Original Article

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# Color stability of glass ionomer-based restorative materials after immersion in various beverages

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**Objective:** The aim of this study was to evaluate the color stability of various glass ionomer-based restorative materials after immersion in different acidic beverages over multiple time points.

**Materials and Methods:** Four restorative materials (n = 36) were tested: conventional glass ionomer (Fuji IX), resin-modified glass ionomer (Fuji II LC), zirconomer (Zirconomer Improve), and giomer (Beautifil X). Specimen discs were fabricated and their baseline color was measured using a spectrophotometer. The specimens were then immersed in one of four media (n = 9): grape juice (pH 3.50), cola (pH 2.67), chocolate milk (pH 6.99), or distilled water (pH 5.97) as a control. The immersion periods were 1 hour, 1 day, and 1 week, with the solutions changed daily. Color measurements were taken at each time point using the CIEDE2000 color system to calculate the color change ($\Delta E_{00}$).

**Results:** Immersion in grape juice and cola resulted in significantly higher color changes across all materials compared with chocolate milk and distilled water. After one week, cola induced substantial color alterations in all materials, while grape juice yielded notable changes in most materials except Zirconomer Improve. Fuji II LC and Fuji IX exhibited significant color differences when immersed in grape juice at all time points. Distilled water and chocolate milk exerted minimal effects on color stability.

**Conclusions:** Immersion in grape juice and cola significantly altered the color across materials, with cola inducing substantial changes after one week and grape juice notably discoloring most materials, except Zirconomer Improve. Fuji II LC and Fuji IX showed significant discoloration from grape juice exposure.

**Keywords:** acidic beverages, color stability, glass ionomers

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## Introduction

Glass ionomer cement (GIC) is a dental material combining glass powder Fluoroaluminosilicate with polyacrylic acid that is used in various dental procedures, especially to prevent tooth decay. GIC forms a chemical bond with enamel and dentin through a reaction between its carboxyl groups and calcium in hydroxyapatite crystals [1]. Fluoride types, e.g., $CaF_2$, $SrF_2$, $LaF_2$, $Na_3AlF_6$, $AlF_3$, are added to GIC for antibacterial properties. Fluoride ions are released into the saliva post-setting, aiding in caries prevention by reducing mineral loss, promoting remineralization, and enhancing enamel resistance to acid. The fluoride release mechanism includes rapid dissolution and gradual diffusion, protecting against new caries near the restoration [2]. Moreover, GIC can be used as a filling material, sealant, liner, or luting cement. It is available in various forms, including

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powder and liquid, pre-dosed capsules, and ready-to-use capsules. Overall, GIC is a versatile and effective material for dental restorations [3].

Resin-modified glass ionomer (RMGI) cement represents an important advancement in dental restorative materials. This hybrid material combines the benefits of conventional glass ionomer cements (GICs) with the enhanced physical and mechanical properties of resin-based materials. The incorporation of resin into the traditional GIC composition improves durability, wear resistance, and setting characteristics, allowing for a more rapid and controlled setting process. RMGI exhibits improved mechanical properties, such as increased compressive and flexural strength, making it suitable for various dental applications [4].

Zirconia-reinforced glass ionomer (Zr-GIC) represents a notable advancement in dental materials, exhibiting improved mechanical properties and durability. The incorporation of zirconia particles into the traditional glass ionomer matrix enhances the material's wear resistance and fracture toughness [5].This modification broadens the applicability of Zr-GIC, rendering it suitable for various dental applications, including restorations and luting procedures, thereby positioning it as a promising development in restorative dentistry [6].

Giomer, an evolution of traditional glass ionomer (GI), has emerged as a notable advancement in dental materials. This hybrid material combines the beneficial properties of glass ionomer with the incorporation of a resin component [7]. The resulting composition enhances the material's strength, durability, and esthetic appeal, making it suitable for various dental procedures, including restorations and preventive applications [7, 8].The development of giomer is significant in modern dentistry, presenting an innovative material with improved properties for clinical use [9].

The color stability of glass ionomer-based restorative materials is a crucial factor in maintaining the aesthetic appearance of dental restorations, particularly in pediatric dentistry. Various intrinsic and extrinsic factors, such as tooth brushing and the consumption of acidic foods and beverages, can contribute to surface modifications and discoloration of these materials. Prolonged color stability is essential for cosmetic reasons and to avoid the additional costs and potential behavioral management challenges associated with frequent replacement due to staining [10]. Oral tissue and restoration staining is influenced by dietary habits, with commonly consumed beverages such as soft drinks, fruit juices, and flavored milk posing potential risks, especially among children [11]. Despite advancements in dental materials, a critical research gap persists in comparing the color stability of glass ionomer-based materials from different manufacturers when exposed to various everyday beverages. Therefore, the aim of this study was to investigate how glass ionomer-based materials respond to different types of beverages and identifying the primary factors influencing their color stability. The null hypotheses were that there are no significant differences in the color stability of glass ionomer-based materials when immersed in the studied liquids over time.

