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Color Stability of Different Provisional Restorative Materials in Energy and Sport Drinks

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Abstract **Background** Provisional restorations must maintain color stability throughout the treatment period, as deterioration in this property compromises esthetic outcomes, and shade selection for the definitive prosthesis. Sports and energy drinks characterized by low pH, citric acid content and synthetic chromogenic agents represent a clinically relevant and increasingly prevalent dietary challenge, yet evidence on their effect on different types of provisional materials remains limited. **Objective:** To evaluate and compare color change (ΔE) of conventional self-curing polymethyl methacrylate (PMMA), bis-acryl composite resin, CAD/CAM 3D-printed resin, and CAD/CAM milled PMMA following immersion in two energy drinks (Red Bull and Power Horse), one sports drink (Gatorade). **Methods:** Disc-shaped specimens (14 mm diameter, 1 mm thickness, shade A2) for the four the four materials were immersed in assigned solutions at 37°C. Measurements were recorded at baseline, 1 day, 1 week, and 2 weeks using a spectrophotometer (Konica Minolta CM-700d) under D65 illumination for color. Three-way linear mixed models were used for statistical analysis; significance was set at $p<0.05$. **Results:** Material, solution, and time all produced considerable effects on both outcomes with some significant interactions. As for color change, immersion solution was the dominant factor ($\eta p^2 = 0.15$). Milled PMMA showed no statistically significant difference ΔE under any condition or time point. Unifast III self-cured resin demonstrated the greatest progressive color change, reaching 2.20±0.96 after 2 weeks in Gatorade. The 3D-printed resin exhibited early high ΔE followed by a plateau, while Protemp 4 composite resin remained largely color-stable. **Conclusion:** CAD/CAM milled PMMA demonstrated superior performance in terms of color change. Conventional self-curing PMMA showed the greatest cumulative deterioration. Sports and energy drink consumption should be considered in provisional material selection and patient counselling.

Key Words Provisional Restorations, Color Stability, Sports Drinks, Energy Drinks, CAD/CAM, 3D-Printed Resin, PMMA, Bis-Acryl Composite Resin

INTRODUCTION

Provisional prostheses paly a fundamental role in the provision of fixed prosthodontic treatment prior to delivery of the definitive restoration, as they provide pulpal tissues protection from bacterial, mechanical, physical and thermal insults, as well as maintain esthetic, function and periodontal health [1]. As a diagnostic blueprint, provisional prostheses facilitate the evaluation of clinical appearance, occlusal stability, phonetics and vertical dimension before clinicians and patients commit to any decision [2]. Therefore, provisional restorations must be able to retain their esthetic and structural integrity under continuous intraoral challenges for an extended period of time, such as cases of full-mouth rehabilitation, during implant osteointegration period, and temporomandibular disorder management [3].

Among the most clinically essential properties of provisional materials are esthetic appearance, favorable surface roughness and color stability [4]. Color stability is a crucial clinical property for provisional restorations as discoloration may result in patient's dissatisfaction, mismatch in shade selection for the definitive prosthesis and require premature provisional restoration replacement. It has been reported that surface roughness and color stability are interdependent as chemically degraded surfaces are highly susceptible to surface roughness and colorant penetration at the same time [5].

Provisional materials are subject to continuous and dynamic challenges in the oral environment, especially to dietary substances with the low pH, high carbohydrate content and those containing artificial colorants that are readily absorbed into the organic matrix of resin-based materials. Notably sports and energy drinks, have gained increasing research interest [6]. The acidic constituents of these dietary substances plasticize the resin matrix, hydrolyze silane linkages and initiate micro-crack formation, through which colorants penetrate and result in resin discoloration, compounding surface deterioration and promoting material surface degradation [6,7].

Provisional materials currently available span a broad spectrum of compositions and fabrication methods. Conventionally fabricated self-curing polymethyl methacrylate (PMMA) and bis-acryl composite resins are still widely used, while CAD/CAM milled PMMA and 3D-printed photopolymer resins have gained increasing popularity as digital alternatives. A systematic review concluded that 3D-printed provisional materials demonstrate superior mechanical properties but inferior physical properties, including color stability, as compared to milled and conventionally fabricated alternatives [8]. Milled PMMA exhibited the lowest surface roughness and microbial adhesion among provisional material categories [9]. However, there is no single ideal material that fully satisfy all biological, esthetic and mechanical requirements simultaneously.

In Saudi Arabia, the substantial increase in the consumption of sports and energy drinks has posed a clinically related problem from the dental restoration perspective. In a national cross-sectional study involving 3,928 Saudi adults, about 30% of subjects, mostly men, of younger age group, and less physically active, consumed energy drinks weekly [10]. Higher consumption rates were reported in earlier regional studies: 45% in Jeddah; 46.73% in Makkah; 71.6% in Riyadh (among college students) [11]. Athletes demonstrate notably higher consumption of sports and energy drinks, with approximately two-thirds of elite athletes reporting regular consumption of at least one such beverage per week [12]. Based on these consumption patterns, the acidic and chromogenic implications of these beverages on provisional restorations in Saudi patients clearly represent common and repeated clinical exposure, not mere theoretical proposition, which calls for direct investigation since there is limited evidence on how provisional restoration materials respond to the exposure of sports and energy drinks.

The objective of this study was to evaluate and compare color stability of four commonly used provisional restorative materials, namely conventional self-curing PMMA, bis-acryl composite resin, 3D-printed resin, and CAD/CAM milled PMMA, following immersion in two energy drinks (Red Bull and Power Horse) and one sports drink (Gatorade) at defined time intervals using distilled water as the control. We hypothesize that there are no statistically significant differences in color stability (ΔE*ab) of the tested provisional restorative materials following exposure to sports and energy drinks at any of the evaluated time intervals.

METHODS

Study Design

This study was conducted as an in vitro experimental study to evaluate and compare color stability (ΔE*ab) of provisional restorative materials following immersion in three commercially available sports and energy drinks and distilled water (as the control) at defined time intervals: at baseline, 1 day, 1 week, and 2 weeks. Material type, immersion solution, and measurement time represented the study's independent variables. To minimize inter-operator variability, only one trained operator performed all specimen preparation, immersion and measurement procedures under standardized laboratory conditions.

Four provisional restorative materials were selected to represent the principal fabrication categories currently available in clinical practice. All materials were used in shade A2 to standardize baseline color across groups. The materials are summarized in Table 1.

Four immersion solutions were used, comprised of two energy drinks, one sports drink and distilled water as the control. Table 2 summarizes the immersion solutions used in the study.

Sample Preparation

A total of 128 disc-shaped specimens (n = 32 per material group; with eight specimens per subgroup for each material according to the material x solution combination) measuring 14 mm in diameter and 1 mm in thickness were fabricated. The specimen dimensions were designed in compliance with ISO 10477:2020 for Polymer-based Crown and Veneering Materials specifications using 3D design software and a standard tessellation language (STL) file was generated for use across all fabrication workflows to ensure dimensional uniformity across groups [13]. Details of fabrication method for each material are listed below:

Fabrication of Conventional Self-Curing PMMA Specimens

A silicone mold produced from the reference STL design was used for the fabrication of self-cured Unifast III specimens. Adhering to the manufacturer's recommended powder-to-liquid ratio, both powder and liquid components were mixed before the mixture was dispensed into the mold during the working phase. Under standardized pressure, a glass slab was placed over the mold (Figure: 1) to ensure a flat surface and eliminate air entrapment. Specimens were allowed to self-cure at room temperature -following manufacturer's instructions- then removed from the mold after complete polymerization.

Fabrication of Bis-Acryl Composite Resin Specimens

Protemp 4 specimens were fabricated using the same silicone mold. The material was dispensed from an auto-mix

Table 1: Provisional Restorative Materials used in the Study

Group	Material Type	Product Name	Manufacturer (Location)	Shade
Group 1	Conventional self-curing PMMA	Unifast III	GC Corporation (Tokyo, Japan)	A2
Group 2	Bis-acryl composite resin	3M™ Protemp™ 4	3M ESPE (St. Paul, MN, USA)	A2
Group 3	CAD/CAM 3D-printed resin	NextDent C&B MFH	NextDent BV (Soesterberg, Netherlands)	A2
Group 4	CAD/CAM milled PMMA	Dentsply Sirona Shaded PMMA Disc	Dentsply Sirona (York, PA, USA)	A2

Table 2: Immersion Solutions used in the Study

Group	Solution	Manufacturer (Location)	Type	pH
Group 1	Red Bull	Rauch Fruchtsäfte GmbH (Austria)	Energy drink	3.3
Group 2	Power Horse	S. Spitz GmbH (Attnang-Puchheim, Austria)	Energy drink	2.7
Group 3	Gatorade	PepsiCo Inc. (Purchase, NY, USA)	Sports drink	2.9
Group 4	Distilled water	Not applicable	Control	7.0



Figure 1: Silicon Mold

cartridge fitted with a mixing tip directly into the mold, ensuring homogeneous mixing and minimizing air inclusion. Specimens were covered with a glass slab and allowed to set for the manufacturer-specified working time before removal from the mold as shown in Figure 1.

Fabrication of CAD/CAM 3D-Printed Resin Specimens

NextDent C&B MFH specimens were fabricated using an STL file transferred to a compatible 3D printer. Specimens were printed at layer thickness of 50 µm and build orientation of 90° to reduce geometric error and minimize anisotropy (the variation in material properties depending on the direction of measurement, which results from the layering of 3D Printing) in surface properties. Following printing, specimens were removed from the build platform and washed in isopropyl alcohol according to the manufacturer's instructions to remove residual uncured resin. Post-curing was performed in a dedicated light-curing unit following the manufacturer-specified duration to maximize the degree of conversion.

Fabrication of CAD/CAM Milled PMMA Specimens

Milled PMMA specimens were produced from pre-polymerized Dentsply Sirona Shaded PMMA discs using a CAD/CAM milling unit. The specimen geometry was designed using (Exocad Dental CAD 3.2 Elefsina software) and the corresponding STL file was transferred to the milling machine. Specimens were milled under standardized parameters and retrieved from the disc following the completion of the milling cycle.

