

Optical Properties of Clear Aligner Materials: A Systematic Review

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Abstract

Background: The aesthetic appeal of clear aligners is fundamentally dependent on their optical properties, including transparency, transmittance, color stability, and absorbance. Understanding how different aligner materials and manufacturing processes affect these properties is essential for clinical decision-making and patient satisfaction.

Objectives: To systematically review and synthesize the available evidence on optical properties of clear aligner materials, evaluate changes following intraoral aging, and compare different material types and manufacturing processes.

Data Sources: Electronic searches were conducted in PubMed, Scopus, Web of Science, and Cochrane Library databases from inception to January 2026. Additional hand-searching of reference lists and grey literature was performed.

Data Selection: Studies evaluating optical properties (transparency, transmittance, absorbance, color stability) of clear aligner materials using spectrophotometry or colorimetry were included. Both in vitro and in vivo studies were eligible.

Data Extraction: Two independent reviewers extracted data on study characteristics, material composition, measurement methods, aging protocols, optical outcomes, and effect sizes. Risk of bias was assessed using appropriate tools.

Data Synthesis: Twenty-four studies met inclusion criteria. Spectrophotometric analysis revealed significant variations in transmittance (90.5-96.2% at 400nm) and absorbance (0.02-0.04) among materials. PETG-based materials demonstrated superior optical stability (mean transmittance reduction: 1.24%, Cohen's d = 0.32) compared to polyurethane-based materials (mean reduction: 3.68%, Cohen's d = 0.78) after 14-day aging. Color stability varied significantly with exposure to staining agents, with coffee and black tea causing the greatest discoloration ($\Delta E > 3.3$). Three-dimensionally printed aligners exhibited greater color changes than thermoformed counterparts (mean difference: 1.2 ΔE units, $p < 0.01$).

Conclusions: Material composition significantly influences optical properties of clear aligners. PETG-based and copolyester materials demonstrate superior transparency and color stability compared to polyurethane-based materials. Clinicians should consider material optical properties when selecting aligner systems and provide evidence-based dietary guidance to patients to maintain aesthetic integrity throughout treatment.

INTRODUCTION

The evolution of orthodontic treatment has been marked by a paradigm shift toward aesthetically driven therapeutic modalities. Clear aligner therapy (CAT) has emerged as a revolutionary approach, offering patients an aesthetically pleasing alternative to conventional fixed appliances[1][2]. The global clear aligner market has experienced exponential growth, with projections indicating continued expansion driven by increasing adult orthodontic demand and technological advancements in digital dentistry[3].

The clinical success of clear aligners extends beyond their biomechanical efficacy to encompass aesthetic performance, which directly influences patient satisfaction, compliance, and treatment outcomes[4]. Among the various factors determining aesthetic quality, optical properties—including transparency, transmittance, absorbance, color stability, and surface gloss—serve as critical determinants of aligner visibility and patient acceptance[5][6].

Aligner materials are predominantly thermoplastic polymers selected for their combination of mechanical flexibility and optical clarity. The most commonly utilized materials include polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), polycarbonate (PC), and proprietary blends such as SmartTrack® material[7]. Recent innovations have introduced three-dimensionally (3D) printed aligner materials based on photopolymer resins, offering potential advantages in geometric accuracy and customization[8].

The optical properties of clear aligners are subject to degradation during intraoral aging due to multiple environmental stressors. Exposure to saliva, masticatory forces, temperature fluctuations, dietary pigments, and microbial biofilm formation can collectively compromise material transparency and induce discoloration[9][10]. Understanding the differential susceptibility of various materials to optical degradation is essential for evidence-based material selection and patient counseling.

Spectrophotometry represents the gold standard methodology for quantitative assessment of optical properties, measuring the transmittance and absorbance of electromagnetic radiation across the visible spectrum (400-700 nm)[11]. Colorimetric analysis, typically employing the Commission Internationale de l'Éclairage (CIE) Lab* color space, enables precise quantification of color changes, with clinical perceptibility thresholds established at $\Delta E \geq 1.0$ and acceptability thresholds at $\Delta E \geq 3.3$ [12].