## Materials and Methods

### Specimen Preparation

A total of 144 standardized disc specimens (7 mm diameter and 1.2 mm thick) were prepared from four glass ionomer-based restorative materials: Beautifil X injectable (Shofu Inc., Kyoto, Japan), Zirconomer (Shofu Inc., Kyoto, Japan), FujiII LC (GC, Tokyo, Japan), and Fuji IX

(GC, Tokyo, Japan) (Table 1). The specimens were divided into four groups (n = 36) based on the material type and then further subdivided into four subgroups (n = 9) using simple random sampling without replacement, based on their exposure to the following beverages: grape juice, cola, chocolate milk, and distilled water (control) (Table 2).

Table 1 Glass ionomer-based restorative materials used in the study.

| Material | Type | Manufacturer | Composition | Lot |
|---|---|---|---|---|
| Beautifil X injectable (BX) | Giomer | Shofu Inc., Kyoto, Japan | Bis-GMA, TEGDMA, Bis-MPEPP, S-PRG filler based on fluoroboroaluminosilicate glass, Polymerization initiator, Pigments and others | 062311 |
| Zirconomer (Zir) | Zirconia reinforced glass ionomer | Shofu Inc., Kyoto, Japan | POWDER: Fluoroaluminosilicate glass, Zirconium oxide, pigments and others<br><br>LIQUID: Polyacrylic acid solution and Tartaric acid | 2301071 |
| FujiII LC (F2) | Resin modified glass ionomer | GC, Tokyo, Japan | Fluoroaluminosilicate glass, Copolymers of polyacrylic acid and maleic acid, HEMA, water, camphoroquinone, and photoinitiator | 2301131 |
| Fuji IX (F9) | Conventional glass ionomer | GC, Tokyo, Japan | Fluoroaluminosilicate glass, polyacrylic acid distilled water, polybasic carboxylic acid | 01220781 |

Table 2 Beverages used in this study

| Product name | Type | Manufacturer | Composition |
|---|---|---|---|
| Tipco | Grape juice | Tipco F&B Co., Ltd., Phra Nakhon Si Ayutthaya, Thailand | Red grape juice from red grape juice concentrate |
| Coca-Cola | Cola | ThaiNamthip Co., Ltd., Bangkok, Thailand | Sugar, Carbonated water, Caramel color, Phosphoric acid, Natural flavors |
| Foremost | Chocolate milk | FrieslandCampina Thailand Pcl., Samutprakarn, Thailand | Recombined partly skimmed milk, Sugar, Anhydrous milk fat, Cocoa powder, Vitamin & mineral premix, Food additives, Natural identical flavor |

The disc specimens were fabricated by a single operator using a standardized metal mold following the manufacturer's instructions. The materials were placed into the metal molds and covered with celluloid sheets on both sides [12] . Gentle pressure was applied using a glass plate to remove excess material. For self-cured materials, the specimens were left undisturbed to allow complete setting according to the manufacturer's recommendations. The light-cured materials were cured using an LED light curing unit (Bluephase N, Ivoclar Vivadent, Zurich, Switzerland) at an intensity of 1,200 mW/cm$^2$ according to the manufacturer's instructions. After preparation, the specimens were stored in airtight containers filled with distilled water at room temperature (25°C) until the color measurements were performed.

### Beverage Immersion and Color Measurement

The study investigated the effects of four different immersion media, comprising three dark-colored beverages – grape juice (pH 3.50), cola (pH 2.67), and chocolate milk (pH 6.99) – as well as distilled water (pH 5.97) as a control. The baseline color of all specimens was measured using a spectrophotometer (Vita Easyshade V, VITA, Germany) before immersion in the beverages. Thirty-six discs of each restorative material were then immersed in 5 mL of their respective solution stored in airtight containers. The specimens were immersed for 1 hour, 1 day, and 1 week, with the solutions changed daily. Before color measurement at each time point, the discs were rinsed with distilled water, dried using paper towels, and their color was measured using the spectrophotometer with a white background. The Commission Internationale de l'Eclairage L*a*b* (CIE L*a*b*) colour measurement was repeated three times. The three values were averaged. The difference in colour after immersion was calculated using the CIEDE2000 ($\Delta E_{00}$) [13]:

