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SEVENTEENTH-CENTURY *FAÇON DE VENISE* GLASS FROM DE TWEE ROZEN GLASSHOUSE, AMSTERDAM

Technology out of Step with Fashion?

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ABSTRACT

De Twee Rozen glasshouse was one of the best-known glasshouses in seventeenth-century Amsterdam and an important producer of glass in the Venetian style. It occupied two sites: initially at Keizersgracht, from 1621, it then moved in 1657 to Rozengracht, further from the center of the city. Production debris recovered from a deposit close to the Keizersgracht site were originally attributed to an earlier glasshouse, but a reinterpretation in light of more recent excavations firmly attributes these glasses to the first location of De Twee Rozen. We present 50 new SEM-EDS analyses of vessel glass, moils, trim-offs, unfinished objects, and production waste from the later site at Rozengracht and compare these with previously published analyses from both sites. Several changes in glass technology appear to have been introduced following the change of location. First, a *cristallo*-type technology, involving the purification of ashes to produce a glass with lower Fe_2O_3 appears to have been used exclusively at Rozengracht. Thus, the introduction of glass production in the Venetian style was not accompanied by the signature Venetian glassmaking technology, which seems to have followed later. Second, the relatively new method of opacification using antimony was introduced, along with other changes, such as the introduction of lead into the cobalt-blue glass used in polychrome decorative canes. The origins of these new technologies are discussed in particular in view of the presence of the chemist Johann Rudolf Glauber at De Twee Rozen and its direction by a Venetian master, Nicalao Stua, from 1667.

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Venice was the leading glass producer of the European Renaissance. Its colorless *cristallo* was superior to other glass, and from the fifteenth century, its elegant and inventive vessels represented the height of fashion and were highly desired. Underpinned by access to high-quality raw materials, innovative technologies, and the virtuoso skills of its artisans, the secrets of the glass industry were closely guarded by the Republic of Venice, with statutes which prohibited Venetian craftsmen from taking their skills elsewhere. In spite of this, in the late sixteenth century the production of glass in the Venetian style spread beyond Italy, and *façon de Venise* (FdV) glass was produced in centers across Europe in the seventeenth century.[1]

The fine attributes of FdV glass have resulted in significant art historical attention,[2] and there have also been a number of regional archaeometric studies of FdV glass allowing comparison with the recipes and compositions of glass made in Venice itself.[3] In spite of this reasonably well-established general picture, however, we have only a limited understanding of the processes whereby the new technologies were transferred to and established in their new situations. An understandable emphasis is frequently placed upon the development in Venice in the mid-fifteenth century of a new method of making the glass material to give a superior, less-tinted colorless glass known as *cristallo*. Its production depended upon the purification of soda-rich ashes from the Levant by dissolution and reprecipitation—in the process removing coloring elements such as iron and titanium—and melting with crushed silica pebbles as opposed to less-pure sand. Such was the renown of Venetian colorless glass that the spread of FdV styles and the introduction of *cristallo* technology are sometimes implied in the literature to have occurred together, or at least are not distinguished.[4] However, it is clear that even high-quality enameled glass made in Venice was sometimes made from less-refined and less-costly *vitrum blanchum*, produced using unpurified Levantine soda ash[5] but using quartz pebbles as a source of silica. Furthermore, analyzed FdV vessels in Antwerp were also made using *vitrum blanchum*.[6] All of this suggests that the transfer of glass production methods and styles from Italy to northwestern Europe was complex and that, as might be expected, the more sophisticated elements of Venetian materials technology trailed the adoption of Venetian styles.

Were the Venetian methods transferred as a package, implemented in a single stage, or was a more gradual approach adopted? Were the new methods adopted in full or selectively? Were changes, improvements, or compromises made, and if so, why? Furthermore, the spread of glass that owes much stylistically to Venice is often implicitly assumed to have been the result of the movement of Venetian emigrés, but while there is considerable evidence for the movement of Italian artisans, other centers, notably Altare (near Genoa), played an important role in this process.[7]

By the early seventeenth century, the Netherlands had become the dominant trading nation in Europe and cities such as Antwerp, Middelburgh, and Amsterdam were leading early adopters of FdV.[8] In the present paper, we discuss the compositions of glass from De Twee Rozen (The Two Roses) glasshouse in Amsterdam, a leading producer of FdV. This glasshouse is unusual in that it provides an informative

1 Andries 2003; Page 2004; Maitte 2009, 2011.

2 Tait 1979; Page 2004.

3 See, e.g., Theuerkauff-Liederwald and Ulitzka 1993; Bronk and others 2000; De Raedt 2001; De Raedt and others 2001; De Raedt, Janssens, and Veeckman 2002; McCray and Warren 2002; Šmit and others 2005; Janssens and others 2013; Cagno and others 2010, 2012; Coutinho and others 2016, 2021; Kunicki-Goldfinger 2021; Veeckman 2002.

4 E.g., Page 2004; Dupré 2010.

5 Verità and Biron 2021.

6 De Raedt, Janssens, and Veeckman 2002.

7 E.g., Maitte 2009, 2011.

8 Liefkes 2004.

chronological dimension due to a known location change between the periods of its earlier and later productions.

DE TWEE ROZEN

The oldest known glasshouse in Amsterdam was recorded in 1597, founded by a Venetian glassmaker, Antonio Obizzo, but it was short lived.[9] A new glasshouse was founded in 1601 by the merchant Jan Janz Carel and run by Jan Hendriksz Soop, his son-in-law; it operated until around 1630. De Twee Rozen glasshouse was founded in 1621 and operated in Amsterdam until 1679.[10] It was undoubtedly one of the most important glasshouses in seventeenth-century Amsterdam.[11] It was also the glasshouse where the alchemist and early chemist Johann Rudolf Glauber (1604–1670) experimented with his innovations in glass technology; and it appears to have been internationally known at the time and is thought likely to be the glasshouse illustrated in the 1669 Latin edition of Christopher Merret's translation of Neri's *L'arte vetraria*[12] as well as in Johann Kunckel's edition of Neri's book, published in 1679.[13]

Originally, De Twee Rozen was situated at Keizersgracht (referred to hereinafter as Phase 1), but it was moved to a new location further from the city center at Rozengracht in 1657 (Phase 2).[14] In 1662 a "touristic" city guide, the *Beschrijvinge der wijdt-vermaarde koopstad Amstelredam* (Description of the widely renowned merchant city Amsterdam) by Melchior Fokkens, was published, with an entire chapter on the glasshouse as one of the wonders of the city. It describes a whole range of drinking vessels manufactured in the glasshouse, including, besides the normal drinking glasses, complete opaque white vessels (*lattimo*) and vessels with blue or white rim edges, goblets with lids, flutes, and various other tablewares.[15] Among the FdV vessels, there are examples made of filigree glass with multicolored canes, ice glass, millefiori glass, and many others types of glass and decorative techniques. Beads and plates of mirror glass also constituted an important part of the production. Amsterdam in the seventeenth century was an important trading center and exported glass, among various other commodities, to almost all of Europe, and De Twee Rozen products would have constituted an important part of this trade.

Abundant glass production material was recovered from the Monumenten en Archeologie, Gemeente Amsterdam (MenA) excavations at Keizersgracht in 1981, found during dredging of the canal as part of sewage works (MenA site KG10). These were originally attributed by Baart[16] to the Soop glasshouse and dated to 1601–1610. However, in 2013 the site was reassessed as the waste from the first site of De Twee Rozen (i.e., 1621–1657).[17] Unfortunately the previous misidentification has been widely quoted in the literature, including in archaeometric studies where glass compositions have been attributed to the Soop glasshouse and/or dated to the period 1601–1610.[18] The erroneous attribution has important implications: it has been used as

9 Hudig 1923, 29; Liefkes 2004.
10 Hudig 1923, 44, 56.
11 Hudig 1923, 44, 45.
12 Hudig 1923, 47; Brain 2008.
13 Loibl 2008.
14 Hudig 1923, 46.
15 Fokkens 1662, 306.
16 Baart 1998.
17 Hulst 2013.
18 De Raedt 2001; Sempowski and others 2001; Baart 2002; Karklins and others 2002; McCray and Warren 2002; also discussed in De Raedt, Janssens, and Veeckman 2002.

a chronological anchor for beads from archaeological sites in North America[19] and as a reference point for the history of glassmaking in Amsterdam.[20]

Excavations at Rozengracht in 2006[21] revealed material from the second location of De Twee Rozen, the period from 1657–1679 (MenA site R021)—Phase 2. **Figure 1** shows the typical examples of colored glass shards excavated there. Unfortunately, no entire objects were unearthed in the excavations.[22] It is from this site that most of the new material analyzed here was derived. Forty-five colored glass fragments from Rozengracht in the collection of the MenA were sampled, including 3 polychrome fragments, to give a total of 50 glasses (24 whites, 26 blues). In addition, we had previously analyzed 24 colorless glasses from the site, and as these have been discussed in only a preliminary way,[23] they are also included here to provide a full understanding of the glass produced at the later site.

For comparative material from Phase 1 (Keizersgracht, site KG10), the initial location of De Twee Rozen, we are largely dependent upon previously published material. We present only a single new analysis, which is of a translucent green glass. Published full major-element analyses of colored glasses from Keizersgracht are limited to 14 samples presented by McCray and Warren,[24] but a neutron activation investigation of bead- and bead production–related material from the site by Karklins and

FIG 1. Examples of the production waste shards from De Twee Rozen glasshouse at Rozengracht, Phase 2, site RO21, which have been analyzed (*clockwise from upper left*): RO21-5-302, RO21-5-329, RO21-5-323, RO21-5-322, RO21-5-335, and RO21-5-305. (Photo: Michel Hulst, MenA, Monumenten en Archeologie, Gemeente Amsterdam)

19 Karklins and others 2002.

20 Pulido Valente and others 2021.

21 Gawronski and others 2010.

22 Although there are several examples of whole vessels tentatively attributed to De Twee Rozen in museums such as the Rijksmuseum in Amsterdam, their origin is uncertain, and they are not included in the discussion in this paper.

23 Kunicki-Goldfinger and Dzierżanowski 2010; Hulst and Kunicki-Goldfinger 2017.

24 McCray and Warren 2002.

others[25] provides a substantial body of information on the colorants and opacifiers used, although the analytical technique could not produce full major-element analyses. In addition, analyses of 38 fragments of weakly colored or colorless glass from the site are provided in De Raedt's thesis[26] and later also discussed by De Raedt and others.[27] Hulst and Kunicki-Goldfinger[28] also analyzed 13 samples of colorless glass, 10 of which had previously been analyzed by De Raedt; and McCray and Warren also analyzed several samples of colorless glass.[29] Overall, these publications provide a useful dataset for the first site of the glasshouse.

Both locations of De Twee Rozen glasshouse at Keizersgracht (Phase 1, marked as KG10) and at Rozengracht, (Phase 2, marked as RO21) and the actual location of the Soop glasshouse (KLO10) are shown on a map of Amsterdam (**Fig. 2**).

METHODS

Forty-six glass fragments from the collection of the MenA were sampled using a diamond tool. The samples were embedded in an artificial resin and polished with diamond pastes down to 0.25 μm grade.

A Nikon SMZ1000 zoom stereomicroscope with a CoolPix 4500 digital camera attachment was used to investigate the structures and morphology of the cross sections, following which they were coated with a thin layer of carbon and analyzed using a CamScan Maxim 2040 scanning electron microscope equipped with Oxford Instruments ISIS or INCA energy dispersive X-ray spectrometers (SEM-EDS) at the School of History and Archaeology, Cardiff University, Cardiff, United Kingdom.

