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SYSTEMATIC REVIEW

Do color stability and translucency differ between 3D printed and milled resin-based fixed dental restorations? A systematic review and meta-analysis

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ABSTRACT

Statement of problem. Whether additive manufactured (AM) and subtractive manufactured (SM) resin-based restorations differ in optical properties after aging and staining is unclear.

Purpose. The purpose of this systematic review and meta-analysis was to evaluate whether AM and SM resin-based dental restoration materials differ in color change (ΔE), translucency (TP), and translucency change (ΔTP).

Material and methods. A systematic search was conducted in the PubMed, Embase, Scopus, Web of Science, and Cochrane Library databases up to January 2025. Eligible studies were English-language, peer-reviewed in vitro investigations comparing AM and SM resin-based fixed dental restorations for ΔE, TP, or ΔTP. Nonresin and noncomparative studies were excluded. Outcomes were synthesized as weighted mean differences (WMDs) using random-effects meta-analysis. Between-study heterogeneity was assessed using Cochrane Q and I^2 statistics and explored through subgroup and random-effects meta-regression analyses (α=.05). Publication bias was evaluated using funnel plots, Begg and Egger tests, and nonparametric trim-and-fill analysis. Risk of bias was assessed using the Quality Assessment Tool for In Vitro Studies (QUIN).

Results. Of 8169 records screened, 37 studies were included. AM resin-based materials showed greater ΔE compared with SM materials (WMD=1.40; 95% CI: 1.33 to 1.46; *P*<.001), with substantial heterogeneity (I^2>99%). Evidence regarding TP differences between AM and SM materials was inconclusive because of high heterogeneity (I^2>99%). ΔTP was greater in AM materials (WMD=−0.29; 95% CI: −0.43 to −0.15; *P*<.001), with high heterogeneity (I^2≈98%).

Conclusions. AM resin-based materials tended to show greater ΔE and ΔTP after aging compared with SM materials, whereas evidence for TP differences was inconclusive. (J Prosthet Dent 2026;136:30-39)

As esthetic excellence is a primary objective in contemporary restorative dentistry,[1–3] clinicians must select materials and techniques that ensure optical and mechanical stability.[1,4–6] The introduction of computer-aided design and computer-aided manufacturing (CAD-CAM) has transformed prosthetic workflows.[4,5,7–16] Subtractive manufacturing (SM), where prepolymerized blocks are milled, remains a widely used approach.[5,17–20] However, its limitations include material waste and geometric constraints.[1,5,7,11,12,21,22] Additive manufacturing (AM) has emerged as a promising alternative, offering reduced waste, design flexibility, and cost benefits.[7,8,11,23,24]

Advancements in resin-based materials have paralleled digital innovations for indirect restorations.[25] Earlier polymerized resins, such as autopolymerized polymethyl methacrylate (PMMA) and composite resins, provided good esthetics but suffered from shrinkage, discoloration, and mechanical limitations.[4,7,9,21,26,27]

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Clinical Implications

In vitro evidence suggested greater color change and translucency loss in printed resin-based materials compared with milled alternatives; however, extreme heterogeneity precluded firm conclusions regarding the magnitude or clinical relevance of these differences.

Resin-matrix ceramics combining the benefits of composite resins and glass-ceramics were developed to enhance mechanical strength, polishability, and repairability.[1,5,6,10,20,28,29] AM ceramic-filled resins offer similar advantages while benefiting from the efficiencies of 3-dimensional (3D) printing.[5,10,25,28,30,31] CAD-CAM materials include pure resin and resin-ceramic blocks.[5,10,20] Pure resins are primarily used for interim restorations.[23,32,33] In contrast, resin-matrix ceramics, with superior strength, wear resistance, and esthetics, have been preferred for definitive restorations.[5,8,12,29,31,34–36] Both techniques process resin-based materials.[12,37] SM uses prepolymerized blocks processed under high temperature and pressure, achieving high degrees of conversion and cross-linking.[1,14,22,24–26,31,36,38–41] AM builds restorations layer by layer, providing design freedom and material efficiency but raising concerns about mechanical and optical properies.[13,28,35,42–45]

Color stability and translucency are critical esthetic parameters.[10,25,26,29,37,39,46,47] Color stability refers to a material's resistance to shade changes from staining agents,[48–52] while translucency describes the extent to which light passes through a material.[31,53] Translucency influences esthetic blending, masking of the underlying discolorations, and the depth of the resin cement polymerization.[31,54] These optical properties are affected by factors such as resin matrix, filler content, polymerization, surface characteristics, degradation, water sorption, chemical reactivity, and exposure to staining agents.[2,6,7,9,18,23–25,27,29,35,37,38,55–60] In AM materials, studies have shown notable color and translucency changes after thermocycling and staining.[2,9,35,61,62] Despite increasing research,[63,64] evidence comparing the esthetic performance of AM and SM resin-based materials remains limited and inconsistent.[3,4,13,46,65] This systematic review aimed to compare color change (ΔE), translucency (TP), and translucency changes (ΔTP) in AM and SM resin-based materials after aging. The null hypothesis was that no significant differences would be observed between additively and subtractively manufactured resin-based fixed dental restorations with respect to color stability, baseline translucency, and translucency change after aging or staining protocols.