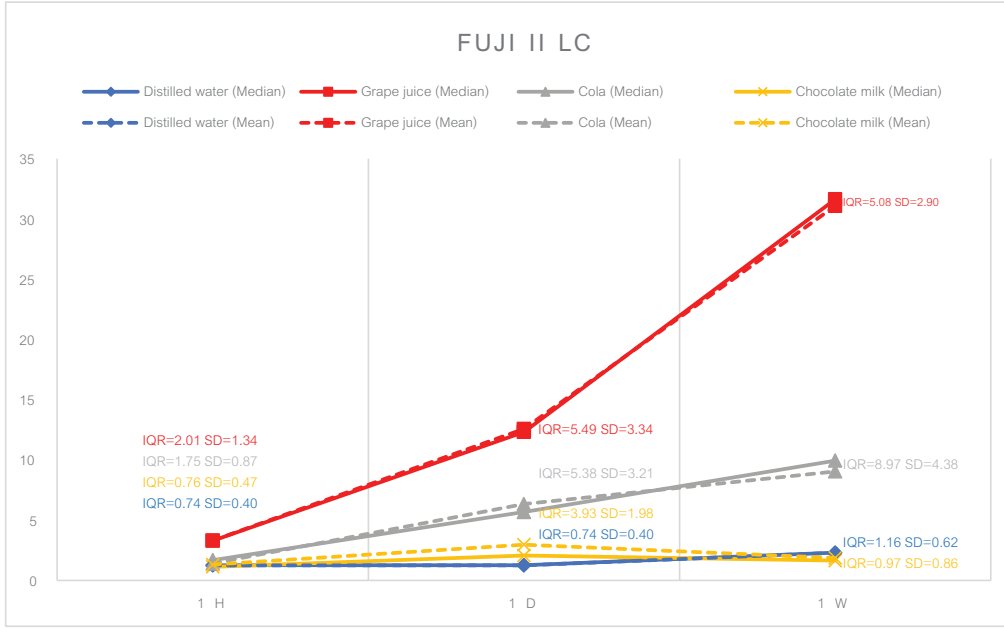
$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}$$

### Data Analysis and Statistical Analysis

The data were statistically analyzed using SPSS version 29.0 (IBM), with a significance level of $p<0.05$. The normality assumption was assessed using the Shapiro-Wilk test. The Kruskal-Wallis test was utilized to assess differences between the means of three or more independent groups in cases where the normality assumption was violated. For comparing the means of three or more dependent groups with non-normally distributed data, the Friedman test was conducted. Post-hoc corrected Bonferroni testing was subsequently employed to identify the specific group or groups responsible for the observed differences.

## Results

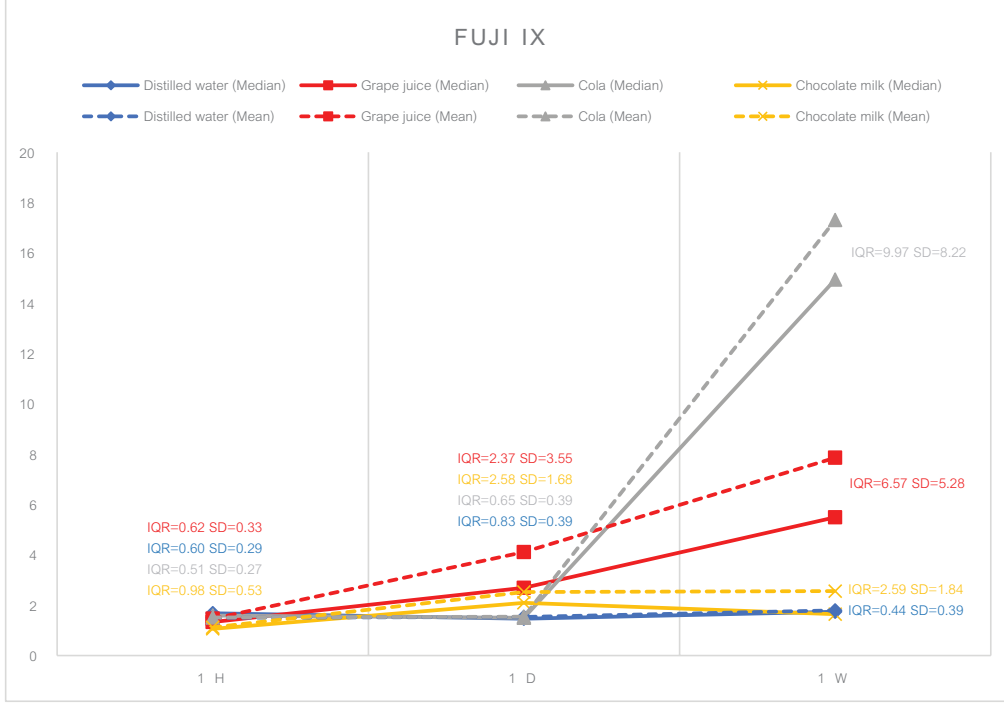
Color Changes after Beverage Immersion: The color changes ($\Delta E_{00}$) of the glass ionomer-based restorative materials after immersion in different liquids (distilled water, grape juice, cola, and chocolate milk) for 1 hour, 1 day, and 1 week are presented in Figures1-4. The results are reported as mean ± standard deviation and median (interquartile range).




