

Influence of temperature and light exposure on UV-vis absorption and colorimetric properties of γ -irradiated soda-lime glass

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ABSTRACT

This study evaluates the effects of temperature variations during ionizing radiation processing on soda-lime glass, as well as the bleaching of γ -irradiated samples through exposure to light radiation. Glass samples were subjected to γ -ray doses ranging from 2 kGy to 25 kGy under two temperature conditions: room temperature and dry ice cooling. The effects of ionizing radiation on samples were analyzed using UV-Vis spectrophotometry and colorimetry. The results indicate that irradiation at dry ice temperatures significantly mitigates radiation-induced darkening compared to irradiation at room temperature. Additionally, subsequent exposure of irradiated glasses to different light wavelengths was investigated, revealing that UVB radiation effectively restores transparency lost due to irradiation. These findings provide valuable insights for the conservation and restoration of glass-based cultural heritage materials, where preserving original visual properties is essential.

1. Introduction

Radiation processing technology, employing gamma rays, finds applications in material modification, waste treatment and sterilization across various fields, including medical, pharmaceutical, food, personal disposables and cultural heritage artifacts (International Atomic Energy Agency, 2006).

For vitreous materials, several studies demonstrated ionizing radiation processing induces color center formation, affecting transparency (Baccaro et al., 2015; Ponta et al., 2017; Rai et al., 2017; Tsai et al., 2014). The effects of gamma ray irradiation on glass materials have been extensively investigated, particularly in studies assessing the viability of glass dosimeters used in irradiation facilities (Fuochi et al., 2009; Madbouly et al., 2021; Mejri et al., 2008; Teixeira and Caldas, 2002). In these cases, the activation of color centers serves as an indicator of the absorbed dose. However, this phenomenon presents a challenge when treating glass objects in contexts where color modification is unacceptable such as cultural heritage artifacts where preserving original characteristics is crucial. Therefore, developing disinfection methods using ionizing radiation that do not compromise the colors or transparency of glass-based cultural heritage materials is highly desirable.

In this context, comparative studies on the influence of temperature during ionizing radiation processing have shown that lower temperatures reduces the secondary effects of irradiation (Craven et al., 2012;

Ramalingam et al., 2018; Walo et al., 2011). This finding may be beneficial for processing of cultural heritage artifacts, as it helps mitigate irradiation-induced damage. Moreover, heat treatments (Caldas and Quezada, 2002; Sendova et al., 2023; Suszynska and Macalik, 2001) commonly used for bleaching irradiated glass are unsuitable for cultural heritage artifacts due to the risk of structural damage. Therefore, alternatives methods for bleaching irradiated glass materials are necessary. Some studies have provided evidence that exposure to light radiation from mercury lamp and solar irradiation can attenuated the color changes induced by ionizing radiation processing (Abd-Allah, 2022; Borgman, 2006).

The objective of this study is to evaluate the influence of temperature during ionizing radiation on mitigating the darkening effect in soda-lime glass and restoring transparency through light-induced bleaching. This work presents an unprecedented investigation into the effects of γ -irradiation at room and dry ice temperatures on commercial glasses, aiming to understand temperature-dependent irradiation effects and introduce a novel alternative bleaching method using light radiation.

In this study, soda-lime glass samples were γ -irradiated at doses ranging from 2 kGy to 25 kGy. Control and irradiated samples were analyzed using UV-Vis absorption spectroscopy and colorimetry to assess changes in glass color properties. Additionally, irradiated samples were exposed to lamps emitting different wavelengths to explore the potential reversal of irradiation-induced darkening on glasses.

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2. Materials and methods

2.1. Glass samples selection and preparation

Glass samples were obtained from the commercial market and subjected to washing with tap water and alcohol. After drying with paper tissue, the soda-lime glass samples were cut into approximately 3.0 cm × 1.0 cm pieces to fit the samples holders for characterization.

Qualitative analysis of glass was performed by Energy Dispersive X-ray Fluorescence Spectrometer EDX-720 (Shimadzu, Japan) resulting in wt%: 74.338 SiO₂, 11.217 Na₂O, 7.569 CaO, 3.462 MgO, 2.763 Al₂O₃, 0.208 K₂O, 0.182 Fe₂O₃, 0.177 SO₃, 0.053 TiO₂, 0.011 Rb₂O, 0.010 ZrO₂, 0.007 CuO, 0.003 SrO.

2.2. Ionizing radiation processing

Ionizing radiation processing of the samples was conducted in air at both room temperature (RT) and dry ice temperature (DI) at the Multipurpose Gamma Irradiation Facility of the Nuclear and Energy Research Institute – IPEN-CNEN/SP, Brazil, located on the University of São Paulo campus. The facility installed current activity is around 13.0 PBq (350 kCi).

The samples were γ -irradiated with absorbed doses of 2, 6, 10, 15 and 25 kGy, with a dose rate of 1 kGy h⁻¹. The PMMA-Harwell dosimetry system (Harwell, United Kingdom) was utilized to estimate the absorbed dose in the irradiated samples.

