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REVIEW ARTICLE

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Color and optical properties of 3D printing restorative polymer-based materials: A scoping review

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Abstract

Objective: Color and optical properties are particularly crucial to mimic natural tooth. This scoping review aimed to present an overview of the literature published on color and optical properties of 3D printing restorative polymer-based materials. The literature search was performed in MED-LINE/Pubmed, Scopus and Web of Science.

Materials and methods: The literature search was conducted in the three databases based on the question: "Are the optical properties and color adequately reported on polymer-based 3D printing dental restorative materials studies?" with no restriction on year of publication. Data were reported and synthesized following PRISMA-ScR statement.

Results: Nine studies fit the inclusion criteria. Five studies focused on evaluating only color stability; three articles assessed the color stability along with mechanical and morphological properties and only one study compared color parameters of 3D printed to conventional polymers. Two studies evaluated translucency parameter and no study was found evaluating scattering, absorption, and transmittance.

Conclusions: Color and optical properties of 3D printed polymers that can be used in restorative dentistry are not adequately evaluated and characterized. Future studies on the influence of experimental printing conditions should include these physical properties to assist on improving esthetics.

Clinical significance: This review shows the scarce literature existing on color and optical properties of 3D printing restorative polymer-based materials. These properties and their study are of outmost importance to create materials that mimic natural tooth to allow clinicians to obtain esthetically pleasant restorations.

KEYWORDS
3D printing, additive manufacturing, color, optical properties, polymer, provisional restoration

1 | INTRODUCTION

Digital technology has leaded to a breakthrough in most fields of dentistry, including restorative dentistry. Traditional dental laboratory procedures have been progressively replaced by the so-called "digital workflow," which consists of three main elements: data acquisition, using digital scanners to transform the object geometry in a digital file; data processing and computer assisted design (CAD), and computer assisted manufacture (CAM) of structures.[1]

The additive manufacturing (AM) technique, 3D printing or rapid prototyping has been suggested as the alternative to the subtractive manufacturing in the digital workflow.[2] This manufacturing approach consists of producing the construct, in layers, directly from 3D digital data and using different raw materials such as polymers (resins and thermoplastic materials), waxes, metals and ceramics. AM provides many advantages including the manufacture of objects with complex dimension and geometry, the reduction of material wastes up to 40%, and the reproduction of details finer than the milling burs can achieve.[3]

Currently, the demand and use of additive processes for dental restoration manufacturing is not significant. However, further growth can and should be expected.[4] Esthetic appearance, wear resistance and dimensional accuracy are important limitations that slow down the progression to functional part manufacture with 3D printing.[5] Additive technology development and clinical applicability will depend on the gradual improvement of the manufacturing process, which implies controlling several variables including the building orientation/direction, the support structure dimension and distribution, and the position of printed parts in the building platform,[3] in addition to improving parameters associated to both printers and printing materials.[5] These variables have an influence in several properties such as printing accuracy, strength, surface morphology, and bacterial response.[6,7]

Regarding 3D printing dental materials, polymers are the most studied, followed by metals. Ceramics are still underdeveloped mainly because of the challenge to produce objects with adequate surface finishing, dimensional accuracy, and structural properties.[5,8] Yet, such materials should fulfill the mechanical and biocompatibility requirements needed for the oral service and satisfy patients and clinicians for the esthetic demands.[5] This is why color and optical properties measurement and characterization,[9–17] and visual color differences evaluation in dentistry[18–23] are of utter importance. Furthermore, several studies[20–25] supported the CIE recommendation[26] to use CIEDE2000,[22] formula to evaluate this color differences.

Additive CAD-CAM technology should aim to manufacture multilayer/multimaterial biomimetic restorations, using materials with improved mechanical and optical properties and color, as it has been suggested with "multi-material 3D printing" or "4D printing."[27] Considering dentistry, this process tries to mimic the structure and properties of a natural tooth.[28] Such conversion of information from natural models to artificial prototypes has opened up the possibility of developing novel research strategies that incorporate 3.8 billion years of evolution,[29] which is thus a very innovative and undoubtedly promising approach. In these new approaches, color, and optical properties[30] are particularly crucial.[27]

Currently, 3D printing dental materials are considered an alternative to conventional procedures such as the subtractive CAD-CAM technology. In order to evolve from such status, it is essential to understand the advantages and disadvantages and the properties of printing materials and structures and to compare them with the