IQR = interquartile range,SD = standard deviation

1h = 1 hour, 1d = 1 day, 1w = 1 week

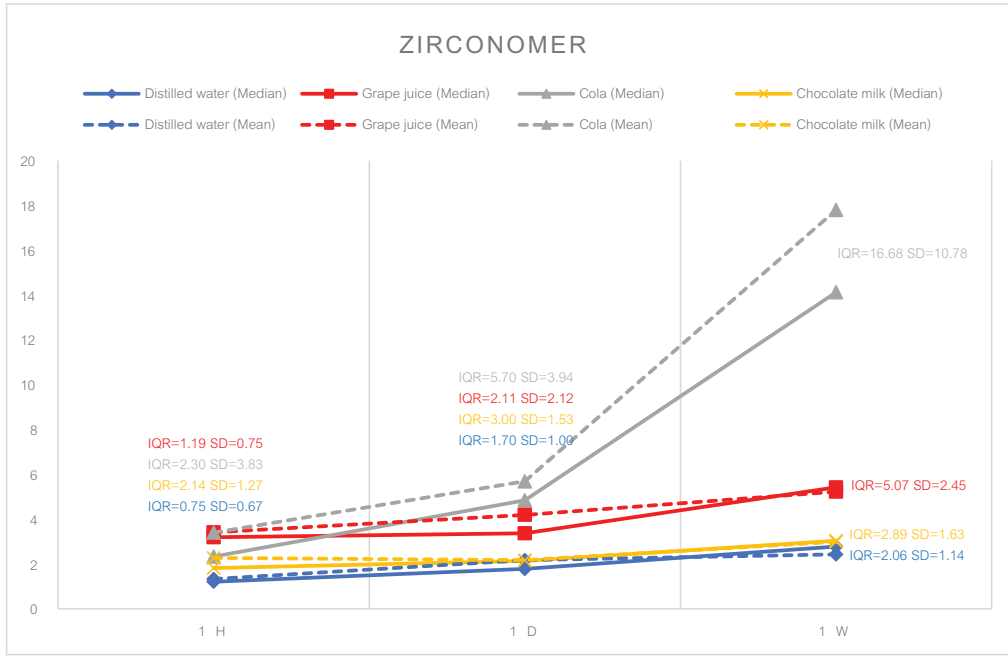
**Figure 1** Color changes (ΔE) of Fuji II LC after immersion in different liquids for various time durations.




IQR = interquartile range, SD = standard deviation

1h = 1 hour, 1d = 1 day, 1w = 1 week

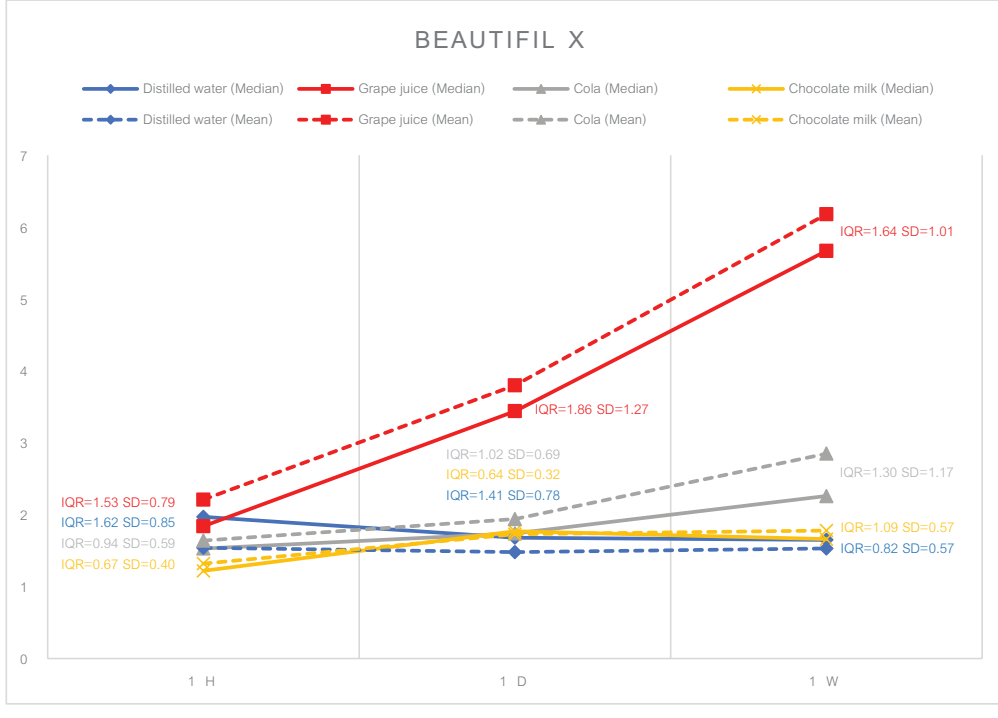
**Figure 2** Color changes (ΔE) of Fuji IX after immersion in different liquids for various time durations.




