled have also been recovered in a number of excavations, both in urban contexts and near military camps [2,3,27,31].

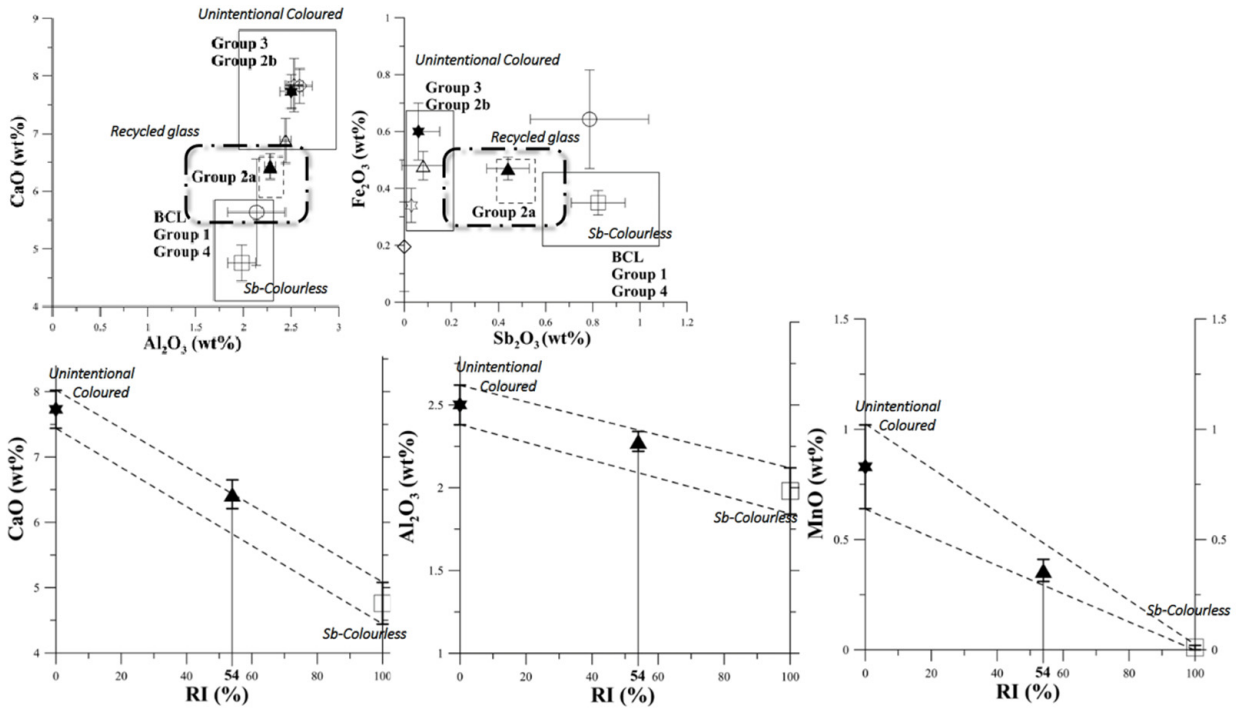

Figure 1. Plots showing the difference between antimony-decoloured and naturally coloured glass in *Iulia Felix* cargo (following [30], modified). Group IC1b from *Iulia Felix* (full triangle) encompasses recycled glass, made with 54% antimony-decoloured glass; the group matches Group 2a identified in [12] and interpreted as partially recycled glass. In fact, the recycling index (RI) reaches 62% of glass antimony-decoloured ([30], modified). Note that the other symbols, reported in the plots, refer to compositional groups identified in the *Iulia Felix* glass assemblage. For more details on them, please refer to [30].

Along with recycling, the reuse of glass objects is attested in Roman times. Referring to the definition given above, reuse occurs when the object loses its initial purpose. From this perspective, cases such as that of the jug recovered in Usk (Wales), whose damaged rim was cut and smoothed without affecting its original usage, is not to be intended as an example of reuse [32]. Differently, cases such as the bottoms of tableware cups and bowls carefully cut out, like attested in the necropolis of Zadar, Croatia, and reused as lids for other containers [33,34], are examples of reuses.

Following the widespread use of glass in the Roman world, the current state of research indicates that it is likely that glass experienced its greater mutability between the late antique and the medieval periods, in terms of both recycling and reuse with the loss of the original function of the objects. The case of Nogara (province of Verona, North-eastern Italy), for instance, has provided valuable insights into the complexities of the glass industry between the 10th and 11th centuries AD [35]. Archaeometric data provided evidence for the occurrence of glass recycling; samples with intermediate chemical compositions between natron and soda plant ash glass were identified, indicating a proclivity for recycling earlier glass, and suggesting a gradual change from natron-based to soda ash-based production technology (Figure 2).