2.3. UV-vis spectrophotometry

Light absorption spectra were carried out using Shimadzu UV-1601PC model UV-Visible spectrophotometer (Shimadzu, Japan), with scan range of 280 to 800 nm. The values were normalized to the films samples thickness to determine the relative absorbance and account for the thickness variations among samples. Absorbance values correspond to the mean of three measurements, and the uncertainty is expressed as the standard deviation. The thickness of the samples was measured three times using a digital micrometer Mitutoyo code n° 156-101 (Mexico), and the average value values was calculated for each sample.

2.4. Colorimetry

Color perception measurements were conducted using the portable reflectance spectrophotometer PCE-CSM 8 with SQC8 color management system, employing 0°/45° measurement geometry and wavelength range of 400 to 700 nm. The total color difference (ΔE) between control and irradiated samples was calculated using the CIELAB 2000 color coordinate system. The equation of ΔE_{00} can be express as follow (Chmielewska-Śmietanko et al., 2018; Mokrzycki and Tatol, 2012; Sharma et al., 2005):

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2} + R_T \left(\frac{\Delta C'}{k_C S_C}\right) \left(\frac{\Delta H'}{k_H S_H}\right) \quad (1)$$

For the analysis of ΔE values, the criteria of Hardeberg (2001) were adopted to classify the perception of color change of the irradiated samples: $\Delta E < 3$ indicates a slightly perceptible effect, $3 < \Delta E < 6$ is perceptible but acceptable, and $\Delta E > 6$ is considered not acceptable.

2.5. Exposure to light radiation

Four types of lamps available on the commercial market, with lowest available power, were selected for emitting light radiation, Table 1. Four expanded polystyrene chambers were manufactured for each type of lamp where each sample of irradiated glass received the light radiation.

Table 1

Lamp specifications.

Type	Manufacturer	Power (w)	Emission spectrum (nm)
Halogen	Ourolux	42	320 – 1100
LED	Ourolux	9	400 – 700
UVA	Nomoy	25	320 – 400
UVB	Nomoy	26	280 – 320

3. Results and discussion

3.1. Temperature effects on ionizing radiation processing

Prior to γ -irradiation, the glass used in this study was transparent. Upon irradiation, the samples exhibited a change in transparency, developing a brownish coloration with increasing intensity proportional to the absorbed doses (Fig. 1).

The attenuation of ionizing radiation effects in the presence of dry ice was visually confirmed, with reduced glass darkening compared to samples irradiated at room temperature. This influence of lower temperatures was further supported by the UV-vis results.

Due to the inherent transparency of glass, the control glass samples exhibited UV-Vis spectra without absorption bands. Upon interaction with ionizing radiation, an increase in opacity and the development of an amber hue were observed, leading to the induction of two bands at 440 nm and 600 nm. These bands are associated with the activation of color centers and nonbridging oxygen hole centers (NBOHCs) in the glass samples (Bishay, 1970; Kadono et al., 2010; Natura and Ehrh, 1999; Sheng et al., 2002; Vanina et al., 2006).

Fig. 2 presents the UV-Vis spectra of the control and irradiated samples at doses ranging from 2 to 25 kGy, both at room temperature (RT) and with dry ice (DI), immediately after each γ -ray irradiation. As the absorbed doses increased, the intensities of the bands at 440 nm and 600 nm also increased. In addition, a slight shift of the absorption toward longer wavelengths (red shift) can be observed after irradiation. This behavior is commonly associated with the formation and evolution of radiation-induced defect centers in the glass network, which modify the electronic structure and broaden the absorption bands, resulting in absorption extending to higher wavelengths (Ezz-Eldin et al., 2008; Fu et al., 2014).

Table 2 presents the specific absorption values of the bands at 440 and 600 nm, obtained from the UV-vis spectra of the samples irradiated at different irradiation doses and in the two conditions of room temperature (RT) and with the use of dry ice (DI). Although the spectra are characterized by broad bands, these wavelengths correspond to the regions where the radiation-induced absorption features are most pronounced. Thus, the absorbance values at these wavelengths were used as reference points to compare the effects of irradiation temperature on optical changes in the glass samples. The experimental uncertainty associated with the measurements has been included, and the percentage variations in absorption between DI and RT were calculated.

The use of dry ice during gamma ray irradiation resulted in spectra that were up to 21% less intense at 440 nm at 10 kGy compared to those samples irradiated at room temperature.

The protective effect of low temperatures can be attributed to the reduction in atomic and molecular mobility within the glass. At subzero

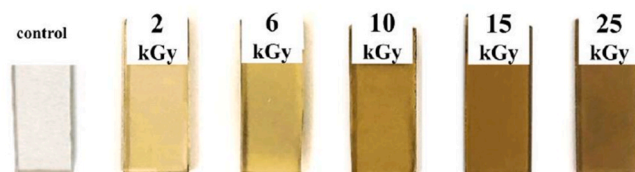


Fig. 1. Appearance of glass samples according to absorbed doses of irradiation processed at room temperature.