IQR = interquartile range, SD = standard deviation

1h = 1 hour, 1d = 1 day, 1w = 1 week

**Figure 3** Color changes (ΔE) of Zirconomer after immersion in different liquids for various time durations.




IQR = interquartile range,SD = standard deviation

1h = 1 hour, 1d = 1 day, 1w = 1 week

**Figure 4** Color changes (ΔE) of Zirconomer after immersion in different liquids for various time durations.

For Fuji II LC (Figure 1), the color changes varied across the different liquids and time durations. The results demonstrated that the greatest increase in color change occurred after 1 day of immersion in grape juice (12.58 ± 3.34, 12.32) and there was an elevated color change after 1 week in grape juice (31.08 ± 2.90, 31.63). Fuji IX demonstrated significant color changes (Figure 2), particularly after 1 day and 1 week of immersion in all liquids. Substantial increases in color change were observed in grape juice (1 day: 4.11 ± 3.55, 2.69; 1 week: 7.86 ± 5.28, 5.49) and cola (1 week: 17.31 ± 8.22, 14.94). Zirconomer exhibited varying color changes (Figure 3), with significant increases observed in all liquids after 1 day and 1 week of immersion. The most notable changes were observed in cola (1 day: 5.69 ± 3.94, 4.84; 1 week: 17.80 ± 10.78, 14.13). Beautifil X displayed moderate color changes (Figure 4), with significant increases after 1 day and 1 week of immersion in grape juice (1 day: 3.80 ± 1.27, 3.44; 1 week: 6.18 ± 1.01, 5.67).

The significant color changes for Fuji II LC, Fuji IX, Zirconomer, and Beautifil X when immersed in various media across different time intervals are presented in Table 3. Fuji II LC exhibited noteworthy color alterations in distilled water, grape juice, and cola over time, with significant changes in distilled water ($p = 0.013$) between 1 day and 1 week, and in grape juice ($p < 0.001$) and cola ($p < 0.001$) between 1 hour and 1 week. Fuji IX demonstrated significant color changes primarily in cola ($p < 0.001$) between 1 day and 1 week and in chocolate milk ($p < 0.001$) between 1 hour and 1 day. Zirconomer demonstrated significant color shifts in distilled water ($p = 0.002$) and cola ($p = 0.010$), particularly between 1 hour and 1 week. Beautifil X presented significant color alterations in grape juice ($p < 0.001$) and cola ($p = 0.005$) between 1 hour and 1 week.

The significant color change across the different time intervals for each material-medium combination is presented in Table 4. After the 1-hour immersion period, Fuji II LC exhibited a significantly greater color change when exposed to grape juice compared with distilled water ($p$=0.003), cola ($p$=0.006), and chocolate milk ($p$=0.003), highlighting grape juice's potent staining effect. Zirconomer and Beautifil X also demonstrated discernible, but selective, color changes with specific beverages. In contrast, Fuji IX displayed remarkable color stability across all tested media after 1 hour of immersion.

At the 1-day immersion time point, the vulnerability of certain materials to color change became more apparent. Fuji II LC showed increased discoloration when immersed in grape juice and cola. Fuji IX, which was unchanged after 1 hour, exhibited noticeable color changes after exposure to grape juice, indicating the potential compromise of its color stability with prolonged immersion. Zirconomer and Beautifil X also exhibited increased color changes with grape juice, cola, and chocolate milk compared with their 1-hour values.