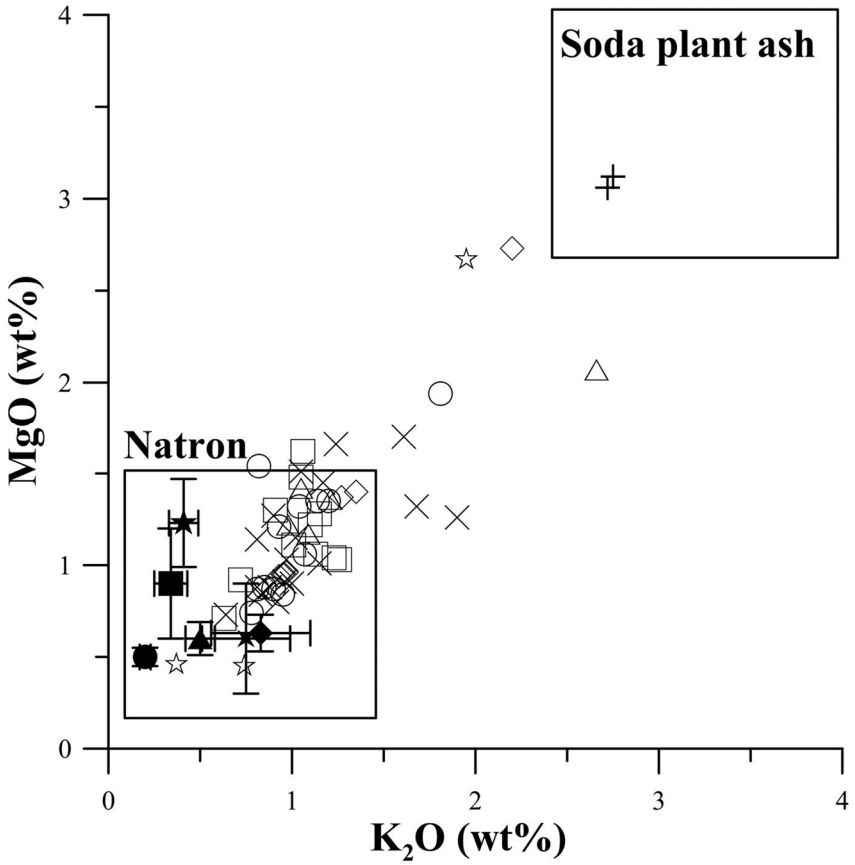

Figure 2. Samples from Nogara with an intermediate natron soda ash as flux, demonstrating the recycling of glass (following [35], modified). The samples from Nogara are subdivided by type: biconical cup (◇), goblet disc foot (△) beaker edge with decoration (□), beaker edge without decoration (○), beaker side (✕), waste glass and mosaic tesserae (☆), bottle ring foot (+). Mean chemical compositions and standard deviations of main compositional natron groups, identified in literature, also shown: "Roman" glass (✶); Levantine I (◆), Levantine II (▲), Egypt I (■), Egypt II (●) and HIMT (✸) (data from [22,23,36–40]). Squared areas: compositional areas of glasses of compositional Group 2.2 of [23]; Carolingian glass [41]; 8th–12th-century natron glass from various Italian sites [42–47] and those obtained with soda plant ash from Grado, Vicenza [48] and Venice [49].

Another type of recycling was also attested in Nogara: SEM and LA-ICP-MS analyses demonstrated that blue and *reticello* decorations found on drinking beakers were obtained by melting earlier mosaic glass tesserae, as shown by the amounts of Co, Cu, Sn, Sb and Pb and the presence of calcium antimonate crystals in the matrix (Figure 3).