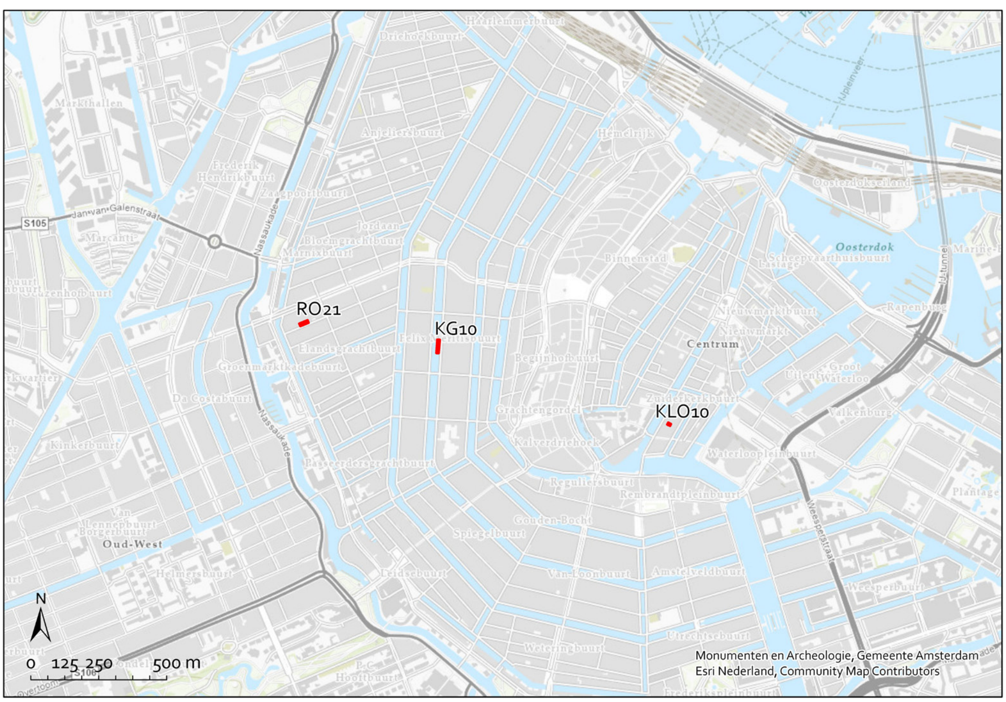

FIG 2. Map of Amsterdam with the glasshouse locations marked: KLO10: Soop glasshouse; KG10: De Twee Rozen at Keizergracht, Phase 1; RO21: De Twee Rozen at Rozengracht, Phase 2. (Map: MenA, Monumenten en Archeologie, Gemeente Amsterdam)

25 Karklins and others 2002.
26 De Raedt 2001.
27 De Raedt, Janssens, and Veeckman 2002.
28 Hulst and Kunicki-Goldfinger 2017.
29 McCray and Warren 2002.

Back-scattered electron (BSE) imaging was used to identify compositional changes on the cross sections of complex samples. For quantitative elemental analysis, the electron beam was rastered at a magnification of 500x over an area of fresh glass for 100 s, at 20 kV accelerating voltage. For complex samples, for the analysis of small areas of interest, the electron beam was rastered at high magnification or used in spot mode. Count-rate on metallic cobalt was around 4000 cps. Standards were pure oxides and minerals, and quantification was carried out using the ZAF method. Oxide weight percents were calculated stoichiometrically. Analytical totals were typically between 98% and 102% and have been normalized to 100% for comparative purposes. Detection limits were about 0.1% for most elements, but higher for SnO_2 and Sb_2O_5, at around 0.3%. Corning Reference Glass B[30] was used as a secondary standard. Good agreement between recommended and analyzed results was obtained in the case of most components (**Table 1**).

RESULTS

Details of samples and their compositions are presented in **Table 2**. The table includes both the new analyses (items 1 and 15–64) as well as the analyses of colorless glasses from De Twee Rozen glasshouse (items 2–14 and 65–88) that were published previously.[31] The table is arranged by the site (Phase 1, KG10: items 1–14; Phase 2, RO21: items 15–88) and color of the sample analyzed. Three complex, multicolored objects are also presented separately in **Table 3**.

Base glasses

All glasses analyzed are of the soda-lime-silica (Na_2O-CaO-SiO_2) type. They have K_2O and MgO contents close to or in excess of 1.5%, as is generally accepted for plant ash glass and is expected for the period. For comparison with literature data, and following standard practice,[32] we calculated *reduced* compositions, excluding components likely to have been associated with the opacifiers and/or coloring agents, and normalized them to 100%. The excluded oxides were Fe_2O_3, ZnO, PbO, CuO, CoO, NiO, and Sb_2O_5. If the normalized/reduced values are used in a figure, they are accompanied by an asterisk.

Two main types of colorless glass were made in Venice at this time: *vitrum blanchum*, which utilized unrefined plant ashes from the Levant with quartz pebbles; and a purer, clearer glass known as *cristallo*, which utilized soda extracted from ash by solution, also with quartz pebbles.[33] Common, weakly colored glass contained more alumina and iron oxide and was made using unrefined plant ash and sand.[34] The two Venetian colorless glass types are well distinguished on a scatter plot for CaO and Na_2O, reflecting the reduction in ash content and enhancement of soda in the *cristallo* process; similar (but not identical) groupings are reflected in the compositions from De Twee Rozen (**Fig. 3a, b**). The samples from Phase 2 (Rozengracht) show two similar groupings but are slightly shifted toward higher CaO and lower Na_2O relative to the Venetian glasses (**Fig. 3a**). The recipe for a *cristallo*-type glass (hereafter designated with a "C") appears to have been frequently used in Phase 2, and the majority of colorless

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30 Brill 1999; Vincenzi and others 2002; Adlington 2017.
31 Hulst and Kunicki-Goldfinger 2017.
32 Brill 1999.
33 Verità 1985, 2013a, b.
34 Verità 1985, 2013a, b.

TABLE 1. Recommended and analyzed compositions for Corning Reference Glass B, in wt %. Recommended values for SiO_2 from Vicenzi and others 2002; for SO_3 and Cl from Adlington 2017; for all others from Brill 1999.

Values	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	CaO	TiO_2	MnO	Fe_2O_3	ZnO	PbO	CuO	Sb_2O_5	SnO_2
Recommended	17.0	1.00	1.03	4.36	61.55	0.82	0.49	0.16	8.56	0.089	0.25	0.34	0.19	0.61	2.66	0.46	0.04
Analyzed (n = 6)	16.5	1.0	1.1	4.2	61.0	0.9	0.6	0.2	8.8	<	0.2	0.4	0.2	0.5	2.9	0.6	<
SD	0.2	0.0	0.0	0.1	0.5	0.1	0.1	0.0	0.2		0.1	0.1	0.1	0.1	0.3	0.2	

TABLE 2. Chemical compositions of glasses from De Twee Rozen glasshouse in Amsterdam, arranged by the site and color and designated in weight percentage (wt %).
KG10 = Keizersgracht; RO21 = Rozengracht; G = green; B = blue; W = opaque white; C = colorless (or not colored intentionally); < = below the detection limit
Items 2–14, 65–88 after Hulst and Kunicki-Goldfinger 2017 (additionally denoted with superscript[a] in column 1)

Item	Sample-color	Site-inv. no.	Object	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	CaO	TiO_2	MnO	Fe_2O_3	ZnO	PbO	CuO	CoO	NiO	Sb_2O_5
1	556-G	KG10–38	production waste	14.2	4.3	3.3	1.5	61.1	0.2	0.4	1.0	9.4	0.2	<	0.9	<	<	3.5	<	<	<
2[a]	540-C	KG10–227	moil?	12.6	5.9	3.0	2.0	64.6	0.2	0.2	0.8	8.9	0.1	0.6	0.7	0.1	0.2	<	<	<	<
3[a]	542-C	KG10–145	vessel remnant (colorless glass with colored threads)	13.3	6.2	3.3	1.6	63.9	0.2	0.3	0.8	8.2	0.1	0.6	0.9	<	0.5	<	<	<	<
4[a]	543-C	KG10–147	vessel remnant (colorless glass with colored threads)	13.5	5.3	3.5	1.7	63.3	0.3	0.3	0.8	9.3	<	0.8	0.9	<	0.2	<	<	<	<
5[a]	544-C	KG10–128	moil?	14.0	5.9	3.1	2.0	65.2	0.3	0.1	0.8	7.4	0.2	0.4	0.7	0.1	<	<	<	<	<
6[a]	545-C	KG10–135	vessel remnant	14.0	4.2	2.4	0.8	65.1	0.2	0.1	1.0	11.2	0.3	0.4	0.4	<	<	<	<	<	<
7[a]	546-C	KG10–132	moil?	13.6	3.8	3.1	1.7	66.6	0.4	0.3	0.8	8.2	<	0.6	0.8	<	<	<	<	<	<
8[a]	547-C	KG10–124	vessel remnant?	14.4	5.6	3.2	1.4	64.5	0.3	0.1	1.0	8.1	0.1	0.4	0.6	0.1	0.1	<	<	<	<
9[a]	548-C	KG10–129	production waste	14.6	5.6	3.4	1.4	63.8	0.2	0.2	1.0	8.3	0.2	0.5	0.8	0.1	<	<	<	<	<
10[a]	549-C	KG10–120	production waste	13.5	4.9	3.1	1.9	64.4	0.3	0.1	0.9	9.5	0.2	0.3	0.8	0.1	<	<	<	<	<
11[a]	550-C	KG10–61	vessel remnant?	13.5	5.3	3.0	0.9	64.0	0.3	0.2	0.9	10.8	<	0.6	0.6	<	<	<	<	<	<
12[a]	628-C	KG10–170	vessel wall (vessel with gilded lion mask)	15.0	3.7	2.7	0.9	64.8	0.3	0.3	1.1	10.3	0.1	0.4	0.4	<	<	<	<	<	<
13[a]	541-C	KG10–126	production waste	12.4	5.0	3.4	2.4	65.4	0.3	0.2	0.9	7.6	0.2	1.4	0.9	<	<	<	<	<	<
14[a]	551-C	KG10–168	remnants of not entirely melted glass in a pot	12.9	1.3	3.5	2.2	72.1	0.7	<	1.1	5.1	0.2	<	0.9	<	<	<	<	<	<
15	568-B	RO21–5–315	production waste (ribbed vessel?)	14.7	4.4	1.6	1.3	67.7	0.3	0.2	0.9	6.1	<	0.5	0.5	0.5	<	1.3	<	<	<
16	569-B	RO21–5–302	production waste	14.7	4.4	1.5	1.4	68.2	0.2	0.2	0.8	6.0	<	0.5	0.5	0.2	<	1.4	<	<	<
17	570-B	RO21–5–311	production waste	14.5	4.4	1.6	1.3	67.9	0.1	0.3	0.8	6.2	0.1	0.4	0.6	0.3	<	1.3	<	<	<
18	571-B	RO21–5–320	production waste	14.2	4.3	1.7	1.5	68.3	0.1	0.2	0.8	6.0	0.1	0.6	0.5	0.2	<	1.3	<	<	<
19	574-B	RO21–5–309	production waste	14.3	4.4	1.5	1.4	68.2	0.1	0.3	0.8	6.1	<	0.4	0.6	0.3	<	1.5	<	<	<

(contd.)