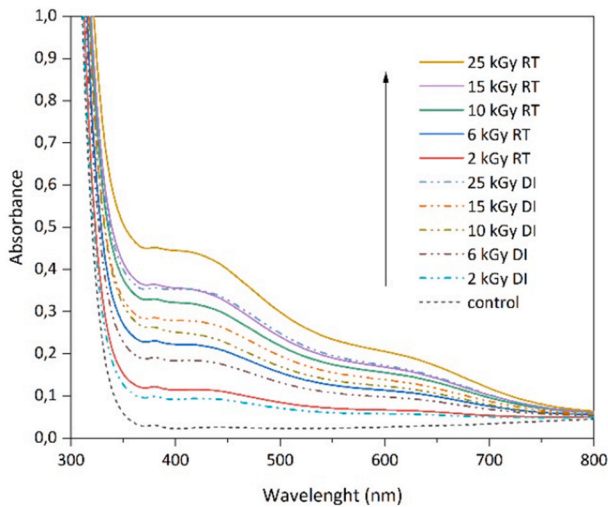


Fig. 2. UV-vis spectra of control and gamma-irradiated samples, in RT (solid lines) and DI (dotted lines).

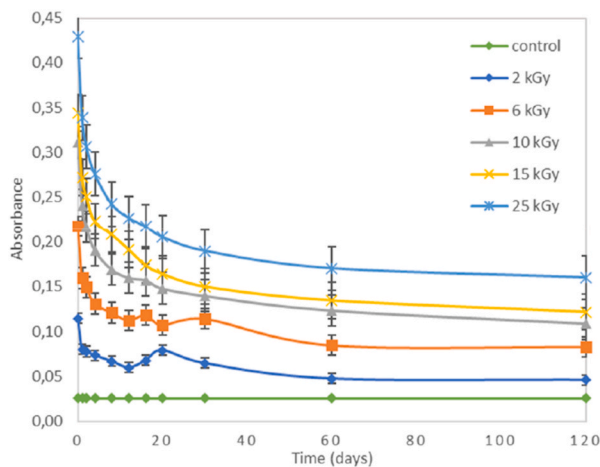
temperatures, the available energy for atomic and molecular movement decreases, reducing the probability of recombination or diffusion of crystalline defects induced by ionizing radiation (Ramalingam et al., 2018; Walo et al., 2011).

Furthermore, the formation and mobility of reactive species, such as free radicals, are restricted at lower temperatures. This effect is particularly relevant for electron beam irradiation, which generates a higher concentration of free radicals compared to gamma radiation (Jastrzebska et al., 2014). Additionally, the cooling effect of dry ice further limits free radical propagation, reducing the formation of defects in the crystalline structure.

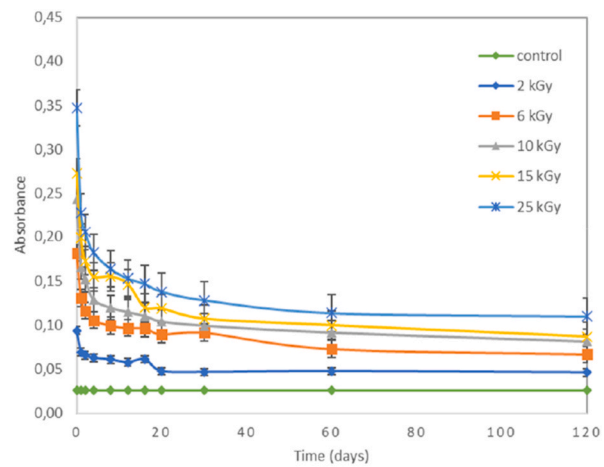
Table 2

Absorption values (A) at wavelengths of 440 and 600 nm of the irradiated samples at RT and DI and their percentage variations.

Dose (kGy)	440 nm			600 nm		
	A _{RT}	A _{DI}	$\Delta A_{DI/RT}$	A _{RT}	A _{DI}	$\Delta A_{DI/RT}$
Control	0.0271 ± 0.0001	0.0271 ± 0.0001	0%	0.0271 ± 0.0001	0.0271 ± 0.0001	0%
2	0.1128 ± 0.0004	0.0929 ± 0.0007	−18%	0.0673 ± 0.0002	0.0583 ± 0.0003	−14%
6	0.2123 ± 0.0003	0.1781 ± 0.0005	−16%	0.1139 ± 0.0002	0.0983 ± 0.0002	−14%
10	0.3031 ± 0.0003	0.2380 ± 0.0008	−21%	0.1559 ± 0.0001	0.1259 ± 0.0004	−19%
15	0.3347 ± 0.0003	0.2667 ± 0.0009	−20%	0.1688 ± 0.0001	0.1388 ± 0.0004	−18%
25	0.4168 ± 0.0007	0.3394 ± 0.0009	−19%	0.2060 ± 0.0005	0.1727 ± 0.0007	−16%



(a)



(b)

Fig. 3. 440 nm band absorption induced by gamma rays at RT (a) and DI (b), until 120 days.