**Table 3** Comparison of color change ($\Delta E_{00}$) after immersion across times

| | Distilled water | | | Grape juice | | | Cola | | | Chocolate milk | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1h-1d | 1d-1w | 1h-1w | 1h-1d | 1d-1w | 1h-1w | 1h-1d | 1d-1w | 1h-1w | 1h-1d | 1d-1w | 1h-1w |
| Fuji II LC | 1.00 | 0.013* | 0.013* | 0.034* | 0.034* | <0.001* | 0.010* | 0.239 | <0.001* | 0.059 | 0.346 | 0.346 |
| Fuji IX | 0.724 | 0.157 | 0.289 | 0.018* | 0.099 | <0.001* | 0.814 | <0.001* | 0.002* | 0.034* | 0.480 | 0.157 |
| Zirconomer | 0.010* | 0.637 | 0.002* | 0.814 | 0.099 | 0.059 | 0.346 | 0.099 | 0.010* | 0.814 | 0.239 | 0.346 |
| Beautifil X | 0.480 | 1.000 | 0.480 | 0.059 | 0.059 | <0.001* | 0.480 | 0.034* | 0.005* | 0.099 | 0.814 | 0.059 |

Note: Values represent $p$-values from the Related-Samples Friedman's Two-Way Analysis of Variance by Ranks. *$p < 0.05$ indicates a significant difference between time intervals.

Table 4 Compare color change ($\Delta E_{00}$) after immersion for 1 hour, 1 day, and 1 week across medias (D=Distilled water, G=Grape juice, C=Coke, M=Chocolate milk)

| | | D-G | D-C | D-M | G-C | G-M | C-M |
|---|---|---|---|---|---|---|---|
| Fuji II LC | 1 h | 0.003* | 0.806 | 0.973 | 0.006* | 0.003* | 0.832 |
| | 1 d | <0.001* | 0.002* | 0.236 | 0.081 | <0.001* | 0.059 |
| | 1 w | <0.001* | 0.024* | 0.474 | 0.060 | <0.001* | 0.003* |
| Fuji IX | 1 h | 0.884 | 0.805 | 0.114 | 0.695 | 0.152 | 0.068 |
| | 1 d | <0.001* | 0.982 | 0.110 | <0.001* | 0.073 | 0.115 |
| | 1 w | 0.005* | <0.001* | 0.746 | 0.125 | 0.013* | <0.001* |
| Zirconomer | 1 h | <0.001* | 0.065 | 0.070 | 0.098 | 0.091 | 0.973 |
| | 1 d | 0.042* | 0.018* | 0.946 | 0.737 | 0.035* | 0.015* |
| | 1 w | 0.035* | <0.001* | 0.576 | 0.046* | 0.123 | <0.001* |
| Beautifil X | 1 h | 0.191 | 0.920 | 0.273 | 0.227 | 0.016* | 0.231 |
| | 1 d | <0.001* | 0.371 | 0.538 | 0.005* | 0.002* | 0.780 |
| | 1 w | <0.001* | 0.024* | 0.576 | 0.027* | <0.001* | 0.089 |

After 1 week of immersion, significant color changes were observed in all materials across various beverages. Grape juice consistently caused the most substantial discoloration, reinforcing its high staining potential. Fuji II LC and Fuji IX demonstrated pronounced susceptibility to color changes with grape juice, cola, and chocolate milk. Zirconomer and Beautifil X followed a similar trend, with chocolate milk contributing to their discoloration as occurred with the other beverages. Unexpectedly, distilled water also induced color alterations in the materials to varying extents.

Significant differences in color change were observed between various material combinations after immersion in different beverages for different time intervals (Table 5). When immersed in distilled water, the Fuji II LC (F2)-Beautifil X (BX) and Zirconomer (Zir)-BX combinations exhibited significant differences after 1 week, with F2 and Zir showing greater color changes than BX. For grape juice, significant color changes occurred in all material combinations and time points, except for the Fuji IX (F9)-BX and Zir-BX combinations. In cola, significant alterations were found in the F2-Zir, F2-BX, F9-Zir, and Zir-BX combinations after 1 day and 1 week, with the exception of the F2-Zir combination after 1 day. Lastly, chocolate milk exhibited significant variations in the F9-Zir combination after 1 hour, with Zir showing a greater color change than F9.

Table 5 Comparison of color changes ($\Delta E_{00}$) between material after immersion

| | | F2-F9 | F2-Zir | F2-BX | F9-Zir | F9-BX | Zir-BX |
|---|---|---|---|---|---|---|---|
| Distilled water | 1 h | 0.353 | 0.973 | 0.347 | 0.336 | 0.991 | 0.330 |
| | 1 d | 0.273 | 0.031 | 0.553 | 0.288 | 0.615 | 0.117 |
| | 1 w | 0.142 | 0.946 | 0.040* | 0.152 | 0.576 | 0.046* |
| Grape juice | 1 h | <0.001* | 0.754 | 0.115 | <0.001* | 0.085 | 0.059 |
| | 1 d | <0.001* | 0.001* | 0.001* | 0.460 | 0.460 | 1.000 |
| | 1 w | <0.001* | <0.001* | <0.001* | 0.502 | 0.893 | 0.421 |
| Cola | 1 h | 0.876 | 0.070 | 0.623 | 0.098 | 0.737 | 0.187 |
| | 1 d | <0.001* | 0.495 | 0.004* | 0.002* | 0.377 | 0.026* |
| | 1 w | 0.046* | 0.085 | 0.032* | 0.788 | <0.001* | <0.001* |
| Chocolate milk | 1 h | 0.561 | 0.081 | 0.823 | 0.020* | 0.421 | 0.128 |
| | 1 d | 0.849 | 0.447 | 0.309 | 0.568 | 0.408 | 0.797 |
| | 1 w | 0.599 | 0.143 | 0.911 | 0.347 | 0.524 | 0.115 |