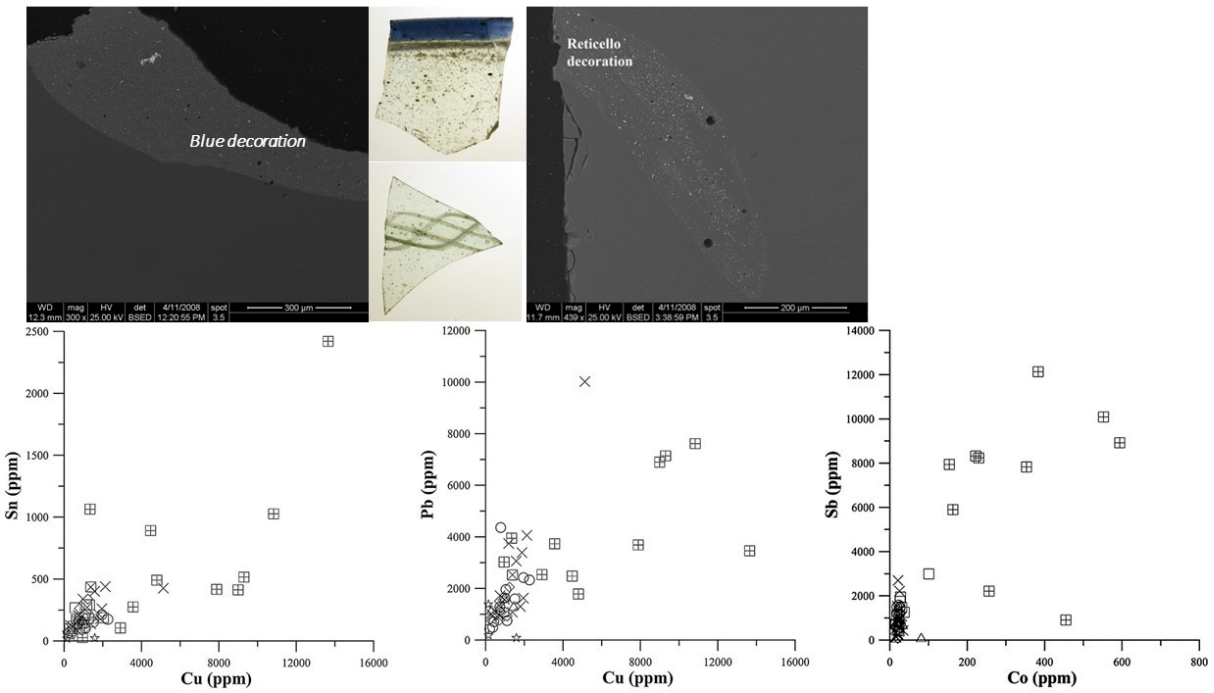

Figure 3. The SEM-BSE images clearly show the different micro-textures of the decorations in medieval samples from Nogara, with respect to the other portions of finds. Contents of Sn, Pb, Sb, Cu, and Co in blue and *reticello* decoration showing the possible reuse of mosaic tesserae as colourant: biconical cup (◇), goblet disc foot (△), body of beaker with decoration (□), decorations of beaker edge (⊞), beaker edge without decoration (○) and beaker side (✕). Note the generally higher content of Cu, Sn, Sb, and Pb and the presence of Co in decorations (following [35], modified). Photos of two beaker walls with blue rim (in the top) and *reticello* decoration (in the bottom) also shown.

Mosaic glass tesserae are a fascinating case study in the recycling and reuse of glass in antiquity. The use of small cubes made of coloured opaque glass is attested since the late Hellenistic period, with specific reference to 2nd–1st century BC multi-coloured bowls to obtain a distinctive three-dimensional decorative pattern [50]. However, coloured and opaque glass reaches its maximum expression in the making of mosaics for architectural decorations. Mosaic tesserae are made of a vitreous matrix within which crystalline phases act as opacifiers and pigments are dispersed [51]. Several cases documented in the literature [52–60] demonstrate how this particular category of glass artefacts has experimented with a variety of recycling and, more importantly, reuse practices. The first and most obvious instance of the recycling of mosaic tesserae is their removal from structures devoid of their original ornamentation for the purpose of reusing them in new apparatuses. There is archaeological and archaeometric evidence in favour of this widespread practice. The study of the mosaics located in the Sacellum of Saint Prosdocimus (basilica of *S. Giustina*, Padua, Italy) is an example [54–56]. The decorative mosaic's construction site dates back to the 6th century AD; however, an analysis of about 200 tesserae revealed that not all of them were made in the same historical period. Some tesserae, in fact, have a vitreous matrix and opacifying agents that are typical of the Roman era and have simply been reused in their original state. Other tesserae, on the other hand, have a late-antique vitreous matrix but Roman-era opacifiers and are, thus, recycled. Others are "new" tesserae, made ad hoc for the Sacellum, a very complex situation that nevertheless brings out a sort of "sustainable"

use of glass. This practice of reusing glass mosaic tesserae has been documented in other geographical areas and historical periods as well [57,61,62]. Recent studies attest to the reuse of tesserae "taken" from pre-existing monuments in the making of the mosaic decorations of the monuments of Syria's first Islamic Caliphate, a practice described by textual sources and partly confirmed by archaeometric analyses. Compositional analyses revealed the presence of both Levantine and Egyptian compositional categories: Apollonia-type and Foy-2 base glass indicate a continuity with the production of mosaic glass tesserae in the late antique Levant; Egypt I glass clearly distinguishes Umayyad tesserae, providing tangible evidence of other legacies [63]. A recent study on a prominent assemblage of glass tesserae from the Great Mosque of Damascus has further demonstrated Egyptian glass's dominance among the coloured tesserae, with other base glass types in circulation prior to the 8th century [64]. It is difficult to say whether these tesserae were simply reused or if the glass was recycled and transformed into