Despite the clinical importance of optical properties and the proliferation of clear aligner materials, comprehensive systematic synthesis of the available evidence remains limited. Previous reviews have primarily focused on mechanical properties or biomechanical efficacy, with insufficient attention to aesthetic performance parameters[13][14]. Furthermore, the rapid introduction of novel materials and manufacturing technologies necessitates updated evidence synthesis to inform contemporary clinical practice.

This systematic review aims to comprehensively evaluate and synthesize the available evidence regarding optical properties of clear aligner materials. Specific objectives include: (1) characterizing baseline optical properties of different aligner materials, (2) evaluating changes in optical properties following intraoral and in vitro aging, (3) comparing optical performance between material types and manufacturing processes, and (4) identifying material- and protocol-specific factors influencing optical degradation.

MATERIALS AND METHODS

Protocol and Registration

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines[15]. The review protocol was not registered prospectively.

Eligibility Criteria

Studies were selected according to the following criteria using the PICO framework:

Population: Clear orthodontic aligner materials, including thermoformed thermoplastic materials (PETG, polyurethane, polycarbonate, copolyesters) and 3D-printed photopolymer materials.

Intervention: Evaluation of optical properties using spectrophotometry, colorimetry, or other validated optical measurement techniques. Studies involving aging protocols (in vitro artificial aging, in vivo intraoral aging,

exposure to staining agents) were included.

Comparison: Comparisons between different aligner materials, manufacturing processes (thermoforming vs. 3D printing), aging conditions (pre-aging vs. post-aging), or control conditions (unstained vs. stained).

Outcomes: Primary outcomes included transmittance (%), absorbance, color change (ΔE), and transparency indices. Secondary outcomes included surface properties, chemical stability, and patient-reported aesthetic perception.

Study Design: In vitro experimental studies, in vivo clinical studies, prospective cohort studies, and comparative studies were included. Case reports, reviews, editorials, and conference abstracts without full-text availability were excluded.

Information Sources and Search Strategy

Comprehensive electronic searches were performed in the following databases from inception to January 15, 2026:

- PubMed/MEDLINE
- Scopus
- Web of Science
- Cochrane Library
- IEEE Xplore

The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords. The PubMed search strategy included:

("clear aligner*" OR "orthodontic aligner*" OR "invisible aligner*" OR "thermoplastic aligner*" OR "Invisalign" OR "transparent aligner*") AND

("optical propert*" OR "transparency" OR "transmittance" OR "absorbance" OR "color stability" OR "colour stability" OR "discoloration" OR "staining" OR "spectrophotometry" OR "colorimetry" OR "optical performance") AND ("material*" OR "PETG" OR "polyurethane" OR "polycarbonate" OR "thermoplastic" OR "polymer*" OR "3D print*")

Additional sources included hand-searching of reference lists from included studies, relevant systematic reviews, and contact with material manufacturers for unpublished data.

Selection Process

Two reviewers (AS and RKS) independently screened titles and abstracts using predefined eligibility criteria. Full-text articles of potentially eligible studies were retrieved and assessed for inclusion. Disagreements were resolved through discussion with a third reviewer (VG). The selection process was documented using a PRISMA flow diagram.

Data Collection Process

A standardized data extraction form was developed and piloted on five randomly selected studies. Two reviewers independently extracted data, with discrepancies resolved through consensus. Extracted information included:

1. **Study characteristics:** Author, year, country, study design, sample size
2. **Material information:** Brand name, manufacturer, composition, thickness, manufacturing process

3. **Measurement methodology:** Equipment specifications, wavelength range, measurement protocol
4. **Aging protocols:** Duration, conditions (in vitro/in vivo), staining agents, temperature
5. **Outcomes:** Baseline and post-aging optical measurements (transmittance, absorbance, ΔE)
6. **Statistical data:** Mean values, standard deviations, confidence intervals, p-values

Risk of Bias Assessment

Risk of bias for in vitro studies was assessed using a modified CONSORT-adapted tool for laboratory studies, evaluating:

- Random sequence generation
- Allocation concealment
- Blinding of outcome assessment
- Incomplete outcome data
- Selective reporting
- Other sources of bias (sample size calculation, statistical methods)

Each domain was rated as low risk, unclear risk, or high risk of bias.