Item	Sample-color	Site-inv. no.	Object	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	CaO	TiO_2	MnO	Fe_2O_3	ZnO	PbO	CuO	CoO	NiO	Sb_2O_5
20	575-B	RO21–5–308	production waste	17.2	3.6	1.4	1.3	68.3	0.2	0.4	0.9	5.1	0.2	0.8	0.4	<	<	0.3	<	<	<
21	577-B	RO21–5–304	production waste	14.4	4.3	1.6	1.5	67.8	0.2	0.3	0.8	5.9	<	0.6	0.5	0.4	<	1.5	<	0.1	<
22	578-B	RO21–5–307	production waste	14.4	4.3	1.6	1.4	68.0	0.1	0.2	0.9	6.0	0.1	0.5	0.6	0.3	<	1.6	<	<	<
23	579-B	RO21–5–321	production waste	14.2	4.2	1.7	1.4	68.1	0.2	0.4	0.8	6.0	<	0.5	0.4	0.4	<	1.7	<	<	<
24	586-B	RO21–5–326	standalone prunt	15.3	4.4	1.4	1.3	67.6	0.1	0.4	0.9	6.2	<	0.2	0.3	0.6	<	1.4	<	<	<
25	588-B	RO21–5–303	production waste	14.5	4.3	1.6	1.4	67.9	0.2	0.3	0.9	6.0	0.2	0.5	0.4	0.2	<	1.6	<	<	<
26	589-B	RO21–5–318	production waste	14.3	4.3	1.7	1.5	67.9	0.3	0.3	0.8	5.8	0.2	0.5	0.7	0.3	<	1.4	<	<	<
27	595-B	RO21–5–305	production waste	14.4	4.4	1.6	1.4	68.8	0.2	0.2	0.8	6.0	<	0.4	0.4	<	<	1.4	<	<	<
28	596-B	RO21–5–312	production waste	14.8	3.4	1.9	1.1	67.8	0.1	0.2	1.0	6.0	0.1	0.5	0.5	0.5	<	2.2	<	<	<
29	598-B	RO21–5–317	production waste	13.9	4.0	1.6	1.2	69.0	0.1	0.1	0.7	6.0	0.2	0.7	0.6	<	<	1.8	<	<	<
30	599-B	RO21–5–310	production waste	14.2	4.2	1.6	1.4	68.4	0.3	0.3	0.8	5.9	<	0.4	0.5	0.3	<	1.5	<	<	<
31	602-B	RO21–5–316	production waste	14.2	4.5	1.6	1.4	68.1	0.3	0.2	0.9	6.2	0.1	0.5	0.5	0.3	<	1.4	<	<	<
32	604-B	RO21–5–306	production waste	14.1	4.4	1.7	1.6	68.0	0.2	0.4	0.8	6.2	<	0.6	0.6	<	<	1.5	<	<	<
33	605-B	RO21–5–314	production waste	14.6	4.3	1.6	1.3	68.2	0.2	0.1	0.8	5.9	<	0.5	0.4	0.4	<	1.5	<	<	<
34	606-B	RO21–5–319	production waste	16.5	3.7	1.5	1.5	67.0	0.3	0.4	0.8	5.4	<	0.3	0.5	0.4	<	1.7	<	<	<
35	610-B	RO21–5–322	production waste	15.2	4.5	1.6	1.3	65.9	0.2	0.4	1.0	5.9	<	<	0.5	0.9	<	2.4	<	<	<
36	611-B	RO21–5–313	production waste	14.9	4.1	1.4	2.3	69.3	0.2	0.3	0.9	4.5	0.2	0.3	0.4	<	<	1.4	<	<	<
37	615-B	RO21–5–324	production waste	14.5	4.1	1.5	1.8	70.2	0.1	0.2	0.9	4.9	<	<	0.3	<	<	1.4	<	<	<
38	581-B	RO21–5–336	production waste (flashed glass: blue&white)	14.6	3.4	1.3	0.7	68.0	0.2	<	1.1	5.0	<	<	<	1.6	<	4.0	<	<	<
39	594-B	RO21–5–288	colorless beaker. Vetro a fili (blue, opaque white and colorless core)	9.8	5.1	2.7	1.5	62.2	0.2	0.2	0.9	10.5	<	<	0.9	<	4.8	0.5	0.6	0.2	<
40	597-B	RO21–5–323	rod with colorless core overlaid with opaque white and outer blue layer	9.0	4.9	2.7	1.7	61.2	0.2	<	0.7	10.1	<	<	1.4	<	6.3	0.5	0.8	0.3	<
41	563-W	RO21–5–294	production waste (opaque white threads on lattimo underlay)	10.5	3.8	3.4	1.4	53.7	0.4	0.4	0.4	14.0	<	<	0.5	<	2.0	<	<	<	9.4
42	565-W	RO21–5–287	production waste (opaque white thread/cane)	13.5	3.4	3.7	1.6	59.6	0.3	0.5	0.5	8.7	0.1	0.2	0.7	<	2.7	<	<	<	4.6
43	573-W	RO21–5–334	production waste	9.6	5.0	3.3	2.1	56.2	0.1	0.6	0.5	13.1	<	<	0.7	<	3.4	<	<	<	5.6
44	587-W	RO21–5–327	production waste	13.4	3.4	3.0	1.4	58.7	<	0.5	0.6	9.9	0.2	<	0.4	<	2.6	<	<	<	5.7
45	593-W	RO21–5–339	production waste	10.0	4.9	3.0	2.0	57.0	0.2	0.5	0.4	12.9	0.2	0.2	0.5	<	2.7	<	<	<	5.5
46	594-W	RO21–5–288	production waste (fragment with opaque white, blue and red threads)	8.4	4.8	3.2	1.7	61.4	0.4	0.5	0.6	11.2	0.1	<	0.6	0.2	3.0	<	<	<	3.8

(contd.)

Item	Sample-color	Site-inv. no.	Object	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	CaO	TiO_2	MnO	Fe_2O_3	ZnO	PbO	CuO	CoO	NiO	Sb_2O_5
47	597-W	RO21–5–323	rod with colorless core overlaid with opaque white and outer blue layer	10.3	3.9	3.3	1.8	54.8	0.3	0.3	0.5	13.1	<	<	0.5	<	3.7	<	<	<	7.5
48	600-W	RO21–5–15	single thread of lattimo	11.0	4.5	2.8	1.2	60.7	0.1	0.5	0.4	9.4	<	0.3	0.5	<	1.8	<	<	<	6.7
49	614-W	RO21–5–16	single thread of lattimo	14.7	3.0	2.6	1.0	59.0	0.3	0.8	0.6	8.1	0.3	<	0.4	<	3.4	<	<	<	5.9
50	621-W	RO21–5–344	production waste	9.5	5.0	3.1	2.0	54.7	0.2	0.6	0.4	13.1	0.1	<	0.7	<	3.5	<	<	<	6.6
51	572-W	RO21–5–335	production waste	10.8	2.6	3.6	1.7	58.4	0.2	0.7	0.4	10.4	<	0.2	0.6	<	3.7	<	<	<	6.6
52	581-W	RO21–5–336	production waste (flashed glass: blue&white)	12.2	2.8	3.4	1.4	59.5	0.3	0.4	0.4	10.3	<	<	0.5	<	3.0	<	<	<	5.7
53	582-W	RO21–5–342	production waste	11.3	2.9	3.7	1.4	58.1	0.3	0.5	0.4	10.8	0.1	0.1	0.7	<	3.5	<	<	<	6.1
54	583-W	RO21–5–330	production waste	11.4	2.5	3.7	1.4	59.6	0.3	0.5	0.5	10.0	<	0.3	0.5	<	3.4	<	<	<	5.9
55	584-W	RO21–5–338	production waste	10.8	2.7	3.6	1.5	59.8	0.3	0.3	0.4	10.4	<	0.2	0.6	<	3.2	<	<	<	6.1
56	585-W	RO21–5–332	production waste (opaque white substrate with violet threads on the surface)	11.6	2.4	3.5	1.5	59.8	0.2	0.7	0.5	9.8	<	0.3	0.5	<	3.2	<	<	<	5.9
57	601-W	RO21–5–328	production waste	11.2	2.6	3.5	1.6	59.1	0.3	0.4	0.4	10.2	<	<	0.6	<	3.3	<	<	<	6.7
58	603-W	RO21–5–333	production waste	10.3	2.6	3.5	1.6	58.2	0.3	0.7	0.4	11.0	0.2	<	0.5	<	3.7	<	<	<	7.2
59	607-W	RO21–5–343	production waste with grains of sand embedded in the surface	10.3	2.9	3.6	2.6	58.8	0.3	0.4	0.3	10.3	<	0.1	0.7	<	3.4	<	<	<	6.4
60	608-W	RO21–5–340	production waste	11.3	2.4	3.7	1.6	59.9	0.3	0.5	0.4	10.0	<	<	0.5	<	3.4	<	<	<	6.0
61	609-W	RO21–5–329	production waste	12.0	2.7	3.4	1.6	59.8	0.3	0.6	0.5	9.9	<	<	0.5	<	3.0	<	<	<	5.6
62	612-W	RO21–5–337	production waste	10.9	2.6	3.4	1.5	59.1	0.3	0.7	0.4	10.3	0.2	0.2	0.8	<	3.6	<	<	<	6.0
63	613-W	RO21–5–331	production waste	11.0	2.6	3.7	1.5	58.6	0.2	0.5	0.4	10.5	<	<	0.5	<	4.0	<	<	<	6.5
64	619-W	RO21–5–341	production waste	11.6	2.8	3.7	1.5	56.6	0.2	0.6	0.4	11.6	0.2	<	0.5	<	3.7	<	<	<	6.6
65[a]	562-C	RO21–5–298	production waste unidentified	14.7	5.1	1.9	1.6	65.6	0.2	0.3	0.9	8.2	<	1.0	0.5	<	<	<	<	<	<
66[a]	563-C	RO21–5–294	Beaker with opaque white vetro a fili	11.1	5.2	2.9	1.5	64.5	0.3	0.4	0.8	11.9	0.2	0.6	0.4	0.1	0.1	<	<	<	<
67[a]	592-C	RO21–5–291	beaker	12.8	4.4	2.8	2.0	64.7	0.4	0.2	0.8	10.2	<	0.9	0.7	0.1	0.1	<	<	<	<
68[a]	594-C	RO21–5–288	beaker with blue and white vetro a fili	11.1	4.4	2.8	1.5	63.9	0.3	0.2	0.8	11.9	<	0.6	0.5	0.2	0.1	<	<	<	<
69[a]	597-C	RO21–5–323	colorless core of multicolored rod	10.8	4.4	2.9	1.8	64.7	0.3	<	0.8	11.4	0.2	0.6	0.7	0.1	0.5	<	<	<	<
70[a]	616-C	RO21–5–284	mirror glass	13.3	4.4	2.7	1.3	64.7	0.2	0.3	0.9	10.8	0.2	0.6	0.5	<	<	<	<	<	<
71[a]	618-C	RO21–5–283	moil	14.8	4.4	2.0	1.6	65.5	0.2	0.3	0.9	8.1	0.1	1.0	0.6	<	<	<	<	<	<
72[a]	620-C	RO21–5–292	moil	14.6	4.4	2.1	1.7	65.2	0.2	0.2	0.9	8.1	0.2	1.1	0.5	0.1	0.1	<	<	<	<
73[a]	488-C	RO21–5-1	moil	14.8	6.1	1.3	1.8	67.6	0.1	0.2	0.6	5.6	0.1	1.2	0.6	<	<	<	<	<	<

(contd.)