Finishing and Polishing

Following fabrication (Figure 2), all specimens from all groups were subjected to a standardized finishing and polishing protocol to ensure surface uniformity across groups and eliminate fabrication-related surface irregularities. Polishing was performed using BUEHLER AutoMet 250 Grinder-Polisher (Buehler, Lake Bluff, IL, USA) with sequential application of silicon carbide abrasive papers at grit 600, 800, 1200, and 1400 at rotational speed of 300 rpm under continuous water cooling, for 60 seconds at each grit level. Following polishing, all specimens were ultrasonically cleaned in distilled water for 5 minutes to remove any surface debris and dried with oil-free compressed air. Visual inspection for visible voids, cracks, or surface defects was subsequently conducted, and specimens with any of these were discarded and replaced.

Konica Minolta CM-700d CM-700d spectrophotometer (Konica Minolta, Tokyo, Japan) was used to measure color stability at each time interval under the same standardized conditions as the baseline measurement. The L*, a*, and b* values recorded at each interval were compared to the respective baseline values for each specimen The total color difference (ΔE*ab*ab) was calculated using the CIE76 formula:

$$\Delta E^*ab = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]}$$

A ΔE*ab value of 1.2 was used as the perceptibility threshold and 2.7 as the acceptability threshold for clinical interpretation of color change outcomes, in accordance with Paravina *et al.* [14].

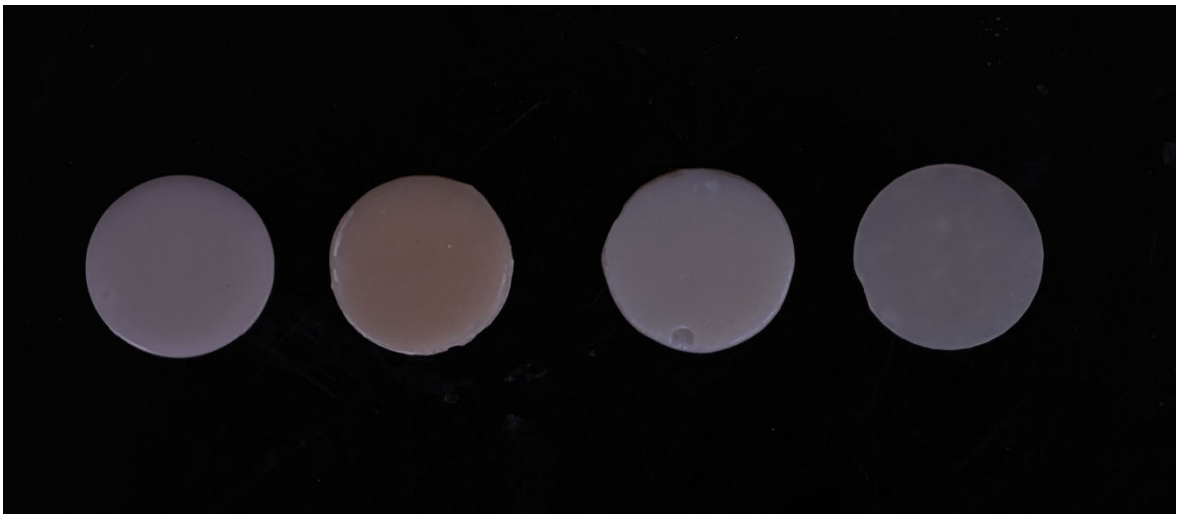


Figure 2: From Left to Right: 1. Milled PMMA 2. Conventional PMMA 3. Bis-Acryl (Protemp) 4- 3D-Printed Resin

Color change between two measurements is quantified using the total color difference, ΔE*ab*ab, calculated from the CIE L*a*b* color space using the CIE76 formula. The formula integrates the differences in all three-color dimensions (i.e., lightness, red–green, and yellow–blue) into a single numerical value that represents the magnitude of color change between baseline and post-immersion measurements [15].

$$\Delta E^*ab^*ab = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]}$$

where ΔL* represents the difference in lightness between the two measurements; Δa* represents the change along the red–green axis; Δb* represents the change along the yellow-blue axis.

ΔE*ab of zero indicates no color change, while increasing values reflect progressively greater color difference from the baseline. Color measurement is performed using a calibrated spectrophotometer under standardized illumination conditions, typically using the D65 standard illuminant, which corresponds to average daylight and a 10-degree standard observer angle [16]. A neutral gray background is used during measurement to minimize the influence of translucency on the recorded values [16].

Perceptibility and Acceptability Threshold Values

The clinical relevance of a calculated ΔE*ab*ab value is determined by established perceptibility (PT) and acceptability (AT) threshold values. Early in vitro studies in the 1980s and 1990s proposed acceptability thresholds for dental color differences in the range of ΔE*ab*ab ≈ 3.3 to 3.7, values that were widely cited for several decades [17,18]. More recently, the multicenter study by Paravina *et al.* established a 50:50% perceptibility threshold (PT) of ΔE*ab*ab = 1.2 and a 50:50% acceptability threshold (AT) of ΔE*ab*ab = 2.7 under simulated clinical conditions [14]. These contemporary thresholds were subsequently incorporated into the ISO/TR 28642 guidance on color measurement in dentistry and are now the most widely applied reference values in dental color stability research [19]. Color changes below the PT are visually imperceptible and carry no clinical consequence; values between 1.2 and 2.7 are perceptible but may remain clinically acceptable; and values exceeding 2.7 indicate discoloration that is both detectable and clinically unacceptable, typically calling for attention or replacement of the provisional material [14,19].

Statistical Analysis

Continuous data are shown as means±standard deviation (SD). Three-way linear mixed models were employed to analyse effects of restorative material, immersion solution and time, along with their two- and three-way interactions on color change (ΔE*ab). The specimen was included as a random intercept because of the repeated nature of measures.

Normality of residuals was inspected by (Q-Q) plots and homoscedasticity was assessed using fitted values plotted against residuals. Because of violated assumptions, a square root transformation of ΔE*ab improved model fit and reduced departures from normality, so a new model was fit with the transformed outcome. Cluster-robust standard errors were calculated at the specimen level, with small-sample correction. Descriptive statistics (means and SDs) used the original data set, without transformations, for ease of interpretation.

Following model fitting, F-tests and pairwise t-tests were used to examine pairwise differences between the estimated marginal means (EMMs) for the color change model. P-values were corrected for multiple comparison with Holm's sequential procedure. The significance level for all tests was $p<0.05$. We report effect sizes for the color change model using partial eta squared (ηp2) and interpret them according to Cohen [20]. We performed all statistical tests using the R statistical software version 4.6.0 for Windows (R Core Team, 2026).

RESULTS

Main and Interaction Effects of Variables

The effects of restorative material, immersion solution, time, and their two- and three-way interactions on color change (ΔE*ab) are summarised in Table 3. All three main effects were statistically significant ($p<0.001$). The largest main effect was attributable to immersion solution ($\eta_p^2 = 0.15$, 95% CI: 0.08–0.22), followed by time ($\eta_p^2 = 0.11$, 95% CI: 0.04–0.18) and restorative material ($\eta_p^2 = 0.05$, 95% CI: 0.01–0.10). The material × solution interaction was significant ($F = 4.09$, $p<0.001$, $\eta_p^2 = 0.11$, 95% CI: 0.03–0.16), as was the material × time interaction ($F = 3.23$, $p = 0.005$, $\eta_p^2 = 0.08$, 95% CI: 0.01–0.13). The solution × time and the three-way (material × solution × time) interactions did not reach statistical significance ($p = 0.503$ and $p = 0.201$, respectively).

Provisional Restorative Material influence on Colour Change

Comparative analysis of the data and summary statistics of ΔE*ab by restorative material are presented in Tables 3 and 4 and Figures 3 to 6. The effect of material was conditional on both the immersion solution and the observation time, consistent with the significant material × solution and material × time interactions reported.

1 Day Figure 3

For Red Bull at 1 day, a significant difference was found among materials ($p<0.001$), with a small effect size ($\eta_p^2 =$ 0.05). The highest ΔE*ab was recorded for 3D-printed resin (0.78±0.18), followed by Protemp (0.45±0.19), Unifast (0.36±0.13), and milled PMMA (0.31±0.13). Post hoc pairwise comparisons indicated that 3D-printed resin showed significantly greater color change than all other materials, with the exception of Protemp.

For Power Horse at 1 day, materials also differed significantly ($p = 0.011$; $\eta_p^2 = 0.04$). ΔE*ab was again highest in 3D-printed resin (0.75±0.35), followed by Protemp (0.42±0.14), Unifast (0.41±0.16), and milled PMMA (0.36±0.23). Post hoc comparisons revealed that the only statistically significant pairwise difference was between 3D-printed resin and milled PMMA.

For Gatorade at 1 day, a significant difference was found among materials ($p<0.001$) with a medium effect size ($\eta_p^2 = 0.17$). The highest ΔE*ab was recorded for 3D-printed resin (1.25±0.35), followed closely by Unifast (1.23±0.61), then Protemp (0.49±0.26) and milled PMMA (0.31±0.15). Post hoc analysis showed that both 3D-printed resin and Unifast had significantly greater color change than Protemp and milled PMMA.

For distilled water at 1 day, a small but statistically significant difference was detected among materials ($p = 0.006$; $\eta_p^2 = 0.04$). The highest ΔE*ab was observed in 3D-printed resin (0.73±0.44), followed by Protemp (0.42±0.22), milled PMMA (0.40±0.22), and Unifast (0.26±0.14). Post hoc comparisons revealed a single significant pairwise difference: 3D-printed resin demonstrated a greater degree of color change than Unifast.