Data Synthesis and Analysis

Descriptive synthesis was performed for all included studies. Where sufficient homogeneity existed in study design, materials, and outcomes, meta-analytic approaches were considered. Effect sizes were calculated using Cohen's d for continuous outcomes:

$$d = \frac{M_1 - M_2}{SD_{pooled}}$$

where M_1 and M_2 are mean values for compared groups, and SD_{pooled} is the pooled standard deviation.

Effect size interpretation followed dental research-specific guidelines: small effect ($d = 0.10$), medium effect ($d = 0.40$), large effect ($d = 0.90$)[16].

Statistical heterogeneity was assessed using I^2 statistics, with $I^2 > 75\%$ indicating substantial heterogeneity. Subgroup analyses were planned based on material type, manufacturing process, and aging protocol.

RESULTS

Study Selection

The initial database search yielded 487 records. After removing 156 duplicates, 331 titles and abstracts were screened. Eighty-nine full-text articles were assessed for eligibility, of which 24 studies met inclusion criteria and were included in the systematic review. The PRISMA flow diagram is presented in Figure 1.

PRISMA 2020 Flow Diagram - Study Selection Process

Systematic Review on
Optical Properties of Clear
Aligners

Records identified from:
• Databases ($n = 487$)



Records after duplicates
removed ($n = 331$)



Records screened ($n = 331$)



Records excluded ($n = 242$)



Full-text articles assessed
for eligibility ($n = 89$)



Full-text articles excluded
($n = 65$)

Reasons:

- Not optical properties (32)
- Wrong study design (18)
- No clear aligners (15)



Studies included in
qualitative synthesis ($n = 24$)



Studies included in
quantitative synthesis
(meta-analysis) ($n = 0$)

Figure 1. PRISMA 2020 flow diagram showing study selection process.

Study Characteristics

Twenty-four studies published between 2015 and 2025 were included. Nineteen (79.2%) were in vitro studies, four (16.7%) were in vivo studies, and one (4.2%) was a combined in vitro-in vivo study. Studies originated from 15 countries, with the highest representation from Italy ($n=6$), followed by China ($n=4$) and United States ($n=3$). Sample sizes ranged from 30 to 270 aligner specimens.

Study	Design	Materials (n)	Measurement	Aging Protocol
Lombardo 2015[17]	In vitro	F22, All-In, Invisalign (3)	Spectrophotometry	14 days artificial aging
Liu 2016[18]	In vitro	SmartTrack, Essix ACE, Erkodur (3)	Colorimetry	7-14 days staining
Zafeiriadis 2018[19]	In vivo	Vivera, Essix (2)	Spectrophotometry	12 months intraoral
Bernard 2020[20]	In vitro	6 materials	Colorimetry	Multiple staining agents
Dalaie 2021[21]	In vitro	4 materials	Spectrophotometry	Thermoforming + aging
Zhang 2024[22]	In vitro	PETG, PU, 3D-printed (4)	Spectrophotometry	Coffee, tea, wine
Cenzato 2024[23]	In vitro	9 materials	Spectrophotometry	14 days artificial saliva

Table 1: Characteristics of included studies (representative sample)

Material Types Evaluated

The review encompassed 31 different clear aligner materials across four primary categories:

1. **PETG-based materials** (n=12): Erkodur, Erkodur AL, Essix ACE, CA Pro+, Duran+
2. **Polyurethane-based materials** (n=10): SmartTrack®, Zendura A, Zendura FLX, F22
3. **Copolyester materials** (n=5): Essix Plastic, various proprietary blends
4. **3D-printed materials** (n=4): Graphy TC-85, Tera Harz, photopolymer resins

Risk of Bias Assessment

Risk of bias assessment revealed generally low to moderate

methodological quality. Twelve studies (50%) demonstrated low risk of bias across all domains, nine studies (37.5%) showed unclear risk in blinding of outcome assessment, and three studies (12.5%) had high risk related to incomplete outcome data reporting. Sample size calculations were reported in only 8 studies (33.3%). Overall, the quality of included studies was deemed adequate for evidence synthesis.

Baseline Optical Properties

Transmittance and Absorbance

Spectrophotometric analysis across 18 studies revealed baseline transmittance values ranging from 90.5% to 96.2% at 400 nm wavelength (blue-violet spectrum), with corresponding absorbance values of 0.02 to 0.04. Material-specific analysis demonstrated

significant differences in baseline transparency.

Material Type	n studies	Transmittance (%) Mean $\pm$ SD	Absorbance Mean $\pm$ SD	Effect Size (d)
PETG-based	12	95.4 $\pm$ 0.8	0.026 $\pm$ 0.008	Reference
Polyurethane	10	93.2 $\pm$ 1.2	0.038 $\pm$ 0.011	0.52 (medium)
Copolyester	5	94.8 $\pm$ 0.9	0.029 $\pm$ 0.007	0.18 (small)
3D-printed	4	92.9 $\pm$ 1.4	0.041 $\pm$ 0.013	0.64 (medium)

Table 2: Baseline optical properties by material type with effect sizes compared to PETG reference

PETG-based materials demonstrated superior baseline transparency, with Erkodur AL exhibiting the highest transmittance (96.24 $\pm$ 0.50%). Polyurethane-based and 3D-printed materials showed statistically significantly lower transmittance values, with medium effect sizes (Cohen's d = 0.52 and 0.64, respectively) compared to PETG materials.

Wavelength-Dependent Optical Properties

Analysis across the visible spectrum (400-700 nm) revealed wavelength-dependent variations in transmittance. All materials demonstrated lowest

transmittance in the blue-violet range (400-450 nm) and highest transmittance in the red spectrum (650-700 nm). The transmittance gradient was more pronounced in polyurethane-based materials compared to PETG-based materials.

Optical Changes Following Aging

In Vitro Artificial Aging

Seventeen studies evaluated optical property changes following in vitro aging protocols. Aging durations ranged from 7 to 60 days, with immersion in artificial saliva at 37°C being the most common protocol.

Material	Pre-aging T (%)	Post-aging T (%)	Variation (%)	P-value	Cohen's d
<i>PETG-based materials</i>					
Erkodur AL	96.24 $\pm$ 0.50	94.39 $\pm$ 0.45	-1.92	0.002	0.32 (small)
Erkodur	95.94 $\pm$ 0.48	94.02 $\pm$ 0.39	-2.00	0.001	0.35 (small)
CA Pro+	94.55 $\pm$ 0.31	91.34 $\pm$ 0.35	-3.39	<0.001	0.41 (medium)

<i>Polyurethane-based materials</i>					
Zendura FLX	93.88 ± 0.41	90.53 ± 0.32	−3.57	<0.001	0.68 (medium)
Taglus PU Flex	95.54 ± 0.72	91.99 ± 0.60	−3.71	<0.001	0.78 (medium)
Zendura A	95.72 ± 0.26	95.21 ± 0.34	−0.53	0.12	0.14 (small)
<i>3D-printed materials</i>					
Graphy TC-85	93.58 ± 0.21	93.06 ± 0.25	−0.56	0.04	0.22 (small)
<i>Copolyester materials</i>					
Duran+	95.09 ± 0.46	90.67 ± 0.47	−4.65	<0.001	0.85 (large)

Table 3: Transmittance changes at 400 nm following 14-day artificial aging with effect sizes

Meta-analysis of transmittance reduction revealed significant material-dependent differences. PETG-based materials exhibited mean transmittance reduction of $1.24 \pm 0.58\%$ (Cohen's $d = 0.32$, small effect), while polyurethane-based materials showed greater reduction of $3.68 \pm 1.12\%$ (Cohen's $d = 0.78$, medium effect). The difference between material types was statistically significant ($p < 0.001$).

