Glass Europe Vol. 3 (2025) 147-163
https://doi.org/10.52825/glass-europe.v3i.2657

Submitted: 21 Mar. 2025 | Accepted: 19 May 2025 | Published: 18 Jun. 2025

Through a Glass Brightly: Islamic Glass Inlays in the Convent of Santa Fe in Toledo (Spain)

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Abstract. The Islamic era left a lasting legacy in the visual and material culture of the Iberian Peninsula. This phenomenon is particularly striking in a rare find of architectural fragments of an arcade with horseshoe-shaped arches in the Convent of Santa Fe in Toledo (Spain). Different coloured glass inlays (turquoise, purple, colourless) were embedded in the iconographic bas-relief made of plaster, an artistic technique that is unparalleled. This study explores the dynamics of glass supply and workshop practices in 11th-century Spain through the chemical analysis of 46 specimens of these glass inlays. Laser ablation inductively coupled plasma mass spectrometry revealed a compositional resemblance but no identity with Iberian soda-rich plant ash glass, pointing to a regional or even local production. The glass assemblage as a whole proved very homogeneous and we were able to identify possible batches in which the individual pieces were probably cut from the same sheet of glass. Despite using the same base glass, the copper-turquoise coloured fragments showed different colouring techniques and combinations of colouring elements. Our findings shed light on the organisation of secondary glass working and material procurement for artistic purposes in Islamic Spain.

Keywords: LA-ICP-MS; Plant Ash Glass; Copper; Turquoise; Islamic Spain; Manganese; Flat Glass; Crown Glass

1. Introduction

The former Convent of Santa Fe is located in the north-eastern part of the city of Toledo (Spain) and currently serves as the headquarters of the *Centro de Arte Moderno y Contemporáneo de Castilla-La Mancha* (CORPO). The architectural complex of the convent is in fact an agglomeration of superimposed structures accumulated over the centuries, dating from the Islamic period to the present day [1]. The convent was founded in 1503 by the Order of the *Comendadoras of Santiago* around a pre-existing church from the mid-13th century. It was built on land donated by King Alfonso VIII within the Alficén, a toponym derived from the Arabic *alḥizām,* the name by which the enclosure of the old Islamic citadel of Toledo was known. The *alḥizām* was originally built above the bridge gate in the year 837 CE on the orders of the Umayyad Emir ʿAbd al-Raḥmān II to house the city governor and his troops [2]. In 932 CE, the citadel and the bridge were rebuilt by the caliph ʿAbd al-Raḥmān III, grandson of ʿAbd al-Raḥmān II [3]. In the first third of the 11th century, after the fall of the Umayyad Caliphate of Cordoba, Toledo became the capital of the Taifa of Toledo. During this period, opulent buildings were erected in the *alḥizām,* which served as the administrative and political centre of the new state [4]. The northern sector, where the Convent of Santa Fe was later built, seems to have housed the palaces [5-8]. Excavations conducted by Fabiola Monzón in the area since

2000 yielded new evidence of these Islamic palaces [7], [8]. Remains of luxurious rooms from the Islamic period were found along the Umayyad wall of the alḥizām, very close to the Chapel of Bethlehem, an Islamic *qubba* that was later converted into a Christian funerary chapel [5], [6]. These rooms feature painted stucco and brick floors. The earliest phase was dated using thermoluminescence (TL) to the middle of the 10th century during the reign of Caliph ʿAbd al-Raḥmān III, while the most recent phase dates to the second half of the 11th century [1]. Nearby, in the northern wing of the cloisters, remains of an arcade with horseshoe-shaped arches were found (Fig. 1), featuring exceptional plasterwork with unique polychrome decorations, including painted and coloured glass. These arcades were demolished in the late 15th century [1]. The presence of the arcades seems to confirm the Arabic sources that mention the magnificent palace complex of *al-Mukkaram*, which was decorated with marble, ivory, and "strips of coloured glass inlaid with pure gold and various figures of animals, birds, trees, etc." built by al-Ma'mun ibn Di-l-Num, sultan of the Taifa of Toledo between 1043 and 1075 CE [7], [8]. The material remains from the Convent of Santa Fe are therefore probably the only archaeological remnant that can be linked to the art of the Taifa palaces.