TABLE 1 Search strategy developed for each database

PubMed	((Dentistry[Mesh] OR dental[Title/Abstract] OR tooth[Title/Abstract] OR "Dentistry, Operative"[Mesh] OR "Dental Materials"[Mesh] OR Prosthodontics[Mesh]) AND (("additive manufactur*"[Title/Abstract] OR "3D print*"[Title/Abstract] OR stereo lithograph* [Title/Abstract] OR "digital light processing"[Title/Abstract] OR "material extrusion"[Title/Abstract] OR "fused deposition modeling"[Title/Abstract] OR "material jetting"[Title/Abstract] OR "multijet printing"[Title/Abstract]) AND (resin*[Title/Abstract] OR polymer*[Title/Abstract] OR material*[Title/Abstract]))) Filters: Journal Article, from 2000/1/1–2021/10/12
Web of Science (WOS)	AB = ((prosthodontics OR dentistry OR dental OR tooth) AND (("additive manufactur*" OR "3D print*" OR stereolithograph* OR "digital light processing" OR "material extrusion" OR "fused deposition modeling" OR "material jetting" OR "multijet printing") AND (resin* OR polymer* OR material*) NOT ("Material* and methods"))) OR TI = ((prosthodontics OR dentistry OR dental OR tooth) AND (("additive manufactur*" OR "3D print*" OR stereolithograph* OR "digital light processing" OR "material extrusion" OR "fused deposition modeling" OR "material jetting" OR "multijet printing") AND (resin* OR polymer* OR material*) NOT ("Material* and methods"))) Refined by: Document types: (ARTICLE) Databases = WOS Timespan = 2000–2021 Search language = Auto
Scopus	((TITLE-ABS-KEY (("additive manufactur*" OR "3D print*" OR stereolithograph* OR "digital light processing" OR "material extrusion" OR "fused deposition modeling" OR "material jetting" OR "multijet printing") AND (resin* OR polymer* OR material*))) AND NOT (ABS ("Material* and methods"))) AND (TITLE-ABS-KEY ((prosthodontics OR dentistry OR dental OR tooth))) AND (LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010) OR LIMIT-TO (PUBYEAR, 2009) OR LIMIT-TO (PUBYEAR, 2008) OR LIMIT-TO (PUBYEAR, 2007) OR LIMIT-TO (PUBYEAR, 2006) OR LIMIT-TO (PUBYEAR, 2005) OR LIMIT-TO (PUBYEAR, 2004) OR LIMIT-TO (PUBYEAR, 2003) OR LIMIT-TO (PUBYEAR, 2002) OR LIMIT-TO (PUBYEAR, 2001) OR LIMIT-TO (PUBYEAR, 2000)) AND (LIMIT-TO [DOCTYPE, "ar"])

currently available materials and technologies.[3] In this context, 3D printing restorative dental materials are defined in the present study as commercially available biocompatible resin-based materials used for AM of fixed partial interim dental restorations. Despite of the relatively large number of recent review papers on 3D printing in dentistry[1–5,31–33] and studies evaluating mechanical properties of 3D printing materials,[34–36] studies addressing questions concerning color characteristics and optical properties of 3D printed restorative dental materials are scarce in the current literature.

Therefore, the aim of the present study was to critically review the available scientific information on color and optical properties of 3D printing restorative resin-based materials.

2 | MATERIALS AND METHODS

2.1 | Protocol and registration

This review was developed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement extended for Scoping Reviews,[37] and the protocol is available at following link: https://doi.org/10.7326/M18-0850. The study approach was based on the Participant, Intervention, Comparison, and Outcome (PICO) framework,[38] resulting in the following study question: Are the optical properties and color adequately reported on polymer-based 3D printing dental restorative materials studies?

This scoping review was registered in the Open Science Framework (OSF) database, with the registration DOI: 10.17605/OSF.IO/QVJ8N and the publication DOI: 10.17605/OSF.IO/QVJ8N.

2.2 | Eligibility criteria

The inclusion criteria for the present review were English written in vitro studies that evaluated the optical properties and/or color of 3D printing resin-based dental restorative materials from peer-reviewed journals.

In contrast, the exclusion criteria were: (1) literature reviews, notes, abstracts, letters, comments, and manufacturer reports; (2) publication in language other than English; (3) in vivo studies; animal studies; (4) in vitro studies evaluating 3D printing resin-based materials not applied to restorative dentistry.