tesserae during construction. Parallels can be drawn with 8th-century glass vessels, where there is a significant decline in Apollonia-type Levantine I, while Foy 2.1 is missing; it appears more likely that the tesserae represent reused material collected from older mosaics or some storage facilities [63]. Al-Maqdisī, al-Ya'qūbī, ibn Zabāla, al-Dinawārī and ibn Rusta report mosaic cubes sent from the Byzantine emperor to Umayyad caliphs, and al-Tabarī also states that the emperor ordered searches for these cubes in ruined cities [63,65]. It should also be noted that the rise of the Umayyad caliphate occurred during a period when the production of mosaics appears to have declined significantly in the Mediterranean basin: between the 7th and 8th centuries, when the number of new buildings adorned with mosaics dropped from more than 50 to 20 and then 9 exemplars [66]. It is possible that the decline in mosaic production resulted in a decrease in demand for tesserae, and thus the use of recovered materials from existing, abandoned monuments was encouraged. In San Vincenzo al Volturno (Isernia, Southern Italy), a case of recycling of opaque coloured tesserae is documented [14]. Combined archaeological and archaeometric studies have provided sound evidence of specific procedures related to colouring window glass. The Monastic Complex of San Vincenzo al Volturno is among the most representative cases. Built in the early 8th century on a late Roman villa, the monastery underwent significant expansion in the 9th century thanks to Abbot Joshua. It became one of the largest monastic complexes in Carolingian Europe, with the installation of temporary workshops for making construction and materials. On October 881, the monastery was sacked and fired by the Saracens. Archaeological surveys underpinned evidence of dedicated glass workshops in the monastic complex: fragments of crucibles with glass adhering to the internal surface, processing waste and fragments of blow pipes have been unearthed. Moreover, a large amount of opaque coloured glass mosaic tiles and coloured and translucent window glass has been recovered. Data from archaeometric analyses demonstrated that glass tesserae from dismantled mosaics were recycled for making coloured window glass, according to the practice described by Theophilus Presbyter in *De Diversis Artibus*. In fact, the text makes specific mention of using mosaic tesserae as pigments for colouring windows. However, it remains unclear, at the current state of knowledge, how widespread this practice was. Unanswered questions regarding whether this practice implied specific cultural meanings, or was exclusively related to economic reasons and the unavailability of materials due to the inflection of commercial traffic that affected the Mediterranean basin between the 8th and 9th centuries [67]. The recycling of mosaic tesserae to be used as a pigment has recently been documented in the production of Viking glass beads in Ribe, Denmark. Here, evidence for the existence of a workshop established in the c. 700 AD has been underpinned, manufacturing monochrome and polychrome beads related to the previous tradition in Western Europe, but developing distinct designs [68]. After the medieval period, coloured glass continued to be used as a pigment. This is the case, for instance, with the smalt found in European paintings as early as the 15th century and used until about the 19th century [69]. Smalt is a finely ground potash-based glass containing cobalt as a colouring agent; conchoidal fracture fragments of translucent blue colour inside the pictorial layer allow us to identify this pigment from