MATERIAL AND METHODS

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and the Cochrane Handbook for Systematic Reviews.[66] The protocol had been registered in the International Prospective Register of Systematic Reviews (PROSPERO) database (CRD42024575625). Based on a predefined population, intervention, comparison, and outcome (PICO) framework (Table 1), the focused question was: "Do 3D printed and milled resin-based fixed dental restorations differ in terms of color stability and translucency?" An electronic search was performed in the PubMed (MEDLINE), Embase, Scopus, Web of Science, and the Cochrane Library databases, with no date restrictions, up to January 2025. Search strategies are provided in Supplemental Table 1 (available online). The reference lists of included and related studies were manually screened, and Google Scholar was searched for additional records. Included studies were English-language, peer-reviewed in vitro investigations comparing the ΔE, TP, or ΔTP of AM and SM resin-based restorations or specimens. Excluded were studies on nonresin materials, conventionally fabricated restorations, and unrelated outcomes. Clinical, animal, ex vivo, pilot studies, case reports or series, reviews, conference abstracts, book chapters, expert opinions, editorials, and letters were excluded, as were records lacking sufficient data.

Two independent reviewers (H.K., S.A.M.) screened the titles and abstracts of all retrieved articles. Duplicates and nonrelevant records were excluded, and full texts of potentially eligible studies were assessed. Disagreements were resolved by consulting a third reviewer (P.D.). Two reviewers (S.A.M., E.K.) independently extracted data using a standardized spreadsheet (Excel; Microsoft Corp), including first author, publication year, country, type and geometry of specimens (shape, thickness, shade, translucency), material and manufacturer, AM parameters (technology, printer, layer thickness, build orientation), SM details (milling system, number of axes), postprocessing, cementation, sample size, outcome measures (formulas, methods or devices, background, aging or staining agents, immersion time), and statistical data (mean,

Table 1. Summary of study design structured according to PICO framework

PICO items	PICO-based study design
P (Population)	Resin-based tooth-supported dental restorations or specimens
I (Intervention)	3D printing technology (additive manufacturing)
C (Comparison)	Milling method (subtractive manufacturing)
O (Outcome)	Color stability, baseline translucency, and translucency change

PICO, population, intervention, comparison, outcome.

standard deviation). Aging protocols were categorized as short-, medium-, or long-term. Artificial toothbrushing cycles of 20 000[67] and 25 000[20] were considered long-term, simulating 7 to 10 years of clinical function. Thermocycling of 5000 and 10 000 cycles represented approximately 6 months[68] and 1 year[69] of service and were also classified as long-term, while 1000 cycles indicated short-term aging.[68,70] In studies with multiple test parameters, each was treated as an independent data point. Discrepancies were resolved by consulting a fourth reviewer (M.J.S.).

Interreviewer agreement for study selection was assessed using the Cohen kappa (κ); values ≥0.80 were deemed acceptable. When outcome measures were comparable or could be converted, weighted mean differences (WMDs) were calculated. Meta-analyses were performed using a random-effects model (DerSimonian and Laird method)[71] in a software program (R version 4.1.2; R Foundation for Statistical Computing; meta package version 4.17–0) and cross-validated using another program (Stata version 14.0; StataCorp LLC). Heterogeneity was evaluated using the Cochran Q and I^2, with $I^2>50\%$ and $P<.05$ indicating significant heterogeneity. Subgroup analyses were conducted to identify potential moderator effects. The robustness of pooled results was tested via sensitivity analysis using the leave-one-out method, sequentially excluding each study to assess its impact. Publication bias was evaluated using the Begg and Egger tests[72] and visualized in funnel plots. If asymmetry indicated bias, the trim-and-fill method was applied to estimate the effect of missing studies. Statistical significance was set at α=.05. To further explore sources of between-study heterogeneity, random-effects meta-regression analyses were conducted. Relevant study-level characteristics associated with within-group variability were included as categorical moderators, coded as dummy variables, with the corresponding overall group serving as the reference category. Regression coefficients (β), 95% confidence intervals, and *P* values were estimated to quantify moderator effects. Changes in between-study variance (τ^2) before and after model adjustment were examined to assess the proportion of heterogeneity explained by each moderator. All models were fitted under a random-effects framework consistent with the primary meta-analyses (α=.05). When key information was missing, corresponding authors were contacted; several responded,[1,4,9,14,23,65] while others did not. Data presented only in figures were extracted by using a software program (PlotDigitizer version 4.3; Optimize Science). When outcomes were not explicitly stated but could be calculated from the text or supplements, the necessary computations were performed. Most studies used the Vita Classical shade guide (VITA Zahnfabrik); those using Vita 3D Master were converted to Vita Classical by an official VITA representative (H.L.). Methodological quality was assessed by 2 reviewers (S.A.M., E.K.) using the Quality Assessment Tool for In Vitro Studies (QUIN),[73] with disagreements resolved by a third reviewer (P.D.).