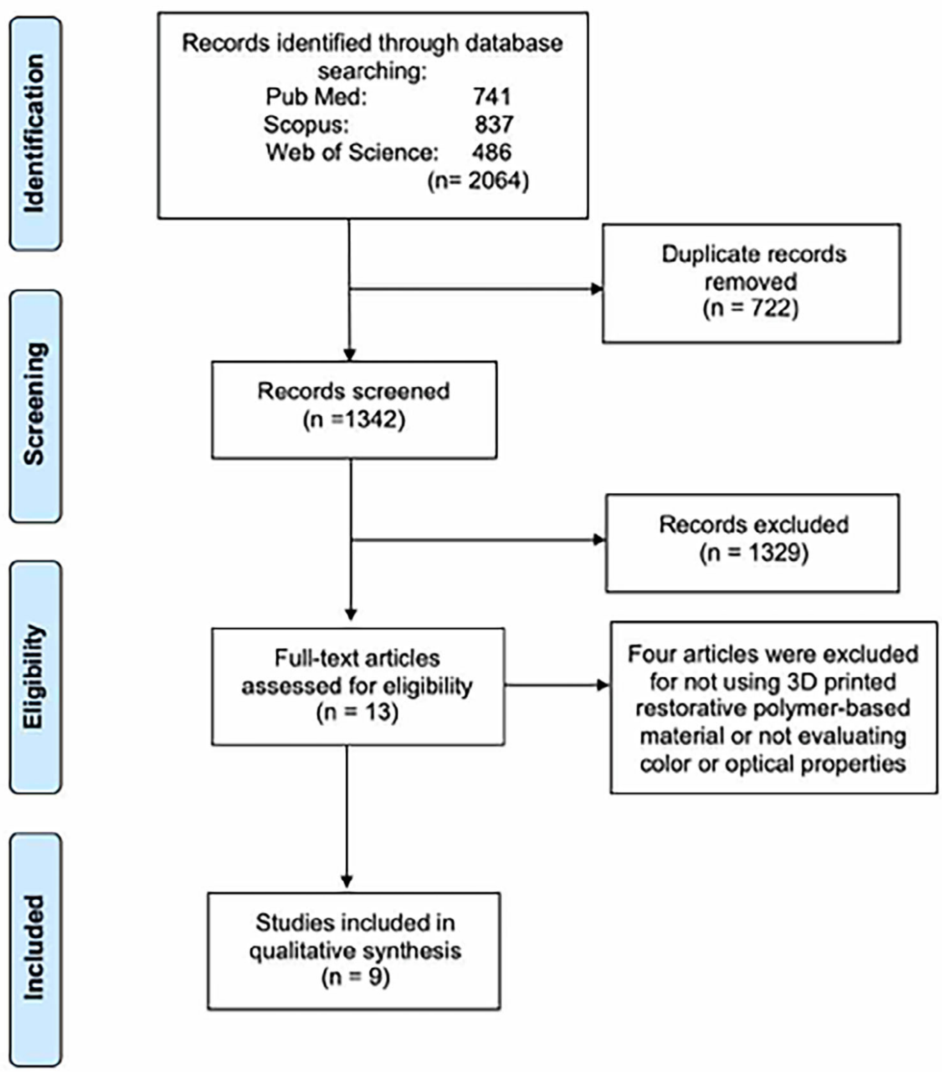

FIGURE 1 PRISMA flow diagram showing the flow of information through the different phases of the present scoping review

2.3 | Information sources and search strategy

The electronic search was carried out on 12th October 2021 considering publications between January 1st 2000 and October 12th 2021 in the following databases: MEDLINE/PubMed, Scopus, and Web of Science. The search strategy was outlined based on PubMed MeSH terms and adapted for each database (Table 1).

2.4 | Selection of sources of evidence

The retrieved documents from each database were exported to Zotero software. Duplicated records were automatically identified and eliminated. Two researchers (Cristina Espinar and Rosa Pulgar) independently screened articles assessing their titles and abstracts for relevance and compliance of eligibility criteria. Retrieved papers were classified as "include," "exclude," or "uncertain." Articles classified as "include" and "uncertain" were read in full for screening by the same investigators. Divergencies in screening of titles/abstracts and full-text articles between the two researchers were solved through discussion. In case of disagreement, a third investigator (María M. Pérez) was consulted. If relevant data were missing or unclear, the corresponding author from such articles was emailed up to three times.