Table 3: Effects of Restorative Material, Immersion Solution, Time, and their Interactions on Color Change (ΔE)

Source	df1	df2	F-value	p-value	PES (95% CI)
Restorative material	3	298.71	5.58	<0.001*	0.05 (0.01 to 0.10)
Solution	3	298.71	17.47	<0.001*	0.15 (0.08 to 0.22)
Time	2	223.04	13.40	<0.001*	0.11 (0.04 to 0.18)
Material * Solution	9	298.71	4.09	<0.001*	0.11 (0.03 to 0.16)
Material * Time	6	224.22	3.23	0.005*	0.08 (0.01 to 0.13)
Solution * Time	6	223.04	0.89	0.503ns	0.02 (0.00 to 0.05)
Material * Solution * Time	18	223.34	1.28	0.201ns	0.09 (0.00 to 0.10)

DF: Degree of Freedom, PES: Partial Eta Squared, CI: Confidence Interval, * Significant ($p<0.05$), ns: Not Significant

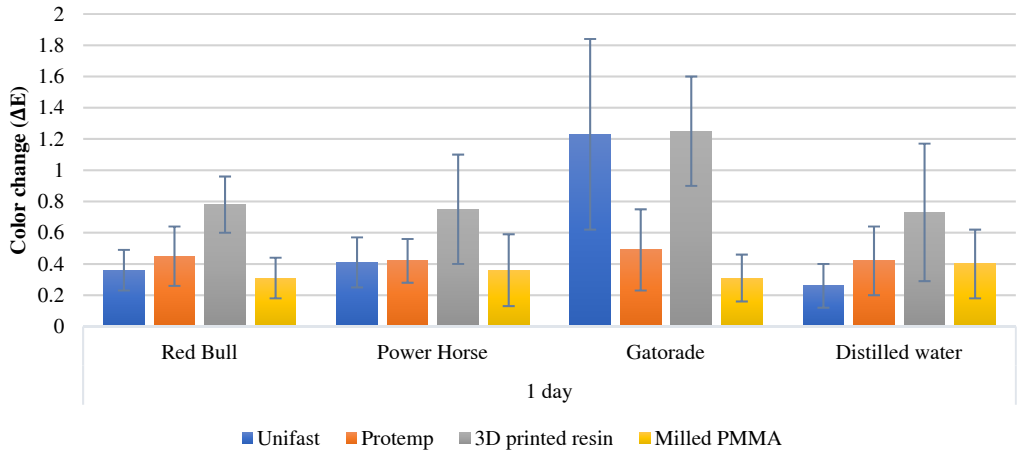


Figure 3: Bar Chart Illustrating Mean and Standard Deviation (Error Bars) Values of Color Change (Δe*Ab) For Different Restorative Materials (1 day)

1 Week (Figure 4)

For Red Bull at 1 week, materials differed significantly ($p<0.001$; $\eta^{p2} = 0.08$). The highest ΔE*ab was recorded for 3D-printed resin (1.10±0.21), followed by Unifast (0.73±0.38), Protemp (0.51±0.16), and milled PMMA (0.43±0.30). Post hoc pairwise comparisons showed that 3D-printed resin had significantly greater color change than the remaining materials, except for Unifast.

For Power Horse at 1 week, a significant difference was detected among materials ($p<0.001$) with a small effect size ($\eta^{p2} = 0.12$). The highest ΔE*ab was found in 3D-printed resin (0.96±0.30), followed by Protemp (0.69±0.18), Unifast (0.53±0.23), and milled PMMA (0.18±0.10). Post hoc analysis indicated that 3D-printed resin had significantly higher color change than all other materials except Protemp, and that Protemp and Unifast had significantly higher color change than milled PMMA.

For Gatorade at 1 week, the difference among materials was significant ($p<0.001$; $\eta^{p2} = 0.14$). Unifast recorded the highest ΔE*ab (1.39±0.34), followed by 3D-printed resin (1.03±0.12), Protemp (0.53±0.27), and milled PMMA (0.41±0.15). Post hoc pairwise comparisons showed that both Unifast and 3D-printed resin had significantly greater color change than Protemp and milled PMMA.

For distilled water at 1 week, materials again differed significantly ($p<0.001$; $\eta^{p2} = 0.06$). The highest ΔE*ab was observed for 3D-printed resin (0.69±0.37), followed by Unifast (0.62±0.26), Protemp (0.40±0.16), and milled PMMA (0.22±0.10). Post hoc analysis showed that milled PMMA had significantly lower color change than the other materials, apart from Protemp.

Two Weeks (Figure 5)

After 2 weeks of immersion, ΔE*ab values reached their highest levels of the observation period, with significant material effects detected across all four solutions.

For Red Bull at 2 weeks, the material effect was significant ($p<0.001$) with a medium effect size ($\eta^{p2} = 0.13$). The highest ΔE*ab was recorded for 3D-printed resin (1.09±0.19), followed by Unifast (1.04±0.57), Protemp (0.67±0.08), and milled PMMA (0.25±0.08). Post hoc pairwise comparisons showed that 3D-printed resin had significantly greater color change than the other materials, except Unifast, and that both Unifast and Protemp demonstrated significantly higher degree of color alteration than milled PMMA.

For Power Horse at 2 weeks, materials differed significantly ($p<0.001$) with a small effect size ($\eta^{p2} = 0.11$). The highest ΔE*ab was observed in Unifast (1.06±0.58), followed by 3D-printed resin (1.01±0.16), Protemp (0.80±0.34), and milled PMMA (0.31±0.18). Post hoc analysis showed that milled PMMA had significantly lower color change than the remaining materials.

For Gatorade at 2 weeks, the difference among materials was significant ($p<0.001$) with a medium effect size ($\eta^{p2} = 0.25$), which was the largest material effect observed in the study. The highest ΔE*ab was recorded for Unifast (2.20±0.96), followed by 3D-printed resin (1.30±0.51), Protemp (0.87±0.45), and milled PMMA (0.35±0.09). All post hoc pairwise comparisons were statistically significant.

For distilled water at 2 weeks, materials also differed significantly ($p<0.001$) with a small effect size ($\eta^{p2} = 0.10$). The highest ΔE*ab was found in Unifast (0.93±0.39), followed by 3D-printed resin (0.67±0.42), Protemp (0.45±0.17), and milled PMMA (0.22±0.09). Post hoc comparisons showed that Unifast had significantly greater color change than all other materials except 3D-printed resin, and that 3D-printed resin had significantly greater color change than milled PMMA.

Effect of Immersion Solution on Color Change

Comparative statistical analysis of ΔE*ab by immersion solution are presented in Table 5 and Figures (7 to 10). Solution effects varied substantially across materials, with Unifast and 3D-printed resin showing the greatest susceptibility to solution-related differences, and milled PMMA showing none at any time point.

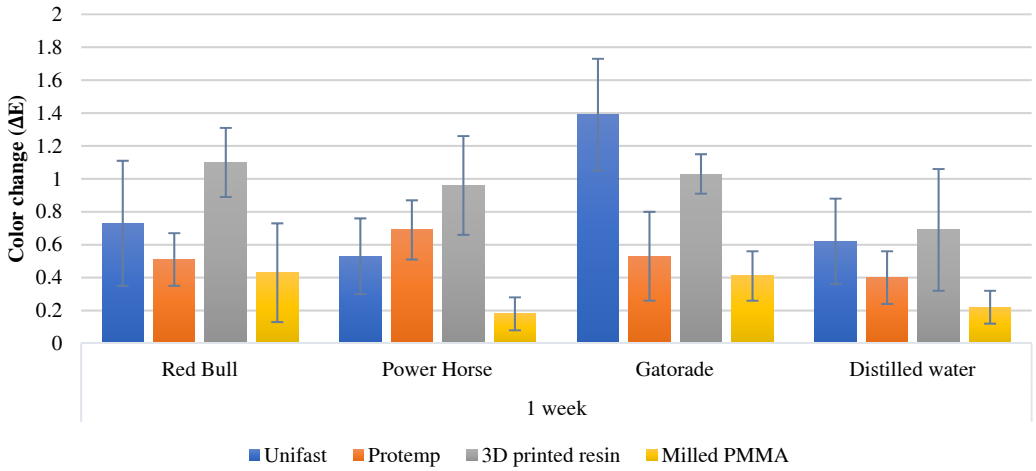


Figure 4: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (Δe*Ab) for Different Restorative Materials (1 Week)

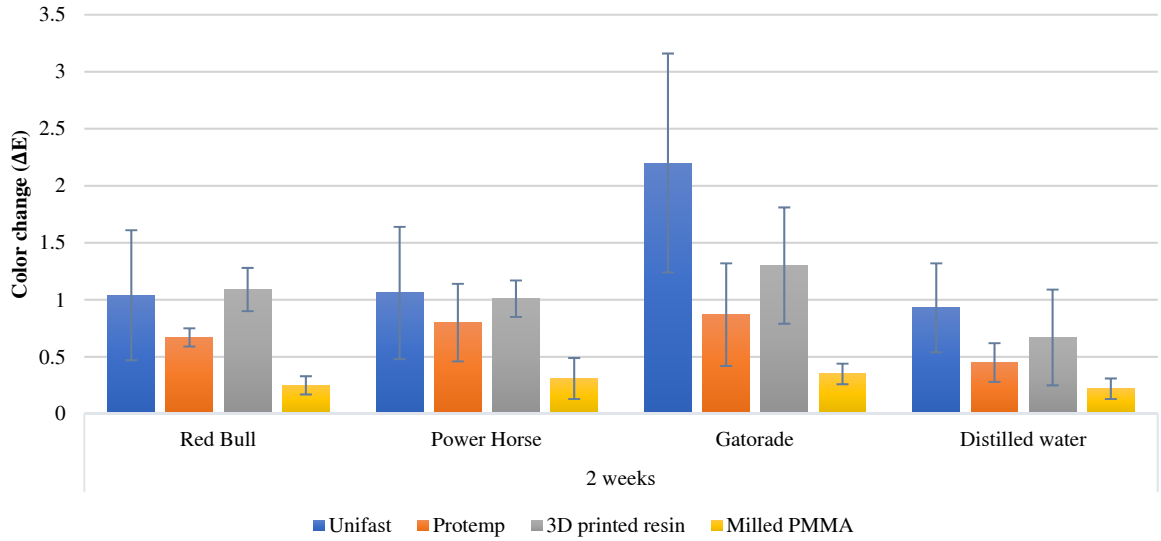


Figure 5: Bar Chart Illustrating Mean and Standard Deviation (Error Bars) Values of Color Change (Δe*Ab) for Different Restorative Materials (2 Weeks)