an archeometric perspective, as the example provided in Figure 4. Here, the detection of elements such as silicon, potassium and cobalt has been highlighted by spot measurements analyses performed using SEM-EDS, allowing these inclusions to be classified as smalt [69].

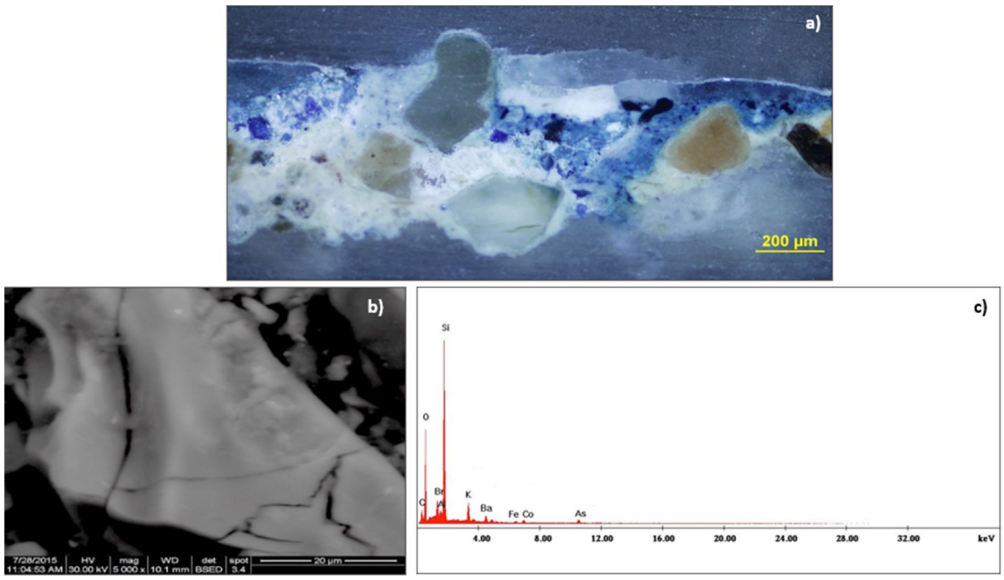

Figure 4. Stratigraphic section obtained from a micro-sample of a 17th-century wall painting. Observation under (**a**) optical microscope, magnification 100X, shows the presence of micrometric translucent blue fragment in the pictorial layer; (**b**) observation under SEM, BSE and (**c**) EDS spot measurements allowed for the detection of elements related to a cobalt-doped glass matrix, identifying the pigment as smalt.

In the making of pictorial layers, colourless powdered glass was extensively used all over Europe during the 15th and 16th centuries [70]. The technological intention behind the addition of glass to paint layers seems to be linked to two key purposes: to facilitate the grinding of specific pigments—such as orpiment—and to accelerate the drying of oil paints, even if glass was not capable of performing this function. It is interesting to note that artists used whatever colourless glass was locally available, as preliminary compositional studies confirm the general geographical distribution found in studies of vessel and window glass. In Italian paintings, soda ash glass is almost exclusively used, whereas in German and Dutch paintings, soda ash glass, wood ash and wood ash–lime glass are present, similar to what has been discovered in archaeological sites [71].