3.2. Decay of irradiation effects over 120 days

In order to evaluate the decay behavior of irradiation effects, the irradiated glass samples were stored in a dark environment to prevent interference from light radiation. Data were collected from the 440 nm band of UV-Vis spectra of samples after irradiation over a period of 120 days. This band was selected because it corresponds to the most prominent radiation-induced absorption region in the spectra, representing the activation of color centers which altered the transparency of the glass, and exhibited greater sensitivity to dose and temporal evolution of the defects. Although a band around 600 nm is also present, its lower intensity and comparatively smaller changes during the monitoring period limited its use for a reliable decay analysis.

Fig. 3 illustrated the decay behavior of the specific absorption values at 440 nm in the UV-vis spectra of samples γ -irradiated at room temperature (RT) and with dry ice (DI), at doses ranging from 2 to 25 kGy.

The response curve shows an initial rapid decay within the first 24 h, followed by a slower decay over the subsequent days, eventually reaching a plateau after 120 days. The oscillations observed between the 16th and 30th day may be attributed to the influence of free radicals. The use of dry ice during irradiation resulted in lower absorption values at 440 nm throughout the entire 120-day period.

Table 3 presents the specific absorption values at 440 nm for samples irradiated with 25 kGy, along with the percentage differences between RT and DI over the 120-day period.

Comparing the temperature conditions during processing, the use of dry ice during irradiation resulted in lower absorption values at 440 nm from the initial processing stage through to the end of the 120-day period. The difference in specific absorption values between DI and RT was 31% at the conclusion of the analyzed period.

Additionally, by calculating ΔE , the recovery of transparency loss induced by irradiation was quantified between the 1st and 120th day, as shown in Fig. 4. A lower value of ΔE indicates a closer resemblance to

Table 3

Absorption values at 440 nm of samples irradiated at 25 kGy under RT and DI conditions and their percentage differences.

Days	A _{control}	A _{RT}	A _{DI}	ΔA _{DI/RT}
0	0.0271 ± 0.0001	0.4291 ± 0.0006	0.3471 ± 0.0005	−19%
1	0.0271 ± 0.0001	0.3386 ± 0.0004	0.2286 ± 0.0003	−32%
4	0.0271 ± 0.0001	0.2759 ± 0.0005	0.1822 ± 0.0006	−34%
8	0.0271 ± 0.0001	0.2423 ± 0.0004	0.1637 ± 0.0005	−32%
16	0.0271 ± 0.0001	0.2170 ± 0.0005	0.1468 ± 0.0004	−32%
30	0.0271 ± 0.0001	0.1894 ± 0.0007	0.1281 ± 0.0005	−32%
60	0.0271 ± 0.0001	0.1700 ± 0.0005	0.1135 ± 0.0007	−33%
120	0.0271 ± 0.0001	0.1597 ± 0.0006	0.1097 ± 0.0005	−31%

the original color and transparency of the glass material. The percentage values shown in the graphs represent the relative reduction of ΔE for samples irradiated under dry ice (DI) conditions compared to those irradiated at room temperature (RT) at the same irradiation dose. Negative percentage values indicate that the color change (ΔE) in DI samples was lower than in RT samples, demonstrating the mitigating effect of low temperature during irradiation.

Table 4 presents the ΔE values recorded on the 1st and 120th for the glass samples irradiated at doses ranging from 2 to 25 kGy. Additionally, the percentage differences between the first and last days of the decay evaluation period were calculated.

Samples irradiated with dry ice exhibited lower values compared to those irradiated at room temperature, confirming the protective effect of negative temperatures during processing. For samples subjected to irradiation at both RT and DI, the ΔE values decreased by 55% and 57%, respectively, after 120 days.

The present results are in agreement with earlier studies by Ezz-Eldin et al. (2008) and Madbouly et al. (2021), which demonstrated that irradiation-induced NBOHC defects are unstable at room temperature, leading to the gradual decay of increased optical density over time.

The observed impacts on transparency and the stability of the brownish tone after the analyzed period are consistent with the studies of Ruller and Friebele (1991) and Kadono et al. (2009), which attribute these effects to the stabilization of irradiation-induced color centers.

Lower ΔE values correspond to a reduced perception of color alteration in the samples. The results indicated that after 120 days, some degree of transparency recovery was observed, particularly in samples irradiated with dry ice, which appeared lighter compared to their immediately irradiated state. However, transparency remained affected, and an amber hue was still present.

Based on the ΔE values obtained, irradiation at disinfection doses starting from 6 kGy resulted in ΔE values exceeding 6 after 120 days, indicating unacceptable color changes in the glass. This suggests the need for complementary strategies to mitigate darkening and restore the optical transparency of the irradiated material.

3.3. Exposure to light radiation

After analyzing the decay behavior of the effects of ionizing radiation processing, this study aimed to investigate the hypothesis that exposure to light radiation could attenuate the increase in opacity and, consequently, contribute to the restoration of transparency in glass samples.

The samples γ-irradiated were placed inside the chambers equipped with different light-emitting lamps for a total exposure period of 60 h. Table 5 presents the appearance of the irradiated samples after exposure to the lamps used in the study.