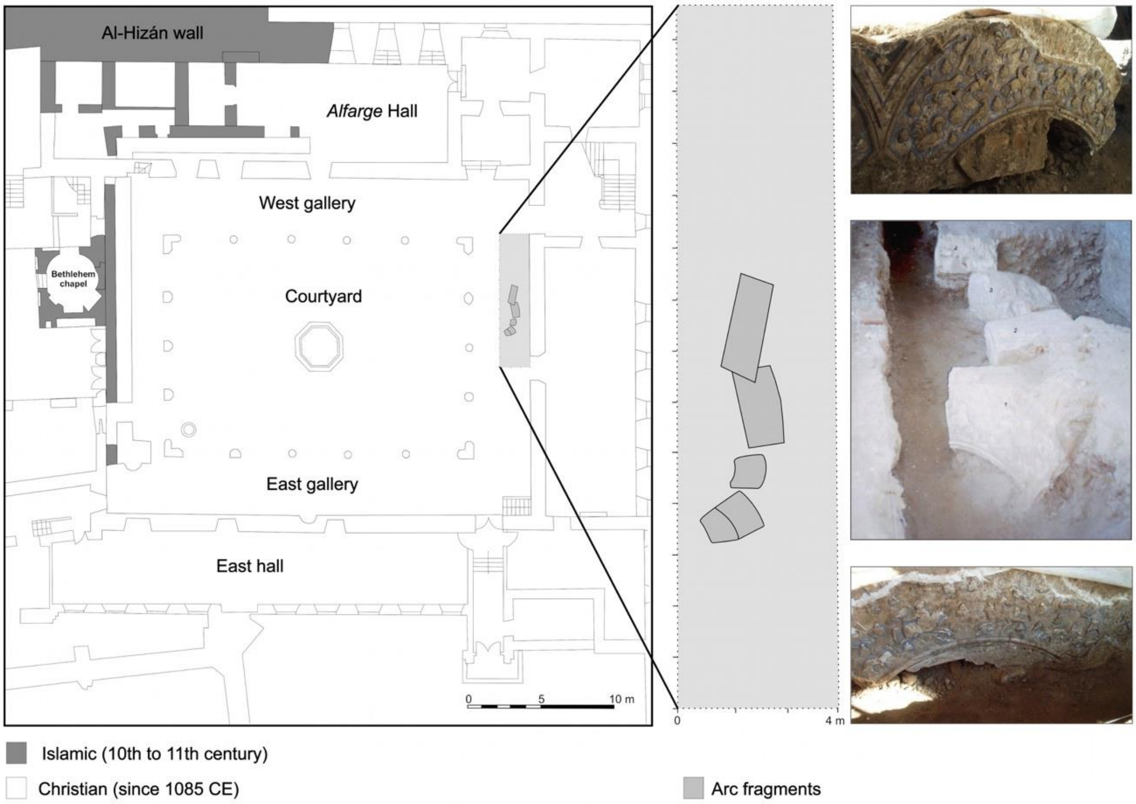

***Figure 1.** Plan of the archaeological excavations with detail of the find spot of the arcades in context of the Convent of Santa Fe (left) and photos of the finds in situ (right); adapted from [1].*

The arches (about 0.7 x 0.75 m) were constructed around a brick core and decorated with an unusual repertoire of motifs moulded in relatively flat plaster relief (Fig. 2). The figures are arranged in semi-circular compositions. On one side, animals and mythological creatures such as sphinxes and harpies appear amidst red scrolls and palmettes, while hunting scenes featuring mounted falconers are depicted on the other side (Fig. 2b). The relief figures are covered in gold leaf on a dark blue background. The remainder of the painted elements in various shades of white, red, yellow, orange, and black are heavily deteriorated. Ten different colouring elements were identified such as lapis lazuli for the blue background, high-purity gold (99.8%), cinnabar, minium, lead white, bone white, orpiment, natural earth pigments, and charcoal. Binders such as animal fat and linseed oil were employed [9]. The intrados of the arches are divided by plaster bands into six-pointed stars further divided into hexagons that enclose zoomorphic figures. The spaces between the figures are filled with bluish green, purple and colourless glass, cut and sometimes painted. Previous analyses carried out on cross-sections of the gypsum adhering to the glass indicate the presence of a white tin layer on the back of these glass pieces. This layer, with an average thickness of 15-30 µm, may have had a reflective function similar to that of mirrors [9].

Figure 2. *Reconstructed arcades now in the Centro de Arte Moderno y Contemporáneo de Castilla-La Mancha (top); fragments of the arcades with decorative details (below). (https://cultura.castillalamancha.es/culturaenredclm/la-arqueria-del-palacio-de-al-mamum-en-toledo-una-obra-singular-dentro-del-arte-andalusi).*

Figurative elements such as human figures, harpies, birds, and horses made of plaster have early Islamic precedents from the 8th century, for example, in Syria and Palestine, in Qasr al-Hayr al-Gharbi, Qasr al-Hayr al-Sharqi, and Khirbat al-Mafjar [10], with more recent parallels in al-Andalus from the 11th century, such as Castell de Formós in Balaguer [11] and the Aljafería of Zaragoza [12]. Somewhat later examples can be found in the Alcázar of Murcia [13], and their use continued in later Christian contexts [9]. These motifs are also common in other decorative arts such as textiles and ivories from the workshops in Cuenca in the Taifa of Toledo [8], [14].

The arcades of Santa Fe are notable for their use of glass. Glass has been used in architectural contexts since antiquity, either in the form of mosaics, windows, opus sectile as well as floor and wall tiles. Probably the most famous examples are the decorated columns from the 6th-century church of Hagios Polyeuktos in Istanbul [15], the aqua-blue floor tiles from the late 8th- to early 9th-century Palace B of Harun al-Rashid in al-Raqqa [16] and, of course, the glass walls in Samarra (Iraq), which were created between 836 and 892 CE [17]. Chronologically and geographically closer are the finds from 10th- to early 11th-century Sabra al-Mansūriya near Kairouan (Tunisia), where flat glass was used in plaster latticework to create stained glass openings and to reinforce the eyes of zoomorphic and anthropomorphic plaster figures [18]. In the Iberian Peninsula, historical sources mention glass-decorated columns in the palace city of Madinat al-Zahra near Cordoba, founded by the Caliph ʿAbd al-Raḥmān III in the 10th century [19], although this has not been confirmed archaeologically [8], [20]. Several examples of flat glass are known from baths and domestic quarters in Córdoba, Almería, Toledo and Murcia [21], [22]. Among the flat glass from Ciudad de Vascos near Toledo is a small polygonal mirror discovered in the mosque of the *Alcazaba*, although its exact function remains unknown [21], [23]. In the 13th century, the combined use of plaster and glass mirrors is documented in Murcia, specifically in Siyâsa [13] and Yecla [24], where motifs painted in red and black have likewise been found [9].