4. Conclusions

The discussion of selected case studies from different geographical areas and historical periods provides further evidence of how recycling and reuse of glass were well-known and established practices in the ancient world.

The analysis of the case studies selected for this paper allows us to reflect on the need to start re-considering recycling in the past under new perspectives, going beyond technological purposes and the economics of material production and processing. The reuse of objects has been the subject of sporadic and not systematic investigations in the field of ancient glass studies, and more attention should be given to a better understanding of the underlying reasons. On the one hand, the reuse of objects or parts of them with a new function may find a logical explanation in the necessity to meet a practical need—as, for example, the bottoms of containers adapted to lids—the reuse and recycling of mosaic tesserae is, on the other hand, considerably more problematic in terms of interpretation. To the current state of knowledge, we do not know how widespread this practice was geographically or chronologically, or whether it had special ideological and/or symbolic meanings.

This paper intends to pave the way for new, more in-depth discussions on the just-introduced notion of "mutability", challenging not only the utilitarian but also the symbolic

justifications for the recycling and reuse of glass products in ancient times for a better understanding of the societies that used them.

Author Contributions: Conceptualisation: S.F., A.S. and T.C.; data curation: A.S. and S.F.; methodology: A.S., S.F., T.C. and M.V.; supervision: M.V. and A.S.; validation: A.S. and M.V.; writing—original draft: S.F. and T.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data here discussed can be found in the referenced papers mentioned in the text.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Rehren, T.; Freestone, I.C. Ancient Glass: From Kaleidoscope to Crystal Ball. *J. Archaeol. Sci.* **2015**, *56*, 233–241. [CrossRef]
2. Paynter, S.; Jackson, C.M. Re-Used Roman Rubbish: A Thousand Years of Recycling Glass. *Post-Class. Archaeol.* **2016**, *6*, 31–52.
3. Sainsbury, V.A. When Things Stopped Travelling: Recycling and the Glass Industry in Britain from First to Fifth Century CE. In *Things That Travelled*; UCL Press: London, UK, 2018; pp. 324–345, ISBN 9781787351172.
4. Duckworth, C.N.; Wilson, A. (Eds.) *Recycling and Reuse in the Roman Economy*; Oxford University Press: Oxford, UK, 2020.
5. Freestone, I.C. The Recycling and Reuse of Roman Glass: Analytical Approaches. *J. Glass Stud.* **2015**, *57*, 29–40.
6. Sainsbury, V.A.; Liu, R. 'Nothing New under the Sun': Rethinking Recycling in the Past–Editorial. *Archaeometry* **2022**, *64*, 1–7. [CrossRef] [PubMed]
7. Sainsbury, V.A.; Bray, P.; Gosden, C.; Pollard, A.M. Mutable Objects, Places and Chronologies. *Antiquity* **2021**, *95*, 215–227. [CrossRef]
8. Stern, M. Roman Glassblowing in a Cultural Context. *Am. J. Archaeol.* **1999**, *103*, 441–484. [CrossRef]
9. Whitehouse, D. Glass in the Price Edict of Diocletian. *J. Glass Stud.* **2004**, *26*, 189–191.
10. Barag, D. Alexandrian and Judaean Glass in the Price Edict of Diocletian. *J. Glass Stud.* **2005**, *47*, 184–186.
11. Stern, E.M. Ancient Glass in a Philological Context. *Mnemosyne* **2007**, *60*, 341–406. [CrossRef]
12. Jackson, C.M. Making Colourless Glass in the Roman Period. *Archaeometry* **2005**, *47*, 763–780. [CrossRef]
13. Silvestri, A.; Molin, G.; Salviulo, G. The Colourless Glass of *Iulia Felix*. *J. Archaeol. Sci.* **2008**, *35*, 331–341. [CrossRef]
14. Schibille, N.; Freestone, I.C. Composition, Production and Procurement of Glass at San Vincenzo Al Volturno: An Early Medieval Monastic Complex in Southern Italy. *PLoS ONE* **2013**, *8*, e76479. [CrossRef]
15. Wardle, A.; Freestone, I.C.; McKenzie, M.; Shepherd, J. *Glass Working on the Margins of Roman London. Excavations at 35 Basinghall Street, City o Ìf London, 2005*; MOLA Monog; Museum of London Archeology: London, UK, 2015.
16. Freestone, I.C.; Gutjahr, M.; Kunicki-Goldfinger, J.; McDonald, I.; Pike, A. Composition, Technology and Origin of the Glass from the Workshop at 35 Basinghall Street. In *Glass Working on the Margins of Roman London*; Wardle, A., Freestone, I.C., McKenzie, M., Sheperd, J., Eds.; Museum of London Archeology: London, UK, 2015; pp. 75–90.
17. Kopytoff, I. The Cultural Biography of Things: Commoditization as Process. In *The Social Life of Things: Commodities in Cultural Perspective*; Appadurai, A., Ed.; Cambridge University Press: Cambridge, UK, 1986; pp. 64–91.
18. Gosden, C.; Marshall, Y. The Cultural Biography of Objects. *World Archaeol.* **1999**, *31*, 169–178. [CrossRef]
19. Jennings, B. Repair, Recycle or Re-use? Creating Mnemonic Devices Through the Modification of Object Biographies During the Late Bronze Age in Switzerland. *Camb. Archaeol. J.* **2014**, *24*, 163–176. [CrossRef]
20. Swift, E. Object Biography, Re-Use and Recycling in the Late to Post-Roman Transition Period and Beyond: Rings Made from Romano-British Bracelets. *Britannia* **2012**, *43*, 167–215. [CrossRef]
21. Degryse, P. *Glass Making in the Greco-Roman World: Results of the ARCHGLASS Project*; Leuven Unversity Press: Leuven, Belgium, 2014. ISBN 9789462700079.
22. Foy, D.; Picon, M.; Vichy, M.; Thirion-Merle, V. Caractérisation Des Verres de La Fin de l'Antiquité En Méditerranée Occidentale: L'émergence de Nouveaux Courants Commerciaux. In Proceedings of the Échanges et Commerce du Verre dans le Monde Antique, Actes du Colloque de l'Association Française pour l'Archéologie du Verre, Aix-en-Provence et Marseille, France, 7–9 June 2001; Foy, D., Ed.; Mergoil: Aix-en-Provence, France, 2003; pp. 41–86.
23. Freestone, I.C.; Gorin-Rosen, Y.; Hughes, M.J. Primary Glass from Israel and the Production of Glass in Late Antiquity and the Early Islamic Period. In *La Route du Verre. Ateliers Primaires et Secondaires du Second Millénaire av. J.-C. au Moyen Âge Actes du colloque organisé en 1989 par l'Association Française pour l'Archéologie du Verre (October, Lyon)*; Nenna, M.-D., Ed.; Maison de l'Orient Méditerranéen Jean Pouilloux: Lyon, France, 2000; pp. 65–83.
24. Gorin-Rosen, Y. The Ancient Glass Industry in Israel. Summary of the Finds and New Discoveries. In *La Route du Verre. Ateliers Primaires et Secondaires du Second Millénaire av. J.-C. au Moyen Âge Actes du colloque organisé en 1989 par l'Association Française pour l'Archéologie du Verre (October, Lyon)*; Nenna, M.-D., Ed.; Maison de l'Orient Méditerranéen Jean Pouilloux: Lyon, France, 2000; pp. 49–63.
25. Whitehouse, D. Glass in the Epigrams of Martial. *J. Glass Stud.* **1999**, *41*, 73–81.
26. Harrison, G.W.M. Martial 1. 41: Sulphur and Glass. *Class. Q.* **1987**, *37*, 203–207.