Item	Sample-color	Site-inv. no.	Object	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	CaO	TiO_2	MnO	Fe_2O_3	ZnO	PbO	CuO	CoO	NiO	Sb_2O_5
74[a]	489-C	RO21–5-2	moil	17.0	3.5	1.3	1.2	69.2	0.2	0.4	0.7	5.1	0.1	0.9	0.3	<	<	<	<	<	<
75[a]	490-C	RO21–5-3	moil	15.2	4.2	1.4	2.2	69.3	0.2	0.2	0.8	4.7	0.1	1.0	0.5	<	<	<	<	<	<
76[a]	558-C	RO21–5–300	production waste unidentified	15.5	4.7	1.4	1.2	68.1	0.1	0.3	1.0	6.1	<	0.8	0.5	<	0.1	<	<	<	<
77[a]	559-C	RO21–5–296	rod	16.0	4.5	1.5	1.5	67.7	0.2	0.3	1.0	6.1	<	0.7	0.4	<	<	<	<	<	<
78[a]	560-C	RO21–5–301	production waste unidentified	14.0	4.8	1.4	1.4	69.8	0.1	0.2	1.0	6.2	<	0.8	0.3	<	<	<	<	<	<
79[a]	561-C	RO21–5–299	production waste unidentified	14.9	3.5	2.1	1.4	68.7	0.1	0.1	0.9	6.3	0.2	1.1	0.4	0.1	0.1	<	<	<	<
80[a]	564-C	RO21–5–295	trim off	16.7	3.6	1.5	1.2	68.6	0.1	0.4	0.9	5.2	<	0.8	0.4	<	0.1	<	<	<	<
81[a]	565-C	RO21–5–287	Colorless rod with opaque white thread inside	16.7	4.1	1.8	1.3	69.7	0.2	0.4	0.8	4.2	<	0.6	0.3	<	<	<	<	<	<
82[a]	566-C	RO21–5–286	beaker	14.0	4.2	1.9	1.3	69.2	0.1	<	1.1	6.6	0.1	1.0	0.4	<	<	<	<	<	<
83[a]	567-C	RO21–5–285	trim off	14.1	4.2	2.0	1.1	69.2	0.2	0.2	1.0	6.4	<	1.0	0.4	0.1	<	<	<	<	<
84[a]	576-C	RO21–5–297	production waste unidentified	15.5	4.4	1.7	1.6	67.9	0.2	0.3	0.8	6.0	0.1	0.9	0.4	<	0.1	<	<	<	<
85[a]	580-C	RO21–5–293	moil	15.7	4.4	1.5	1.4	67.9	0.3	0.3	0.9	6.1	0.1	0.8	0.5	0.1	<	<	<	<	<
86[a]	590-C	RO21–5–289	winged goblet	14.6	4.4	1.5	1.0	70.1	0.2	0.1	0.9	5.5	<	0.5	0.4	<	0.3	<	<	<	<
87[a]	591-C	RO21–5–290	moil	12.8	4.4	1.7	1.4	71.7	0.3	0.1	1.0	6.4	0.1	0.9	0.6	0.1	<	<	<	<	<
88[a]	617-C	RO21–5–282	drop	14.2	4.4	2.2	1.3	69.4	0.3	0.2	1.0	6.5	0.1	0.7	0.4	0.1	<	<	<	<	<

TABLE 3. Chemical compositions of the single parts of complex glass fragments from De Twee Rozen glasshouse at Rozengracht (site RO21) in Amsterdam. Results are in weight percentage. < - below the detection limit; B – blue; W – opaque white; C – colorless.

Item in table 2	Sample-color	Inv. no.	Object	Na_2O	K_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	CaO	TiO_2	MnO	Fe_2O_3	ZnO	PbO	CuO	CoO	NiO	Sb_2O_5
38	581-B	RO21–5–336	production waste (flashed glass: blue&white).	14.6	3.4	1.3	0.7	68.0	0.2	<	1.1	5.0	<	<	<	1.6	<	4.0	<	<	<
52	581-W			12.2	2.8	3.4	1.4	59.5	0.3	0.4	0.4	10.3	<	<	0.5	<	3.0	<	<	<	5.7
39	594-B	RO21–5–288	beaker with blue and opaque white vetro a fili. **Fig. 9a, b**.	9.8	5.1	2.7	1.5	62.2	0.2	0.2	0.9	10.5	<	<	0.9	<	4.8	0.5	0.6	0.2	<
46	594-W			8.4	4.8	3.2	1.7	61.4	0.4	0.5	0.6	11.2	0.1	<	0.6	0.2	3.0	<	<	<	3.8
68[a]	594-C			11.1	4.4	2.8	1.5	63.9	0.3	0.2	0.8	11.9	<	0.6	0.5	0.2	0.1	<	<	<	<
40	597-B	RO21–5–323	rod with colorless core overlaid with opaque white and outer blue layer. **Fig. 8a, b**.	9.0	4.9	2.7	1.7	61.2	0.2	<	0.7	10.1	<	<	1.4	<	6.3	0.5	0.8	0.3	<
47	597-W			10.3	3.9	3.3	1.8	54.8	0.3	0.3	0.5	13.1	<	<	0.5	<	3.7	<	<	<	7.5
69[a]	597-C			10.8	4.4	2.9	1.8	64.7	0.3	<	0.8	11.4	0.2	0.6	0.7	0.1	0.5	<	<	<	<

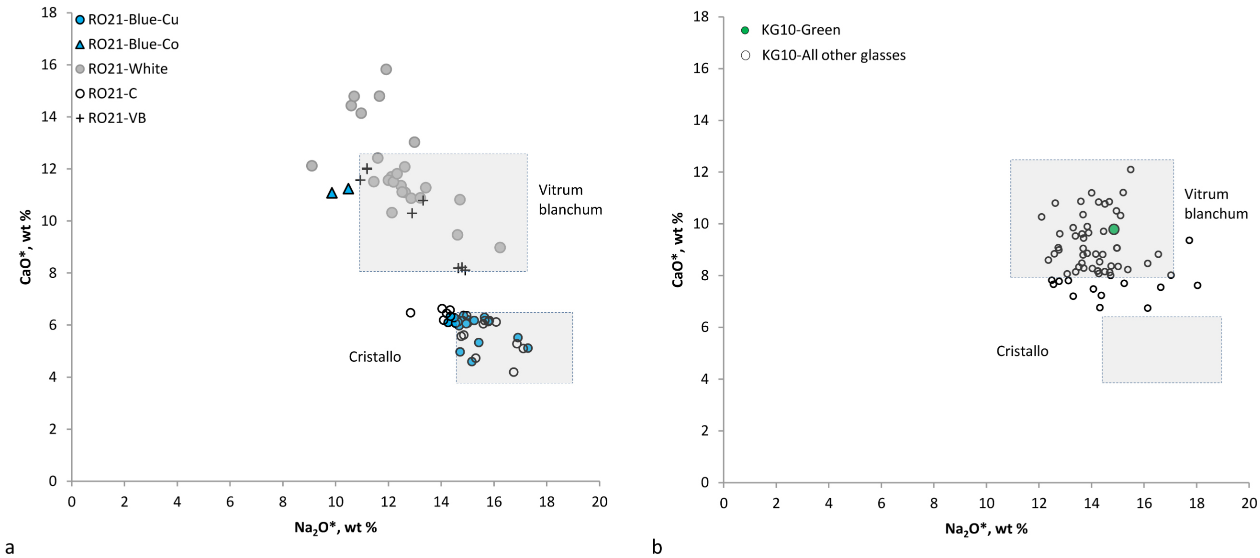

FIG 3. Scatter plots for CaO and Na_2O reduced concentrations for the glasses from De Twee Rozen glasshouse; gray rectangular boxes indicate fields characteristic for Venetian *vitrum blanchum* and *cristallo* (after Verità 2013a): (a) Glasses from Rozengracht, Phase 2 (site RO21), analyzed blue and opaque white glasses from the present study highlighted; (b) Glasses from Keizersgracht, Phase 1 (site KG10) (after De Raedt 2001, McCray and Warren 2002, Hulst and Kunicki-Goldfinger 2017), analyzed green glass from the present study highlighted. C = *cristallo* type (refined ash), VB indicates *vitrum blanchum* type (unrefined ash). (Graphic: the authors)

fragments analyzed so far also represent this technological type. However, among the colored glasses from this site, only Cu-rich blues (**Table 2**, items 35–38) fit the *cristallo* group while all other colors—opaque white (**Table 2**, items 41–64) and Co-rich blue (**Table 2**, items 39–40)—have lime and soda contents similar to those of *vitrum blanchum*. In contrast, *cristallo*-type glass does not appear to be present in the analyses from the earlier Phase 1 glasshouse at Keizersgracht, where the samples match Venetian *vitrum blanchum* in terms of CaO and Na_2O (**Fig. 3b**). There are three Phase 1 (Keizersgracht) samples (KG10/5/C[35]; AmSo/KG10-1/1[36]; KG10-168, see **Table 2**, item 14) which have lower CaO contents, approaching those of the *cristallo*-type group. However, all also have relatively high alumina, and the only well-described sample among these is a contaminated glass from a clay pot (KG10-168).[37] These three glasses are excluded from further discussion.

While glassmaking in Venice depended on imported plant ash from the Levant, other European glasshouses made use of barilla, a more accessible ash made from halophytic plants from the western Mediterranean region, particularly Spain.[38] The concentration of potassium is generally considered to discriminate between Levantine and barilla ashes, and while 4–4.5 wt % K_2O is often indicated as the threshold value,[39] the maximum reported value in Venetian *cristallo* is 3.65%.[40] The reduced compositions of glasses from both locations of De Twee Rozen glasshouse are shown on

35 McCray and Warren 2002.
36 De Raedt 2001.
37 Hulst and Kunicki-Goldfinger 2017.
38 Neri (1612) 2006, 75.
39 E.g. Cagno and others 2010, 2012; Occari, Freestone, and Fenwick 2021.
40 Verità 2013a. Nevertheless, the wine stone could also be a source of some potassium in Venetian glass of the discussed period, as the oldest mention about its use is from the mid-fifteenth century; see, e.g., Zecchin 1997.

a scatter plot for MgO and K_2O in **Figure 4**, along with analyses of Venetian *cristallo* and *vitrum blanchum*. Note the separation of the Venetian *cristallo* and *vitrum blanchum* in terms of MgO, reflecting the removal of insoluble magnesia during ash purification, and that this same pattern is reflected in the De Twee Rozen glasses but at higher K_2O concentrations, with those for the majority of De Twee Rozen's products above about 3.4% (to the right of line A on **Figure 4**). This high K_2O reflects the use of Spanish barilla ash rather than Levantine ash in its production (see above).[41] Previously, a threshold value of 4–4.5% has been used to delineate the boundary between barilla and Levantine ashes, but it appears that the present lower value of 3.4% is more appropriate. Furthermore, the boundaries between the different categories of glass are not absolute—there is some potential overlap with occasional outliers plotting in the regions of another group. A small portion of De Twee Rozen's products are characterized by a significantly lower K_2O, similar to that expected from glass made from Levantine ash. The majority with K_2O below 3.4% are a group of 14 opaque whites from Phase 2 (**Table 2**, items 51–64), although another 10 opaque whites (**Table 2**, items 41–50) are spread across the range of K_2O for barilla ash (**Fig. 4**). The low-K_2O group has some similarity to Levantine ash on the basis of our criterion and will be further discussed below.