This raises the question of the origin of the glass fragments used in Santa Fe. Material and written sources clearly indicate that glass was produced in al-Andalus from local raw materials since the first quarter of the 9th century CE [25], [26]. However, there is neither archaeological nor textual evidence of a glass workshop in Toledo before the 12th century CE [21]. As for coloured flat glass, the material evidence from Sabra al-Mansūriya indicates that here, the blue and purple stained glass was imported in the 10th century [18]. The cargo of the Serçe Limani ship that sank off the western coast of Turkey in the third decade of the 11th century also contained coloured sheet glass, which testifies to the far-flung trade of this type of vitreous material at the time [27]. Similarly, there are written sources that speak of trade contacts between the Maghreb, Egypt and the Levant and the Iberian Peninsula in the 11th century [28], and the archaeological records of the Taifa kingdoms in Spain occasionally contain material (including glass) and objects of distant origin (e.g. [21], [23], [29], [30]). The most obvious conclusion from these initial observations is that glass was still widely traded in the Taifa period. At the same time, the arts and sciences were actively promoted by the Taifa kings, leading to a flourishing local production of art and architecture and the establishment of workshops. In the 11th century, the Iberian Peninsula was fragmented into rival political entities (the *taifas*) competing for supremacy and legitimacy, which is often reflected in the material and visual culture of the different regions [8]. The present paper aims to determine the origin of the glass used for the architectural decoration in Toledo on the basis of the chemical analysis of 46 fragments from Santa Fe. Our data support the hypothesis that, by the 11th century CE, there were glassmaking and glass working workshops in the centre of the Iberian Peninsula, possibly specialising in the production of flat glass.

2. Materials and Methods

2.1 Context and selection of samples

The remains of the arcades were found broken into four large pieces in the northern wing of the cloisters of the Convent of Santa Fe (Fig. 1). The context was a rubble fill made of late medieval material, which was sealed by a lime mortar floor that was probably created during renovation work in the convent at the end of the 15th and the beginning of the 16th century [1]. The results of the archaeological excavation indicate that the arcades were part of a pavilion. The arches were restored and reassembled by the *Instituto del Patrimonio Cultural de España* (IPHE) for public display in what is the former Convent of Santa Fe, now the *Centro de Arte Moderno y Contemporáneo de Castilla-La Mancha*.

Numerous loose plaster fragments with embedded pieces of flat glass were found in connection with the arcades, together with various flat glass pieces no longer attached to their plaster support. These remains, which could not be reassembled into the arches, are kept in the Museo de Santa Cruz in Toledo. 46 samples were selected from this collection to give a representative cross-section of the colours (colourless, purple, bluish green and turquoise; Fig. 3, Table S1). Samples of about 2 mm in size were taken without compromising their conservation. Some of the bluish green and purple fragments have characteristic folded and fire-rounded rims that represent the edges of crown glass panes with a diameter of approximately 30 cm (SF003, 004, 005, 008, 012, 016, and 043). The colourless glass, on the other hand, may well have been cut from blown glass cylinders [9]. The analysed collection also included one glass tube (SF030).

2.2 LA-ICP-MS

The samples were analysed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at IRAMAT-CEB in Orléans (France), using a well-established analytical protocol for glass [31]. Small fragments were mounted in epoxy resin and ground to obtain a clean surface. A sample was ablated using a Resonetics M50E excimer 193 nm laser with an energy of 5 mJ, a pulse frequency of 10 Hz and a spot size diameter of 100 µm that was reduced for the purple samples to avoid saturation caused by high manganese concentrations. After a pre-ablation of 15s, measurements were taken for about 27s. The ablated material was transported by an argon/helium flow (1 l/min Ar + 0.65 l/min He) to the plasma torch of a Thermo Fisher Scientific ELEMENT XR mass spectrometer where the ions were separated according to their mass/charge ratio. The signal intensities were converted into fully quantitative results, using a combination of an internal standard (^{28}Si) and a series of external glass standards (NIST610, Corning B, C, D and APL1, an archaeological glass for chlorine). To keep track of the accuracy and precision of the analytical results, reference glasses (NIST612, Corning A, B, C and D) were analysed repeatedly at regular intervals, the results of which are given in Table S2.

Figure 3. *Photos of the glass inlays from the Convent of Santa Fe analysed in this study by LA-ICP-MS.*

3. Results

3.1 Base glass features

The LA-ICP-MS data (Table S1) identify all glass samples, with the exception of one high lead glass fragment (Santa Fe 025), as high magnesia (2.7–4.7 wt% MgO), high soda (12–21 wt% Na_2O) plant ash glass typical of the early Islamic period (Fig. 4). The potash content is moderate (1.4–3 wt% K_2O), while phosphorus is comparatively high (0.5–0.9 wt% P_2O_5). Most of the bluish green samples have high and variable lead contents (1–22 wt% PbO), as well as copper and tin that affect the absolute concentrations of the elements associated with the base glass (Table S1; Fig. 4b, c). To facilitate comparability of the data and to characterise the silica source, we either use element ratios or reduced compositions where the main additives (Cu, Sn, Sb, Pb) were removed from the dataset and then normalised [32]. Therefore, the above-mentioned compositional ranges are considerably more constrained after data reduction (e.g. 3.5–4.8 wt% MgO; 16–21 wt% Na_2O). In addition to the high lead glass, two samples (Santa Fe 019 & 034) were singled out as outliers due to different trace element profiles.