2.5 | Data charting

The articles fulfilling the eligibility criteria were submitted for critical analysis by two independent reviewers (Cristina Espinar and Rosa Pulgar). A customized data extraction form was generated using Microsoft Word (Microsoft Corporation, Redmond, WA, EUA) to collect the following data:

- Details of the study. Authors, country (institution location of the corresponding author), year, and journal of publication.
- Objective of the study
- Material characteristics. Type of polymer-based material, brand name, sample size, and shade.
- Method information. Evaluated parameters, properties and concepts, stereolithography technology and 3D printer used, and measuring devices.
- Conclusions of the study

2.6 | Synthesis of results

This study focused on critically review the available scientific information on color and optical properties of 3D printing restorative polymer-based materials. The collected data were summarized through a descriptive analysis. A qualitative data synthesis was conducted since a quantitative analysis seemed impractical, hence the narrative quality of the present study.

TABLE 2 List of excluded articles with reasons for exclusion

Excluded articles	Reason for exclusion
Schweiger J, Beuer F, Stimmelmayr M, et al. Histoanatomic 3D-printing of dental structures. Br Dent J 2016; 221: 555–560	Not using 3D printed restorative polymer-based material Not evaluating color or optical properties
Cristache CM, Luminita O, Didilescu AC et al. Color changes and stainability of complete dentures manufactured using PMMA-TiO2 nanocomposite and 3D printing technology-one year evaluation. Rev Chim 2018; 69(2): 463–468	Not using 3D printed restorative polymer-based material
Gruber S, Kamnoedboon P, Özcan M et al. Cad-cam complete denture resins: an in vitro evaluation of color stability. J Prosthodont 2021; 30(5):430–439	Not using 3D printed restorative polymer-based material
Zandinejad A, Revilla-León M. Additively manufactured dental crown with color gradient and graded structure. J Prosthodont 2021; 30(9):822–825	Not evaluating color or optical properties

3 | RESULTS

A total of 741 articles were identified from Medline/Pubmed, 837 from Scopus and 486 from Web of Science (Figure 1). After eliminating duplicates (722) and removing the articles that, according to title and abstract, did not meet the eligibility criteria (1329), 13 full-text articles were assessed for eligibility. After full-text reading, four articles were excluded for neither using 3D printed restorative polymer-based material nor evaluating color or optical properties (Table 2). The third reviewer (María M. Pérez) was consulted to resolve disagreements in two articles. A manual review of the references included in the nine selected articles was also conducted resulting in no additional articles to be included. Therefore, nine articles[39–47] were included in the qualitative analysis and their relevant information is presented on Table 3.

All the studies were published between 2020 and 2021. Korean authors published four studies,[40,43,44,46] with three of them coming out of the Yonsei University (South Korea).[40,43,46] The remaining studies were conducted in the United States of America (USA),[41,45,47] Chile,[39] and Brazil.[42] Most studies were published in the Journal of Prosthetic Dentistry[41,42,47] and Materials.[43,46] The other articles were published in the Journal of Advanced Prosthodontics,[44] International Journal of Computerized Dentistry,[39] Journal of Prosthodontics[45] and Polymers.[40]

Considering the polymer type, two articles compared 3D printing polymers to CAD/CAM-milled resin blocks and conventional polymers (acrylic resin, bis-acryl or resin-based composite);[39,44] two articles compared 3D printing polymers to CAD/CAM-milled resin blocks;[43,47] two articles compared conventional polymers to 3D printing polymers;[41,42] and three studies evaluated only 3D printing polymers.[40,45,46] It is worth mention that all 3D printing polymers used in restorative

TABLE 3 Studies in chronological and alphabetical order reporting color and optical properties of 3D printing of restorative materials