Summing up, the majority of De Twee Rozen glasses, with the possible exception of a group of 14 opaque whites and 1 colorless glass from Phase 2 as well as 2 colorless glasses and 1 opaque white from Phase 1, were melted with the use of western Mediterranean (high K_2O) barilla-type ash or its refined product. It is an open question whether the low-potash samples were melted with Levantine ashes or a batch of barilla ash with a similarly low concentration of potassium.

The reduced Al_2O_3 concentrations for the majority of De Twee Rozen products lie between 0.7 and 2.9% (**Fig. 5**), with a single outlier from the Phase 1 site having 3.6% of alumina.[42] (Note: This sample is not shown on the plots as it lies off scale). Both *cristallo* and *vitrum blanchum* from Venice were made using crushed quartz pebbles and

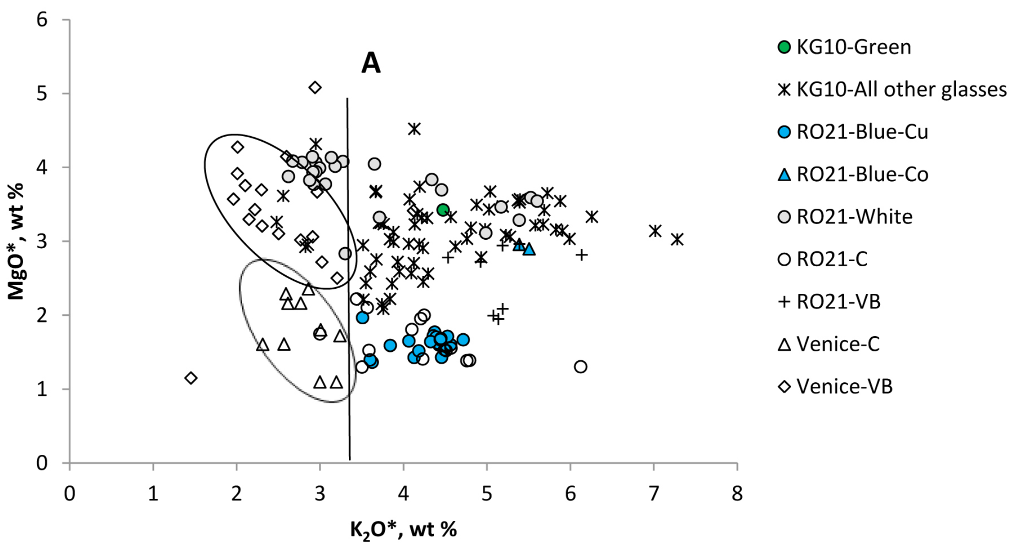

FIG 4. Scatter plot for MgO and K_2O normalized concentrations for the analyzed glasses and for all published glasses from both locations of De Twee Rozen (sites KG10-Phase 1 and RO21-Phase 2; after De Raedt 2001, McCray and Warren 2002, Hulst and Kunicki-Goldfinger 2017); ellipses indicate areas characteristic for the majority of Venetian *vitrum blanchum* and *cristallo* objects (after Verità 1985, 2013a). Line A at 3.4 wt % K_2O marks the inferred boundary separating most glass made with Levantine ash from that made with barilla. (Graphic: the authors)

41 De Raedt, Janssens, and Veeckman 2002.
42 McCray and Warren 2002.

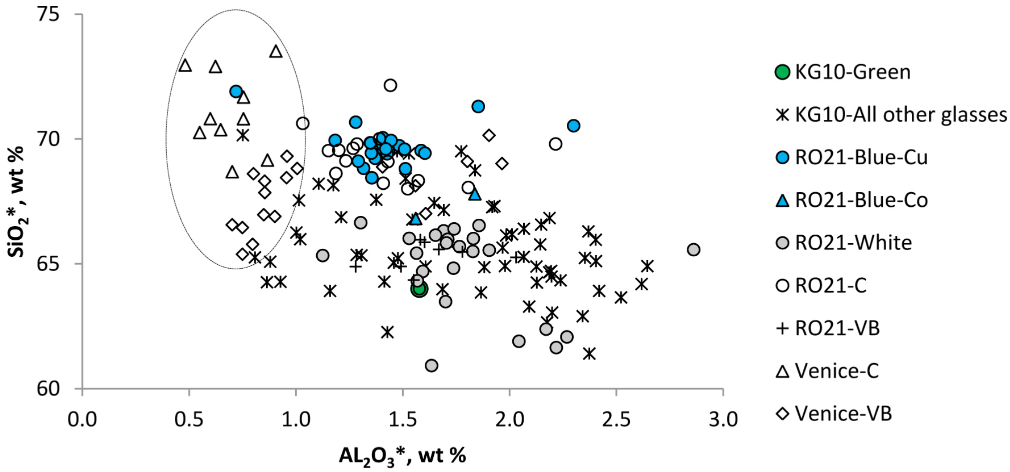

FIG 5. Scatter plot for SiO_2 and Al_2O_3 normalized concentrations for the analyzed colored glasses and for all other published glasses from both locations of De Twee Rozen (sites KG10-Phase 1 and RO21-Phase 2; after De Raedt 2001, McCray and Warren 2002, Hulst and Kunicki-Goldfinger 2017); ellipse indicates areas characteristic for the majority of Venetian *vitrum blanchum* and *cristallo*, melted with the use of pebbles (after Verità 1985, 2013a). (Graphic: the authors)

typically have Al_2O_3 below one percent, so it seems likely that both De Twee Rozen glasshouses utilized sand as a silica source.

The *cristallo*-like colorless glasses and Cu-rich blues from Phase 2 are characterized by the highest SiO_2/Al_2O_3 ratios from both locations of the glasshouse and can therefore be inferred to have used the best-quality raw materials (**Fig. 5**). However, the opaque whites from Phase 2 contain significantly lower SiO_2/Al_2O_3 ratios, which is also characteristic of the majority of glasses from Phase 1, including the single green glass, and is consistent with the use of a less-pure ash or silica source.

The quality of the raw materials can also be assessed by the content of iron oxide, which is an indicator of sand quality but also was deliberately reduced by refining the ash. **Figure 6** illustrates that the lowest contents of Fe_2O_3 as well as of Al_2O_3 are characteristic of Venetian *cristallo* and then for *vitrum blanchum*. Phase 2 *cristallo*-type (both Cu-rich blues and colorless) has on average twice as much of these oxides as Venetian *cristallo*. However, iron contents of some of the samples from Phase 1 are significantly higher still (**Fig. 6**), suggesting that lower-quality sand was used. Nevertheless, it looks as if there were various qualities of sand used in both phases of De Twee Rozen glasshouse.

The common decoloring agent in use across Europe in the seventeenth century was pyrolusite (MnO_2). For the best-quality glasses in Venice—*cristallo* and to lesser extent *vitrum blanchum*—there is correlation between contents of Fe_2O_3 and MnO, as pyrolusite was added directly to the melted batch at the glassworking stage depending on the amount needed to minimize the color, rather than as a fixed concentration.[43] However, in a scatter plot for Fe_2O_3 against MnO (**Fig. 7**), we can see that in the case of the glasses from De Twee Rozen, independent of location, there is no correlation between Fe_2O_3 and MnO. High MnO is characteristic of the *cristallo*-like Phase 2 glasses, ranging from 0.x to 1.2%, as well as some of the Phase 1 colorless samples. Moreover, MnO is below detection limits (about 0.1%) in many of the colored glasses such as green, Co-rich blues, some opaque whites (Sb-rich), and one Cu-rich blue from Phase 2, as well as one opaque white (Sn-rich) from Phase 1—sample 6W published by McCray and Warren.[44] Generally, all opaque whites from both locations have MnO below 0.3%. Cu-rich blues from

43 Verità 2013b.
44 McCray and Warren 2002.

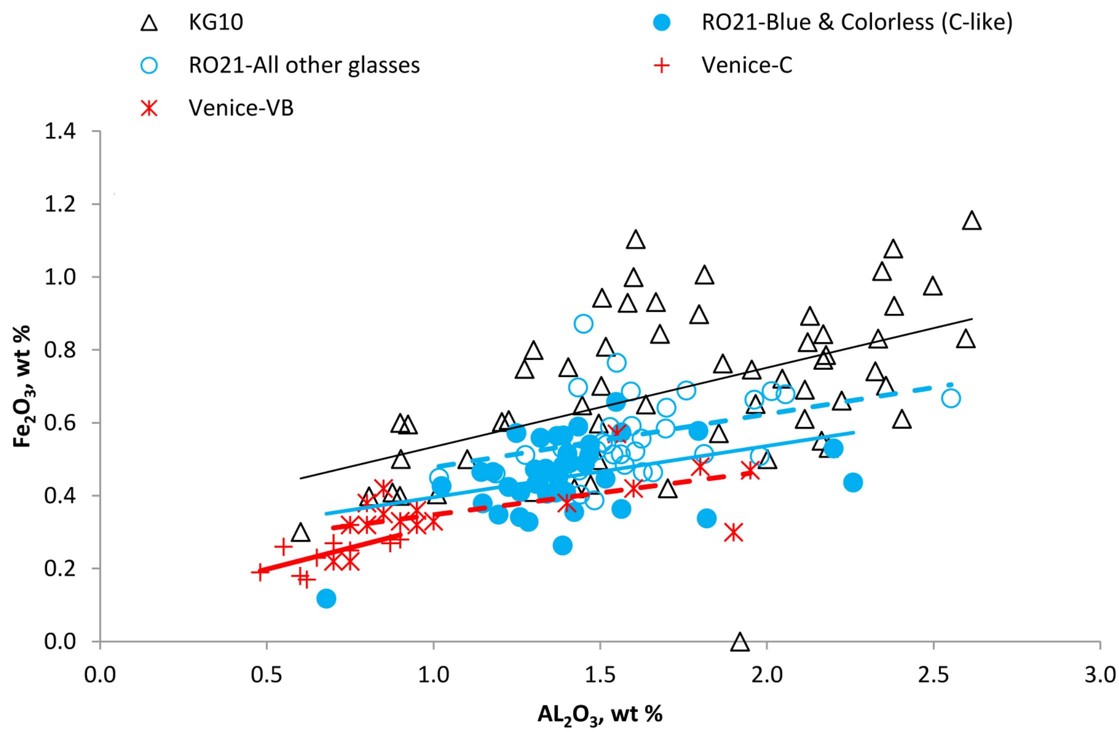

FIG 6. Scatter plot for Fe_2O_3 and Al_2O_3 concentrations for the analyzed glasses and for other published glasses from both locations of De Twee Rozen glasshouse (sites KG10 and RO21; after De Raedt 2001, McCray and Warren 2002, Hulst and Kunicki-Goldfinger 2017), and for Venetian *vitrum blanchum* and *cristallo* (after Verità 1985, 2013a). A few glasses with very high Fe_2O_3 are not shown. The highest content of Fe_2O_3 (3.3%) was in a red glass from Phase 1 (Keizersgracht, site KG10; McCray and Warren 2002) and was probably added to promote the color. (Graphic: the authors)

