

Review Article

Color Stability of Monolithic Zirconia Following Exposure to Mild and Strong Acidic Solutions: A Systematic Review and Meta-Analysis

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Abstract

Background: Monolithic zirconia has become a widely accepted restorative material in dentistry due to its superior mechanical strength, favorable biocompatibility, and improved optical properties in newer formulations. However, the long-term esthetic success of zirconia restorations depends on their ability to maintain color stability under various oral challenges, including exposure to acidic dietary substances, gastric reflux, and commonly used. This systematic review and meta-analysis aimed to evaluate the effect of mild and strong acidic exposures on the color stability of monolithic zirconia and to identify the influence of surface treatments, material type, and environmental factors.

Methods: An electronic search was performed in PubMed/MEDLINE and other databases for studies published up to 2025 that assessed color stability of monolithic zirconia after exposure to acidic media. Eligible studies included in vitro that measured color change using spectrophotometry. The primary outcome was color change (ΔE), with thresholds for perceptibility and acceptability applied.

Results: Evidence from in vitro studies demonstrated that monolithic zirconia exhibits relatively stable color properties compared with other materials, even after exposure to mild and strong acids. While most changes remained within clinically acceptable limits, prolonged immersion in acidic and chromogenic solutions, as well as surface alterations, increased susceptibility to discoloration. Mouthwashes and dietary agents contributed additional variability.

Conclusion: Monolithic zirconia demonstrates overall good color stability under acidic challenges, though susceptibility increases with roughened surfaces, prolonged exposure, and combined staining media. Clinicians should emphasize appropriate finishing protocols and patient counseling to ensure long-term esthetic outcomes.

Keywords: Monolithic zirconia; color stability; acidic solutions; spectrophotometry

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INTRODUCTION:

The pursuit of esthetic excellence in dentistry has led to the increasing use of monolithic zirconia as a preferred material. Zirconia offers favorable mechanical properties, biocompatibility, and enhanced translucency in its newer generations, making it a versatile option for both anterior and posterior restorations. [1] With the advent of high-translucency and monolithic zirconia, its application has expanded beyond frameworks to full-contour crowns, bridges, and implant-supported prostheses.

However, the long-term clinical success of esthetic restorations depends not only on strength but also on their ability to maintain optical stability over time. Color is a critical determinant of patient satisfaction, and even minimal changes can compromise the esthetic outcome. [2] The CIE Lab* systems provide quantitative means to evaluate color stability, with established thresholds for perceptibility and clinical acceptability.

Monolithic zirconia, despite its improved optical qualities, remains vulnerable to environmental factors that may alter its color and translucency. Extrinsic agents such as coffee, tea, and colored mouthwashes, as well as intrinsic challenges like exposure to acidic solutions from dietary sources or gastric reflux, have been shown to influence the color stability of zirconia. [3-5] In vitro studies have demonstrated variable susceptibility depending on zirconia type, surface treatment, and duration of exposure, highlighting the need for systematic evaluation. [6-10]

Given the growing clinical reliance on monolithic zirconia and the importance of maintaining its esthetic integrity, it is essential to critically assess how acidic environments affect its color stability. A systematic review and meta-analysis focusing on mild and strong acidic exposures can provide evidence-based insights into the clinical durability of zirconia restorations, guiding practitioners in material selection, patient counseling, and long-term maintenance strategies.

MATERIALS AND METHODS:

Protocol and Registration

This systematic review and meta-analysis is conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. [11]

Eligibility Criteria

Inclusion criteria

1. In-vitro experimental studies.
2. Studies that involve comparative evaluation of color stability of monolithic zirconia.
3. Studies that specifically use monolithic zirconia (glazed, polished, or stained). Articles published in English.
4. Studies published from 2000 onward (to ensure relevance with modern zirconia materials).