Note: *$p<0.05$ indicates a statistically significant difference.

## Discussion

The present study evaluated the color stability of four glass ionomer-based restorative materials (conventional glass ionomer, resin-modified glass ionomer, giomer, and zirconia-reinforced glass ionomer) when immersed in distilled water, grape juice, cola, and chocolate milk for 1 hour, 1 day, and 1 week. The findings highlighted the varying impact of different beverages on color change in the materials. Therefore, the null hypothesis of no difference in color stability was rejected. The extent of discoloration depended on the material type, beverage, and immersion duration. Substantial variability or dispersion was observed in the data for many conditions, with the standard deviation or interquartile range exceeding 50% of the central tendency measure. This marked variability could arise from high variance within the data or relatively low central tendency values.

This study evaluated the color changes in various GI-based materials after being immersed in solutions for 7 days. The immersion protocol was adopted from Alacote-Mauricio, *et al* [14], then extended to 7 days to create extreme conditions of repeatedly consumed beverages by children. The results might not represent real beverage consumption in the oral cavity, but enhance the changes in color of each GI-based material after exposure to the tested solutions (distilled water, grape juice, cola, and chocolate milk).

Fruit juices, flavored milks, and carbonated drinks are popular among children, unlike coffee and red wine, which were used in previous studies [12, 14] and do not reflect children's beverage choices. Chocolate milk, cola, and grape juice are better examples of beverages preferred by children and can be used for comparison in future studies [15–20].

The evaluation of the beverages' effects on the tested materials revealed a significant correlation between pH and the extent of color variation changes. Acidic beverages such as cola (pH = 2.67) and grape juice (pH = 3.50), which are comparable to previous studies [14, 18], induced more substantial alterations compared with the neutral chocolate milk (pH = 6.99) across all three materials: conventional glass ionomer (Fuji IX), resin-modified glass ionomer (Fuji IILC), and zirconomer. Despite that distilled water having a lower pH and does not conform to any study's expected outcomes [18]. It seems like they are missing a sentence before this one based on this one, they need to say something about the effect of DI on the color change relative to choc milk These findings suggest that the acidic nature of the beverages plays a critical role in the degradation and staining of these materials.

The observed effects of grape juice can be attributed to the presence of acids, which may have disrupted the ionomer matrix, leading to the release of metal cations from the glass particles. Consequently, this acid attack could have resulted in increased surface roughness, facilitating the entrapment of pigments on the material's surface [21, 22]. Additionally, the presence of flavonols, commonly referred to as tannins, in grape juice may have contributed to the more pronounced color changes observed. These polyphenolic compounds are known for their intense coloration and robust flavors, potentially exacerbating the staining effect [23].

In contrast, cola, despite its similar acidic pH, may have exhibited less impact on color alteration due to the absence of these pigmented tannin compounds. However, its acidity could still have affected the ionomer matrix, leading to surface roughness changes and potential staining from other colorants present in the beverage [24].

The evaluation of color stability changes in glass ionomer-based restorative materials following immersion in various beverages is of paramount importance in predicting their clinical performance. In this study, the CIE L*a*b* colorimetric system and digital spectrophotometry were employed to objectively quantify the color changes. This approach eliminates subjective variabilities in color perception, enabling consistent monitoring of color alterations over time [25]. The literature establishes a threshold of $\Delta E_{00} \leq 3.3$ as the clinically acceptable value for color variation, which serves as a reference point for interpreting the obtained results [26].

A noteworthy observation in the present study was the significant color alteration exhibited by Fuji II LC, the conventional glass ionomer cement, after one week of immersion in various media, deviating from the color changes observed at earlier time points. This phenomenon can be attributed to the inherent water-absorbing characteristics of glass ionomer cements, particularly the resin-modified variant (RMGIC) [27–29]. The water sorption capacity of these materials can lead to consequential changes in their color over time.