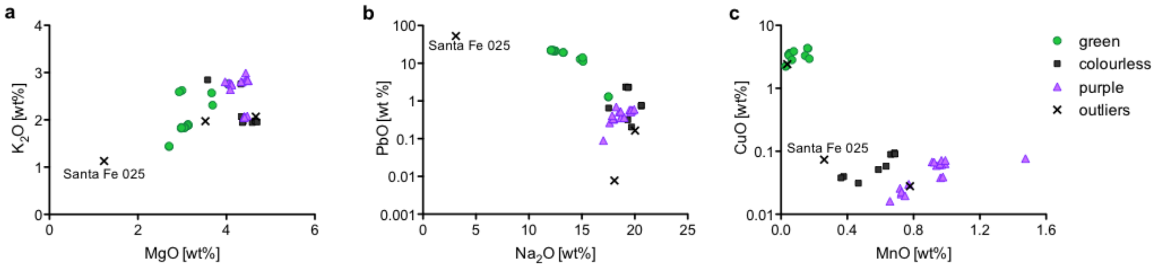

Figure 4. *LA-ICP-MS data of elements related to the fluxing agent and colouration of the glass from Santa Fe, separated by the sample colours; (a) elevated MgO and K_2O together with (b) high Na_2O contents identify the fragments from Santa Fe as soda-rich plant ash glass, while most of the green samples have elevated PbO; (c) MnO and CuO are identified as the main colourants in the purple and the green glass, respectively. Non-reduced data are shown (Table S1).*

The elements attributed to the silica source include Al, Ti, Fe, Y, Zr, Nb, rare earth elements (REE), Hf and Th [33], [34]. All the glass samples show a relatively uniform composition with low silica-related impurities such as aluminium (1–1.7 wt% Al_2O_3), titanium (0.05–0.09 wt% TiO_2), and iron oxide (0.4-0.6 wt% Fe_2O_3), and very low zirconium (17–34 ppm Zr). The interelement correlations are exceptionally high ($R > 0.8$) between Al_2O_3, TiO_2 and the lanthanide rare earths and high field strength elements such as Zr, Hf, Nb and Th. In particular Al_2O_3 and TiO_2 are very strongly correlated, as are Th and some of the light REEs (Fig. 5a, b). To compare the trace and rare earth element patterns of the different colour groups, the reduced data were normalised to the earth's upper continental crust (MUQ; [35]). The results demonstrate that the glass from Santa Fe is depleted in trace and REEs compared to the earth crust and exhibits a pronounced negative Eu anomaly (Fig. 5c). Negative Eu anomalies are especially abundant in granites as a result of the fractionation of Eu^{2+} and Eu^{3+}, the preferential incorporation of Eu^{2+} in plagioclase that is then separated during magmatic processes [36]. The trace and REE fractionation in all 43 glass samples from Santa Fe (excluding the three outliers) is virtually identical. Particularly the bluish green and purple traces overlap for most elements, whereas the colourless glass shows slightly lower values across all traces and REEs. The differences are probably due to impurities introduced with the colouring agents, like barium and uranium that are associated with the manganese-bearing minerals in both the colourless and purple glass (Fig. 5c; [37]). In view of these similarities in composition, it is very likely that the glass used for the plaster inlays in Santa Fe derived from the same parental primary glassmaking.

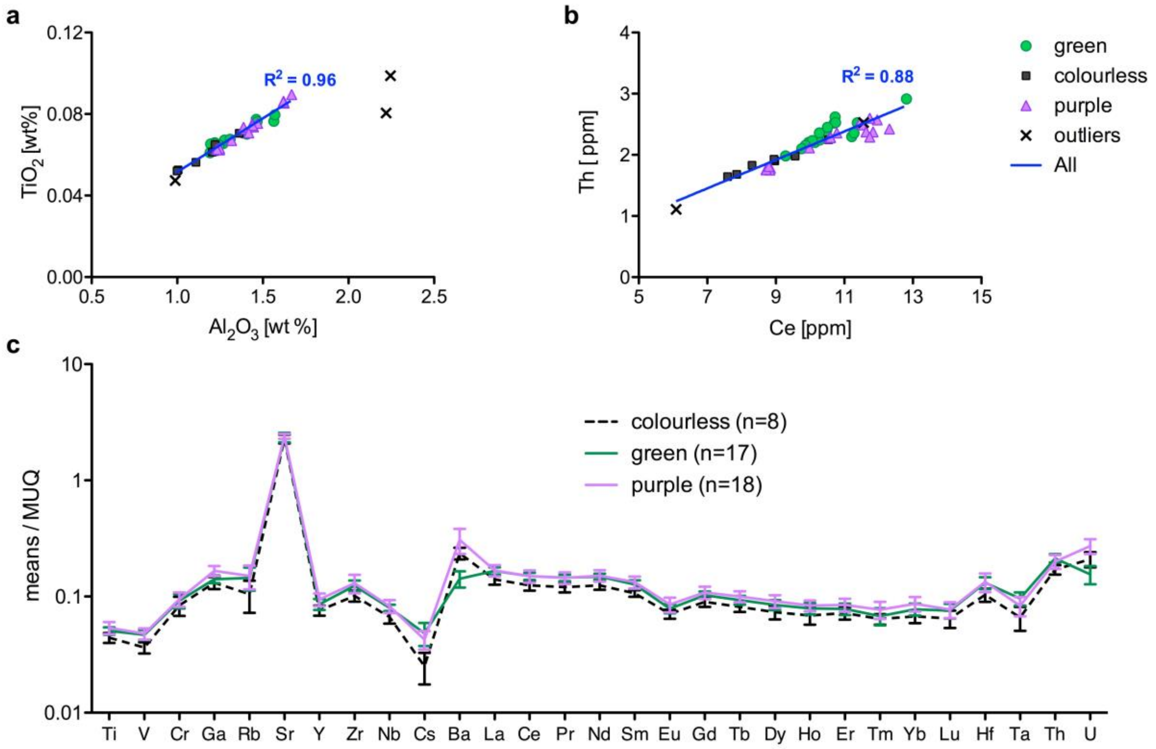

Figure 5. *LA-ICP-MS data of silica-related elements of the glass from Santa Fe separated by colour; (a) Al_2O_3 and TiO_2 show a very strong positive linear correlation; (b) high correlation is also evident between Th and Ce; (c) average trace element patterns divided by colour groups normalised to the upper continental crust (MUQ, [35]). All data were reduced and normalized.*