RESULTS

From 8169 records retrieved, 4617 reached title and abstract screening (κ=0.96). Forty articles underwent full-text review, with 3 excluded (κ=1): 2 lacked optical evaluations,[74,75] and one[76] was without an aging process. Ultimately, 37 studies were included (Fig. 1). The studies had been published between 2020 and 2024. A total of 34 studies evaluated ΔE,[1–9,11–14,20,21,23–30,35–39,42,46,65,77–79] 10 studies assessed TP,[10,20,23,28,29,32,36,46,79,80] and 9 studies analyzed ΔTP.[12,23,25,28,29,36,37,46,79] In the AM group, the technologies used were digital light processing (DLP) (n=26),[2–6,8,11–14,20,21,23,24,26,28–30,32,37,38,42,46,77,78,80] digital light synthesis (DLS) (n=1),[6] liquid crystal display (LCD) (n=4),[1,7,42,65] LCD-based stereolithography (SLA) (n=1),[79] PolyJet (n=1),[38] and SLA (n=15).[2,5,6,9–11,13,14,25,27–29,35,39,42] AM materials consisted of acrylic-based resin (n=2),[27,38] composite resin (n=12),[2,3,7,9,14,21,24,32,38,39,77,79] methacrylate-based resin (n=8),[2,9,14,23,24,26,32,42] resin-ceramic (n=21),[1,4–6,8,10–13,20,25,28–30,35–37,42,46,78,80] and urethane acrylate-based resin (n=4).[6,42,46,65] SM materials included graphene-reinforced PMMA (n=1),[46] PMMA (n=16),[2–4,6,7,14,21,23,24,26,27,38,39,42,65,77] polycarbonate (n=2),[2,14] resin-ceramic (n=24),[1,2,5,6,8–14,20,25,28–30,32,35–37,46,78–80] and short-fiber-reinforced composite (n=1).[32] Finally, 23 studies evaluated short-term,[1,2,4–9,11–13,21,24,25,29,35–39,42,65,79] 3 studies medium-term,[6,38,77] and 13 studies long-term[3,5,6,14,20,23,26–28,30,42,46,78] changes (Supplemental Tables 2–4, available online).

The meta-analysis of color stability (Supplemental File 1, available online) showed greater ΔE in AM than in SM materials (WMD=1.40; 95% CI: 1.33–1.46; *P*<.001), with substantial heterogeneity (I^2=99.51%, *P*<.001). Given the marked variability across studies, the pooled estimate should be interpreted as indicating a consistent directional trend rather than a generalizable effect size. Leave-one-out analysis demonstrated numeric stability of the pooled estimate (WMD range: 1.363–1.410), with no single study materially influencing the results. Several subgroups (Supplemental Table 5, available online) showed substantially reduced heterogeneity (I^2<50%), including studies using specific CAD software and printer systems, 2.5-mm specimen thickness, B1 shade, 3-unit fixed dental prostheses, standardized layer thickness (60 μm), defined postprocessing protocols, and aging conditions involving ultraviolet-B exposure or orange-juice staining. The Egger test indicated significantly small-study effects (*P*<.001),