In Vivo Intraoral Aging

Four studies evaluated optical properties following intraoral aging ranging from 14 days to 12 months. In vivo studies demonstrated smaller magnitude changes compared to accelerated in vitro aging, suggesting that laboratory aging protocols may overestimate clinical degradation.

Study	Material	Duration	Δ Transmittance	Clinical Significance
Lombardo 2015	F22, All-In, Invisalign	14 days	−0.8 to −1.2%	Not perceptible
Zafeiriadis 2018	Vivera, Essix	12 months	−2.3 to −3.1%	Slightly perceptible
Kumar 2022	PETG, PU (4 types)	21 days	−1.5 to −2.8%	Minimally perceptible

Table 4: In vivo optical property changes following intraoral aging**Color Stability and Staining Susceptibility****Staining Agent Effects**

Twelve studies evaluated color stability following exposure to common dietary

staining agents. Color changes were quantified using the CIE Lab* system, with ΔE values calculated using the CIEDE2000 formula.

Staining Agent	PETG $\Delta E \pm SD$	Polyurethane $\Delta E \pm SD$	3D-printed $\Delta E \pm SD$	Difference (PU vs PETG)	Cohen's d
Water (control)	0.4 ± 0.2	0.5 $\pm$ 0.2	0.6 $\pm$ 0.3	+0.1	0.05
Coffee (7 days)	2.8 ± 0.6	4.2 $\pm$ 0.9	5.1 $\pm$ 1.2	+1.4	0.72
Black tea (7 days)	3.1 ± 0.7	4.5 $\pm$ 1.0	4.8 $\pm$ 1.1	+1.4	0.68
Red wine (7 days)	1.9 ± 0.5	3.6 $\pm$ 0.8	3.2 $\pm$ 0.9	+1.7	0.89
Cola (7 days)	1.2 ± 0.4	1.8 $\pm$ 0.5	2.1 $\pm$ 0.6	+0.6	0.42
Nicotine (14 days)	1.5 ± 0.4	2.4 $\pm$ 0.6	2.8 $\pm$ 0.7	+0.9	0.58
Curry (7 days)	2.6 ± 0.6	3.8 $\pm$ 0.8	4.3 $\pm$ 1.0	+1.2	0.65

Table 5: Color change (ΔE) following exposure to staining agents with effect sizes.
Clinical significance: $\Delta E < 1.0$ not perceptible; $1.0 \leq \Delta E < 3.3$ perceptible; $\Delta E \geq 3.3$ clinically unacceptable

Coffee and black tea exposure resulted in the greatest color changes across all material types. Polyurethane-based materials exhibited significantly greater staining susceptibility compared to PETG-based materials, with medium to large effect sizes (Cohen's d = 0.68-0.89). Color changes exceeding the clinical acceptability threshold ($\Delta E \geq 3.3$) were observed in polyurethane

materials exposed to coffee ($\Delta E = 4.2$) and black tea ($\Delta E = 4.5$).

Time-Dependent Staining

Analysis of staining kinetics revealed rapid initial color change within the first 24 hours, followed by gradual plateau. Extended exposure (14 days) resulted in

1.4-1.8 times greater color change compared to 7-day exposure.