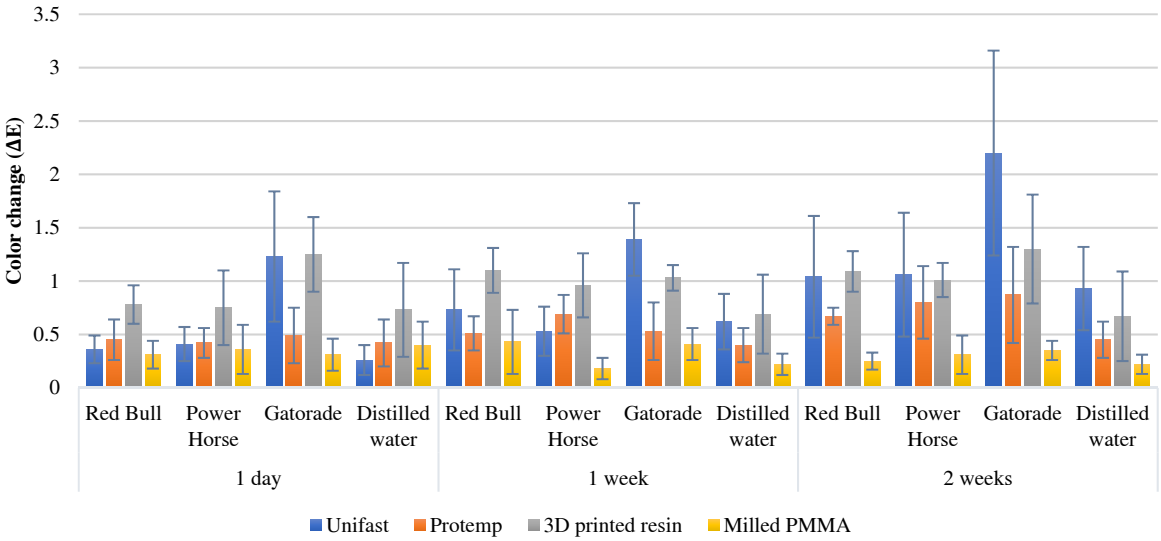


Figure 6: Comparative Analysis and Summary Statistics of Color Change (Δ E*Ab) for Selected Restorative Materials

Table 4: Comparison of Statistical Difference for the Effect of Immersion Solution on Color Change (Δ E) for the Different Restorative Materials

Time	Solution	Color change (ΔE*ab) (Mean±SD)				p-value	PES (95% CI)
		Unifast	Protemp	3D printed resin	Milled PMMA		
1 day	Red Bull	0.36±0.13B	0.45±0.19AB	0.78±0.18A	0.31±0.13B	<0.001*	0.05 (0.01 to 0.10)
	Power Horse	0.41±0.16AB	0.42±0.14AB	0.75±0.35A	0.36±0.23B	0.011*	0.04 (0.00 to 0.08)
	Gatorade	1.23±0.61A	0.49±0.26B	1.25±0.35A	0.31±0.15B	<0.001*	0.17 (0.10 to 0.24)
	Distilled water	0.26±0.14B	0.42±0.22AB	0.73±0.44A	0.40±0.22AB	0.006*	0.04 (0.00 to 0.09)
1 week	Red Bull	0.73±0.38AB	0.51±0.16B	1.10±0.21A	0.43±0.30B	<0.001*	0.08 (0.03 to 0.14)
	Power Horse	0.53±0.23B	0.69±0.18AB	0.96±0.30A	0.18±0.10C	<0.001*	0.12 (0.06 to 0.19)
	Gatorade	1.39±0.34A	0.53±0.27B	1.03±0.12A	0.41±0.15B	<0.001*	0.14 (0.07 to 0.21)
	Distilled water	0.62±0.26A	0.40±0.16AB	0.69±0.37A	0.22±0.10B	<0.001*	0.06 (0.01 to 0.12)
2 weeks	Red Bull	1.04±0.57AB	0.67±0.08B	1.09±0.19A	0.25±0.08C	<0.001*	0.13 (0.07 to 0.20)
	Power Horse	1.06±0.58A	0.80±0.34A	1.01±0.16A	0.31±0.18B	<0.001*	0.11 (0.04 to 0.17)
	Gatorade	2.20±0.96A	0.87±0.45C	1.30±0.51B	0.35±0.09D	<0.001*	0.25 (0.17 to 0.33)
	Distilled water	0.93±0.39A	0.45±0.17BC	0.67±0.42AB	0.22±0.09C	<0.001*	0.10 (0.04 to 0.16)

PES: Partial Eta Squared, CI: Confidence interval, Values with Different Superscripts within the Same Horizontal Row are Significantly Different, * Significant (p<0.05)

Table 5: Comparative Analysis and Statistical Summary of Color Change (ΔE*ab) for Different Solutions

Time	Restorative material	Color change (ΔE*ab) (Mean±SD)				p-value	PES (95% CI)
		Red Bull	Power Horse	Gatorade	Distilled water		
1 day	Unifast	0.36±0.13B	0.41±0.16B	1.23±0.61A	0.26±0.14B	<0.001*	0.15 (0.08 to 0.22)
	Protemp	0.45±0.19A	0.42±0.14A	0.49±0.26A	0.42±0.22A	0.933ns	0.00 (0.00 to 0.01)
	3D printed resin	0.78±0.18B	0.75±0.35B	1.25±0.35A	0.73±0.44B	0.004*	0.04 (0.01 to 0.09)
	Milled PMMA	0.31±0.13A	0.36±0.23A	0.31±0.15A	0.40±0.22A	0.891ns	0.00 (0.00 to 0.01)
1 week	Unifast	0.73±0.38B	0.53±0.23B	1.39±0.34A	0.62±0.26B	<0.001*	0.10 (0.04 to 0.16)
	Protemp	0.51±0.16A	0.69±0.18A	0.53±0.27A	0.40±0.16A	0.149ns	0.02 (0.00 to 0.05)
	3D printed resin	1.10±0.21A	0.96±0.30AB	1.03±0.12AB	0.69±0.37B	0.039*	0.03 (0.00 to 0.07)
	Milled PMMA	0.43±0.30A	0.18±0.10A	0.41±0.15A	0.22±0.10A	0.051ns	0.03 (0.00 to 0.07)
2 weeks	Unifast	1.04±0.57B	1.06±0.58B	2.20±0.96A	0.93±0.39B	<0.001*	0.13 (0.06 to 0.20)
	Protemp	0.67±0.08AB	0.80±0.34AB	0.87±0.45A	0.45±0.17B	0.032*	0.03 (0.00 to 0.07)
	3D printed resin	1.09±0.19A	1.01±0.16AB	1.30±0.51A	0.67±0.42B	0.001*	0.05 (0.01 to 0.10)
	Milled PMMA	0.25±0.08A	0.31±0.18A	0.35±0.09A	0.22±0.09A	0.445ns	0.01 (0.00 to 0.03)

PES: Partial Eta Squared, CI: Confidence Interval, Values with different superscripts within the same horizontal row are significantly different, * Significant (p<0.05), ns: Not Significant

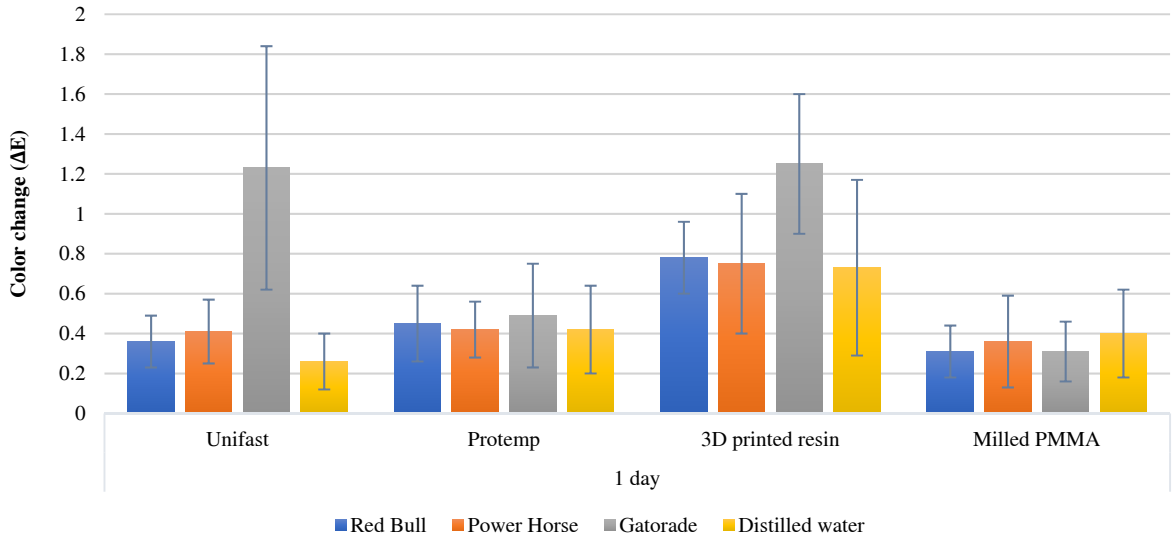


Figure 7: Bar Chart Illustrating Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for Different Solutions (1 Day)

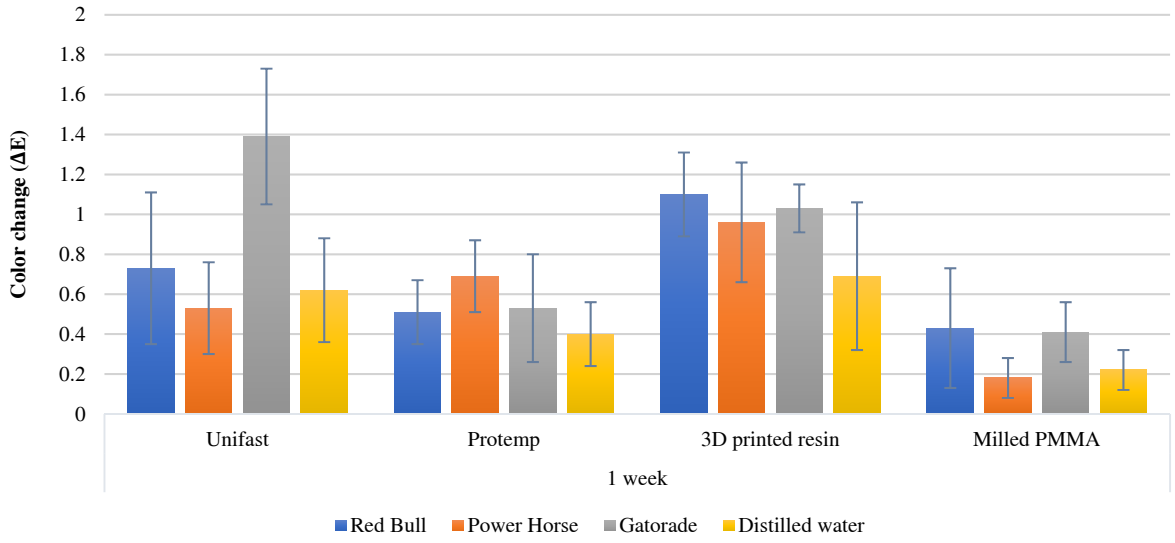


Figure 8: Bar Chart Showing Mean And Standard Deviation (Error Bars) Values Of Color Change (ΔE*Ab) For Different Solutions (1 Week)