Another marker that proved effective in characterising the silica source of soda-rich plant ash glass from different geographical regions is the Th/Zr ratio [34]. For the Santa Fe glass, the ratios of Th/Zr are surprisingly high ($> 70 \cdot 10^{-3}$). Islamic plant ash glass from other regions of the Islamic world such as Sicily, the Levant, Egypt, Mesopotamia and the Maghreb have consistently much lower Th/Zr ratios ($< 30 \cdot 10^{-3}$; Fig. 6a). Only glass from the Iberian Peninsula approximately contemporary tends to show increased Th/Zr ratios ($> 30 \cdot 10^{-3}$). Due to its high chemical affinity with La and Ce, thorium occurs in combination with the lanthanides, for instance, in monazite-bearing sands. The high correlation between Ce and Th and between Ce and La, the latter with a ratio of about 2:1 (Table S1), seems to confirm the use of monazite-bearing sands for the production of the glass from Santa Fe. Monazite-Ce is the most common member of the monazite group and present as an accessory element in granitic igneous rocks (https://www.mindat.org/min-2751.html). This in turn could also explain the negative Eu anomaly.

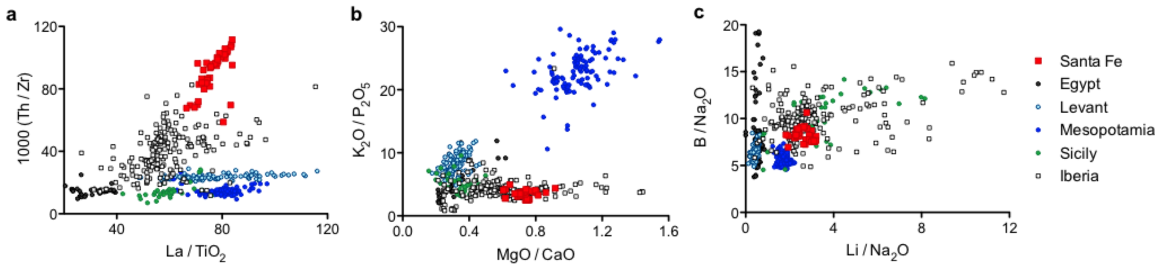

Figure 6. *Base glass features of the samples from Santa Fe in red compared to datasets from different regions of the Islamic world. (a) La/TiO_2 and Th/Zr ratios separate the data from Santa Fe from most other published data possibly associated with Iberian glass; (b) the glass from Santa Fe has relatively high MgO/CaO and low K_2O/P_2O_5 ratios similar to other early Islamic glass from Iberia; (c) elevated Li/Na_2O and moderate B/Na_2O ratios characterise the glass from Santa Fe similar to the Iberian reference group. Data sources: Egyptian glass [38]; Tyre-type P1 Levantine glass [39]; Mesopotamian glass [17]; Iberian glass [23]; Sicilian plant ash glass [40].*

3.2 Plant ash component

Meanwhile, the alkali and alkaline earth elements, mainly associated with the fluxing agent (i.e. plant ash), are also similar between the Santa Fe samples and glass from the Iberian Peninsula dating to the 10th to 12th centuries CE (Fig. 6b). They are characterised by relatively high magnesia concentrations in relation to lime, while the potash to phosphorus ratios tend to be much lower compared to other regional production groups. In fact, Iberian glass shows some of the lowest K_2O/P_2O_5 ratios of early Islamic soda-rich plant ash glass. In contrast, the magnesium contents and thus the MgO/CaO ratios can be fairly high, similar to those of Mesopotamian glass assemblages [34]. Another distinguishing feature of the samples from Santa Fe are elevated lithium values, in which respect they again correspond to Iberian glass of the early Islamic period (Fig. 6c). Typical of Iberian plant ash glass is the variation in composition in the ash-related elements (Li, Mg, P, K, Ca), which is not unexpected because ash is by its very nature highly variable and either reflects the use of different plant types, geological environments, harvest season or pre-treatments of the ash [41], [42]. In comparison, the glass from Santa Fe shows a relatively narrow range of the alkali and alkaline earth elements, suggesting that they were probably made using similar plant ash or closely controlled recipes.