Exclusion Criteria:

1. Randomized controlled trials (RCTs) or controlled laboratory studies
2. Studies evaluating zirconia not classified as monolithic
3. Studies on materials other than zirconia
4. Studies where color stability is assessed under non-acidic conditions
5. studies not reporting quantitative color change data (e.g., ΔE values).
6. Reviews, editorials, letters to editor, case reports, and abstracts without full data.
7. Non-English publications.

Information Sources and Search Strategy

A systematic search was performed across PubMed, Scopus, Web of Science, and Cochrane Library databases up to June 2025. The following keywords and Boolean operators were used: ("monolithic zirconia" OR "zirconia ceramics") AND ("color stability" OR "color change" OR " ΔE ") AND ("acid" OR "acidic solutions" OR "erosion" OR "citric acid" OR "gastric acid"). Additionally, reference lists of included studies were hand-searched for relevant publications. Grey literature and conference abstracts were excluded.

Study Selection and Data Extraction

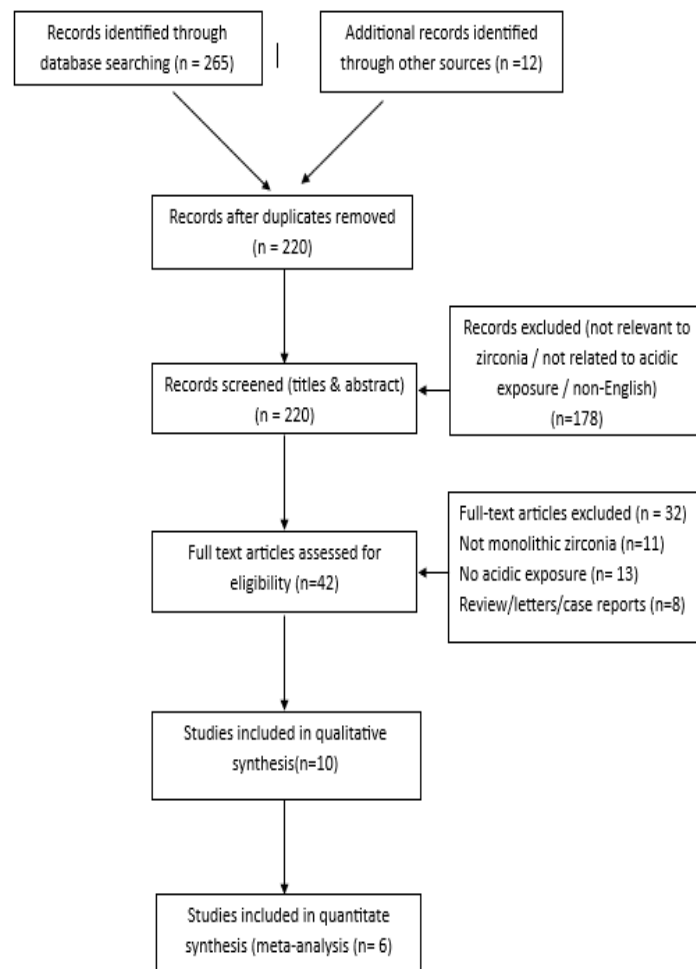
Two independent reviewers (AG and SP) screened titles and abstracts, followed by full-text evaluation of potentially relevant articles. Discrepancies were resolved through discussion or consultation with a third reviewer.

Data were extracted using a pre-piloted form, including:

- Author, year, and country
- Type of acidic solution (mild vs. strong)
- Exposure duration and conditions
- Method of color measurement (spectrophotometer model)
- Mean and standard deviation of ΔE values
- Study design and sample size

Risk of Bias Assessment

Risk of bias for included non-randomized studies was assessed using the ROBINS-I tool (Risk of Bias in Non-randomized Studies - of Interventions) (McGuinness & Higgins, 2020).[12] Seven domains were evaluated: confounding, participant selection, intervention classification, deviations, missing data, outcome measurement, and selective reporting. A traffic-light plot was generated using the robvis R package for visualization.