27. Keller, D. Social and Economic Aspects of Glass Recycling. In Proceedings of the TRAC 2004: Proceedings of the Fourteenth Annual Theoretical Roman Archaeology Conference, Durham, UK, 26–27 March 2004; Bruhn, J., Croxford, B., Grigoropoulos, D., Eds.; Oxbow Book: Oxford, UK, 2005; pp. 65–78.
28. Aurimma, R. (Ed.) *Nel Mare Dell'intimità: L'archeologia Subacquea Racconta l'Adriatico: Trieste, ex Pescheria—Salone Degli Incanti, 17 Dicembre 2017—1 Maggio 2018*; Gangemi: Roma, Italy, 2012. ISBN 9788849285604.
29. Babbini, L. *Operazione Iulia Felix: Lo Scavo Subacqueo Della Nave Romana Rinvenuta Al Largo Di Grado*; Edizioni Della Laguna: Gorizia, Italy, 1994.
30. Silvestri, A. The Coloured Glass of *Iulia Felix*. *J. Archaeol. Sci.* **2008**, *35*, 1489–1501. [CrossRef]
31. Munro, B. Recycling, Demand for Materials, and Landownership at Villas in Italy and the Western Provinces in Late Antiquity. *J. Rom. Archaeol.* **2012**, *25*, 351–370. [CrossRef]
32. Price, J.; Cottam, S. *Romano-British Glass Vessels: A Handbook*; Council for British Archeology: York, UK, 1998.
33. Perović, Š. Novo Spoznaje o Restauraciji i Recikliranju Stakla u Antici. In Proceedings of the 8. Susreti Restauratora i Preparatora HMD-a, Proceedings of the Conference, Sisak, Croatia, 5–6 May 2016; pp. 60–63.
34. Eterovic Boziac, A.; Stefanac, B. *Ancient Glass. Catalogue of the Permanent Exhibition of the Museum of Ancient Glass of Zadar*; Museum of Ancient Glass: Zadar, Croatia, 2021.
35. Silvestri, A.; Marcante, A. The Glass of Nogara (Verona): A "Window" on Production Technology of Mid-Medieval Times in Northern Italy. *J. Archaeol. Sci.* **2011**, *38*, 2509–2522. [CrossRef]
36. Brill, R.H. Scientific Investigations of the Jalame Glass and Related Finds. In *Excavations at Jalame, Site of a Glass Factory in Late Roman Palestine*; Wienberg, G.D., Ed.; University of Missouri Press: Columbia, MO, USA, 1988; pp. 257–293.
37. Freestone, I.C. Chemical Analysis of 'Raw' Glass Fragments. In *Excavations Ati Carthage. The British Mission*; Hurst, H.R., Ed.; Oxford University Press: Oxford, UK, 1994; Volume II, 1, p. 290.
38. Freestone, I.C.; Greenwood, R.; Gorin-Rosen, Y. Byzantine and Early Islamic Glassmaking in the Eastern Mediterranean: Production and Distribution of Primary Glass. In *Hyalos, Vitrum, Glass. History, Technology and Conservation of Glass and Vitreous Materials in the Hellenistic World, Proceedings of the 1st International Conference (Rhodes, Greece, 1-4 April 2001)*; Kordas, G., Ed.; Glasnet Publications: Athens, Greece, 2002; pp. 167–174.
39. Nenna, M.-D.; Picon, M.; Vichy, M. Ateliers Primaires et Secondaires En Egypte à l'époque Gréco-Romaine. In *La Route du Verre. Ateliers Primaires et Secondaires du Second Millénaire av. J.-C. au Moyen Âge Actes du colloque organisé en 1989 par l'Association Française pour l'Archéologie du Verre (October, Lyon)*; Nenna, M.-D., Ed.; Maison de l'Orient Méditerranéen Jean Pouilloux: Lyon, France, 2000; pp. 97–112.
40. Foster, H.E.; Jackson, C.M. The Composition of 'naturally Coloured' Late Roman Vessel Glass from Britain and the Implications for Models of Glass Production and Supply. *J. Archaeol. Sci.* **2009**, *36*, 189–204. [CrossRef]
41. Wedepohl, K.H. Chemical Composition of Medieval Glass from Excavations in West Germany. *Glas. Sci. Technol.* **1997**, *70*, 246–255.
42. Brill, R.H. *Chemical Analysis of Early Glasses*; The Corning Museum of Glass: Corning, NY, USA, 1999; Volume 2: Tables, ISBN 0-87290-143-2.
43. Bimson, M.; Freestone, I.C. An Analysis of Blue Glass from the Enamel. In *San Vincenzo al Volturno 3: The Finds from the 1980–86 Excavations*; Mitchell, J., Hansen, I.L., Eds.; Centro Italiano di Studi Sull'alto Medioevo: Spoleto, Italy, 2001; pp. 285–286.
44. Mirti, P.; Davit, P.; Gulmini, M.; Sagui, L. Glass Fragments from the Crypta Balbi in Rome: The Composition of Eighth-Century Fragments. *Archaeometry* **2001**, *43*, 491–502. [CrossRef]
45. Verità, M.; Renier, A.; Zecchin, S. Chemical Analyses of Ancient Glass Findings Excavated in the Venetian Lagoon. *J. Cult. Herit.* **2002**, *3*, 261–271. [CrossRef]
46. Uboldi, M.; Verità, M. Scientific Analyses of Glasses from Late Antique and Early Medieval Archeological Sites in Northern Italy. *J. Glass Stud.* **2003**, *45*, 115–137.
47. Freestone, I.C.; Dell'Acqua, F. Early Medieval Glass from Brescia, Cividale and Salerno, Italy: Composition and Affinities. In Proceedings of the Il Vetro Nell'alto Medioevo. Atti Delle VIII Giornate Nazionali di Studio, Spoleto, Italy, 20–21 April 2002; Dell'Acqua, F., Ed.; Editrice La Mandragora: Imola, Italy, 2005; pp. 65–75.
48. Silvestri, A.; Molin, G.; Salviulo, G. Roman and Medieval Glass from the Italian Area: Bulk Characterization and Relationships with Production Technologies. *Archaeometry* **2005**, *47*, 797–816. [CrossRef]
49. Verità, M.; Zecchin, S. La Tecnologia Vetraria Veneziana Del XV-XVI Secolo Attraverso Le Analisi Di Reperti in Vetro d'uso Comune. *Quad. Friulani Archeol.* **2009**, *XIX*, 237–248.
50. Tatton-Brown, V.A.; Gudenrath, W. (Eds.) *Glass 2. Catalogue of Greek and Roman Glass, Volume 2: Non-Blown and Early Blown Glass*; British Museum press: London, UK, 2002.
51. Vandini, M.; Fiorentino, S. From Crystals to Color: A Compendium of Multi-Analytical Data on Mineralogical Phases in Opaque Colored Glass Mosaic Tesserae. *Minerals* **2020**, *10*, 609. [CrossRef]
52. Fiorentino, S.; Chinni, T.; Vandini, M. Ravenna, its mosaics and the contribution of archeometry. A systematic reassessment on literature data related to glass tesserae and new considerations. *J. Cult. Herit.* **2020**, *46*, 335–349. [CrossRef]
53. Gallo, F.; Silvestri, A. Medieval Glass from Rocca Di Asolo (Northern Italy): An Archaeometric Study. *Archaeometry* **2012**, *54*, 1023–1039. [CrossRef]
54. Silvestri, A.; Tonietto, S.; Molin, G.; Guerriero, P. The Palaeo-Christian Glass Mosaic of St. Prosdocimus (Padova, Italy): Archaeometric Characterisation of Tesserae with Copper- or Tin-Based Opacifiers. *J. Archaeol. Sci.* **2014**, *42*, 51–67. [CrossRef]