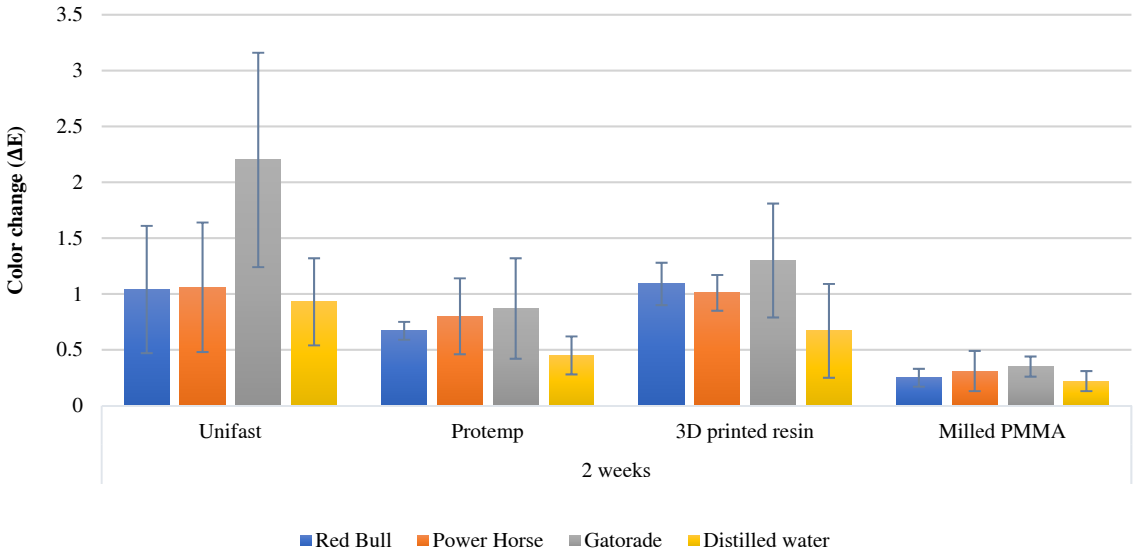


Figure 9: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for the Tested Solutions (2 Weeks)

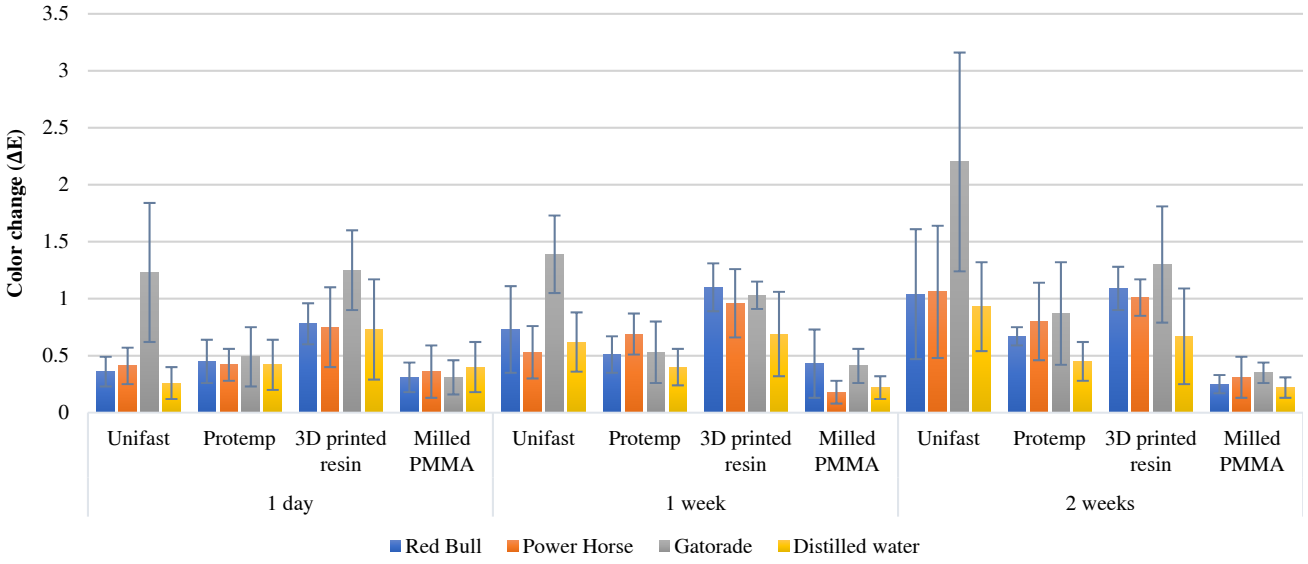


Figure 10: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for the Tested Solutions

1 Day (Figure 7)

For Unifast at 1 day, a significant difference in ΔE*ab was observed across solutions ($p<0.001$) with a medium effect size ($\eta_p^2 = 0.15$). The highest ΔE*ab was found in Gatorade (1.23±0.61), followed by Power Horse (0.41±0.16), Red Bull (0.36±0.13), and distilled water (0.26±0.14). Post hoc comparisons showed that Gatorade produced significantly greater color change than the other three solutions.

For Protemp at 1 day, no significant difference was detected across solutions ($p = 0.933$; $\eta_p^2 = 0.00$). ΔE*ab values were closely clustered, with Gatorade at 0.49±0.26, Red Bull at 0.45±0.19, distilled water at 0.42±0.22, and Power Horse at 0.42±0.14.

For 3D-printed resin at 1 day, solutions differed significantly ($p = 0.004$; $\eta_p^2 = 0.04$). The highest ΔE*ab was recorded in Gatorade (1.25±0.35), followed by Red Bull (0.78±0.18), Power Horse (0.75±0.35), and distilled water (0.73±0.44). Post hoc analysis showed that Gatorade produced significantly greater color change than the remaining solutions.

For milled PMMA at 1 day, no significant difference was detected across solutions ($p = 0.891$; $\eta_p^2 = 0.00$). ΔE*ab values were uniformly low: distilled water (0.40±0.22), Power Horse (0.36±0.23), Gatorade (0.31±0.15), and Red Bull (0.31±0.13).

1 Week (Figure 8)

For Unifast at 1 week, solutions differed significantly ($p<0.001$; $\eta_p^2 = 0.10$). The highest ΔE*ab was found in

Gatorade (1.39±0.34), followed by Red Bull (0.73±0.38), distilled water (0.62±0.26), and Power Horse (0.53±0.23). Post hoc comparisons showed that Gatorade produced significantly greater color alteration than the other solutions.

For Protemp at 1 week, no significant difference was detected across solutions ($p = 0.149$; $\eta_p^2 = 0.02$). Values ranked as Power Horse (0.69±0.18), Gatorade (0.53±0.27), Red Bull (0.51±0.16), and distilled water (0.40±0.16).

For 3D-printed resin at 1 week, a significant solution effect was detected ($p = 0.039$; $\eta_p^2 = 0.03$). The highest ΔE*ab was found in Red Bull (1.10±0.21), followed by Gatorade (1.03±0.12), Power Horse (0.96±0.30), and distilled water (0.69±0.37). Post hoc analysis showed that Red Bull produced significantly higher color change than distilled water.

For milled PMMA at 1 week, no significant difference was detected across solutions ($p = 0.051$; $\eta_p^2 = 0.03$). ΔE*ab values ranged from Red Bull (0.43±0.30) to Gatorade (0.41±0.15), distilled water (0.22±0.10), and Power Horse (0.18±0.10).

2 Weeks (Figure 9)

For Unifast at 2 weeks, solutions differed significantly ($p<0.001$) with a medium effect size ($\eta_p^2 = 0.13$). The highest ΔE*ab was found in Gatorade (2.20±0.96), followed by Power Horse (1.06±0.58), Red Bull (1.04±0.57), and distilled water (0.93±0.39). Post hoc comparisons showed that Gatorade produced significantly greater color change than the other three solutions.

For Protemp at 2 weeks, a significant solution effect was detected ($p = 0.032$; $\eta_p^2 = 0.03$). The highest ΔE*ab was found in Gatorade (0.87±0.45), followed by Power Horse (0.80±0.34), Red Bull (0.67±0.08), and distilled water (0.45±0.17). Post hoc analysis showed that Gatorade produced significantly higher color change than distilled water.

For 3D-printed resin at 2 weeks, solutions differed significantly ($p = 0.001$; $\eta_p^2 = 0.05$). The highest ΔE*ab was found in Gatorade (1.30±0.51), followed by Red Bull (1.09±0.19), Power Horse (1.01±0.16), and distilled water (0.67±0.42). Post hoc analysis showed that distilled water produced significantly lower color change than the other solutions, apart from Power Horse.

For milled PMMA at 2 weeks, no significant difference was detected across solutions ($p = 0.445$; $\eta_p^2 = 0.01$). Mean ΔE*ab values were Gatorade (0.35±0.09), Power Horse (0.31±0.18), Red Bull (0.25±0.08), and distilled water (0.22±0.09). Lastly, a comparison of the effect of immersion solutions is summarised in Table 5.

Effect of Time on Color Change

Comparisons of ΔE*ab across the three time points (1 day, 1 week, 2 weeks), stratified by material and solution, are presented in Table 6 and Figures (11 to 15). The time effect was material-dependent and broadly absent in 3D-printed resin and milled PMMA, reflecting the significant material × time interaction reported.

The effect of time on color change differed markedly across materials and solutions, with Unifast demonstrating the most consistent time-dependent increases, and milled PMMA showing no significant change over time regardless of the immersion solution.

Unifast

For Unifast immersed in Red Bull, ΔE*ab increased progressively across time points ($p<0.001$; $\eta_p^2 = 0.11$), from 0.36±0.13 at 1 day to 0.73±0.38 at 1 week and 1.04±0.57 at 2 weeks. All post hoc pairwise comparisons reached statistical significance.