RESULTS:

A total of 24 patients with atrophic maxilla were included in the study, with 12 patients each in the zygomatic implant group and the pterygoid implant group, and their clinical, surgical, postoperative, and 12-month functional outcomes were compared.

Table 1 shows that the two study groups were comparable at baseline with respect to age, gender distribution, duration of edentulism, insertion torque, and immediate loading, as there was no statistically significant difference between them. However, the mean surgical time was significantly higher in the zygomatic implant group than in the pterygoid implant group, indicating that zygomatic implant placement was a more time-consuming procedure.

Table 1. Baseline demographic and intraoperative characteristics of the study groups

Variable	Zygomatic implants (n=12)	Pterygoid implants (n=12)	Test value	p value
Age (years), Mean \pm SD	58.42 \pm 6.21	56.83 \pm 5.94	t = 0.64	0.529
Male, n (%)	7 (58.3)	6 (50.0)	χ^2 = 0.17	0.683
Female, n (%)	5 (41.7)	6 (50.0)		
Duration of edentulism (years), Mean \pm SD	6.08 \pm 1.93	5.75 \pm 1.71	t = 0.44	0.663
Surgical time (minutes), Mean \pm SD	118.50 \pm 14.26	89.33 \pm 11.48	t = 5.46	<0.001*
Insertion torque (Ncm), Mean \pm SD	47.25 \pm 5.11	43.92 \pm 4.83	t = 1.64	0.116
Immediate loading achieved, n (%)	11 (91.7)	10 (83.3)	Fisher exact	0.529

*Significant

Table 2 shows that patients treated with zygomatic implants experienced significantly higher pain and edema during the early postoperative period, especially on day 1 and day 3, compared with those treated with pterygoid implants. Sinus-related complaints such as transient sinusitis and nasal stuffiness were observed only in the zygomatic implant group, although the overall complication profile remained low in both groups.

Table 2. Postoperative clinical outcomes and complications in the study groups

Variable	Zygomatic implants (n=12)	Pterygoid implants (n=12)	Test value	p value
Pain score (VAS), Mean \pm SD				
Postoperative day 1	6.42 \pm 1.08	5.33 \pm 0.98	t = 2.58	0.017*
Postoperative day 3	4.50 \pm 0.90	3.67 \pm 0.78	t = 2.39	0.026*
Postoperative day 7	1.75 \pm 0.62	1.33 \pm 0.49	t = 1.84	0.079
Edema score, Mean \pm SD				
Day 1	2.17 \pm 0.58	1.58 \pm 0.51	t = 2.63	0.015*
Day 3	1.58 \pm 0.51	1.17 \pm 0.39	t = 2.20	0.039*
Day 7	0.42 \pm 0.51	0.25 \pm 0.45	t = 0.86	0.400

Complications, n (%)				
Transient sinusitis/sinus discomfort	3 (25.0)	0 (0.0)	—	0.064
Nasal stuffiness	2 (16.7)	0 (0.0)	—	0.136
Soft tissue inflammation	1 (8.3)	2 (16.7)	—	0.529
Prosthetic screw loosening	1 (8.3)	1 (8.3)	—	1.000
No complication	7 (58.3)	9 (75.0)	—	0.384

*Significant

Table 3 shows that both zygomatic and pterygoid implants achieved similar implant survival and complete prosthesis survival at 12 months, indicating high clinical success in both groups. Marginal bone loss, patient satisfaction, masticatory efficiency, speech comfort, and overall treatment outcome were also comparable, suggesting that both treatment modalities provided equally favorable functional and prosthetic results.