Article	Publication year/country/journal	Objective	Type(s) of studied polymer(s)	Sample size	3D technology applied/printers	Evaluated properties and parameters	Measuring device	Conclusions
Atria P. et al.[39]	2020 Chile Int J Comput Dent	To evaluate roughness, color stability and color masking as assessed through the RTP of different provisional restauration materials before and after water thermocycling	*3D printing polymers* (Raydent C&B Temporary; 3DMaterials, Seoul, Korea). versus *Conventional polymers* Acrylic resin (Marche 66 shade, Marche, Santiago, Chile); bis-acrylic resin (Protemp A2 shade; 3 M ESPE, St Paul, MN, USA versus *CAD-CAM milled resin blocks* (TelioCAD A2 shade; Ivoclar Vivadent, Shaan, Liechtenstein)	10	SLA Printer: ANYCUBIC Photon	*Color stability + other material properties + color masking ability + translucency* – CIELAB color space -CIEDE2000 metric (ΔE_{00}) -Color differences -RTP	Clinical spectrophotometer (VITA Easy-Shade®)	1. CAD/CAM PMMA was the most stable resin 2. Autopolymerizing PMMA and bis-acryl–based resin showed good behavior overall for SR, for both thicknesses, but CAD/CAM PMMA showed better behavior than them for CS and color masking. 3. For all parameters analyzed, 3D-printed resin obtained the least reliable values. 4. Raydent 3D-printing resin significantly decreased its SR and CS values over time
Kim D. et al.[40]	2020 South Korea Polymers	To evaluate the changes in the properties of various 3D printed crown and bridge resins, according to post-curing time	*Only 3D printing polymers* Nextdent C&B (Nextdent, Soesterburg, The Netherlands), Nextdent C&B MFH (Nextdent, Soesterburg, The Netherlands), ZMD-1000B temporary (Dentis, Daegu, Korea), and DIOnavi C&B (DIO Inc. Busan, Korea) . Shade not specified	20	DLP Printers: Veltz D2 (Hepsiba, Seoul, Korea) (DLP) and Zenith D 3D printer (Dentis, Daegu, Korea) (DLP)	*Color stability + other material properties* -CIELAB color space -CIEDE2000 metric (ΔE_{00}) -Color difference	Colorimeter (CR321 Chromameter, Minolta, Osaka, Japan)	1. Changes with post-curing time were observed in color tone of the 3D printed resin 2. A minimum of 60 min post-curing time is necessary to achieve a good overall clinical performance of the printed resin 3. Future studies are necessary to analyze the various parameters that influence 3D printing and post-curing processes

(Continues)

TABLE 3 (Continued)

Article	Publication year/country/journal	Objective	Type(s) of studied polymer(s)	Sample size	3D technology applied/printers	Evaluated properties and parameters	Measuring device	Conclusions
Revilla-León M. et al.[41]	2020 USA J Prosthet Dent	To measure and compare color dimensions of different additively manufactured (AM) and conventional interim restorative materials	*3D printing polymers* FreePrint temp (Detax); E-Dent 400 (Envisiontec); NextDent C&B (NextDent); NextDent C&B MFH (NextDent); Med620 VEROGlaze (Stratasys). versus *conventional polymers* One autopolymerizing bis-acryl composite interim material (Protemp 4 temporization material, 3 M-ESPE); one autopolymerizing acrylic resin interim material (New outline Anaxdent dentin, Anaxdent) Shade: A3,5 or equivalent	60	DLP Printers: -Rapid Shape D30 (Rapid Shape) (DLP) -EnvisionTEC VIDA (EnvisionTEC) (SLA) -Object Eden 260VS; Stratasys (polyjet printer)	*Color parameters* -CIELAB color space -CIEDE2000 and CIELAB metrics -L*a*b*coordinates -Color difference	Clinical spectrophotometer (Vita EasyShade Advance 4.0; Vita Zahnfabrik, Bad Sackingen, Germany)	1. 3D printing resins showed different L* color values compared with conventional temporary resins 2. 3D printing resin subgroups showed significant color differences in all three-color dimensions. These differences were evaluated as clinically perceptible and unacceptable color discrepancies 3. The 3D resins evaluated did not match conventional temporary resins in any CIELAB color dimension, except for Free Print Temp and E-Dent 400 resins in the (L*) color dimension 4. CIEDE2000 color difference values were consistently lower than CIE76 values. This resulted in an approximate acceptable color difference threshold of 4.6 with the CIEDE2000 formula

TABLE 3 (Continued)