For Unifast immersed in Power Horse, a significant time effect was detected ($p<0.001$; $\eta_p^2 = 0.10$). ΔE*ab rose from 0.41±0.16 at 1 day to 0.53±0.23 at 1 week and 1.06±0.58 at 2 weeks. Post hoc comparisons showed that the 2-week value was significantly higher than at both earlier time points.

For Unifast immersed in Gatorade, time had a significant effect ($p<0.001$; $\eta_p^2 = 0.10$). ΔE*ab values were 1.23±0.61 at 1 day, 1.39±0.34 at 1 week, and 2.20±0.96 at 2 weeks. Post hoc analysis indicated that the 2-week value was significantly higher than at both earlier time points.

For Unifast immersed in distilled water, ΔE*ab increased significantly across time ($p<0.001$) with a medium effect size ($\eta_p^2 = 0.13$), from 0.26±0.14 at 1 day to 0.62±0.26 at 1 week and 0.93±0.39 at 2 weeks. All post hoc pairwise comparisons were statistically significant.

Protemp

For Protemp immersed in Red Bull, no significant time effect was detected ($p = 0.101$; $\eta_p^2 = 0.02$), although a modest upward trend was observed: 0.45±0.19 at 1 day, 0.51±0.16 at 1 week, and 0.67±0.08 at 2 weeks.

For Protemp immersed in Power Horse, a significant time effect was detected ($p = 0.006$; $\eta_p^2 = 0.04$). ΔE*ab rose from 0.42±0.14 at 1 day to 0.69±0.18 at 1 week and 0.80±0.34 at 2 weeks. Post hoc analysis indicated that the 1-day value was significantly lower than the values at the two later time points.

For Protemp immersed in Gatorade, time had a significant effect ($p = 0.008$; $\eta_p^2 = 0.04$). ΔE*ab values were 0.49±0.26 at 1 day, 0.53±0.27 at 1 week, and 0.87±0.45 at 2 weeks. Post hoc comparisons showed that the 2-week value was significantly higher than at both earlier time points.

For Protemp immersed in distilled water, no significant time effect was detected ($p = 0.862$; $\eta_p^2 = 0.00$). ΔE*ab values were essentially flat across the observation period: 0.42±0.22 at 1 day, 0.40±0.16 at 1 week, and 0.45±0.17 at 2 weeks.

Printed Resin

For 3D-printed resin immersed in Red Bull, no significant time effect was detected ($p = 0.054$; $\eta_p^2 = 0.03$), with values of 0.78±0.18 at 1 day, 1.10±0.21 at 1 week, and 1.09±0.19 at 2 weeks.

For 3D-printed resin immersed in Power Horse, no significant time effect was detected ($p = 0.105$; $\eta_p^2 = 0.02$). ΔE*ab values were 0.75±0.35 at 1 day, 0.96±0.30 at 1 week, and 1.01±0.16 at 2 weeks.

Table 6: Comparative Analysis and Statistical Summary of Color Change (ΔE*ab) for Different Times

Restorative material	Solution	Color change (ΔE*ab) (Mean±SD)			p-value	PES (95% CI)
		1 day	1 week	2 weeks		
Unifast	Red Bull	0.36±0.13C	0.73±0.38B	1.04±0.57A	<0.001*	0.11 (0.04 to 0.18)
	Power Horse	0.41±0.16B	0.53±0.23B	1.06±0.58A	<0.001*	0.10 (0.03 to 0.18)
	Gatorade	1.23±0.61B	1.39±0.34B	2.20±0.96A	<0.001*	0.10 (0.03 to 0.18)
	Distilled water	0.26±0.14C	0.62±0.26B	0.93±0.39A	<0.001*	0.13 (0.06 to 0.22)
Protemp	Red Bull	0.45±0.19A	0.51±0.16A	0.67±0.08A	0.101ns	0.02 (0.00 to 0.07)
	Power Horse	0.42±0.14B	0.69±0.18A	0.80±0.34A	0.006*	0.04 (0.00 to 0.10)
	Gatorade	0.49±0.26B	0.53±0.27B	0.87±0.45A	0.008*	0.04 (0.00 to 0.10)
	Distilled water	0.42±0.22A	0.40±0.16A	0.45±0.17A	0.862ns	0.00 (0.00 to 0.02)
3D printed resin	Red Bull	0.78±0.18A	1.10±0.21A	1.09±0.19A	0.054ns	0.03 (0.00 to 0.07)
	Power Horse	0.75±0.35A	0.96±0.30A	1.01±0.16A	0.105ns	0.02 (0.00 to 0.06)
	Gatorade	1.25±0.35A	1.03±0.12A	1.30±0.51A	0.336ns	0.01 (0.00 to 0.04)
	Distilled water	0.73±0.44A	0.69±0.37A	0.67±0.42A	0.907ns	0.00 (0.00 to 0.01)
Milled PMMA	Red Bull	0.31±0.13A	0.43±0.30A	0.25±0.08A	0.279ns	0.01 (0.00 to 0.05)
	Power Horse	0.36±0.23A	0.18±0.10A	0.31±0.18A	0.116ns	0.02 (0.00 to 0.06)
	Gatorade	0.31±0.15A	0.41±0.15A	0.35±0.09A	0.584ns	0.00 (0.00 to 0.03)
	Distilled water	0.40±0.22A	0.22±0.10A	0.22±0.09A	0.071ns	0.02 (0.00 to 0.07)

PES: Partial Eta Squared, CI: Confidence Interval, Values with different superscripts within the same horizontal row are significantly different, * Significant (p<0.05), ns: Not Significant

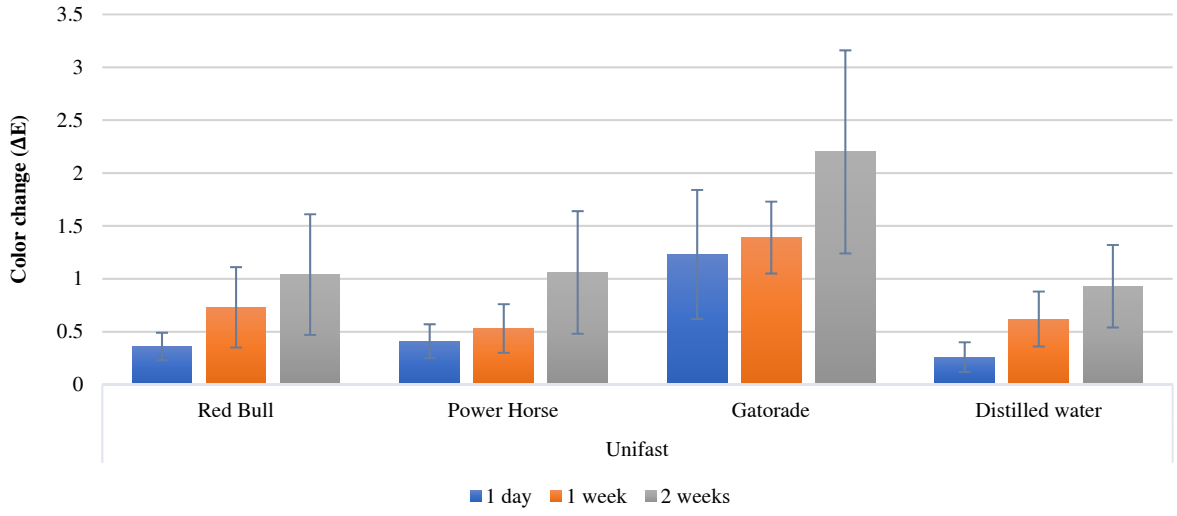


Figure 11: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for Different Times (Unifast)

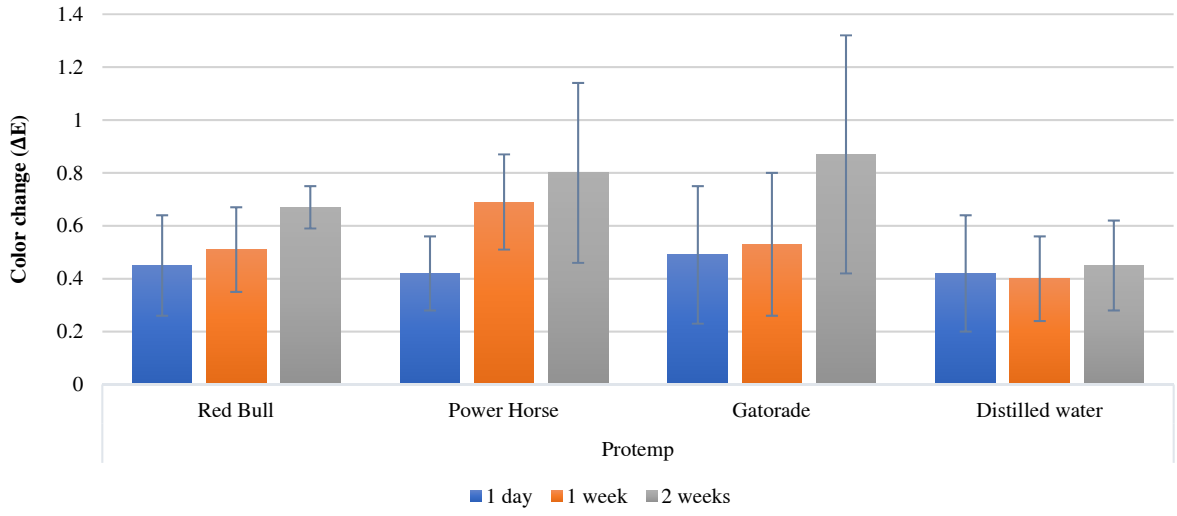


Figure 12: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) For Different Times (Protemp)