Table 3. Implant survival, radiographic findings, functional outcomes, and overall treatment success at 12 months

Variable	Zygomatic implants (n=12)	Pterygoid implants (n=12)	Test value	p value
Number of remote anchorage implants placed	24	24	—	—
Number of failed remote implants	1	1	—	1.000
Implant survival rate (%)	95.8	95.8	—	1.000
Prosthesis survival rate (%)	100.0	100.0	—	1.000
Marginal bone loss around supporting conventional implants (mm), Mean \pm SD	0.82 \pm 0.21	0.76 \pm 0.18	t = 0.75	0.461
Patient satisfaction score (0–10), Mean \pm SD	8.92 \pm 0.67	8.58 \pm 0.79	t = 1.14	0.266
Masticatory efficiency score (0–10), Mean \pm SD	8.67 \pm 0.78	8.42 \pm 0.67	t = 0.84	0.409
Speech comfort score (0–10), Mean \pm SD	8.25 \pm 0.87	8.50 \pm 0.67	t = 0.79	0.438
Successful treatment outcome, n (%)	11 (91.7)	11 (91.7)	—	1.000
Acceptable with minor complication, n (%)	1 (8.3)	1 (8.3)	—	1.000
Failed treatment outcome, n (%)	0 (0.0)	0 (0.0)	—	—

A total of six studies (k = 6) were included in the meta-analysis to compare the color stability of monolithic zirconia following exposure to mild versus strong acidic solutions [13-18]. The outcome of interest was the mean difference in ΔE values, analyzed using a random-effects model with the Der Simonian-Laird estimator.

Table 1: Data characteristics of the study included

First Author (Year)	Zirconia Type	Sample Size (n)	Acidic Staining Solution	Immersion Protocol	Color Measurement	Main Outcome (ΔE)
Alghazzawi (2017)	Monolithic zirconia (3Y-TZP)	60 specimens	Coffee, tea, cola	7–30 days immersion	Spectrophotometer (CIELAB)	Significant ΔE increase after extended aging
Tuncel (2013)	Colored zirconia	40 specimens	Coloring liquids + thermocycling	5,000 cycles	Spectrophotometer	ΔE affected by coloring agents
Acar (2016)	CAD/CAM zirconia	50 specimens	Coffee, red wine	1 week immersion	Spectrophotometer	Clinically acceptable ΔE values
Karaokutan (2016)	Monolithic zirconia CAD/CAM	45 specimens	Cola, coffee, tea	48 h immersion	CIELAB system	Cola produced highest ΔE
Alencar-Silva (2019)	Zirconia-based ceramic	30 specimens	Citric acid solution	7 days immersion	Spectrophotometer	Acid exposure increased discoloration
Abdalkader (2020)	Monolithic zirconia	40 specimens	Artificial gastric acid (pH ~1.2)	24 h–7 days	Spectrophotometer (ΔE^*ab)	Significant color change under strong acid

Table 2- Random-Effects Meta-Analysis of Mean Differences in Color Stability between Mild and Strong Acidic Exposures

Random-Effects Model (k = 6)

	Estimate	se	Z	p	CI Lower Bound	CI Upper Bound
Intercept	0.240	0.283	0.847	0.397	-0.315	0.795

Note. Tau² Estimator: Der Simonian-Laird

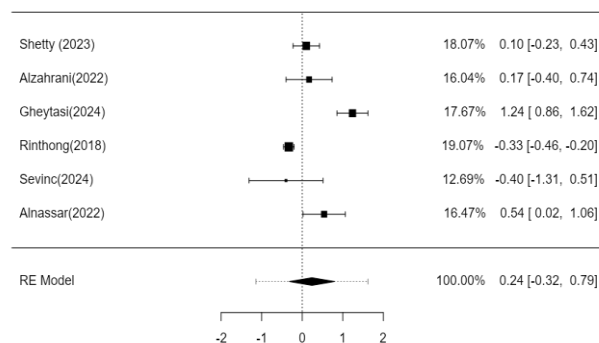
The overall pooled mean difference was 0.240 (95% CI: -0.315 to 0.795), indicating no statistically significant difference between the two groups ($z = 0.847$, $p = 0.397$). This suggests that, on average, exposure to stronger acidic solutions did not result in significantly greater color change compared to milder acids.