Visually, exposure to the UVB lamp result in a faster reversal of the darkening effect and promoted greater transparency in the irradiated samples. Colorimetric readings were performed at 10-h intervals throughout the exposure period, as presented in Table 6. The uncertainty associated with colorimetric measurements was ±0.2 ΔE units, according to the instrument specifications.

For the 2 kGy dose, the halogen lamp achieved ΔE<6 (considered an acceptable change according to the Hardeberg scale) only after 50 h of exposure, whereas the LED lamp reached this level after 30 h. The UVA lamp showed promising results, achieving an acceptable value of ΔE (5.388) after 20 h of exposure. However, the UVB lamp demonstrated the most significant effect, reducing ΔE from 10.828 to 4.172 within the first 10 h of exposure, shifting from an unacceptable to an acceptable color change. After 20 h of exposure, ΔE further decreased to 2.743, indicating minimal perceptible color alteration.

For doses of 6, 10, 15 and 25 kGy, only the UVB lamp was able to reduce ΔE values to below 6, with the exposure time varying according to the irradiation dose. At doses of 2 and 6 kGy, values of ΔE<3, indicated minimal color change. For doses of 10, 15 and 25 kGy, the values of ΔE<6 suggested acceptable changes in glass transparency.

The halogen, LED and UVA lamps failed to achieve ΔE values low enough to restore the transparency of the irradiated samples. Thus, the UVB lamp proved to be the most effective in mitigating the opacity effect induced by ionizing radiation, promoting the recovery of glass transparency.

Additionally, the effects of ionizing radiation processing under dry ice conditions were evaluated. Table 7 presents the ΔE values obtained for samples processed at negative temperatures.

For samples irradiated using dry ice, the performance of the radiation emitted by the lamps followed the same trend observed under room temperature conditions. The UVA lamp effectively reduced ΔE < 6 at doses of 2 and 6 kGy, while the UVB lamp achieved this effect at all doses tested.

Notably, when UVB radiation was applied to samples processed with dry ice, time required to restore transparency was reduced by 10 h compared to samples irradiated at room temperature. This short exposure time is advantageous, as it minimizes prolonged interaction of the vitreous material with light radiation, potentially reducing the risk of

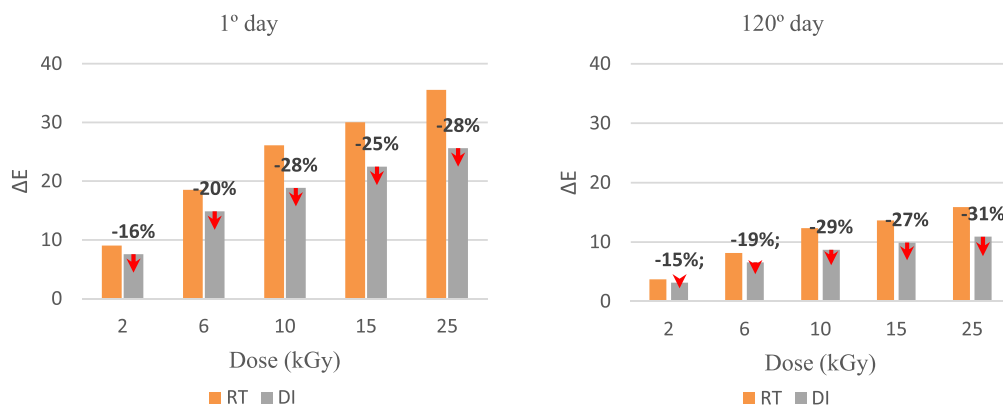


Fig. 4. ΔE values after 1 day and 120 days of gamma irradiation. Percentage values indicate the relative reduction in color change for DI samples compared to RT samples at the same dose. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 4
ΔE values calculated on the 1st and 120th days after irradiation with gamma rays, at doses of 2 to 25 kGy, and their percentage differences.

Dose (kGy)	RT			DI		
	Day 1	Day 120	Δ	Day 1	Day 120	Δ
2	9.023 ± 0.2	3.703 ± 0.2	−59%	7.558 ± 0.2	3.158 ± 0.2	−58%
6	18.519 ± 0.2	8.148 ± 0.2	−56%	14.863 ± 0.2	6.560 ± 0.2	−56%
10	26.104 ± 0.2	12.338 ± 0.2	−53%	18.845 ± 0.2	8.699 ± 0.2	−54%
15	30.024 ± 0.2	13.643 ± 0.2	−55%	22.472 ± 0.2	9.903 ± 0.2	−56%
25	35.542 ± 0.2	15.880 ± 0.2	−55%	25.615 ± 0.2	10.894 ± 0.2	−57%

Table 5
Appearance of irradiated samples after exposure to lamps.