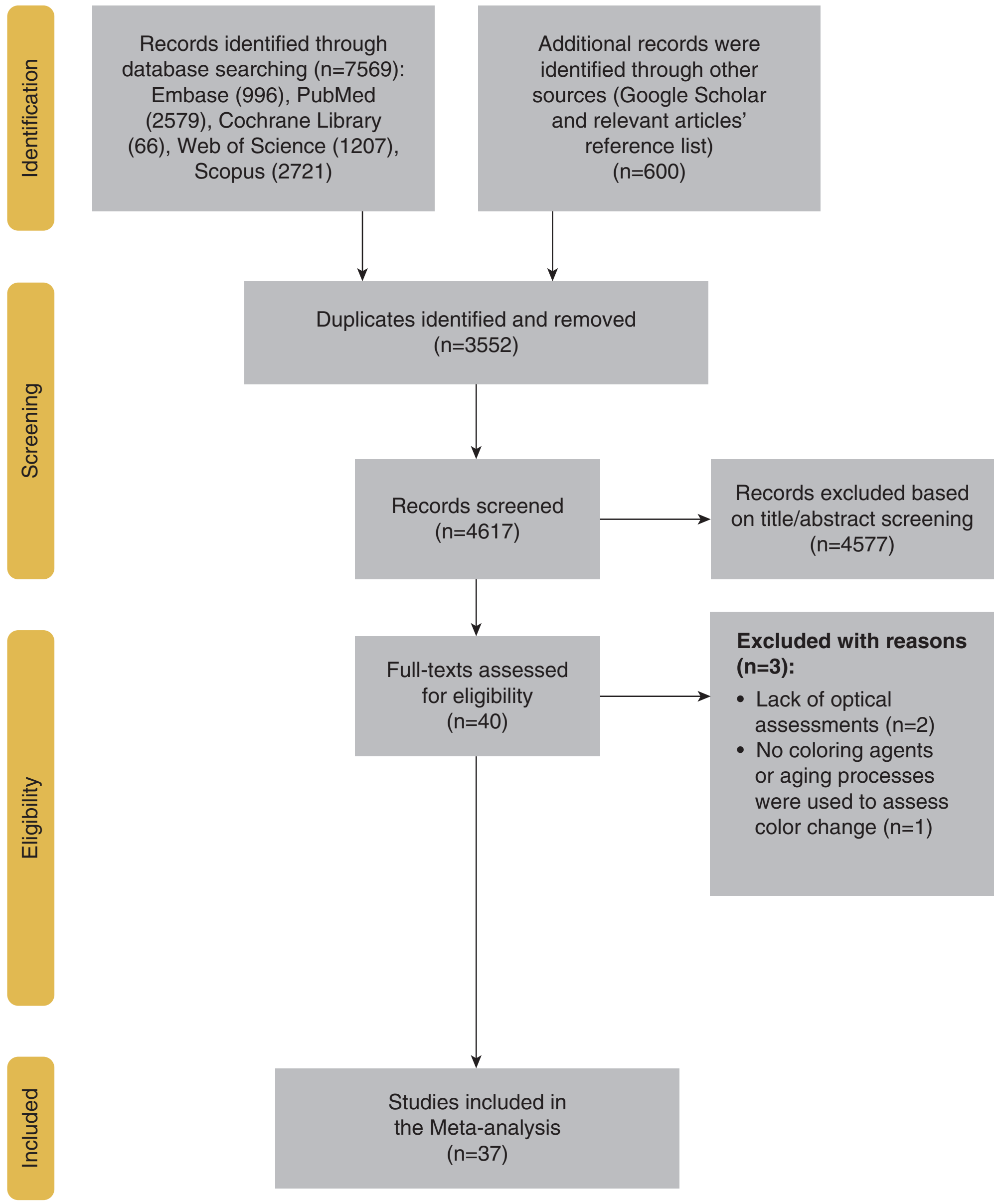

Figure 1. PRISMA flow diagram illustrating study selection process and detailing number of records identified, screened, assessed for eligibility, and ultimately included in qualitative and quantitative syntheses.

supported by funnel plot asymmetry (Fig. 2A), and trim-and-fill analysis estimated up to 9 potentially missing studies. After adjustment, the pooled effect size was attenuated (WMD=0.152; 95% CI: 0.077–0.228) but remained statistically significant, suggesting inflation of effect magnitude while preserving directional consistency. Meta-regression for ΔE identified significant associations for several AM technologies, with lower ΔE for DLP and LCD (β=−0.96 and −1.04, respectively; P<.001) and higher ΔE for SLA and nonreported technologies (β=0.91 and 2.11, respectively; P<.001), whereas PolyJet was not significant (P=.907); however, printer technology explained only a small proportion of heterogeneity (τ^2 reduction ≤2.6%) (Table 2).

The second meta-analysis (Supplemental File 2, available online) showed no statistically significant difference in TP between AM and SM materials (WMD=–0.07; 95% CI: –0.59–0.45; P=.788); however, heterogeneity was extreme (I^2=99.71%, P<.001), precluding interpretation of the pooled estimate as a shared effect. Leave-one-out sensitivity analysis demonstrated numeric stability of the pooled estimate (WMD range: –0.179–0.026) but did not mitigate the high heterogeneity. Subgroup analyses were conducted to explore potential sources of variability (Supplemental Table 6, available online). Regression-based Egger testing did not indicate statistically detectable small-study effects for TP (P=.177), although results should be interpreted