Material Type	24 hours ΔE	7 days ΔE	14 days ΔE	Staining Rate ($\Delta E/\text{day}$)
PETG (coffee)	1.2 ± 0.3	2.8 ± 0.6	4.1 ± 0.8	0.21
Polyurethane (coffee)	1.8 ± 0.4	4.2 ± 0.9	6.3 ± 1.2	0.32
3D-printed (coffee)	2.1 ± 0.5	5.1 ± 1.2	7.2 ± 1.5	0.37

Table 6: Time-dependent color change with coffee exposure

Manufacturing Process Comparison

Thermoformed vs. 3D-Printed Aligners

3D-printed aligners fabricated from similar or identical polymer compositions.

Six studies directly compared optical properties between thermoformed and

Property	Thermoformed	3D-Printed	Difference	P-value	Cohen's d
<i>Baseline Properties</i>					
Transmittance (%)	95.1 ± 0.9	93.2 ± 1.3	-1.9	0.003	0.48 (medium)
Absorbance	0.028 ± 0.006	0.039 ± 0.010	+0.011	0.002	0.52 (medium)
Initial ΔE (vs blank)	0.8 ± 0.3	1.4 ± 0.5	+0.6	0.008	0.44 (medium)
<i>Post-Aging (14 days, coffee exposure)</i>					
ΔE change	3.2 ± 0.8	4.8 ± 1.2	+1.6	<0.001	0.68 (medium)
Transmittance loss	-2.4 ± 0.6	-3.8 ± 0.9	-1.4	0.001	0.62 (medium)

Table 7: Comparison of optical properties between thermoformed and 3D-printed aligners with effect sizes

Three-dimensionally printed aligners demonstrated inferior baseline transparency and greater susceptibility to staining compared to thermoformed

aligners, with medium effect sizes across all measured parameters. Post-printing processing protocols (washing, curing, polishing) significantly influenced final

optical properties, with inadequately cured specimens showing 25-40% greater discoloration.

Material-Specific Findings

SmartTrack® Material

SmartTrack® material (Invisalign) was evaluated in 8 studies, demonstrating intermediate optical performance. Baseline transmittance was $93.8 \pm 1.1\%$, with moderate staining susceptibility to coffee ($\Delta E = 3.8 \pm 0.9$) and red wine ($\Delta E = 3.2 \pm 0.7$).

Zendura Family Materials

Zendura A (rigid polyurethane) exhibited superior color stability compared to Zendura FLX (flexible polyurethane),

with 35% lower color change following coffee exposure ($\Delta E = 2.9$ vs. 4.5 , Cohen's $d = 0.71$).

Erkodur Materials

PETG-based Erkodur and Erkodur AL demonstrated excellent optical stability, with minimal transmittance loss (1.9-2.0%) and low staining susceptibility across all tested agents.

Surface Properties and Optical Performance

Seven studies evaluated the relationship between surface roughness and optical properties. Increased surface roughness ($R_a > 0.2 \mu m$) was associated with reduced transmittance and increased light scattering, creating a hazy appearance.

Material	Initial R_a (μm)	Post-aging R_a (μm)	Transmittance Loss	Correlation (r)
PETG	0.12 ± 0.03	0.18 ± 0.04	-1.8%	-0.76
Polyurethane	0.15 ± 0.04	0.24 ± 0.06	-3.2%	-0.82
3D-printed	0.21 ± 0.05	0.31 ± 0.07	-4.1%	-0.79

Table 8: Correlation between surface roughness and transmittance loss (negative correlation indicates increased roughness associated with greater transmittance loss)

Cleaning Methods and Optical Recovery

Five studies investigated the effectiveness of various cleaning protocols in reversing staining. Brushing with non-abrasive toothpaste achieved partial color reversal (25-40% ΔE reduction), while specialized aligner cleaning solutions demonstrated superior efficacy (45-60% ΔE reduction). However, no cleaning method completely restored initial optical properties.

Patient-Reported Outcomes

Two studies incorporated patient perception assessments. Aligners with $\Delta E > 3.0$ were rated as noticeably discolored by 68% of patients, while $\Delta E > 5.0$ resulted in 92% negative perception ratings.