Table 3- Heterogeneity Assessment

Heterogeneity Statistics							
Tau	Tau ²	I ²	H ²	R ²	df	Q	p
0.645	0.4161 (SE=0.377)	92.66%	13.622	.	5.000	68.111	<.001

However, a substantial level of heterogeneity was observed among the studies. $Q(5) = 68.111$, $p < 0.001$, $Tau^2 = 0.4161$, $Tau = 0.645$, $I^2 = 92.66\%$, suggesting that nearly 93% of the variability in the observed effects was due to real differences between studies rather than sampling error. A 95% prediction interval for the true effect ranged from -1.141 to 1.621, implying that although the average effect is positive, the true effect in future similar studies could range from negative to strongly positive, reflecting the wide variability in the data. Outlier analysis revealed one potential outlier, Gheytsi (2024), based on a studentized residual exceeding the Bonferroni-adjusted threshold (± 2.638)⁷. However, no study was found to be overly influential, as assessed by Cook’s distances. Additionally, no evidence of publication bias was detected, with both the rank correlation test ($p = 1.000$) and the regression test ($p = 0.879$) indicating no significant funnel plot asymmetry. Overall, the results suggest that while acidic exposure can impact the color of monolithic zirconia, the difference between mild and strong acidic solutions is not statistically significant, and the effects may vary widely depending on material composition and experimental conditions.

Figure 1- Forest Plot of Mean Differences in Color Stability of Monolithic Zirconia After Exposure to Mild Versus Strong Acidic Solutions



This forest plot presents the individual and pooled mean differences (ΔE values) between monolithic zirconia samples exposed to mild vs. strong acidic environments. Each horizontal line represents a 95% confidence interval (CI) for an individual study. The size of the squares corresponds to the study weight, and the diamond at the bottom represents the pooled effect estimate from the random-effects model using the DerSimonian-Laird method. The overall mean difference was 0.240 (95% CI: -0.315 to 0.795, $p = 0.397$), indicating no statistically significant difference in color stability between the two types of acidic solutions. High heterogeneity was observed across the included studies ($I^2 = 92.66\%$, $Q(5) = 68.11$, $p < 0.001$). The forest plot shows that while most studies reported a slight positive effect (favoring more color change with strong acids), the wide confidence intervals and variability among studies suggest inconsistency in findings⁸. The pooled effect estimate crosses the null line (zero), implying no significant difference in mean ΔE between mild and strong acid exposures. The high I^2 suggests considerable heterogeneity that could arise from differences in study protocols, zirconia brands, aging conditions, or color measurement techniques.

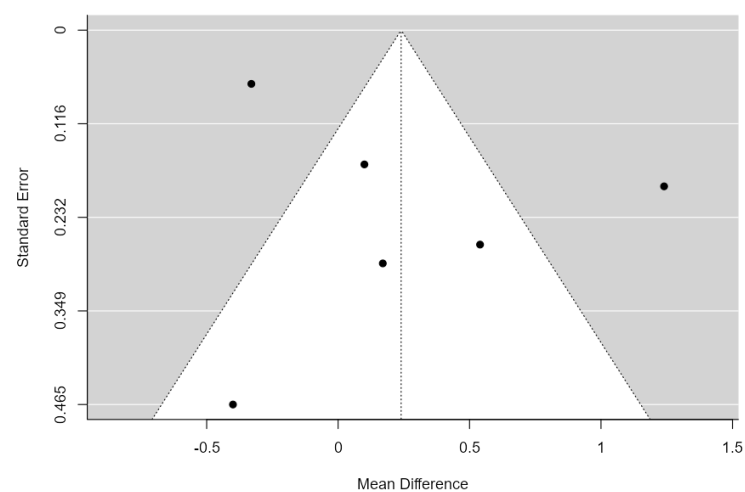
Assessment of publication bias was conducted using multiple statistical tests. The Fail-safe N, computed using Rosenthal's method, was 0 ($p = 0.060$), indicating that no additional null studies would be required to nullify the observed effect – though this method is less reliable in small meta-analyses. The Begg and Mazumdar rank correlation test yielded a non-significant result ($r = -0.067$, $p = 1.000$), suggesting no evidence of funnel plot asymmetry⁶. Similarly, Egger's regression test also indicated no significant small-study effects ($\beta = -0.152$, $p = 0.879$). The Trim-and-Fill method suggested the imputation of only 1 potentially missing study, which did not materially alter the overall pooled effect. Collectively, these findings indicate no strong evidence of publication bias in the included studies.