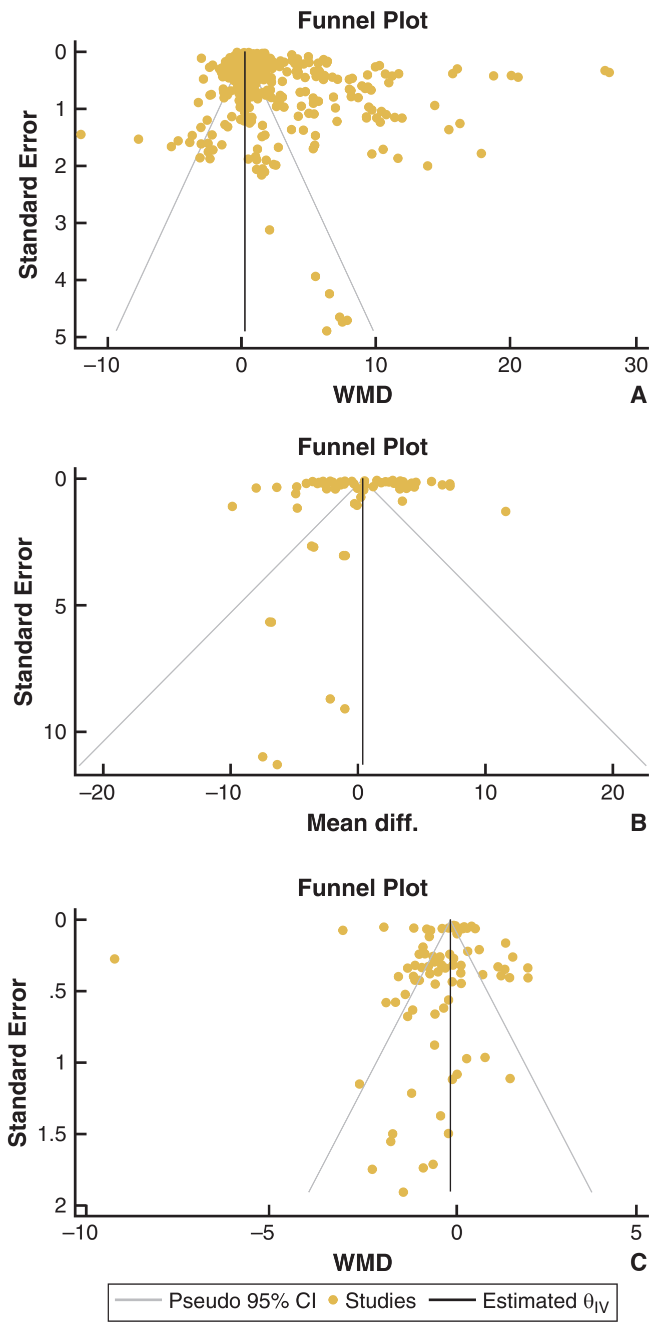

Figure 2. Funnel plots illustrating publication bias assessment for primary outcomes. A, Color stability. B, Baseline translucency. C, Translucency change. 95% CI, 95% confidence interval; WMD, weighted mean difference; θW, weighted pooled effect estimate.

cautiously given the extreme heterogeneity and potential funnel plot nonlinearity (Fig. 2B). Metaregression showed that printer technology was not a significant moderator (P>.05 for all), with minimal change in between-study variance (τ^2 reduction ≤0.7%) (Table 2). Overall, the evidence regarding TP differences between AM and SM materials remains inconclusive.

The third meta-analysis (Supplemental File 3, available online) showed greater translucency loss in AM

Table 2. Metaregression results assessing influence of various moderators on optical outcomes of additively manufactured resin-based materials

Outcome	Moderator domain	Moderator (vs reference)	β coefficient	95% CI	*P* value	τ^2 (baseline model)	τ^2 (meta-regression)	τ^2 reduction (%)
ΔE	—	Overall (intercept)	0.212	0.184 to 0.240	<.001	0.529	0.5138	2.9
	Printer technology	DLP	−0.956	−1.089 to −0.822	<.001	0.529	0.5158	2.5
		SLA	0.908	0.770 to 1.045	<.001	0.529	0.5155	2.6
		LCD	−1.044	−1.519 to −0.568	<.001	0.529	0.5289	0.0
		Polyjet	0.030	−0.482 to 0.543	.907	0.529	0.5290	0.0
		Not reported	2.112	1.726 to 2.498	<.001	0.529	0.5249	0.8
	Study quality	Quality score	1.286	1.163 to 1.408	<.001	0.529	0.4279	19.1
TP	—	Overall (intercept)	0.862	−0.214 to 1.939	.116	6.011	5.980	0.5
	Printer technology	DLP	−0.306	−1.518 to 0.906	.621	6.011	5.975	0.6
		SLA	−0.512	−1.760 to 0.737	.422	6.011	5.971	0.7
		Not reported	7.498	3.752 to 11.243	<.001	6.011	6.001	0.2
	Study quality	Quality score	0.878	−0.283 to 2.038	.138	6.011	6.120	—
ΔTP	—	Overall (intercept)	−0.302	−0.443 to −0.161	<.001	0.428	0.4230	1.2
	Printer technology	DLP	0.594	0.318 to 0.870	<.001	0.428	0.4231	1.1
		SLA	−0.568	−0.846 to −0.290	<.001	0.428	0.4230	1.2
		Not reported	−0.227	−0.940 to 0.486	.532	0.428	0.4282	0.0
	Study quality	Quality score	−0.092	−0.336 to 0.152	.461	0.428	0.3128	26.9