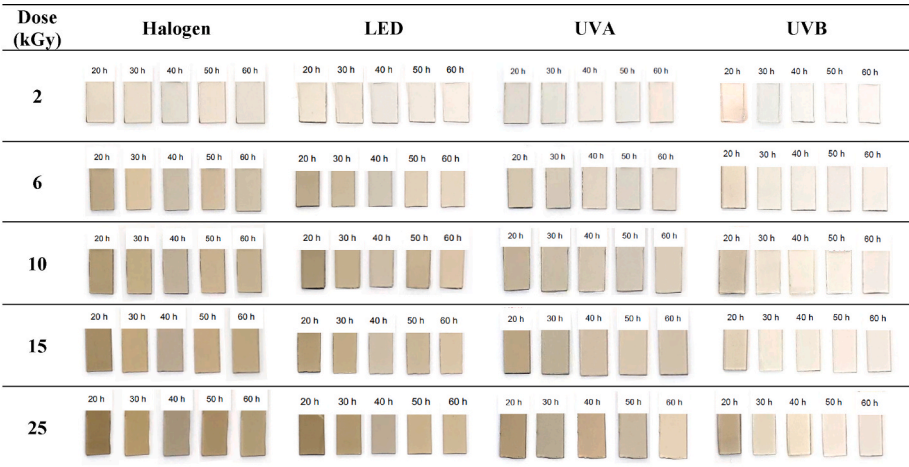


Table 6
ΔE values according to lamp type and exposition time for γ-irradiated samples at RT.

Dose (kGy)	Lamp	ΔE _{0h}	ΔE _{10h}	ΔE _{20h}	ΔE _{30h}	ΔE _{40h}	ΔE _{50h}	ΔE _{60h}
2	UVA	10.375	6.905	5.388	4.635	4.002	3.661	3.296
	UVB	10.828	4.172	2.743	2.072	1.609	1.430	1.206
	LED	10.096	7.152	6.181	5.684	5.045	4.737	4.333
	Halogen	10.505	8.317	7.343	6.791	6.295	5.911	5.418
6	UVA	20.771	14.349	10.757	9.327	8.066	7.300	6.569
	UVB	22.556	10.696	7.415	5.269	4.225	3.767	3.027
	LED	21.662	16.459	14.564	13.595	12.275	11.626	10.717
	Halogen	21.638	17.637	15.944	15.000	14.058	13.289	12.370
10	UVA	26.988	18.604	14.297	12.298	10.538	9.472	8.520
	UVB	27.752	13.613	9.630	6.890	5.492	4.855	4.007
	LED	26.492	20.331	18.037	16.878	15.340	14.542	13.421
	Halogen	27.482	21.554	19.644	18.647	17.503	16.630	15.532
15	UVA	33.256	21.703	17.411	14.885	12.709	11.436	10.326
	UVB	33.296	17.692	11.324	8.545	7.140	5.356	4.726
	LED	32.347	25.458	21.624	19.757	18.693	17.306	16.483
	Halogen	32.663	28.829	24.783	22.689	21.617	20.300	19.351
25	UVA	36.860	26.580	20.391	17.444	15.071	13.727	12.596
	UVB	36.459	19.270	12.990	10.355	7.495	6.650	5.346
	LED	36.062	28.410	25.132	23.468	21.383	20.250	18.760
	Halogen	37.102	30.914	27.865	26.267	24.563	23.264	21.533

additional damage.

The superior effect of UVB radiation can be attributed to its shorter wavelength compare to UVA and visible radiation emitted by LED and halogen lamps. This shorter wavelength provides higher photon energy, sufficient to break C–H and Si–C bonds (Wang et al., 2021). Consequently, UVB energy facilitates the release of trapped electrons, allowing their recombination with NBOHC, promoting the recovery of glass transparency (Kadono et al., 2009).

4. Conclusion

This study evaluated the influence of irradiation temperature on the optical alterations induced in glassy materials and explored a post-treatment approach for recovering transparency using UVB light exposure.

The results demonstrate that gamma irradiation performed at low temperature, using dry ice, reduces the formation of radiation-induced color centers. This effect was evidenced by lower absorbance values in

Table 7 ΔE values according to lamp type and exposition time for γ -irradiated samples at DI.

Dose (kGy)	Lamp	ΔE_{0h}	ΔE_{10h}	ΔE_{20h}	ΔE_{30h}	ΔE_{40h}	ΔE_{50h}	ΔE_{60h}
2	UVA	10.375	5.800	4.526	3.893	3.361	3.075	2.769
	UVB	10.828	3.505	2.305	1.740	1.352	1.201	1.013
	LED	10.096	6.008	5.192	4.774	4.238	3.979	3.640
	Halogen	10.505	6.986	6.168	5.705	5.288	4.965	4.551
6	UVA	20.771	11.479	8.606	7.462	6.453	5.840	5.256
	UVB	22.556	8.557	5.932	4.215	3.380	3.014	2.422
	LED	21.662	13.167	11.651	10.876	9.820	9.301	8.574
	Halogen	21.638	14.110	12.755	12.000	11.246	10.631	9.896
10	UVA	26.988	13.395	10.294	8.854	7.587	6.820	6.135
	UVB	27.752	9.801	6.934	4.961	3.954	3.495	2.885
	LED	26.492	14.638	12.987	12.152	11.045	10.470	9.663
	Halogen	27.482	15.519	14.144	13.426	12.602	11.974	11.183
15	UVA	33.256	16.277	13.058	11.164	9.531	8.577	7.745
	UVB	33.296	13.269	8.493	6.409	5.355	4.017	3.545
	LED	32.347	19.094	16.218	14.818	14.019	12.980	12.362
	Halogen	32.663	21.622	18.587	17.017	16.213	15.225	14.514
25	UVA	36.860	19.138	14.682	12.560	10.851	9.884	9.069
	UVB	36.459	13.875	9.353	7.456	5.397	4.788	3.849
	LED	36.062	20.455	18.095	16.897	15.396	14.580	13.507
	Halogen	37.102	22.258	20.063	18.912	17.685	16.750	15.504

the characteristic bands and smaller ΔE values when compared with samples irradiated at room temperature, indicating a reduced alteration in optical appearance.