The diminished color stability observed in glass ionomer cements can be ascribed to the polyacid components in their composition [30]. These polyacids can undergo degradation, contributing to color alterations. Additionally, the hybrid nature of RMGICs, characterized by a relatively high mean filler size range of approximately 1.8 μm [19, 27], may render them more susceptible to color changes.

When Fuji II LC was immersed in acidic media with low pH levels, such as grape juice and cola, substantial color changes were observed. This can be explained by the acidic nature of these immersion media, which can increase surface roughness [20, 27, 31]. Grape juice and

cola contain polyphenolic compounds that can bind to the material's surface, causing color changes and affecting the surface texture as mentioned earlier. Furthermore, the capacity of the material's matrix to absorb water can contribute to alterations in color.

After immersing Fuji IX in distilled water, it is noteworthy that no discernible change in color was observed. This lack of alteration is hypothesized to be linked to the absence of Hydroxyethyl Methacrylate (HEMA) as a component in Fuji IX. Unlike some other dental materials, HEMA is known for its water-absorbing properties, which can influence color changes in the presence of moisture. However, given that Fuji IX does not contain HEMA, the lack of color variation in distilled water immersion suggests that water absorption may not be a contributing factor in this specific case [19, 32].

The investigation into Zirconomer's behavior upon immersion in various media revealed distinct temporal patterns. In distilled water, alterations were evident after the initial hour to the first day, whereas no changes were observed in grape juice over the same time frame. Conversely, exposure to cola elicited modifications after a week, paralleling the pattern observed in Fuji II LC. In contrast, chocolate milk did not induce any discernible changes in Zirconomer throughout the evaluated period. These findings highlight the complex interplay between the material's composition and the specific properties of the immersion media, which govern the nature and kinetics of the observed changes. The rapid alterations observed in distilled water can be attributed to the water-absorbing characteristics of Zirconomer, which can lead to swelling and potential matrix degradation [33]. Conversely, the delayed response to cola may be attributed to the gradual penetration of acidic components, resulting in matrix disruption and potential pigment adsorption over time [21]. The absence of changes in grape juice and chocolate milk during the initial stages could be ascribed to the lack of aggressive components or the presence of protective agents that mitigate immediate degradation [23].

The evaluation of Beautifil X's behavior in different immersion media revealed remarkable color stability, particularly in distilled water and chocolate milk, where no discernible changes were observed. This superior performance can be attributed to the high content of triethylene glycol dimethacrylate (TEGDMA) in its composition [34]. TEGDMA is known for its hydrophobic nature, which enhances the material's resistance to water sorption and subsequent degradation [35]. In contrast, the acidic environments created by grape juice and cola induced relatively higher color alterations in Beautifil X, albeit to a less extent compared with other materials evaluated in this study [21]. This observation suggests that although the material's high TEGDMA content confers excellent color stability under neutral conditions, its performance is still influenced by the presence of aggressive acidic components and potential pigment adsorption [36]. Notably, when tested alongside other dental restorative materials, Beautifil X exhibited the highest color stability, further substantiating the positive impact of its unique composition on this critical property. These findings underscore the importance of optimizing material formulations to enhance color stability and overall aesthetic longevity, particularly in the presence of various dietary and environmental challenges encountered in the oral cavity.

It is crucial to acknowledge certain inherent limitations within the scope of this study. The experimental design lacked an intraoral approach, thus failing to replicate the authentic anatomical tooth structure and the dynamic interactions with oral cavity bacteria and saliva. This limitation could potentially compromise the generalizability

of the study's findings to real-life scenarios within the oral environment. Moreover, the study might be considered somewhat exaggerated compared with everyday life contexts. This is notably evident in the continuous exposure of materials, such as chocolate milk and grape juice throughout the experimental duration. In reality, individuals do not regularly consume these substances in such a consistent manner, prompting concerns regarding the realistic representation of the study's conditions.

These limitations underscore the importance of approaching the results with caution and warrant a careful interpretation while extrapolating them to broader implications for oral health. Subsequent research endeavors could benefit from mitigating these constraints by incorporating intraoral simulations and adopting a more nuanced portrayal of habitual dietary patterns. This approach would contribute to enhancing the ecological validity of the study and, consequently, bolster the reliability of its conclusions.

## Conclusion

Color stability evaluations revealed that grape juice and cola caused substantially higher color changes across materials compared with chocolate milk and distilled water. A one-week cola immersion induced significant color changes in all materials, while grape juice yielded notable changes, except in Zirconomer. Fuji II LC and Fuji IX exhibited significant color differences when immersed in grape juice at all time points. Distilled water and chocolate milk minimally affected the color stability across the materials. These findings highlight the impact of beverage composition, particularly acidity, and pigments, on the color stability of glass ionomer restoratives, underscoring the importance of material selection and patient education for optimal aesthetic outcomes.

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