AM, additive manufacturing; CI, confidence interval; DLP, digital light processing; TP, translucency parameter; β, regression coefficient; ΔE, color change; ΔTP, translucency change; τ^2, between-study variance.

Table 3. Quality assessment results of in vitro studies using QUIN Tool

Study	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Total Score	Risk of Bias Calculation (%)	Risk of Bias Interpretation
Shin et al[2]	2	0	2	2	2	0	2	2	0	0	2	2	16	66.66	Medium-risk
Atria et al[23]	2	0	1	2	1	0	NA	2	0	0	2	1	11	50	Medium-risk
Song et al[38]	2	0	2	2	1	0	0	1	0	0	2	2	12	50	Medium-risk
Alharbi et al[35]	2	0	2	2	2	2	1	2	0	0	2	2	17	70.83	Low-risk
Mangoush et al[32]	2	0	2	2	1	0	NA	2	0	0	2	1	12	54.54	Medium-risk
Nam et al[14]	2	0	2	2	1	0	NA	1	0	0	2	2	12	54.54	Medium-risk
Yao et al[3]	2	0	2	2	2	0	0	2	0	0	2	2	14	58.33	Medium-risk
Intralawan et al[37]	2	2	2	2	2	0	2	2	2	0	2	2	20	83.33	Low-risk
Shenoy et al[27]	2	2	1	1	1	1	NA	1	0	0	1	1	11	50	Medium-risk
Taşın et al[39]	2	2	2	2	2	1	0	2	0	0	2	2	17	70.83	Low-risk
Bozoğulları and Temizci[5]	2	0	2	2	2	0	1	2	1	0	2	2	16	66.66	Medium-risk
Çakmak et al[20]	2	2	2	2	2	0	NA	2	2	0	2	2	18	81.81	Low-risk
Çakmak et al[30]	2	0	2	2	2	0	2	2	2	0	2	2	18	75	Low-risk
De Castro et al[42]	2	0	2	2	2	0	0	2	0	0	2	2	14	58.33	Medium-risk
Ellakany et al[24]	2	2	2	2	2	0	0	2	0	0	2	2	16	66.66	Medium-risk
Karaoğlanoğlu et al[11]	2	2	2	2	2	0	2	2	0	0	2	2	18	75	Low-risk
Sayed et al[26]	2	2	2	2	1	2	0	2	2	2	2	2	21	87.5	Low-risk
Abdel Sadek et al[7]	2	2	2	2	1	2	2	1	0	0	2	2	18	75	Low-risk
Bek Kurklu and Sonkaya[25]	2	2	2	2	2	0	0	2	0	0	2	2	16	66.66	Medium-risk
Sayed et al[77]	2	2	2	2	2	2	2	2	0	0	2	2	20	83.33	Low-risk
Krajangta et al[12]	2	2	2	2	2	2	2	2	0	0	2	2	20	83.33	Low-risk
Nagai et al[6]	2	2	2	2	2	2	0	2	0	0	2	2	18	75	Low-risk
Taşın and Ismatullaev[28]	2	2	2	2	2	2	NA	2	0	0	2	2	18	81.81	Low-risk
Yildirim et al[65]	2	0	2	2	2	1	NA	2	0	0	2	2	15	68.18	Medium-risk
Yılmaz et al[46]	2	0	2	2	2	0	NA	2	0	0	2	2	14	63.63	Medium-risk
Pereira Sanchez et al[29]	2	2	2	2	2	0	2	2	0	0	2	2	18	75	Low-risk
Al-Akhali et al[4]	2	0	2	2	2	1	1	2	0	1	2	2	17	70.83	Low-risk
Vichi et al[80]	2	0	2	2	2	0	NA	2	0	0	2	2	14	63.63	Medium-risk
Alaa and Al-Shamma[8]	2	2	2	2	1	0	NA	2	0	0	2	2	15	68.18	Medium-risk
Alalawi et al[9]	2	2	2	2	1	0	0	2	0	0	2	2	15	62.5	Medium-risk
Albrecht et al[78]	2	2	2	2	2	0	0	2	0	0	2	1	15	62.5	Medium-risk
Aydin et al[10]	2	0	2	2	2	1	NA	2	0	0	2	2	15	68.18	Medium-risk
Jain et al[21]	2	2	2	2	2	2	2	2	0	0	2	2	20	83.33	Low-risk
Karademir et al[1]	2	2	2	2	2	1	0	2	0	0	2	2	17	70.83	Low-risk
Özer et al[13]	2	2	2	2	2	1	1	2	0	0	2	2	18	75	Low-risk
Tanaka et al[22]	2	2	2	2	2	2	0	2	0	0	2	2	18	75	Low-risk
Tokar et al[36]	2	2	2	2	1	0	0	2	0	0	2	2	15	62.5	Medium-risk