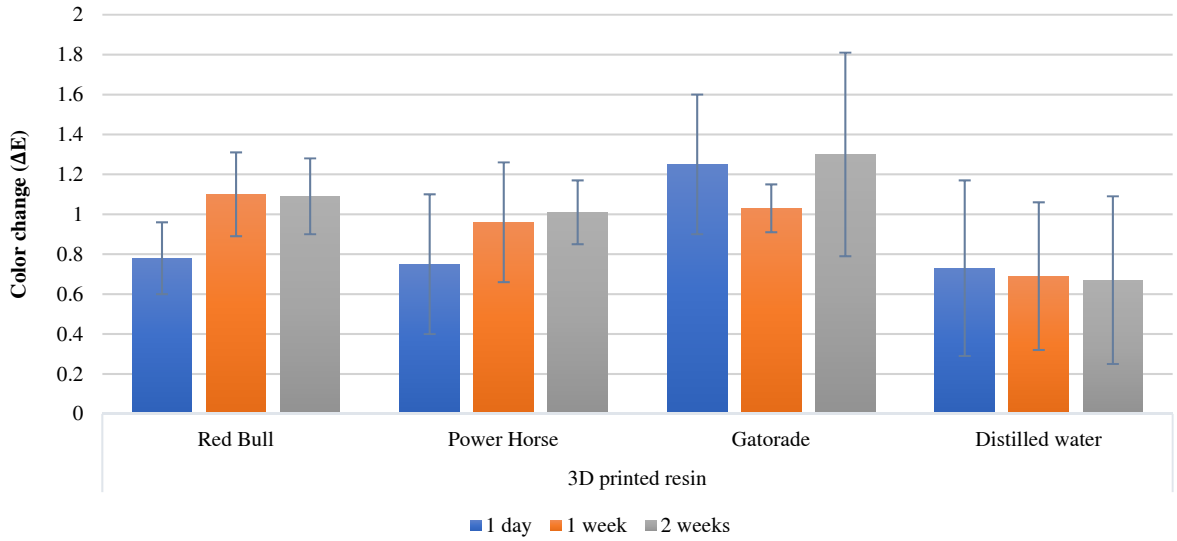


Figure 13: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for Different Times (3D Printed Resin)

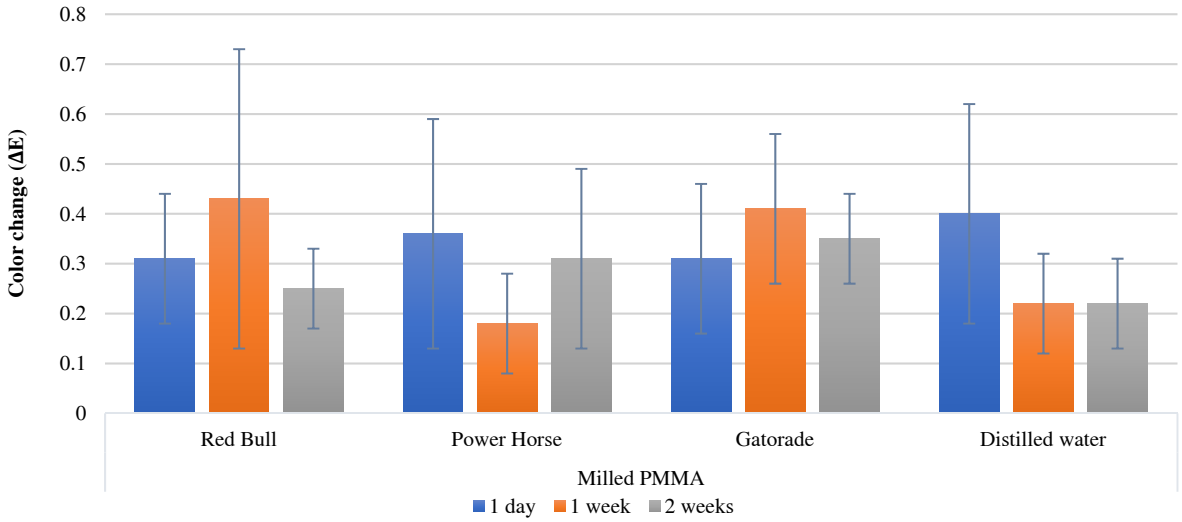


Figure 14: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for Different Times (Milled PMMA)

For 3D-printed resin immersed in Gatorade, no significant time effect was detected ($p = 0.336$; $\eta_p^2 = 0.01$). ΔE*ab values were 1.25±0.35 at 1 day, 1.03±0.12 at 1 week, and 1.30±0.51 at 2 weeks, without a clear directional trend.

For 3D-printed resin immersed in distilled water, no significant time effect was detected ($p = 0.907$; $\eta_p^2 = 0.00$). ΔE*ab values were stable across the observation period: 0.73±0.44 at 1 day, 0.69±0.37 at 1 week, and 0.67±0.42 at 2 weeks.

Milled PMMA

For milled PMMA immersed in Red Bull, no significant time effect was detected ($p = 0.279$; $\eta_p^2 = 0.01$). ΔE*ab values were 0.31±0.13 at 1 day, 0.43±0.30 at 1 week, and 0.25±0.08 at 2 weeks.

For milled PMMA immersed in Power Horse, no significant time effect was detected ($p = 0.116$; $\eta_p^2 = 0.02$). ΔE*ab values were 0.36±0.23 at 1 day, 0.18±0.10 at 1 week, and 0.31±0.18 at 2 weeks.

For milled PMMA immersed in Gatorade, no significant time effect was detected ($p = 0.584$; $\eta_p^2 = 0.00$). ΔE*ab values were 0.31±0.15 at 1 day, 0.41±0.15 at 1 week, and 0.35±0.09 at 2 weeks.

For milled PMMA immersed in distilled water, no significant time effect was detected ($p = 0.071$; $\eta_p^2 = 0.02$). ΔE*ab values were 0.40±0.22 at 1 day, 0.22±0.10 at 1 week, and 0.22±0.09 at 2 weeks.

DISCUSSION

Color stability is defined as the ability of a restorative material to retain its original color over time when subjected

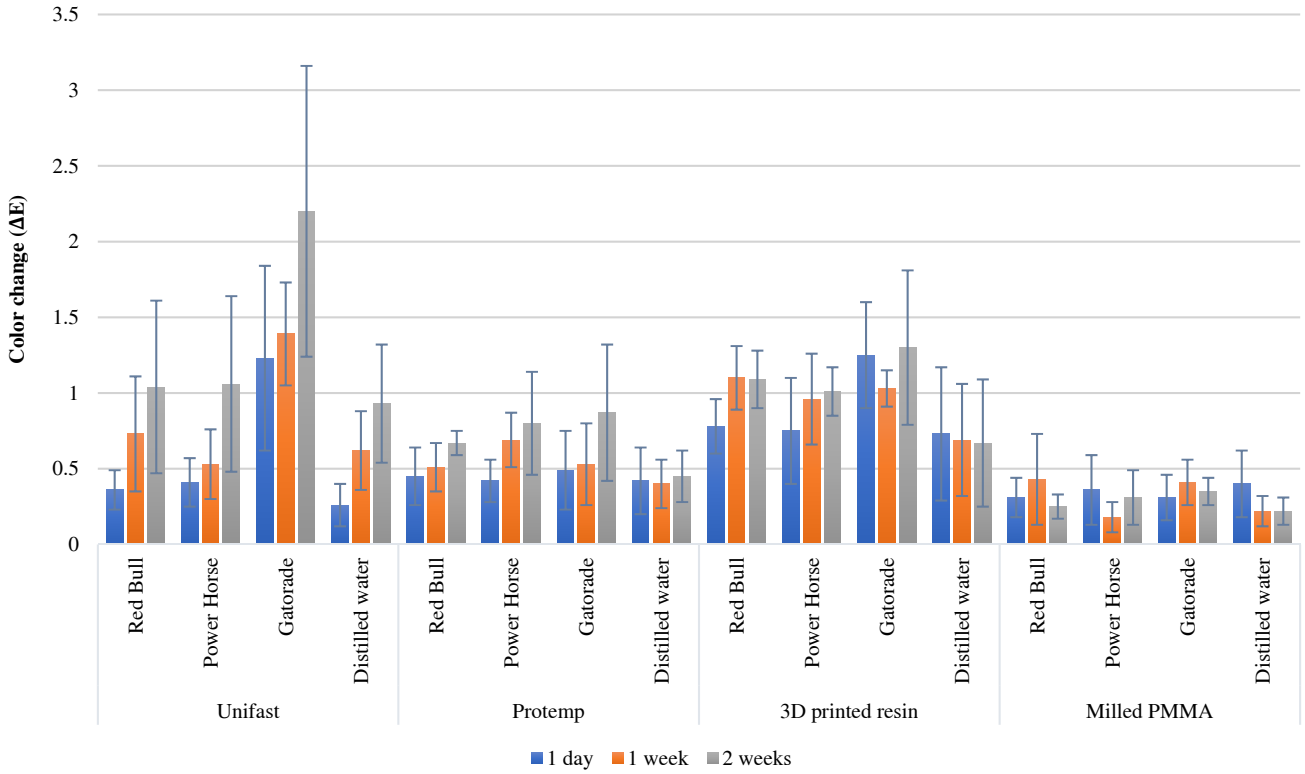


Figure 15: Bar Chart Showing Mean and Standard Deviation (Error Bars) Values of Color Change (ΔE*Ab) for Different Times

to the chemical, mechanical and thermal challenges of the intraoral environment. It is one of the most clinically important esthetic properties of provisional restorations, particularly those placed in visible anterior or premolar regions and retained for extended treatment periods [21]. Discoloration of a provisional restoration leads to esthetic failure and patient dissatisfaction, may result in the selection of an incorrect shade for the definitive prosthesis and can necessitate premature replacement of the interim material before treatment completion [5]. The color of any restorative material is influenced by three interrelated perceptual dimensions [22].:

- Hue, which defines the dominant wavelength of the color and represents the attribute by which a color is identified by its name such as red, blue, yellow or green
- Value, which describes the degree of lightness or darkness relative to white and black
- Chroma: Represents the intensity or saturation of the hue
- Accurate and reproducible measurement of color and color change in dental materials requires objective instrumentation, most commonly spectrophotometry that overcomes the well-documented unreliability of visual shade matching [23]

Intrinsic and extrinsic factors influence the color stability of provisional restorative materials. Intrinsic factors are linked to the materials chemical composition, degree of polymerization, monomer polarity, filler content and distribution as well as the presence of amine-based initiator systems. For instance, the presence of tertiary amine co-initiators (that undergo oxidative color change over time) of bis-acryl composite resins causes intrinsic yellowing, independent of dietary exposure [24]. The higher susceptibility of residual unreacted monomers to chemical change and water sorption as compared to a fully cross-linked matrix- leads to incomplete polymerization, promoting intrinsic discoloration.