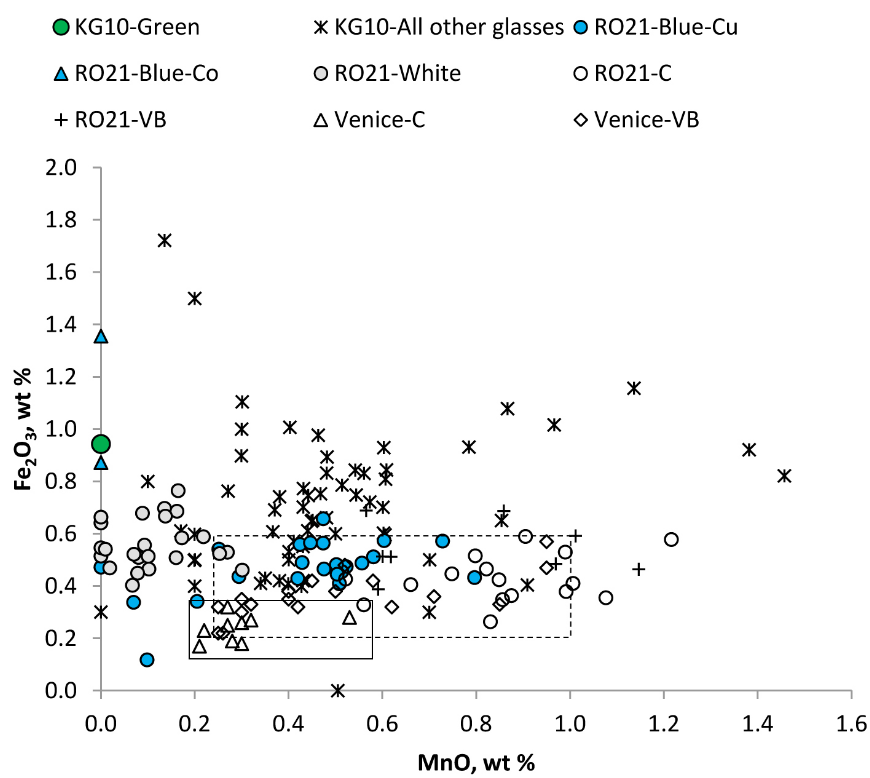

FIG 7. Scatter plot for Fe_2O_3 and MnO concentrations for glasses from both locations of De Twee Rozen (this study, and after De Raedt 2001, McCray and Warren 2002, Hulst and Kunicki-Goldfinger 2017); rectangular boxes indicate areas characteristic for Venetian *vitrum blanchum* and *cristallo* (after Verità 1985, 2013a). (Graphic: the authors)

Phase 2 constitute, from this point of view, a very different group of colored glasses—for the majority of them, MnO content is in the range 0.4–0.6% (with the maximum content reaching about 0.8%). This could suggest that copper colorant was added to a previously prepared batch of *cristallo*-type glass that already contained pyrolusite. Good control would have been required to ensure that the base glass was sufficiently oxidized to produce the blue color due to Cu^{2+} while not over-oxidized so that the blue was spoiled by the formation of purple Mn^{3+}. On the other hand, we also can expect that manganese could be added to the batch as well as copper or brass, as can be found in some historical recipes of the period and discussed further below.

Blue Colorants

Among the glasses of various blue shades, two subgroups may be distinguished: Cu-rich and Co-rich (**Table 2**, items 15–38 and items 39–40, respectively). They differ from each other in shade, chemical composition, and use in the final glass product. Cu-rich glass forms the larger group of 24 fragments and is significantly lighter than the Co-colored glass. All these samples were taken from production waste, presumably from production of vessels, or from fragments of vessels. The CuO content for over 80% of the Cu-rich blue vessel glasses is in a narrow range of 1.3–1.8% (**Table 2**). Copper blues are normally richer in zinc with a typical content of 0.3%, indicating the use of oxidized copper alloy ("scale") as a colorant. They also contain on average 0.5% of MnO.

As previously mentioned, all the Cu-rich blue vessel glasses from Phase 2 were based on a *cristallo*-type base glass. According to written sources, translucent blue glass was typically prepared in Venice also based on *cristallo* formulation,[45] which is confirmed by chemical analyses of genuine Venetian objects.[46]

Co-rich blues represent a second type of blue from Phase 2, represented in the present study by only two examples (**Tables 2** and **3**, items 39, 40; samples 594 and 597), both of which are thin blue layers within complex multicolored decoration (**Figs. 8a, b; 9a, b**). The color of these glasses is much more intense and deep than of Cu-rich ones. Both Co-rich glasses contain about 0.7% CoO, about 0.25% NiO, about 0.5% CuO, as well as Fe_2O_3 (0.9 and 1.4% respectively) and PbO (4.8 and 6.3% respectively). The glasses are relatively rich in lime (about 10%) and thus they do not follow the approach characteristic of Venetian *cristallo*. Their composition is quite similar to the blues manufactured earlier at Keizersgracht (Phase 1) and analyzed by McCray and Warren.[47] Both examples represent Co-Ni type of blues with a CoO/NiO ratio about 3. The known cobalt ores in the seventeenth century were sourced mainly from the mining district of Schneeberg in the Erzgebirge on the German-Czech border.[48] Although not homogenous,[49] they typically contained As and are represented as a Co-As-Ni type. In the present case, no signal from As was detected. This is of potential interest, as several Venetian vessel glasses preliminarily dated to the second half of the sixteenth century through the seventeenth century[50] contain no arsenic, and one of these contains over 6% PbO, which has not been observed in Renaissance Venetian glass. However, it is

45 E.g., Moretti and Toninato 2011.
46 E.g., Verità and Zecchin 2008.
47 McCray and Warren 2002.
48 See, e.g., Colomban, Kırmızı, and Şimşek Franci 2021; Gratuze and others 1992, 1995, 1996.
49 See, e.g., Zlámalová Cílová, Gelnar, and Randáková 2020.
50 Biron and Verità 2012, table 2, sample nos. OA7566, OA1014.

very similar to the composition of our two Co-rich glasses from Rozengracht. Unfortunately, we are unable at the present time to confirm unequivocally the absence of As because of the limitations of our measurement technique, where there is an overlap of the Mg-Kα and As-Lα X-ray peaks which may mask low levels of As.

Regarding the colors of these glasses and their names, "it is necessary to underline that the definition of the color obtained [in the discussed time] doesn't always seem to correspond to the definition that we would give today," as Watts and Moretti noted.[51] Considering only two sources, the anonymous recipe book from the mid-sixteenth century and *L'arte vetraria* by Antonio Neri from 1612, one can encounter many names, such as blue, deep blue, sky color, turquoise, sea-green, lapis lazuli, and others. Generally, in these sources, two main groups of blues can be distinguished based on the raw materials used as the coloring agents. One group involved the use of zaffer (crystalline cobalt pigment) as a colorant with or without copper and manganese, while the other used copper or brass, also with or without manganese. However, some recipes, from this point of view, are intermediate ones. In most cases, Co-rich glasses are called blue or deep blue, while all the other terms from the above list concern Cu-rich glass. But there are exceptions, often causing terminological confusion. Recipe X from the anonymous recipe book concerns a blue glass based on *cristallo* and obtained with the use of manganese and copper without any opacifying agent, and it is entitled: "To make Arabico [opaque aquamarine color] a very showy deep blue, more than blue (and called so)."[52] The same source also lists other blues called turquoise or just blue. When copper or brass was the main coloring agent, even with an addition of small amount of zaffer, Neri used such names as sky, sea-green, turquoise, lapis lazuli, and

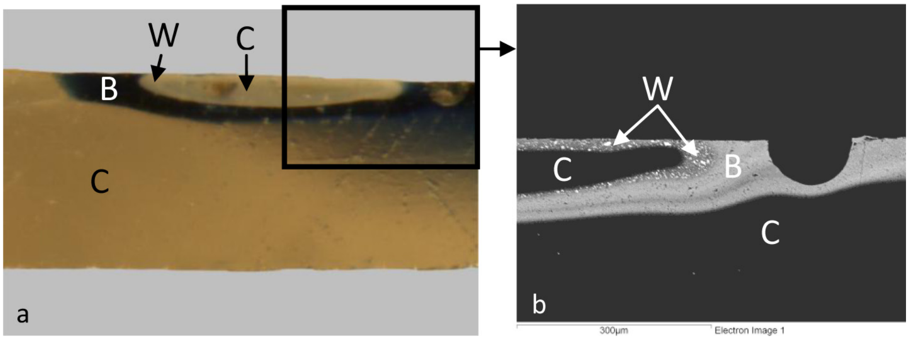

FIG 8. Cross sections of a fragment (RO21-5-288) of a colorless (C) vessel with Co-blue (B) and opaque white (W) inlaid decoration, *vetro a fili* (flattened and embedded multicolored cane with colorless core?) (sample no. 594): (a) Optical microscope image; (b) BSE image of black-framed area in (a). Scale below (b). (Photos: Jerzy J. Kunicki-Goldfinger)

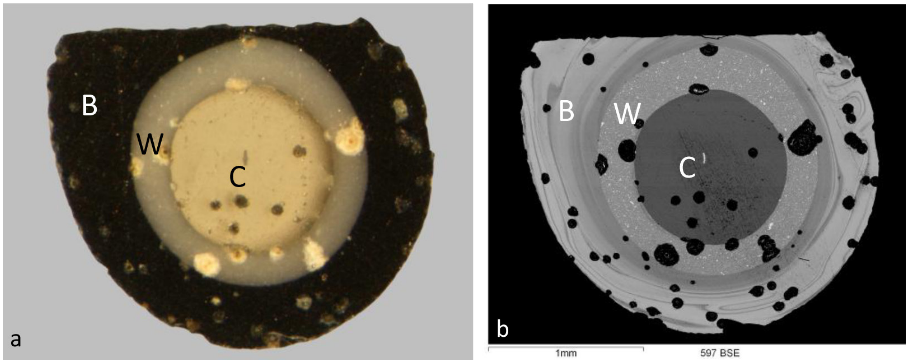

FIG 9. Cross sections of a cane (RO21-5-323) with colorless (C) core overlaid with opaque white (W) and outer Co-blue (B) layer (sample no. 597): (a) Optical microscope image; (b) BSE image at the same magnification. Scale below (b). (Photos: Jerzy J. Kunicki-Goldfinger)

51 Moretti and Toninato 2011, 43.
52 Moretti and Toninato 2011, 53; table 3 on p. 46.

so on. In his Chapter 36, he discusses "a blew or Turcois, a principal color in this art."[53] Moreover, various recipes deal with enamels, pastes, or opacified glasses that imitate a variety of stones, such as sapphire, lapis lazuli, aquamarine, and turquoise. Thus, in some cases it is quite difficult now to unambiguously separate and name correctly these groups of glasses. In this paper, to avoid confusion, we use the terms Cu- and Co-rich blue based on chemical composition rather than on historical terms or names.