C1, Clearly stated aims/objectives; C2, Detailed explanation of sample size calculation; C3, Detailed explanation of sampling technique; C4, Details of comparison group; C5, Detailed explanation of methodology; C6, Operator details; C7, Randomization; C8, Method of measurement of outcome; C9, Outcome assessor details; C10, Blinding; C11, Statistical analysis; C12, Presentation of results. Scoring; 2, Adequately Specified; 1, Inadequately Specified; 0, Not Specified; NA, Not Applicable.

than in SM materials (WMD=–0.29; 95% CI: –0.43– –0.15; P<.001), with negative values indicating greater loss in the AM group. Heterogeneity was high (I^2=97.93%, P<.001), and leave-one-out analysis confirmed numeric stability of the pooled estimate (WMD range: –0.313 to –0.199) without reducing heterogeneity. Several subgroups (Supplemental Table 7, available online) showed substantially reduced heterogeneity (I^2<50%), including studies using specific CAD software, Form3 (Formlabs Inc) or Varseo XS (BEGO) printers, 60-µm layer thickness, Permanent C&B material (Graphy), B1 shade, standardized postprocessing protocols, and short immersion times (1 to 3.5 days) using black tea or detox water. Assessment of small-study effects yielded discordant results: Egger test was not statistically significant (P=.374), whereas Kendall rank correlation indicated funnel plot asymmetry (Fig. 2C) (P=.001), suggesting potential publication bias under conditions of extreme heterogeneity. The trim-and-fill did not impute additional studies and did not materially alter the pooled estimate, likely reflecting limited method sensitivity rather than bias. Metaregression for ΔTP showed higher ΔTP for DLP (β=0.59, P<.001) and lower ΔTP for SLA (β=–0.57, P<.001); however, τ^2 reduction was minimal, indicating persistent heterogeneity (Table 2).

Sixteen studies had a low risk of bias, 21 a medium risk, and none a high risk (Table 3). Subgroup analyses showed significant ΔE differences in both low-risk (WMD=0.693; P<.001) and medium-risk studies (WMD=2.211; P<.001), whereas for ΔTP only low-risk studies reached significance (WMD=–0.226; P<.001). TP differences were not significant in either subgroup. Heterogeneity remained high, indicating that stratification by study quality alone did not explain between-study variability. Meta-regression (Table 2) showed that higher study quality was associated with greater ΔE (β=1.29; P<.001) with a 19.1% reduction in τ^2, while study quality was not a significant moderator for TP; for ΔTP, study quality explained a substantial proportion of heterogeneity (τ^2 reduction=26.9%) without a systematic shift in effect size.

DISCUSSION

AM resin-based materials showed inferior color stability and greater translucency loss after aging than SM materials, whereas evidence for baseline translucency differences was inconclusive. Accordingly, the null hypothesis that no significant differences would be observed between additively and subtractively manufactured resin-based fixed dental restorations with respect to color stability, baseline translucency, and translucency change after aging or staining protocols was partially rejected.

Color stability, measured by CIELab (ΔEab)[49] and the more accurate CIEDE2000 (ΔE00)[50] reflects a material's ability to resist discoloration. The observed WMD of 1.40 between the AM and SM groups lies within the perceptibility and acceptability thresholds for ΔE00 (0.8–1.8) and ΔEab (1.2–2.7).[51,52] However, AM materials showed significantly greater ΔE, likely because of intrinsic factors.[2,3,5,13,24,27,28,33,35,38,61,65] The polymer network formed during 3D printing has lower cross-linking density and potentially higher residual monomer content, making it more susceptible to water sorption and hydrolytic degradation,[4,5,13,15,16,24,27,28,31,43,65] facilitating stain penetration.[4,13,24,28,38,39,43,46,65] Methacrylate-based AM resins showed the highest ΔE, potentially because of their low filler content.[5,28,31,36,42,46,65] Thicker specimens also discolored more, likely from insufficient light penetration and lower conversion at deeper layers.[28,31,46] Lighter shades (A1, A2) were more prone to staining, possibly because of lower opacifier content and higher transparency, which exposes the resin matrix to greater interaction with colorants.[28,31,46] Inadequate postprocessing intensified discoloration by leaving unreacted monomers on the surface.[5,13,28,39,44,46,57] Among staining agents, curry, grape juice, and coffee were found to cause the most discoloration, and longer aging further amplified this effect, especially in AM materials, highlighting their greater susceptibility.[2,3,5,13,17,19,23,28,33,34,38–41,44,45,47,55,56,61,63,64]