In addition, UVB light exposure promoted a significant decrease in the opacity of irradiated samples, suggesting that this method can be used as a non-thermal alternative to conventional heat treatments commonly applied for bleaching irradiated glass. Due to its low heat emission, this approach may be particularly relevant for the treatment of radiation-sensitive materials, such as those found in cultural heritage collections. However, the underlying mechanisms involved in this process should be addressed in future research.

Overall, the findings indicate that the combination of low-temperature irradiation and subsequent UVB exposure represents a promising strategy to mitigate radiation-induced optical degradation in vitreous materials.

CRediT authorship contribution statement

Maria Luiza E. Nagai: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.
Pablo A.S. Vasquez: Writing – original draft, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- Abd-Allah, R., 2022. From decolorization to solarization of historical glass: a review. *Adv. Res. Conserv. Sci.* 3, 30–41. <https://doi.org/10.21608/arcs.2022.135911.1025>.
- Baccaro, S., Cemmi, A., Di Sarcina, I., Menchini, F., 2015. Gamma rays effects on the optical properties of cerium-doped glasses. *Int. J. Appl. Glass Sci.* 6, 295–301. <https://doi.org/10.1111/ijag.12131>.
- Bishay, A., 1970. Radiation induced color centers in multicomponent glasses adli. *J. Non-Cryst. Solids* 3, 54–114.
- Borgman, V.A., 2006. Kinetics of photoinduced recombination of hole-type color centers in silicate glasses. *Glass Phys. Chem.* 32, 280–286. <https://doi.org/10.1134/S1087659606030047>.
- Caldas, L.V.E., Quezada, V.A.C., 2002. Influence of thermal treatments on the response decay of glass radiation detectors. *Radiat. Protect. Dosim.* 100, 433–436.
- Chmielewska-Śmietanko, D., Gryczka, U., Migdał, W., Kopeć, K., 2018. Electron beam for preservation of biodeteriorated cultural heritage paper-based objects. *Radiat. Phys. Chem.* 143, 89–93. <https://doi.org/10.1016/j.radphyschem.2017.07.008>.
- Craven, E., Hasanain, F., Winters, M., 2012. Minimizing material damage using low temperature irradiation. *Radiat. Phys. Chem.* 81, 1254–1258. <https://doi.org/10.1016/j.radphyschem.2012.01.013>.
- Ezz-Eldin, F.M., Mahmoud, H.H., Abd-Elaziz, T.D., El-Alaily, N.A., 2008. Response of commercial window glass to gamma doses. *Phys. B Condens. Matter* 403, 576–585. <https://doi.org/10.1016/j.physb.2007.09.074>.
- Fu, X., Song, L., Li, J., 2014. Radiation induced color centers in cerium-doped and cerium-free multicomponent silicate glasses. *J. Rare Earths* 32, 1037–1042. [https://doi.org/10.1016/S1002-0721\(14\)60180-0](https://doi.org/10.1016/S1002-0721(14)60180-0).
- Fuochi, P., Corda, U., Lavalle, M., Kovács, A., Baranyai, M., Mejri, A., Farah, K., 2009. Dosimetric properties of gammaand electron-irradiated commercial window glasses. *Nukleonika* 54, 39–43.
- Hardeberg, J.Y., 2001. Acquisition and Reproduction of Color Images: Colorimetric and Multispectral Approaches.
- International Atomic Energy Agency, 2006. Gamma Irradiation for Radiation Processing 6–9.
- Jastrzebska, A., Kaminski, A., Grazka, E., Marowska, J., Sadlo, J., Gut, G., Uhrynowska-Tyszkiewicz, I., 2014. Effect of gamma radiation and accelerated electron beam on stable paramagnetic centers induction in bone mineral: influence of dose, irradiation temperature and bone defatting. *Cell Tissue Bank.* 15, 413–428. <https://doi.org/10.1007/s10561-013-9406-9>.
- Kadono, K., Itakura, N., Akai, T., Yamashita, M., Yazawa, T., 2010. Formation of color centers in a soda-lime silicate glass by excimer laser irradiation. *J. Phys. Condens. Matter* 22, 088/0953-8984/22/4/045901. <https://doi.org/10.1088/0953-8984/22/4/045901>.
- Kadono, K., Itakura, N., Akai, T., Yamashita, M., Yazawa, T., 2009. Effect of additive ions on the optical density and stability of the color centers induced by X-ray irradiation in soda-lime silicate glass. *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms* 267, 2411–2415. <https://doi.org/10.1016/j.nimb.2009.04.014>.
- Madbouly, A.M., Alazab, H.A., Borham, E., Ezz-Eldin, F.M., 2021. Study of gamma radiation dosimeter and radiation shielding parameters of commercial window glass. *Appl. Phys. A Mater. Sci. Process.* 127, 1–14. <https://doi.org/10.1007/s00339-021-04889-9>.
- Mejri, A., Farah, K., Eleuch, H., Ben Ouada, H., 2008. Application of commercial glass in gamma radiation processing. *Radiat. Meas.* 43, 1372–1376. <https://doi.org/10.1016/j.radmeas.2008.05.010>.
- Mokrzycki, W., Tatol, M., 2012. Color difference Delta E - a survey. *Mach. Graph. Vis.* 20, 383–411.
- Natura, U., Ehrh, D., 1999. Formation of radiation defects in silicate and borosilicate glasses caused by UV lamp and excimer laser irradiation. *Glas. Sci. Technol. -Frankfurt am Main* 72, 295–301.
- Ponta, C.C., Havermans, J.B.G.A., Tran, Q.K., Cortella, L., 2017. Effects of ionizing radiation on materials. In: *Uses of Ionizing Radiation for Tangible Cultural Heritage Conservation*. International Atomic Energy Agency, Vienna, pp. 61–91.
- Rai, V.N., Mukherjee, C., Jain, B., 2017. Optical properties (uv-vis and ftir) of gamma irradiated polymethyl methacrylate (pmma). *Indian J. Pure Appl. Phys.* 55, 775–785.
- Ramalingam, S., Samsuddin, S.M., Yusof, N., Mohd, S., Hanafi, N.N., Min, N.W., Mansor, A., 2018. Performance of cooling materials and their composites in