Water sorption is the fundamental process, where the adsorption and absorption of chromogenic substances from dietary and oral hygiene sources leads to extrinsic discoloration. The absorption of water by provisional resins contributes to the swelling of the organic matrix, making it increasingly permeable, which triggers colorant penetration into the material's subsurface layers [24]. Surface roughness expands the total surface area available for colorant adhesion and creates micro-retentive features that promote the accumulation and removal resistance of chromogenic particles by rinsing or brushing; all of these further amplify extrinsic staining [25]. The magnitude of the resulting color change is independently influenced by the type and concentration of chromogen in the immersion medium, acidity of the beverage, duration of exposure and degree of polymerization of the material, with their effects accumulating over time in a progressive and largely irreversible manner [24].

Color stability has consistently demonstrated significant differences across the four main categories of provisional

restorative materials. The industrially pre-polymerized, homogeneous, and highly dense matrix (that limits water absorption and ingress of exogenous colorants) of milled CAD/CAM PMMA establish it to be the best material that can resist discoloration [26]. Meanwhile, conventional self-curing PMMA is more susceptible to staining, which increases with surface porosity (resulting from hand-mixing and extended beverage exposure), resulting in intermediate color stability [24]. With superior handling properties and initial esthetic appearance, bis-acryl composite resins exhibit greater color change than PMMA-based materials following immersion in chromogenic media, partly due to their higher polarity and greater affinity for water-soluble staining agents [24]. 3D-printed resins have consistently demonstrated the greatest susceptibility to discoloration, with clinically perceptible ΔE*ab values observed even after brief exposure to staining solutions. Multiple pathways for colorant penetration promote rapid and pronounced discoloration, as a result of the combination of the layered microstructure of 3D-printed materials and their comparatively lower degree of polymerization and higher water sorption relative to milled alternatives [27].

Color change varied more across materials than across solutions, but the immersion solution accounted for the largest main effect on ΔE*ab. The pattern of color response was material-dependent: only Unifast III showed progressive color change across time in every solution, two provisional materials (Protemp 4 and the 3D-printed resin) responded selectively, and the milled PMMA showed no statistically significant change with either solution or time. The clinical thresholds for CIELAB color differences established by Paravina *et al.* place the 50:50% perceptibility threshold at ΔE*ab*ab = 1.2 and the 50:50% acceptability threshold at ΔE*ab*ab = 2.7; an older clinical acceptability limit of ΔE*ab*ab = 3.3 has also been used in dental color stability research [18,14]. Most ΔE*ab values in the present study fell below the perceptibility threshold of 1.2, with the cell values exceeding perceptibility involving primarily Gatorade immersion. No mean cell value exceeded the modern acceptability threshold of 2.7, although the highest single value (Unifast III following 2 weeks of immersion in Gatorade, 2.20±0.96) approached this limit, and the standard deviation indicates that some samples in this group may have exceeded it.

Unifast III recorded the highest ΔE*ab of the study and was the only material in which color change progressed consistently across all four solutions, including the control distilled water. The progression observed following immersion in distilled water alone suggests that water sorption may itself alter the optical properties of this material, with the additional contribution of chromogen uptake accounting for the larger values seen in the chromogenic solutions. The progressive ΔE*ab pattern observed for Unifast III following Red Bull immersion is broadly consistent with Yılmaz *et al.* who reported statistically significant time-dependent color changes in three bis-acryl resin composites and CAD/CAM PMMA following Red Bull immersion over 28 days, with PMMA more resistant to discoloration than the bis-acryl materials tested; the present study extends this observation to conventional self-cure PMMA, which Yılmaz *et al.* did not test [28]. The 3D-printed resin recorded the highest ΔE*ab at 1 day across all four solutions but showed no statistically significant additional progression beyond that time point. A possible explanation is early uptake of accessible chromogenic species into the printed microstructure, with subsequent uptake limited by diffusion through an increasingly loaded matrix [29,30]. Protemp 4 remained statistically stable for color throughout most of the observation period, with only a small solution effect emerging at 2 weeks following immersion in Gatorade. Milled PMMA showed no statistically significant color change in any solution at any time point, consistent with the dense and homogeneous matrix attributable to industrial high-temperature, high-pressure polymerization [31]. Shenoy *et al.* similarly reported significantly better color stability for milled CAD/CAM PMMA compared with 3D-printed PMMA following thermocycling aging, supporting the present finding that milled CAD/CAM PMMA was the most color-stable material in the study [32].

Protemp 4 is frequently reported as one of the bis-acryl materials with the largest ΔE*ab following immersion in coffee, tea, and red wine studies, a finding that disagrees with the present observation of statistical color stability for Protemp 4 following immersion in sports and energy drinks [22]. A direct material-pair comparison supports a beverage-chemistry interpretation: Gujjari *et al.* tested DPI self-cure PMMA and Protemp 4 with tea, coffee, and cola in artificial saliva and reported Protemp 4 as significantly less color-stable than PMMA, whereas in the present study the ranking is reversed with Protemp 4 found to be the most stable and Unifast III the least stable [33]. The same material category therefore behaves differently depending on the chromogenic agents in the beverage challenge, consistent with a beverage-chemistry effect rather than a property of the dimethacrylate matrix itself.

Gatorade produced the largest ΔE*ab in most material × time combinations, particularly for Unifast III and the 3D-printed resin. Red Bull and Power Horse produced broadly similar ΔE*ab values in most combinations, with neither energy drink consistently dominating the other. Distilled water produced measurable progressive ΔE*ab only in Unifast III compared to all tested materials. The differences in color response across the chromogenic solutions reflect variation in colorant composition between sports and energy drinks beyond what pH alone would predict, as well as the broader distinction between the synthetic colorants used in sports and energy drinks and the polyphenolic chromogens (tannins, chlorogenic acids) commonly used in published color-stability studies of provisional materials [33,34] This distinction is supported by Abdel Sadek *et al.* who reported continued color progression in NextDent C&B MFH beyond 2 weeks following immersion in coffee and cola, a finding consistent with the plateau pattern observed in the current

research in the same material following immersion in sports and energy drinks, suggesting that the difference is driven by beverage chromogens rather than by the material [34].

Within the limitations of the present in vitro study, the findings suggest that material-specific considerations for provisional restoration service in patients who consume sports and energy drinks. CAD/CAM milled PMMA showed the most stable performance for both color and surface roughness across all tested conditions and may therefore be preferred when aesthetic stability and surface integrity are clinical priorities, particularly in the anterior zone, during extended provisional periods, or in full-mouth rehabilitation cases [31,35,36]. Where milled PMMA is not feasible, the conventional self-cure PMMA (Unifast III) showed the largest cumulative changes on both outcomes and may be less suitable for extended provisional use where regular sports and energy drink exposure is anticipated. The bis-acryl composite (Protemp 4) and the 3D-printed resin represent intermediate options with condition-specific vulnerabilities: early color change in the 3D-printed resin and a late-onset roughness increase in Protemp 4 following immersion in Power Horse. For patients with frequent sports or energy drink consumption, dietary counselling may be considered as part of provisional restoration planning. Podgorski *et al.* specifically recommend appropriate selection of restorative materials combined with patient dietary counselling for individuals who frequently consume sports drinks, while Tanthanuch *et al.* demonstrated that material choice itself influences the magnitude of surface and color changes following sports and energy drink exposure, supporting consideration of material category as part of clinical decision-making for this patient population [37,38].

Because surface roughness significantly affects color stability, recall protocols based on visual color evaluation alone may not detect ongoing surface deterioration [39]. Regular re-polishing of provisional restorations may be appropriate for patients with habitual sports and energy drink use, as polishing has been reported to reduce roughness in acrylic and bis-acryl provisional resins and to enhance subsequent staining resistance [5,40]. For 3D-printed provisional restorations specifically, chairside surface sealing at delivery has been suggested as a way to reduce early surface roughness susceptibility associated with the inter-layer microstructure characteristic of additively manufactured materials, as reported by Tasin *et al.* and Angwaravong *et al.* [29,33]. The present study contributes to the growing recognition of sports and energy drink consumption as a dietary factor relevant to provisional material performance, a factor distinct from coffee or red wine in its low pH, citric acid content, and synthetic colorant profile. These findings may support the addition of sports and energy drink consumption history to patient assessment for provisional treatment, alongside established factors such as bruxism, xerostomia, and parafunctional habits.

Limitations

This study has several limitations that should be considered when interpreting its findings. The in vitro design, while allowing rigorous standardisation and control of experimental variables, does not fully replicate the complexity of the oral environment. Salivary buffering, pellicle formation, thermal cycling, masticatory loading, and continuous pH fluctuations were not simulated, and the static immersion protocol represents a more aggressive exposure than the intermittent beverage contact experienced clinically; the magnitude of degradation observed may therefore overestimate the rate of change expected in vivo [37,38].

Only three commercially available beverages were evaluated alongside a distilled water control, and pH and titratable acidity values were derived from published literature rather than independently measured. A single shade and brand of each provisional material were tested; other formulations within the same material categories — particularly the expanding range of 3D-printed resins — may behave differently based on monomer system, filler content, and post-curing protocol [41]. The evaluation was confined one outcome measured over a two-week period and did not address other clinically relevant properties such as flexural strength, hardness, water sorption, or marginal adaptation. Direct conversion of in vitro immersion time to clinical service duration is inherently approximate, and temporal findings should be interpreted accordingly.

CONCLUSION

Within the limitations of this in vitro study, the following conclusions can be drawn:

- Material type, immersion solution, and immersion time all influenced color change (ΔE*ab)
- ΔE*ab responses varied according to material and were not uniformly observed across all conditions
- CAD/CAM milled PMMA exhibited excellent color stability with sports and energy drink challenge, with no statistically significant color change detected under any solution at any time point
- The conventional self-curing PMMA (Unifast III) had the most cumulative color change with time, especially under Gatorade at 2 weeks
- 3D-printed resin (NextDent C&B MFH) had the highest color change on the first day followed by a plateau in color progression throughout the entire study period
- Protemp 4 (bis-acryl composite resin) showed relative color stability against sports drinks
- Gatorade was the most chromogenic solution, producing the most significant color change in all tested materials
- Color change showed material- and condition-specific trends with multiple non-significant categories

Recommendations

Future research should incorporate dynamic oral simulation conditions, longer observation periods, a wider range of beverages and material formulations, and additional mechanical and physical outcome measures. In vivo and clinical studies are ultimately needed to validate these

findings and inform evidence-based guidance for provisional material selection and dietary recommendations during prosthodontic treatment.

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