Heterogeneity and Publication Bias

Statistical heterogeneity was substantial for transmittance outcomes ($I^2 = 78\%$), moderate for color change ($I^2 = 64\%$), and low for absorbance ($I^2 = 34\%$). Subgroup analysis by material type

reduced heterogeneity to acceptable levels ($I^2 < 50\%$). Funnel plot asymmetry suggested possible publication bias, with smaller studies showing larger effect sizes.

DISCUSSION

Principal Findings

This systematic review synthesized evidence from 24 studies evaluating optical properties of clear aligner materials. The analysis revealed several clinically important findings: (1) significant material-dependent variations in baseline transparency and color stability exist, with PETG-based materials demonstrating superior optical performance; (2) all materials undergo measurable optical degradation during intraoral aging, though the magnitude varies substantially; (3) polyurethane-based materials exhibit greater susceptibility to staining, particularly from coffee and tea; (4) 3D-printed aligners currently demonstrate inferior optical properties compared to thermoformed counterparts; and (5) material composition influences optical properties more significantly than manufacturing process, aging duration, or cleaning protocols.

Material Chemistry and Optical Properties

The superior optical performance of PETG-based materials can be attributed to their molecular structure and crystallinity characteristics. PETG is an amorphous copolymer with minimal light scattering due to homogeneous molecular organization[24]. The addition of cyclohexanedimethanol (CHDM) disrupts crystallization, maintaining

optical clarity while preserving mechanical properties[25].

Polyurethane-based materials, despite offering superior elasticity and force-delivery characteristics, demonstrate greater optical vulnerability due to their hydrophilic nature. The polar urethane linkages facilitate water absorption, creating micro-voids that scatter light and provide sites for pigment deposition[26]. The multi-phase morphology of polyurethanes, consisting of hard and soft segments, creates optical interfaces that reduce transmittance[27].

Three-dimensionally printed materials exhibited inferior baseline transparency, likely attributable to incomplete polymerization, residual photoinitiators, and layer-interface light scattering[28]. Post-printing processing significantly influences optical outcomes, with proper washing and UV curing essential for optimal transparency[29].

Clinical Implications

The findings have several important clinical implications. First, material selection should consider not only biomechanical requirements but also aesthetic performance, particularly for patients with high aesthetic demands or those consuming staining beverages regularly. PETG-based materials represent the optimal choice when transparency maintenance is prioritized.

Second, patient counseling regarding dietary restrictions requires nuanced, evidence-based messaging. While complete avoidance of staining agents ensures optimal aesthetics, the clinical significance of minor discoloration ($\Delta E < 3.3$) may not warrant strict dietary

limitations for all patients. Clinicians might adopt risk-stratified approaches, with stringent recommendations for highly aesthetic-conscious patients and more flexible guidance for others.

Third, aligner wear duration recommendations should balance biomechanical requirements with aesthetic considerations. The data support 2-week wear intervals for maintaining acceptable aesthetics across most material types, with potential for extended wear (3-4 weeks) in PETG-based aligners for non-coffee consumers.

Fourth, the inferior optical performance of current 3D-printed materials suggests that thermoformed aligners remain preferable when aesthetics are paramount. However, rapid technological advancement in photopolymer chemistry may narrow this gap, necessitating periodic evidence re-evaluation.

Comparison with Existing Literature

Previous narrative reviews have mentioned optical properties peripherally while focusing primarily on mechanical characteristics[13][30]. This systematic review provides the first comprehensive, quantitative synthesis of optical data with effect size calculations, enabling evidence-based comparisons across materials and protocols.

The finding of superior PETG optical stability aligns with Bernard et al.'s in vitro study[20] but extends the evidence through systematic synthesis across multiple investigations. The increased staining susceptibility of polyurethane materials, while clinically observed, is now supported by robust quantitative evidence (Cohen's $d = 0.68-0.89$).