- maintaining freezing temperature during irradiation and transportation of bone allografts. *J. Orthop. Surg.* 26, 1–8. <https://doi.org/10.1177/2309499018770906>.
- Ruller, J.A., Friebele, E.J., 1991. The effect of gamma-irradiation on the density of various types of silica. *J. Non-Cryst. Solids* 136, 163–172. [https://doi.org/10.1016/0022-3093\(91\)90131-O](https://doi.org/10.1016/0022-3093(91)90131-O).
- Sendova, M., Jim, A., Crawford, C.L., 2023. In situ optical microspectroscopy Study of isothermal bleaching of γ -Irradiated international simple glass. *ACS Phys. Chem.* <https://doi.org/10.1021/acsphyschemau.3c00020>.
- Sharma, G., Wu, W., Dalal, E.N., 2005. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. *Color Res. Appl.* 30, 21–30. <https://doi.org/10.1002/col.20070>.
- Sheng, J., Kadono, K., Utagawa, Y., Yazawa, T., 2002. X-ray irradiation on the soda-lime container glass. *Appl. Radiat. Isot.* 56, 621–626. [https://doi.org/10.1016/S0969-8043\(01\)00238-X](https://doi.org/10.1016/S0969-8043(01)00238-X).
- Suszynska, M., Macalik, B., 2001. Optical studies in gamma-irradiated commercial soda-lime silicate glasses. *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms* 179, 383–388. [https://doi.org/10.1016/S0168-583X\(00\)00695-9](https://doi.org/10.1016/S0168-583X(00)00695-9).
- Teixeira, M.I., Caldas, L.V.E., 2002. Dosimetric properties of various colored commercial glasses. *Appl. Radiat. Isot.* 57, 407–413. [https://doi.org/10.1016/S0969-8043\(02\)00127-6](https://doi.org/10.1016/S0969-8043(02)00127-6).
- Tsai, H.S., Chao, D.S., Wu, Y.H., He, Y.T., Chueh, Y.L., Liang, J.H., 2014. Spectroscopic investigation of gamma radiation-induced coloration in silicate glass for nuclear applications. *J. Nucl. Mater.* 453, 233–238. <https://doi.org/10.1016/j.jnucmat.2014.07.002>.
- Vanina, E.A., Chibisova, M.A., Sokolova, S.M., 2006. Effect of radiation bleaching in sodium-silicate glasses. *Glas. Ceram. (English Transl. Steklo i Keramika)* 63, 366–367. <https://doi.org/10.1007/s10717-006-0124-7>.
- Walo, M., Przybytniak, G., Nowicki, A., Awieszkowski, W., 2011. Radiation-induced effects in gamma-irradiated PLLA and PCL at ambient and dry ice temperatures. *J. Appl. Polym. Sci.* 122, 375–383. <https://doi.org/10.1002/app.34079>.
- Wang, Z., Qian, L., Peng, X., Huang, Z., Yang, Y., He, C., Fang, P., 2021. New aspects of degradation in silicone rubber under uva and uvb irradiation: a gas chromatography–mass spectrometry study. *Polymers* 13, 1–12. <https://doi.org/10.3390/polym13132215>.