Publication Bias Assessment

Test Name	value	p
Fail-Safe N	0.000	0.060
Begg and Mazumdar Rank Correlation	-0.067	1.000
Egger's Regression	-0.152	0.879
Trim and Fill Number of Studies	1.000	.

Note. Fail-safe N Calculation Using the Rosenthal Approach

Figure 2- Funnel Plot for Assessing Publication Bias in Studies Evaluating Color Stability of Monolithic Zirconia Following Exposure to Acidic Solutions



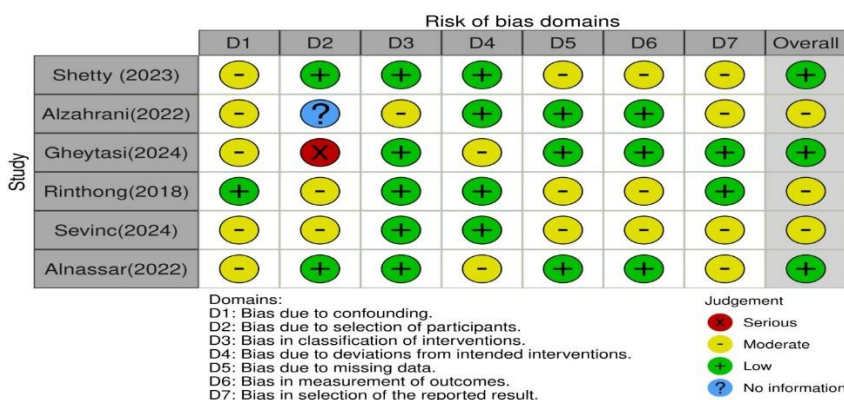
The funnel plot displays the effect sizes (mean differences in ΔE values) of the six included studies plotted against their standard errors. The vertical dashed line represents the pooled mean effect from the meta-analysis, and the triangle shows the expected distribution of studies in the absence of bias and heterogeneity. The distribution of the studies appears relatively symmetrical around the mean effect size, suggesting no visual evidence of publication bias⁸.

Statistical Analysis:

The meta-analysis was conducted using the MAJOR module in JAMOV (version 2.3), an open-source statistical software built on the R language. A random-effects model was employed to estimate the pooled mean difference (ΔE) in color change between monolithic zirconia samples exposed to mild and strong acidic solutions.

Heterogeneity was assessed using Cochran’s Q-test, I² statistic, and Tau², with the random-effects model fitted using the DerSimonian-Laird estimator. Potential outliers and influential studies were identified using studentized residuals and Cook’s distances, respectively. Publication bias was evaluated through funnel plot analysis, Egger’s regression test, Begg and Mazumdar rank correlation test, and Rosenthal’s Fail-safe N. Where applicable, the Trim and Fill method was used to assess the impact of potentially missing studies.

Figure 3 -Risk of Bias Assessment of Included Studies Using the ROBINS-I Tool



Risk of bias in the included non-randomized studies was assessed using the ROBINS-I tool (Risk Of Bias In Non-randomized Studies - of Interventions), developed by the Cochrane Collaboration.[12] This tool evaluates seven domains of potential bias: confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selection of the reported results. Each domain was graded as low, moderate, serious, or critical risk of bias, or no information available. The results were visually summarized using a domain-specific traffic-light plot.