TP was assessed in both the CIELab and CIEDE2000 systems.[54] The results suggest that the reported TP values for AM materials often overlapped with those of SM alternatives but with extreme heterogeneity. AM resins based on urethane acrylate and methacrylate also showed higher TP than SM analogs, possibly because of lower filler content and more homogeneous matrices, factors that improved light transmission but may have increased degradation and water uptake during aging.[31,36,46] In contrast, AM resin-ceramic materials showed lower TP than SM versions, attributed to the more refined filler distribution in prepolymerized blocks.[31,46] Specimen thickness influenced results, with thinner specimens showing greater TP because of reduced scattering and absorption.[10,23,31,44,46,59,61] Postprocessing, especially water-washing, postpolymerization, and polishing, was linked to improved TP by creating smooth surfaces,[28,30] while insufficient finishing increased surface roughness and light scattering.[13,28,31,33,44] Reported differences were generally below the established 50:50% perceptibility and acceptability thresholds for both CIEDE2000 (0.62, 2.62 units) and CIELab (1.33, 4.43 units).[60]

ΔTP was significantly greater in AM materials than in SM controls, consistent with the higher water sorption, plasticization, and resin matrix degradation observed in them.[31,44,46,60] This was because of lower cross-linking and incomplete polymerization, which facilitated water and pigment diffusion and increased light scattering over time.[5,15,16,31,45,46,55,63] Greater specimen thickness and high layer heights further exacerbated the issue by limiting uniform polymerization.[31,46] Accelerated aging intensified ΔTP in all materials, but AM groups showed the greatest changes. Although most ΔTP values remained below the clinical acceptability threshold (ΔTP00=2.62),[60] the observed directional trend raises potential concerns for AM restorations in esthetically demanding areas. Surface roughness may also explain these optical differences. Studies report higher roughness in AM materials, even after polishing,[5,7,11,14,20,22,24,30] attributed to layer-by-layer deposition, step artifacts, and interlayer porosity, especially at higher layer thicknesses or with inadequate postprocessing. Increased surface roughness increased chromogen adherence and light scattering, promoting both discoloration and gloss loss.[11,12,20,24,30]

Given the substantial heterogeneity, these findings should be interpreted cautiously, and contextualization using perceptibility and acceptability thresholds should be considered indicative rather than definitive. Although AM offers advantages in customization, speed, and cost, its limitations in optical stability should be considered during treatment planning, AM materials may be suitable for interim restorations, whereas SM materials may remain a more predictable option for definitive restorations in esthetically demanding situations.

This review is limited by its reliance on in vitro studies, which may not fully replicate intraoral conditions. Substantial heterogeneity across outcomes limited the interpretability and generalizability of pooled estimates; accordingly, results should be viewed as directional trends, and nonsignificant findings as inconclusive. The assessment of publication bias was constrained by extreme heterogeneity, and selective reporting cannot be excluded despite trim-and-fill analyses. Although metaregression identified study quality as a contributor to heterogeneity for selected outcomes, residual variability remained, and risk-of-bias tools may not fully capture methodological issues such as pseudoreplication or measurement-related dependencies.

CONCLUSIONS

Based on the findings of the current study, the following conclusions were drawn:

1. AM resin-based materials generally showed greater color change and translucency loss after aging compared with SM materials; however, because of substantial heterogeneity, these findings should be interpreted as indicating a consistent directional trend rather than a uniform or generalizable effect.
2. Owing to substantial heterogeneity, evidence regarding baseline translucency differences between AM and SM resin-based materials remains inconclusive. Nevertheless, reported baseline translucency values largely overlapped and were commonly below the perceptibility and acceptability thresholds described in the literature, suggesting no consistent directional separation between manufacturing methods, rather than a definitive or generalizable difference.

DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

APPENDIX A. SUPPORTING INFORMATION

Supplemental data associated with this article can be found in the online version at doi:10.1016/j.prosdent.2026.02.015.

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Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review and editing, Visualization. **Pedro Diaz:** Conceptualization, Methodology, Validation, Investigation, Resources, Project administration, Writing – original draft. **Hooman Khanzadeh:** Software, Formal analysis. **Erfan Khorasani:** Formal analysis, Investigation, Data curation, Writing – original draft. **Jesús Peláez:** Validation, Writing – review and editing, Supervision, Project administration. **María J Suárez:** Methodology; Writing – review and editing, Supervision, Project administration.

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