55. Silvestri, A.; Tonietto, S.; Molin, G.; Guerriero, P. The Palaeo-Christian Glass Mosaic of St. Prosdocimus (Padova, Italy): Archaeometric Characterisation of Tesserae with Antimony- or Phosphorus-Based Opacifiers. *J. Archaeol. Sci.* **2012**, *39*, 2177–2190. [CrossRef]
56. Silvestri, A.; Tonietto, S.; Molin, G. The Palaeo-Christian Glass Mosaic of St. Prosdocimus (Padova, Italy): Archaeometric Characterisation of 'Gold' Tesserae. *J. Archaeol. Sci.* **2011**, *38*, 3402–3414. [CrossRef]
57. Silvestri, A.; Maltoni, S.; Serra, C.L. Searching for Insights on Production Technologies in the Late-Antique/Byzantine Period: Glass Tesserae from Tyana (Cappadocia, Turkey). *J. Archaeol. Sci. Rep.* **2022**, *42*, 103381. [CrossRef]
58. Schibille, N.; Neri, E.; Ebanista, C.; Ammar, M.R.; Bisconti, F. Something Old, Something New: The Late Antique Mosaics from the Catacomb of San Gennaro (Naples). *J. Archaeol. Sci. Rep.* **2018**, *20*, 411–422. [CrossRef]
59. James, L. *Mosaics in the Medieval World. From Late Antiquity to the Fifteenth Century*; Cambridge University Press: New York, NY, USA, 2017.
60. Schibille, N.; Lehuédé, P.; Biron, I.; Brunswic, L.; Blondeau, É.; Gratuze, B. Origins and Manufacture of the Glass Mosaic Tesserae from the Great Umayyad Mosque in Damascus. *J. Archaeol. Sci.* **2022**, *147*, 105675. [CrossRef]
61. Vandini, M.; Arletti, R.; Cirelli, E. Five Centuries of Mosaics Glass at Saint Severus (Classe, Ravenna). *Ocnus. Quad. Sc. Spec.* **2014**, *22*, 91–108.
62. Arletti, R.; Fiori, C.; Vandini, M. A Study of Glass Tesserae From Mosaics in the Monasteries of Daphni and Hosios Loukas (Greece). *Archaeometry* **2010**, *52*, 796–815. [CrossRef]
63. Fiorentino, S. A Tale of Two Legacies: Byzantine and Egyptian Influences in the Manufacture and Supply of Glass Tesserae under the Umayyad Caliphate (661–750 AD). *Heritage* **2021**, *4*, 2810–2834. [CrossRef]
64. Schibille, N. *Islamic Glass in the Making: Chronological and Geographical Dimensions*; Leuven University Press: Leuven, Belgium, 2022.
65. Fiorentino, S. *Fragile Connections, Persistent Methodology. A Tailor-Made Archaeometric Protocol to Investigate Technological and Cultural Issues in the Supply of Glass Tesserae under the Umayyad Caliphate*; University of Bologna: Bologna, Italy, 2019.
66. James, L.; Soproni, E.; Bjørnholt, B. Mosaics by Numbers. Some Preliminary Evidence from the Leverhulme Database. In *New Light on Old Glass: Recent Research on Byzantine Mosaics and Glass*; Entwistle, C., James, L., Eds.; The British Museum: London, UK, 2013; pp. 310–329.
67. Fiorentino, S.; Tronca, D. Heaven Is a Place on Earth. Un Progetto Sul Significato Del Vetro Dalla Storia Dell'oggetto Alla Storia Dell'immaginario. In Proceedings of the La multidisciplinarietà nella ricerca sul vetro. XX Giornate Nazionali di Studio sul Vetro, Ravenna, Italy, 18–19 May 2019; Uboldi, M., Lerma, S.G., Vandini, M., Eds.; Fantigrafica Srl: Cremona, Italy, 2022; pp. 261–265.
68. Barfod, G.H.; Feveile, C.; Sindbæk, S.M. Splinters to Splendours: From Upcycled Glass to Viking Beads at Ribe, Denmark. *Archaeol. Anthropol. Sci.* **2022**, *14*, 180. [CrossRef]
69. Eastaugh, N.; Walsh, V.; Chapin, T.; Siddall, R. *Pigment Compendium: A Dictionary and Optical Microscopy of Historical Pigments*; Elsevier: Amsterdam, The Netherlands, 2008.
70. Lutzenberger, K.; Stege, H.; Tilenschi, C. A Note on Glass and Silica in Oil Paintings from the 15th to the 17th Century. *J. Cult. Herit.* **2010**, *11*, 365–372. [CrossRef]
71. Spring, M. Colourless Powdered Glass as an Additive in Fifteenth- and Sixteenth-Century European Paintings. *Natl. Gall. Tech. Bull.* **2012**, *33*, 4–26.