3.3 Batches of glass

The glass from Santa Fe is so homogenous that several samples of the same colour may have come from a single batch. The relative standard deviations (coefficient of variation CV) of eight out of 18 bluish green fragments (Santa Fe 005, 006, 007, 031, 033, 035, 040, 044) are presented in figure 7, alongside the CV of repeated measurements (n = 9) of Corning A for the major and minor elements, and NIST 612 for the trace elements (Table S1 & S2). Given that the CVs of the Santa Fe samples are equivalent to or below those of the instrumental precision of the analysis, the composition of these eight bluish green glass fragments is sufficiently similar to conclude that they originated from the same batch. The somewhat increased CV in the archaeological glass compared to the analytical uncertainties for some of the trace elements can be explained by the absolute contents of the measured components. Specifically, the concentrations of REEs in NIST 612 are typically between 30 ppm and 40 ppm, while those of the archaeological glass samples are in the sub-ppm range, which inevitably reduces the analytical precision and increases the CV. Nonetheless, the CVs are still well within 5% relative. Tight compositional groups among some of the purple fragments also suggest they might be the product of a single batch. Three possible batches may thus be identified that differ from one another in the absolute contents of, for example, aluminium, manganese and other additives such as copper, tin, antimony and lead (Table S1). The CV of these elements tends to exceed that of the standards. This deviation may be due to poor mixing and insufficient homogenisation of the batch during secondary processing and the addition of colorants, and does not reflect the fluctuations of the primary raw glass.

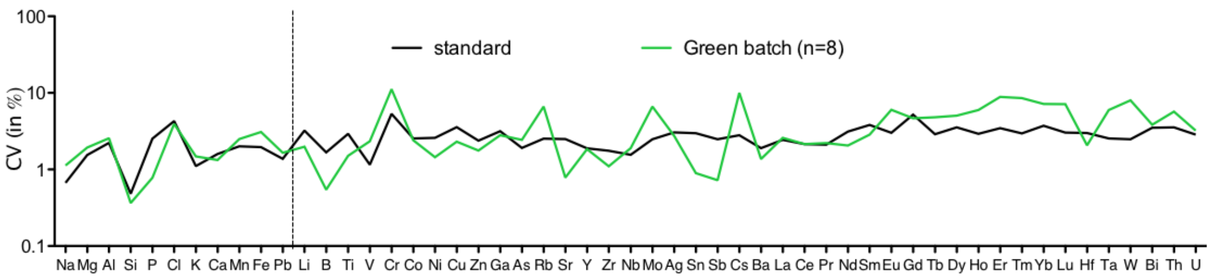

Figure 7. *Coefficient of variation (CV = σ/μ) of repeated LA-ICP-MS measurements (n=9) of Corning A for major and minor elements (Na to Pb) and NIST 612 for trace elements (Li to U) in black (standards) compared to the CV of a possible batch of eight green samples (Santa Fe 005, 006, 007, 031, 033, 035, 040, 044). The CV of the archaeological glass is close to or below the CV of the standards for elements with comparable absolute concentrations, supporting the interpretation of the group of samples as a batch. The vertical line indicates the different standards used, i.e. Corning A (left) and NIST 612 (right).*

3.4 Colouring agents and their impurities

The narrow range of compositions of most Santa Fe glass samples allows for easier identification and correlation of colorants and associated impurities. As mentioned above, the main chromophores in the glass from Santa Fe are copper and manganese. More specifically, copper in its Cu^{2+} state is likely responsible for the turquoise green colour [43], while the main acting chromophore in the purple glass is Mn^{3+} [44], [45]. The MnO contents of the colourless glass, where manganese is presumably present as Mn^{2+}, range from 0.36–0.69 wt%, while the purple glass has 0.66–1.48 wt% of manganese oxide (median of 0.95 wt%). The overlap in manganese concentrations between the colourless and purple samples is somewhat surprising and confirms that the perceived colours are dependent not only on the concentration of the chromophores, but above all on the thermal processes during glassmaking and the oxidation state, alkalinity and basicity of the melt [46]. The iron oxide concentrations in both groups of samples are relatively constant (0.4–0.6 wt%); they do not appear to be affected by the presence of the manganese additive and to not differentially impact the perceived colour. Some of the trace elements in the purple and colourless samples are elevated compared to the bluish green samples, especially Ba and U (Fig. 5). In general, however, a fairly clean manganese source must have been used that did not significantly augment the trace and/or rare earth element levels.

When comparing the elements that are typically associated in one way or other with colouring agents, the colourless samples differ noticeably from the purple ones only in Mn, Mo and Sn (Fig. 8a). The purple samples have higher Mn and Mo, but are lower in Sn, which may be the result of contamination by the layer of tin that was applied to the fragments [9]. The bluish green samples are characterised by their high Cu (2.24–4.35 wt% CuO) and high Pb contents (1.28–22.2 wt% PbO). Here, As, Ag, Sb, and Bi are also elevated, while Fe, Zn and Sn remain within the range of the colourless and purple glass. Copper does not clearly correlate with any of these elements, instead As and Sb show a strong positive correlation with Pb, while Ag correlates with Sn. The lead-containing raw material was evidently added independently of the copper colourant. Nevertheless, Pb is likely to indirectly influence the colour of the glass, because it induces changes in the glass transition temperature (T_g), the geometric environment of the Cu^{2+} and Cu^{+} cations and their ratio [43]. This is apparent in the variations of the colour tone. For example, the colour of sample 006 with 3.5 wt% CuO is clearly shifted towards green compared to fragment 024 with only 2.2 wt% CuO, while the lead concentrations remain at the 20 wt% mark (Table S1). In contrast, sample 037 has the highest copper (4.3

wt% CuO) and lowest lead content (1.3 wt% PbO). In terms of the perceived colour, it is closer to sample 024 with only a slight greenish tint (Fig. 8b). This colour behaviour reflects on the one hand the role of absolute copper concentrations in the generation of the colour, and on the other the effects of thermal treatment and/or viscosity of the glass melt. A series of reproduction experiments have found a red shift of the absorption spectra (i.e. greener glass) at higher copper concentrations or higher melting temperatures [43]. Both parameters appear to lower the copper redox ratio $\frac{Cu^{2+}}{Cu_{tot}}$ in favour of Cu^{+}. Concurrently, high lead concentrations are thought to prevent cluster formation and affect copper distribution thus modifying the colour from blue to green [47]. In short, the final colour is the result of a combination of factors, including the concentration of chromophore, the base glass composition and heat treatments. The differences among the bluish green samples from Santa Fe thus reflect different secondary processing methods.