White Opacifiers

The opaque white samples include vessel glass as well as various decorative elements, typically threads or thin layers in multicolored canes. The Phase 2 white glasses analyzed here were opacified with antimony, presumably present as calcium antimonate (mean Sb_2O_5 6.2% with a range of 3.8–9.4%) (**Table 2**, items 41–64; **Fig. 10**). They differ without exception from the whites manufactured in Phase 1 of the glasshouse, which were always opacified with tin oxide (SnO_2).[54]

Taken as a group, the opaque whites from Phase 2 spread across the boundary of 3.4% K_2O, taken here as the lower limit of glass made with barilla-type ash (see **Figure 4**, line A). Of the 24 analyzed examples of antimony-opacified white glasses, the bigger and more homogeneous group of 14 fragments is of the low-potash type (**Table 2**, items 51–64). They form a tight group marked on **Figure 11** within the ellipse and may represent the products of a single campaign of production. Their iron oxide and alumina contents group them firmly with the sand-based glasses of De Twee Rozen, rather than Venetian glass (see **Figure 7**). The remaining 10 opaque whites are placed along line B on **Figure 11** and are more clearly made of barilla-type ash. The majority of these (6 fragments) represent threads, canes, rods, or other decorative elements, while 4 are undefined, indicating that various ashes were used in Phase 2 for the production of *lattimo* vessels and for decoration.

The antimony-opacified whites also contain elevated lead with an average of 3.2% PbO (see **Figure 10**). There is no correlation between lead and antimony in these glasses, but they appear to have been introduced to the glass batch in the same ratio,

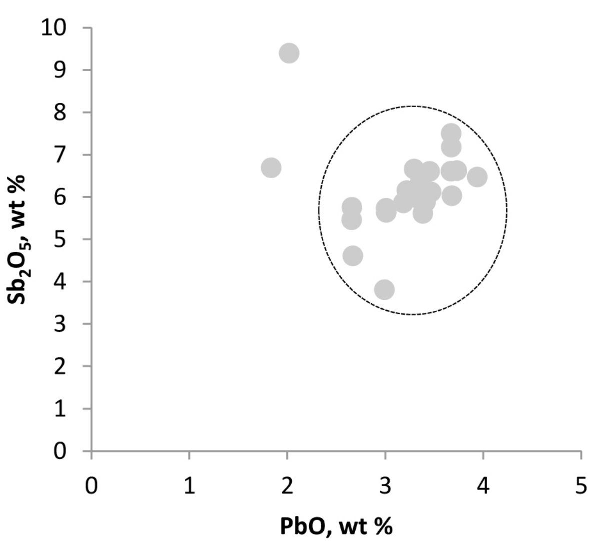

FIG 10. Scatter plot for Sb_2O_5 and PbO concentrations for opaque whites from Phase 2 (Rozengracht, site RO21). (Graphic: the authors)

53 Moretti and Toninato 2011, 114–116.

54 McCray and Warren 2002; for partial analyses of a large number of tin-opacified whites from Keizersgracht, see Karklins and others 2002.

which, excluding two outliers, equals about 1.8 (see **Figure 10**). As noted above, the opaque whites from Rozengracht have relatively low manganese contents (see **Figure 7**), and in contrast to the colorless and blue glasses, their base glass was made using unpurified ash (*vitrum blanchum*–type). These special compositional characteristics of the opaque whites have a technological explanation. Recent experimental work on the technology of antimony-opacified glass from the Roman period has shown that high lime promotes the formation of calcium antimonate crystals in the glass, increasing its opacity.[55] Hence, there was an advantage in the use of a high-lime unpurified ash in the base glass of opaque white. Magnesium oxide is also frequently elevated in Roman antimony-opacified white glass, which may also have benefited the opacification process.[56] The use of a *vitrum blanchum*–type composition rather than a *cristallo*-type is likely to have been of real benefit to the production of opaque white glass, due to its higher alkaline earth oxides (see **Figures 3, 4**). Furthermore, a few percentage points of lead oxide has also been shown to facilitate opacification.[57] The oxidizing properties of antimony will have minimized any adverse effects on color due to the additional iron, so that neither a *cristallo*-type formulation nor the addition of manganese were required in these opaque white glasses. The inclusion of around 10% by weight of lead, plus antimony oxides in the glass composition explains in part the concentration of Rozengracht opaque white glasses below the 3.4% K_2O threshold that distinguishes the use of barilla from Levantine ash in **Figure 4**, but even if corrected for around 10% of these oxides, a number of the whites have low potash if barilla rather than Levantine ash had been used. The explanation for this may lie in the fact that a number of the whites have CaO values in excess of either the Venetian *vitrum blanchum* glasses which use Levantine ash, or the Phase 1 *vitrum blanchum*–type glasses based upon barilla ash (see **Figure 3**). This may imply that a separate ash source, high in lime, was used to promote the crystallization of calcium antimonate opacifier in these glasses.

The chlorine contents of the Rozengracht opaque white glasses are lower than those in colorless glasses and glasses of other colors from the glasshouse. In contrast, they have slightly higher contents of sulfur (**Fig. 12**). This may reflect the residual sulfur from the derivation of antimony from its sulfide ore, stibnite (Sb_2S_3), while the loss of chlorine may have resulted from the need to heat the glass at high temperatures to

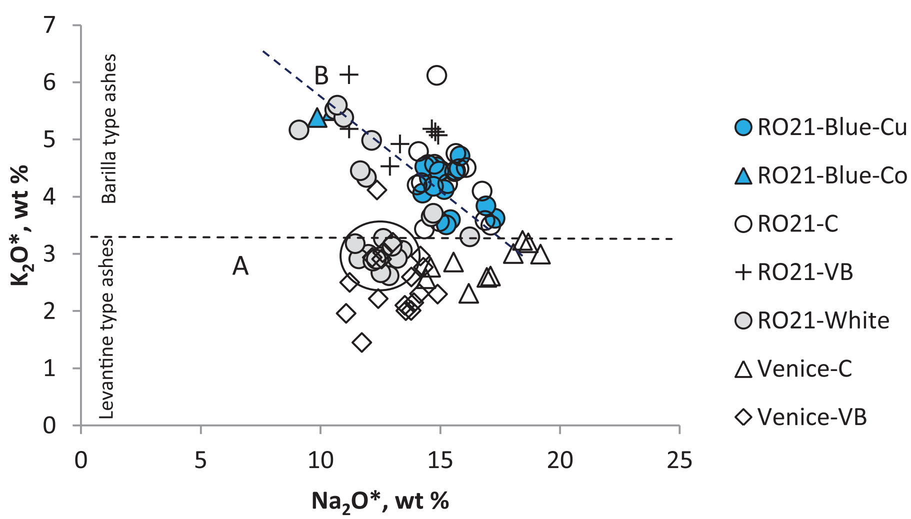

FIG 11. Scatter plot for K_2O and Na_2O normalized concentrations for the analyzed glasses from Phase 2 (Rozengracht, site RO21) and Venetian *vitrum blanchum* and *cristallo* glasses (after Verità 1985, 2013a). (Graphic: the authors)

55 Paynter and Jackson 2019.
56 Schibille and others 2020.
57 Boschetti and others 2020.

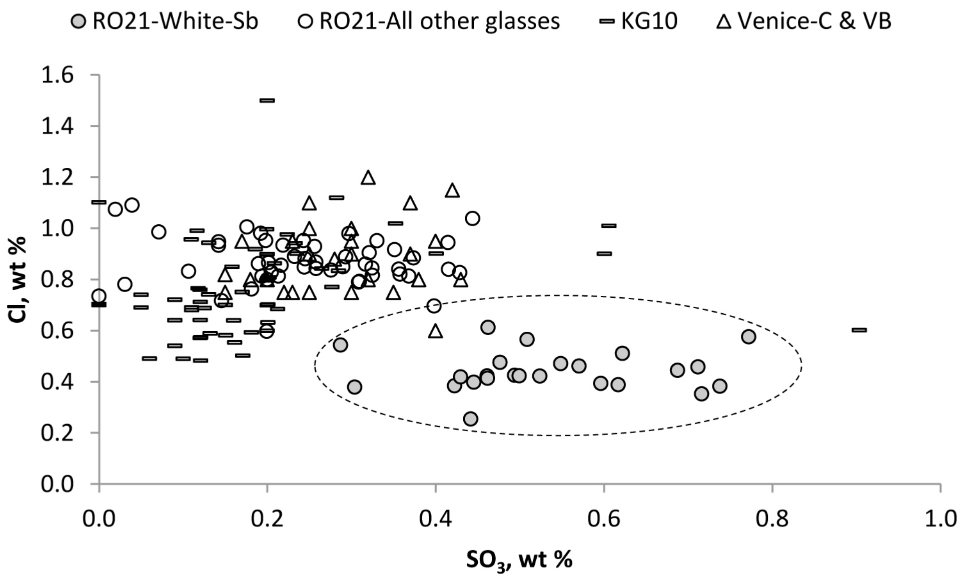

FIG 12. Scatter plot for Cl and SO_3 concentrations for opaque whites from Rozengracht (site RO21) and for all other glasses from De Twee Rozen glasshouse Phases 1 (KG10) and 2 (RO21) as well as for Venetian *cristallo* and *vitrum blanchum*. (Graphic: the authors)

homogenize the antimony content, as suggested for the same phenomenon observed in Roman antimony-opacified white glass.[58] However, we did not find any correlation between Sb and S in our samples.

DISCUSSION

The present analysis allows us to add a chronological dimension to the introduction of "Venetian" glassmaking technologies at De Twee Rozen and compare them with the introduction of the manufacture of glass vessels in Venetian forms. It appears that the earlier production in Phase 1 was based upon a simple mixture of sand and unpurified barilla ash. Although this glass shows some similarities in composition to Venetian *vitrum blanchum*, it should be emphasized that the silica source for *vitrum blanchum* was much purer, with low alumina and iron oxide and based upon crushed pebbles from the River Ticino rather than sand.[59] The use of the term *vitrum blanchum* to describe this type of northern European product is problematic, as it differs not only in the detail of its chemical composition but also in technological approach: it used sand and western Mediterranean barilla ash rather than pebbles and Levantine *rochetta*. This type of formulation was widely used, for example, in northern France from at least the end of the sixteenth century[60] as well as in Spain and in Italy from earlier times.[61] Therefore, while the production of *façon de Venise* vessels at De Twee Rozen may be associated with Venetian glass*working* techniques, this does not appear to have been accompanied by a specifically Venetian glass*making* technology, as the sand–soda ash glass formulation used was widely established across much of northern and southern Europe at this time. It is clear that, at least in this case, the spread of FdV production and Venetian *cristallo* technology are not closely linked.

The data indicate that a Venetian-type *cristallo* technology was well established sometime after the move to Rozengracht in 1657 (Phase 2). This was almost 40 years

58 Freestone and Stapleton 2015.
59 E.g. Jacoby 1993.
60 Barrera and Velde 1989a, 1989b.
61 E.g., Cagno and others 2012; Gliozzo and others 2021; Schibille 2022; Occari, Freestone, and Fensick 2021.

after the establishment of De Twee Rozen and the production of glass in the Venetian style in Amsterdam. We cannot, however, be sure of the precise date at which *cristallo* technology was introduced at De Twee Rozen, as the nature of the deposited glass-production materials means that they may each represent short periods of production in their respective locations.