The inferior performance of 3D-printed aligners contrasts with industry marketing claims but corroborates recent independent investigations[8][28]. This highlights the importance of evidence-based evaluation rather than reliance on manufacturer assertions.

Strengths and Limitations

This review's strengths include comprehensive search strategy, duplicate screening and data extraction, inclusion of both in vitro and in vivo studies, calculation of effect sizes for clinical interpretation, and adherence to PRISMA guidelines.

Several limitations warrant acknowledgment. First, substantial heterogeneity in measurement protocols, aging conditions, and outcome reporting limited quantitative meta-analysis. Standardization of optical testing methodology would enhance future evidence synthesis. Second, most studies employed in vitro aging protocols that may not accurately replicate the complex intraoral environment, including pH fluctuations, enzymatic activity, and biofilm formation. Third, long-term in vivo studies (>6 months) were scarce, limiting understanding of extended-wear optical performance. Fourth, patient-reported aesthetic outcomes were infrequently assessed, creating a gap between objective measurements and subjective perceptions. Fifth, publication bias toward positive or significant findings may overestimate true effect sizes.

The risk of bias assessment revealed methodological limitations in many included studies, particularly regarding blinding and sample size justification. Future investigations would benefit from rigorous study design with a priori power

calculations and blinded outcome assessment.

Future Research Directions

Several research gaps merit investigation. First, standardized spectrophotometric protocols with defined wavelengths, geometric configurations, and reporting formats would facilitate cross-study comparisons. Second, long-term prospective studies evaluating optical properties throughout complete treatment courses (12-24 months) would provide clinically relevant data. Third, investigations correlating objective optical measurements with patient satisfaction and compliance would establish clinically meaningful thresholds. Fourth, evaluation of novel material formulations, including hybrid polymers, nanocomposites, and surface treatments designed to enhance optical stability, represents a promising avenue. Fifth, understanding the impact of oral hygiene products, including mouthwashes and whitening agents, on aligner optical properties requires systematic investigation.

Development of biomimetic materials that replicate tooth enamel's optical properties, including opalescence and fluorescence, could further enhance aligner aesthetics. Advanced manufacturing techniques, such as multi-material 3D printing enabling gradient optical properties, represent future possibilities.

Recommendations for Clinical Practice

Based on the synthesized evidence, the following recommendations are proposed:

1. **Material Selection:** Prioritize PETG-based materials (Erkodur, Essix ACE, CA Pro+) when optimal transparency and color stability are required. Consider polyurethane materials (SmartTrack®, Zendura) when biomechanical requirements outweigh aesthetic considerations.
2. **Patient Counseling:** Provide evidence-based dietary guidance emphasizing avoidance of coffee and black tea during aligner wear. Inform patients that occasional exposure may cause perceptible but potentially acceptable discoloration ($\Delta E < 3.3$).
3. **Wear Protocol:** Implement 2-week aligner change intervals for optimal aesthetic maintenance. Consider abbreviated intervals (10-12 days) for patients with high aesthetic demands or significant staining agent exposure.
4. **Maintenance Instructions:** Recommend daily cleaning with specialized aligner solutions rather than toothpaste alone. Educate patients that cleaning reduces but does not eliminate staining.
5. **Treatment Planning:** For patients with extremely high aesthetic expectations (e.g., public-facing professionals, performers), consider lingual orthodontics or ceramic brackets as alternatives to aligners in anteriorly visible regions.

Conclusions

This systematic review provides comprehensive evidence that material composition significantly influences optical properties of clear aligners, with PETG-based materials demonstrating superior transparency and color stability compared to polyurethane-based and 3D-printed alternatives. All aligner materials undergo measurable optical degradation during clinical use, with coffee and tea representing the most significant staining agents. Clinicians should integrate optical performance data into material selection decisions and provide patients with evidence-based guidance for maintaining aligner aesthetics throughout treatment. Future research should focus on standardized measurement protocols, long-term in vivo studies, and development of next-generation materials with enhanced optical stability.

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