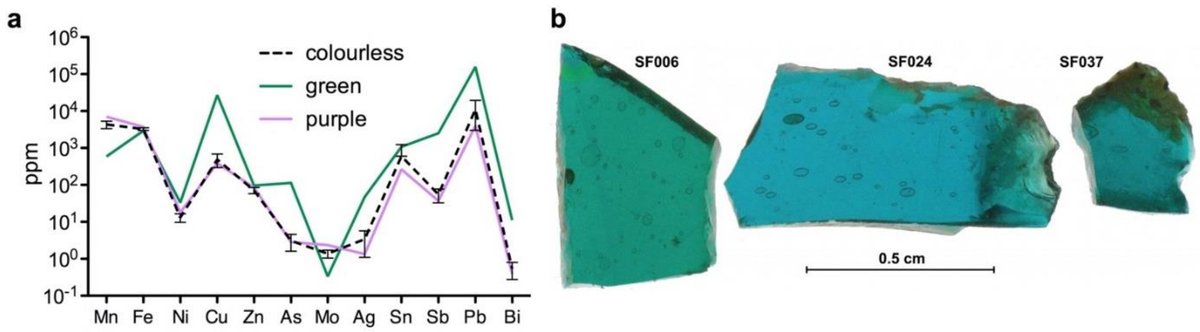

Figure 8. *Differences in the colouration of the glass. (a) mean concentrations of elements related to the colouring agents according to colour group; (b) photos of three different bluish green/turquoise samples taken under identical conditions with an optical microscope. The apparent differences in colour tone are likely the result of varying combinations of copper and lead.*

4. Discussion

4.1 Provenance of the base glass

The analytical results allow us to advance a hypothesis for the production (both primary and secondary) and sourcing of the glass used for the arcades in the Convent of Santa Fe in Toledo. The composition and homogeneity of the glass, which contrasts with published data of glass assemblages from other Mediterranean regions suggests a local or at least regional glass production. The glass used in Toledo certainly does not come from the eastern Mediterranean, nor from Mesopotamia or Central Asia. Sicily and the Maghreb can likewise be ruled out as places of origin. Comparing the elements related to the silica source and especially the elemental ratios, it is clear that the Santa Fe glass differs considerably from all published datasets (Fig. 6). The Santa Fe glass is characterised by a combination of low Al, Ti and Zr concentrations and proportionally elevated Th contents, strongly correlated with light REEs. This suggests the presence of monazite in the silica raw materials. A certain degree of overlap, albeit limited, between the Santa Fe data and other Iberian glass assemblages confirms a compositional affinity.

Analytical data published to date show that early Islamic glass from the Iberian Peninsula varies greatly with respect to the base glass components, with differences over one order of magnitude for some elements such as aluminium and titanium [34]. The glass from Santa Fe is at the lower (clean) end of the Iberian compositions. Only a few analysed early Islamic glass samples from Córdoba, Pechina, nearby Ciudad de Vascos and Murcia have compositions that are similarly low in aluminium and titanium (Fig. 9). Nevertheless, the Santa Fe glass shows the same aluminium to titanium regression as, for example, the glass from Vascos and

Murcia. The consistency in the proportions of these elements indicate that the glass from Santa Fe derived from an Iberian source, which has not yet been located. The combination of low aluminium and titanium with surprisingly high Th/Zr ratios is not commonly encountered in other glass assemblages and is likely the result of the use of different silica sources. No trace elements from the twelfth-century workshop in Murcia have been published, which can therefore not be completely excluded as a possible source of the raw glass. Given the tight composition of the glass from Santa Fe for all elements except the chromophores, we assume that the raw glass came from a single primary workshop and that this workshop may have been located nearby. The Taifa court of al-Maʾmūn in Toledo was a culturally and artistically thriving environment in the 11th century. The artistry of the arcade is a testimony to the artistic renewal of the Taifa Kingdom of Toledo, and may well have been part of the visual propaganda to underline the cultural identification and to legitimise and consolidate power [8]. It is therefore conceivable that glassmaking had been established in the Taifa Kingdom, not least to ensure the supply of glass for the palace.

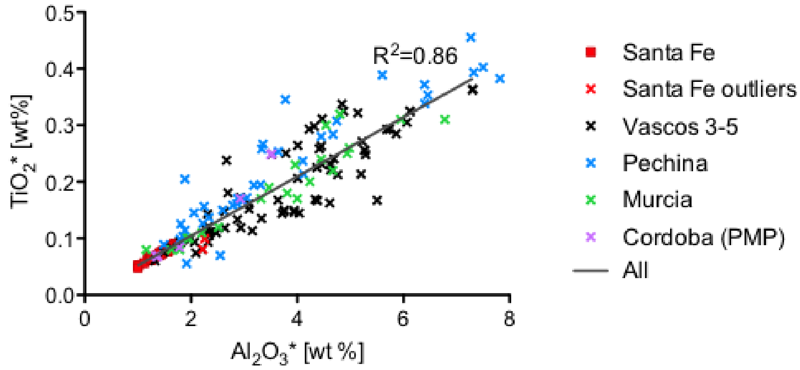

Figure 9. *Al_2O_3 and TiO_2 contents of the glass inlays from Santa Fe compared to other Iberian glass data from Vascos, Pechina, Murcia and Córdoba (PMP), showing a common regression line. Data sources: Córdoba (PMP) glass [25]; Ciudad de Vascos [23]; unpublished data for Pechina; Murcia [48].*