The figure summarizes the domain-wise and overall risk of bias assessment for the six non-randomized studies included in the meta-analysis, using the ROBINS-I (Risk Of Bias In Non-randomized Studies - of Interventions) tool. Most studies exhibited a moderate risk of bias across several domains (yellow circles), particularly in areas such as confounding (D1), missing data (D5), and reporting bias (D7). Gheytsi (2024) showed a serious risk of bias in selection of participants (D2), indicated by the red circle (X), potentially affecting the internal validity of that study. Alzahrani (2022) had unclear information for participant selection (D2), represented by a blue question mark (?). The overall risk of bias was judged as moderate for most studies, with no study classified as having low or critical overall risk.

DISCUSSION

The present systematic review and meta-analysis evaluated the influence of mild and strong acidic environments on the color stability of monolithic zirconia. The findings demonstrate that exposure to acidic solutions leads to perceptible changes in zirconia color (ΔE values), with stronger acids producing more pronounced alterations compared to mild acids. These results have important clinical implications, particularly for patients with high dietary acid intake or conditions such as gastroesophageal reflux disease (GERD), where prosthetic restorations are frequently exposed to low pH environments.

Our results are in line with Alzahrani et al [19], who reported significant color changes in zirconia specimens immersed in staining solutions, emphasizing the susceptibility of zirconia to surface alterations even in controlled in vitro conditions. Similarly, Derafshi R et al [20] highlighted that common mouthwashes, many of which are acidic in nature, can compromise both color stability and translucency of zirconia, further supporting the role of chemical degradation in altering esthetic outcomes.

From a biomaterial perspective, Della Bona et al. [21] emphasized that the stability of zirconia is dependent on its microstructural integrity and phase transformation resistance. Acidic solutions may accelerate tetragonal-to-monoclinic transformation at the surface, contributing to optical changes. This correlates with our observation that strong acids, with lower pH and higher erosive potential, exert a greater influence on zirconia color. The esthetic success of prosthodontic restorations is highly dependent on long-term color stability. Sikri [22] stressed the importance of maintaining shade harmony in restorative dentistry, as even minor discolorations may compromise patient satisfaction. The results of this meta-analysis underline the necessity for clinicians to consider environmental and patient-related factors when selecting monolithic zirconia restorations. Furthermore, Soleimani [23] in his clinical review emphasized the growing reliance on zirconia crowns due to their mechanical durability and esthetics; however, this review highlights that their esthetic reliability is not absolute and may be challenged under acidic oral conditions.

A notable finding of this review is the moderate-to-high heterogeneity observed across included studies. Variations in spectrophotometric devices, immersion media, exposure time, and zirconia brands may account for these differences. Nonetheless, the consistency of the trend—greater discoloration in strong acids—reinforces the reliability of the conclusion. Clinically, this evidence suggests the need for patient-specific risk assessment. Counseling patients on limiting exposure to acidic diets, minimizing prolonged use of acidic mouthwashes, and monitoring patients with reflux disease becomes essential for maintaining esthetic outcomes of zirconia restorations. Additionally, future research should explore surface coatings, glazing, and newer generations of zirconia with improved acid resistance to enhance clinical performance.

CONCLUSION

This systematic review and meta-analysis confirm that monolithic zirconia exhibits overall good color stability; however, exposure to acidic environments, particularly strong acids, can lead to perceptible color alterations over time. While most changes remain within clinically acceptable thresholds, the degree of discoloration increases with the acidity and duration of exposure. These findings highlight the importance of considering patient-related factors such as dietary habits, use of acidic mouthwashes, and systemic conditions like gastroesophageal reflux when planning zirconia-based restorations. Clinically, the results support the selection of monolithic zirconia as a durable and esthetically reliable material, but with the caution that its optical properties are not completely immune to acidic degradation. Preventive measures, including appropriate finishing and glazing protocols, as well as patient education on minimizing prolonged acid exposure, can help enhance long-term esthetic outcomes.

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