It should not be surprising that the introduction of glassworking techniques and styles preceded the introduction of *cristallo*-type technology to purify the plant ash and reduce the tint of "colorless" glass, as the types of know-how that had to be acquired for these technologies were very different. Blowing a glass object is an embodied skill, learned by experience and in practice exercised with only limited reflective decision-making—the skilled artisan's responses to changes in workshop conditions, glass temperature, viscosity, vessel form, and so on are almost intuitive.[62] A glassblower who had experience making other forms could, with practice, have learned to produce FdV forms through observation and application of their pre-existing skills. Manufacture of a standard soda ash–based glass, more or less equivalent to Venetian *vitrum blanchum* but using sand rather than crushed pebbles, would also have been a procedure fairly familiar to those who had previously melted inland wood ashes with sand to make a potash-rich glass. However, in Venice, the preparation and mixing of raw materials and their melting and coloration was the province of a specialist craftsman, a *conciatore*.[63] *Cristallo* was based upon practices which were not yet widely known or understood—it required the purifying of the ash by a procedure of dissolution and evaporation, then the replacement of some of the lost lime and magnesia (probably in the form of an addition of *vitrum blanchum* to the batch),[64] and direct personal experience of the process would have been extremely beneficial, if not essential. Artisans who blew the vessels would not necessarily have possessed the experience and know-how to replicate the arcane practices involved in *cristallo* technology. It is therefore understandable that these two types of knowledge would have spread at different speeds and in different ways.

A second change that occurred around the time of the 1657 change in location was the introduction of opacification with antimony. Antimony was the typical opacifier in glass from the Late Bronze Age up until the fourth century CE, when the supply of antimony appears to have failed.[65] Antimony continues to be found in decorative glasses in later objects, such as enamels and glass tesserae in mosaics, but is generally considered to represent recycled older material.[66] From the fourth century, tin oxide (cassiterite) became a primary opacifying agent and was dominant in medieval and Renaissance Venetian glass as well as in European glasshouses manufacturing FdV glass. The oldest known recipes for opaque white glass date from the sixteenth century and are included in the anonymous recipe book.[67] Recipes and archaeometric analysis consistently indicate that tin was always accompanied by lead, typically in ratios from 1:2 to 3:1,[68] which is similar to the ratios in opaque whites from De Twee Rozen Phase 1, in the range from 1:1 to 3:1.[69]

The first direct written reference to the use of antimony in making *lattimo* comes from 1640, when such a recipe appeared in the Darduin manuscript.[70] It was less expensive

62 E.g. O'Connor 2005; Liardet 2009.
63 McCray 1999.
64 Veritá 2014.
65 Tite, Pradell, and Shortland 2008.
66 Freestone 2015.
67 Moretti and Toninato 2011, 22–23.
68 Moretti and Hreglich 1984; Verità 2014.
69 McCray and Warren 2002.
70 Verità and Zecchin 2008; Moretti and Toninato 2011, 24.

than tin and the opacification seems to have been no less effective.[71] It therefore appears that De Twee Rozen glasshouse was moved to its second location at Rozengracht only a dozen or so years after the first known written mention of the use of antimony to produce *lattimo*. Corroboration of the possibility that De Twee Rozen was an early adopter of antimony opacification in white glass depends upon the availability of analytical data. Verità and Biron[72] note the use of lead antimonate yellow in Venetian enameled glass from the fifteenth century, but at this time white was invariably made using tin oxide opacifier. However, Verità and Zecchin[73] identified antimony opaque white enamel on a Venetian polychrome goblet from the second half of the sixteenth century which contained 3.50% Sb_2O_3 (i.e., 3.9% Sb_2O_5), although unlike the Rozengracht white glass, it contained only 0.12% PbO. Several authors have identified apparently isolated examples of the use of antimony opacification in seventeenth-century glass (in vessels excavated in London[74] and Portugal,[75] and in beads excavated in North America[76]). While the use of antimony to produce opaque white glass in Venice may therefore have begun earlier than its mention by Darduin, at present its earlier occurrence elsewhere appears to have been limited. Experiments with antimony and glass have been reported based on a crucible recovered from an alchemical laboratory at Oxford;[77] and in his 1662 commentary on Neri's *L'arte vetraria*, Merret provides a recipe for the use of antimony to color enamel glass white, which he describes as "…whilst a secret of great value, but now commonly enough known to the furnaces,"[78] suggesting that this understanding had been achieved only recently. The exceptional characteristics of the opaque white glasses—the use of a relatively pure plant ash base, the addition of lead, the omission of manganese decolorizer—all point to the sophistication of this technology and that, wherever it was developed, it must have been preceded by substantial developmental work and experimentation. If this particular approach was not developed at De Twee Rozen, the knowledge was presumably imported as a package.

Another novel approach observed in the Phase 2 assemblage is the coloration of translucent blue glass, which was typically prepared in Venice based on *cristallo* formulation, according to written sources.[79] This is also confirmed by chemical analyses by various researchers,[80] and our results are consistent with these findings. These translucent blue fragments (often called turquoise, sky color, or so on, as already mentioned) of vessels or production wastes that can be linked with the production of vessels were colored with brass (CuO 1.3–1.8% and ZnO 0.3% on average) with the possible addition of manganese (0.5% on average). Though there are many recipes from the discussed period (e.g., *L'arte vitraria* by Neri) describing coloration of glass with the use of brass and manganese (or without manganese), there is very scarce comparative material among the archaeological and/or historical artifacts that have been analyzed. The enamels or other forms of decoration described in the literature as turquoise are typically opacified and are almost manganese free; some of them also contain a small amount of cobalt.[81] A seventeenth-century

71 Verità and Zecchin 2008.
72 Verità and Biron 2021.
73 Verità and Zecchin 2008.
74 Turner and Rooksby 1959.
75 Lima and others 2012.
76 Hancock, Aufreiter, and Kenyon 1997.
77 Veronesi and Martinon-Torres 2022.
78 Neri (1612) 2006, 365.
79 E.g., Moretti and Toninato 2011; Neri (1612) 2006.
80 E.g., Verità and Zecchin 2008.
81 Biron and Verità 2012; Thornton and others 2014; Verità and Biron 2015, 2021.

blue goblet (?) with millefiori rods from the Monastery of Santa Clara-a-Velha in Portugal constitutes an exception. It is decorated with transparent turquoise blue, among other decoration containing 4.03% CuO and 0.47% MnO; however, it represents *vitrum blanchum*–type technology rather than *cristallo*.[82] We did not find in the literature any example of a translucent blue (turquoise?) Cu-rich glass with similar composition to our Cu-rich glasses from Rozengracht, which was the body glass of a vessel as opposed to a decorative element. From this point of view, Amsterdam's Cu-rich blues might represent a less common technology of vessel-glass coloring in the seventeenth century.

Overall, glassmaking techniques appear to have been far more sophisticated in Phase 2 than those used in Phase 1. Just how these purification and coloration technologies came to be introduced at De Twee Rozen is open to speculation, but it may be pertinent that the director of production from 1667 was Nicalao Stua, a Venetian master.[83] Stua is likely to have had direct knowledge of Venetian glassmaking methods and might have introduced them. Second, it is tempting to see a role for the chemist and alchemist Johann Rudolf Glauber, who from time to time rented a furnace at the Rozengracht glasshouse for his experiments, including the coloration of glass. Glauber had also experimented with the purification of wood ash to produce potassium salts of higher quality.[84] He can be expected to have been interested in the techniques used to purify the ashes and color the glass. Unfortunately, the extent of their interaction at Rozengracht is unknown, and there is a comment that Glauber had ceased using the glass furnaces by 1663, apparently before the arrival of Stua,[85] although he is known to have worked in Amsterdam until 1670.

It has been suggested that the development of lead crystal glass in late seventeenth-century England was in part dependent upon the importation of the practice of adding lead, from the Netherlands.[86] We have not identified any colorless high-lead glass at Rozengracht, but lead oxide concentrations of up to 4% occur in the antimony-opacified white glasses, while up to 6.3% occurs in cobalt blue. This is considerably less lead than present in successful English crystal, but Brain expresses the view that the earliest English crystal would have contained significantly less than 16% PbO. A further point of interest is his suggestion that the earliest English crystal utilized a method for the addition of lead to glass proposed by Glauber in 1651,[87] before the move of De Twee Rozen to Rozengracht.

CONCLUSIONS

The recognition that the Keizersgracht site represents production material from Phase 1 (1621–1657) of the De Twee Rozen glasshouse has allowed the rare opportunity to compare production from two periods of a glasshouse in northern Europe known to have been manufacturing glass *à la façon de Venise.* New analytical data, mainly from De Twee Rozen's Phase 2 at Rozengracht, have been compared with earlier analyses and have allowed the identification of a number of technological changes which were introduced during the 50 years of operation of the glasshouse.

In particular, it has been possible to identify the introduction after the glasshouse's change in location of the purification of the barilla plant-ash flux, following

82 Lima and others 2012, table 3, no. V 108.
83 Loibl 2008, 70.
84 Loibl 2008, 67.
85 Brain 2008, 108, quoting from Hudig 1923.
86 Brain 2008.
87 Brain 2008, 112.

the approach to *cristallo* used in Venice, as well as the introduction of antimony rather than tin as an opacifier in white glass, a technology which was relatively new in Venice itself and which appears to have required a distinctive base glass with high-alkaline earth oxides and the addition of lead. Other distinctive approaches of the Rozengracht period include the production of translucent copper blue in a *cristallo*-type glass matrix. It appears that the glass from the Phase 1 period was overwhelmingly based upon a simple sand–plant ash mixture, whereas in Phase 2 a more sophisticated technology used *cristallo*-type glass, except for specific colors.

We have drawn particular attention to the lag between the introduction of FdV glass and the introduction of *cristallo*-type technology. Although not often explicitly acknowledged in the literature, this difference in the rate of spread of the fashion for FdV glass vessels and the technology needed to produce glass of the highest quality (and on which the reputation of the Venetian glass industry was based) is to be expected. The types of knowledge required were the provinces of different craftsmen in Venice itself. The relatively slow spread of the know-how needed to make *cristallo* may even have been a contributing factor in the development of other crystal glass types in England and Bohemia. It emphasizes the need for more chemical analysis of well-dated glass assemblages of the period so that the changes that occurred may be better understood.

De Twee Rozen serves as a good example showing that products of one glasshouse do not have to be characterized by the same chemical composition and that a glasshouse operating over several dozen years may produce glasses which differ significantly in technology and composition. Had the material from the two periods been present in a single dump, the sequence of changes would have been almost impossible to confirm or even identify.

The role, if any, that the presence from time to time of Glauber at De Twee Rozen had in the development of the new technologies used there is unclear, but in view of his interests in glass coloration, in the purification of ashes, and the addition of lead to glass, it is very tempting to speculate that he had some influence.

The material analyzed here is still not sufficiently comprehensive to produce robust conclusions in all areas, especially with regard to Phase 1 of the glasshouse operation at Keizersgracht (1621–1657). On the other hand, considering all of the work drawn upon here, it is arguable that the production of no other glasshouse in northern Europe manufacturing FdV glass has been so thoroughly studied. The present results therefore constitute material of importance for further comparative studies of FdV glass in Europe, with a view to tracing the origins of individual items, as to date it has not been possible to connect the majority of FdV objects to any specific glasshouse. Furthermore, this paper provides the first such detailed approach to De Twee Rozen products, in which the compositions are connected to specific objects, information which is missing in a number of previous publications.

The comparative material for the discussed glasses from De Twee Rozen is very small. We hope that further studies on Venetian glass and glass of the vessels made in the Venetian style, especially from the seventeenth century, will allow us to clarify, advance, and possibly correct our present findings. There is an absolute need for trace-element data on the vessels as well as more research on the composition of glass used to decorate vessel glass. There is also a need to advance research on glass beads from both locations of the glasshouse De Twee Rozen. These bead and vessel glass technologies did not have to be the same. But the beads might be quite close to the technology of polychrome canes and other decorative colored elements applied during the manufacturing of the vessels.

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