4.2 Significance of the batch – primary and secondary production

The recognition of batches implies a unique secondary melting and colouring event, as well as the simultaneous procurement of the batch material by the end-user [49], [50]. It is perhaps not surprising to identify batches in flat glass fragments from a single architectural decoration and indicates that the batch samples may actually have been cut from a single glass sheet that was formed by the cylinder or crown glass technique. It is often near impossible to distinguish the two based on small fragments. Batch 1 of eight bluish green glass also encompasses a piece of folded rim (SF 005) with a curvature that points to the crown glass technique. The fragments range in thickness between 0.9 mm and 1.6 mm and the largest dimension is about 5 cm. These features confirm the production of a crown glass with a diameter of at least 30 cm that could be cut into small pieces of flat glass with a relatively uniform thickness, avoiding the thick central area (known as bull's eye) of the crown pane.

The compositional similarities in the base glass composition of all fragments across the different colours (except the outliers) can be furthermore attributed to the output of a single primary glass production. This implies that the glass was most likely specifically acquired for the decoration of the arcades found at Santa Fe within a reasonably short period of time, and that the flat glass was probably a commissioned work. It is quite possible that the different coloured glasses were produced in the same secondary workshop with a single provision of raw glass. A joint primary and secondary production is also plausible. The similarity in composition and the fact that the bluish green glass tends to have manganese levels above the silica background, while the purple pieces have copper and lead as impurities may be indicative of workshop contamination rather than the admixture of glass cullet per se. This further implies that manganese was added only at the secondary production stage and not during primary production as often observed elsewhere [51], [52]. If so, we may need to revise our current model of classifying Islamic plant ash glass, insofar as manganese cannot necessarily be used as a distinguishing feature of primary production events. Instead, the use of manganese may be colour dependent. As recently discussed, Islamic opaque turquoise glass has an unusually low manganese content [53]. The presence of manganese in its Mn^{3+} form can potentially shift the colour from a bright turquoise blue to a duskier shade [53]. Perhaps the glassmakers also used manganese-free glass for transparent turquoise glass in order to avoid this effect.

4.3 Colouring techniques

The model of a single secondary workshop appears at odds with the differences in the colouring technology seen in the bluish green fragments, where the copper and lead concentrations vary considerably while the two elements are not correlated. The negative correlation of sodium and lead can easily be explained by a dilution effect, but as we have seen, copper and lead were added independently. If we assume a single workshop, this variance in composition must reflect different protocols and crucibles. The realisation that different colouring techniques were used to achieve similar optical effects may contain important information about the lack of standardisation of secondary glass processing and colouring in medieval Spain.

It is difficult to say to what extent the relationship between the copper and lead contents and the resulting colour were fully understood and/or desired. The differences in colour of the bluish green fragments are only visible when viewed in transmitted light, which would be the case with window panes, but not with the inlays of the arcades. However, the glassmakers would most certainly notice the colour nuances when blowing and spinning the disc on the pontil to produce the crown windowpane, provided there was sufficient light in the workshop. Ultimately, the final color was more likely to be the result of trial and error than deep understanding of the different factors that determine the colour. The different combinations of colourants thus appear surprising and might indicate that the exact hue was not considered the most important feature.

5. Conclusion

This article discusses the analytical data of a relatively unusual assemblage of flat glass from Islamic Spain. LA-ICP-MS analyses and comparison with legacy data demonstrated that the elemental composition of the glass inlays from the Convent of Santa Fe in Toledo differ from other Islamic glass found across the Islamic world, particularly in terms of its trace element contents. The Santa Fe glass shows characteristics that are in line with an Iberian production, but no direct match has been identified. This suggests a hitherto unknown primary glass production, possibly within the realm of the Taifa of Toledo in the 11th century. Our results corroborate the existence and multiplication of plant ash glassmaking in the Iberian Peninsula during the Islamic period, predating the archaeological evidence from Murcia by more than a century. The inlays also add to the few known flat glass pieces recovered from such an early date in Spain. This raises the possibility that window glass (crown glass) was more widespread in the Islamic world than previously assumed and awaits to be discovered.

Data availability statement

All data reported in this study (Tables S1 and S2) are made available for download from the online EU Open Research Repository Zenodo at https://www.doi.org/10.5281/zenodo.15490893.

Underlying and related material

Supplementary materials are available at https://www.doi.org/10.5281/zenodo.15490893.

Author contributions

Conceptualisation NS, JdJA; Data curation NS, JdJA; Formal analysis NS, JdJA; Funding acquisition NS; Investigation NS, JdJA, FMM; Resources NS, FMM; Visualization NS, JdJA; Writing original draft NS.

Competing interests

The authors declare that they have no competing interests.

Funding

This project has received funding from the European Research Council under the European Union's Horizon 2020 - Research and Innovation Framework Programme (GlassRoutes, grant agreement No. 647315 to NS). The funding organisation had no influence in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgement

We thank Concepción Martin Morales and Margarita González Pascual of the Instituto del Patrimonio Cultural de España (IPCE) for their support in the preparation of this work. We would also like to thank Yasmina Cáceres who made the drawings and collaborated in the documentation work and Jacobo Fernandez for his invaluable advice. We are grateful to the Consejería de Cultura de Castilla-La Mancha and the Santa Cruz Museum of Toledo and their staff, namely Jaime Gallardo and Antonio Davila for their help and for granting us access to the archaeological materials.

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