Article	Publication year/country/journal	Objective	Type(s) of studied polymer(s)	Sample size	3D technology applied/printers	Evaluated properties and parameters	Measuring device	Conclusions
Scotti CK. et al.[42]	2020 Brazil J Prosthet Dent	To compare the physical and surface properties of a 3D-printed resin with those of materials used for interim restorations	*3D printing polymers* NextDent C&B MFH, 3D Systems versus *Conventional polymers* Bisacryl resin (Protemp 4, 3 M ESPE); a conventional composite resin (Filtek Z350XT, 3 M ESPE). Shade A2	7	No information	*Color stability + other material properties* -CIELAB color space -CIELAB metric (ΔE^*_{ab}) -Color stability -Color difference	Clinical spectrophotometer (Vita EasyShade V; Vita Zahnfabrik, Bad Sackingen, Germany)	1. Better mechanical and surface properties were observed in 3D-printed resins than in bis-acrylic resin, supporting its use for temporary restorations. However, its use in esthetic areas or for long-term provisional restorations is of concern due to its reduced color stability
Shin JW. et al.[43]	2020 South Korea Materials	To evaluate the discoloration resistance and color stability of CAD/CAM block and 3D printing materials by evaluating color changes upon exposure to staining foods	*3D printing polymers* Nextdent C&B (Vertex-Dental B.V, Soesterberg, The Netherlands), and Denture teeth A2 Formlabs resin (Formlabs Inc., Sommerville, MA, USA). versus *CAD-CAM milled resin blocks* Polycarbonate (Polycarbonate block, Line dental lab, Seoul, Korea), PMMA (Vipi block, Vipi, São Paulo, Brazil), and dispersed-filler composite (MAZIC Duro, Vericom Co., Chuncheon, Korea) Shade not specified on all materials	10	DLP and SLA Printers: Nextdent ND5100 (DLP) and Form 3 Formlabs (SLA)	*Color stability* -CIELAB color space -CIEDE2000 metric (ΔE_{00}) -L*a*b*coordinates -Color difference	Colorimeter (Minolta Cr321 Chromameter, Minolta, Osaka, Japan)	1. CAD/CAM blocks materials (including polycarbonate, PMMA, and dispersed-filled composite) have higher CS than 3D printing resins (Nextdent C&B and Formlabs resins) 2. Several colorants significantly discolored the materials compared to distilled water. Among them, the most discoloration was caused by curry 3. The discoloration increased with the storage period

(Continues)

TABLE 3 (Continued)

Article	Publication year/country/journal	Objective	Type(s) of studied polymer(s)	Sample size	3D technology applied/printers	Evaluated properties and parameters	Measuring device	Conclusions
Song SY. et al.[44]	2020 Korea J Adv Prosthodont	To investigate and compare the color stability of provisional restorative materials fabricated by 3D printing, dental milling, and conventional materials	*3D printing polymers* E-Dent 100, EnvisionTEC and VeroGlaze, Stratasys, USA versus *Conventional polymers* AlikeTM; GC Co. and Luxatemp automix plus, DMG, Germany versus *CAD-CAM milled resin blocks* PMMA Disk, Yamahachi Dental Co., Japan and TelioCAD, Ivoclar Vivadent AG, Liechtenstein Shade A2	10	No information	*Color stability* -CIELAB color space -CIELAB metric (ΔE^*_{ab}) -L*a*b*coordinates -Δa^*, Δb^*, ΔL^* -Color difference	Colorimeter Spectrocolorimeter: Xrite Benchtop Spectrophotometer Color i5 (X-Rite, Inc, Grand Rapids, MI, USA)	1.The degree of discoloration was associated with drinks that have pigments and increase with time. Irrespective of the materials and solutions, visually perceptible color difference values were demonstrated 2. Discoloration was greater after 8 weeks in PMMA milling and 3D-printing resins 3. Future studies including longer observations may be necessary since the patterns of change with long-term observation varied
Almejrad M. et al.[45]	2021 USA J Phrosthodont	To evaluate the color stability of 3D-printed interim restorations with different surface treatments while immersed in various staining solutions or beverages (artificial saliva, tea, coffee and wine) for 6 months	*Only 3D printing polymers* NextDent Crown & Bridge, shade A3.5 (NextDent B.V., Soesterburg, The Netherlands)	10	DLP -Printer: MAX; Asiga	*Color stability* -CIELAB color space -CIELAB metric (ΔE^*_{ab}) -Color difference -Lightness difference (ΔL)	Clinical spectrophotometer Digital spectrophotometer CM-2600d (Konica Minolta)	1. Significant discoloration was observed in 3D printed resins after 6-months immersions in artificial saliva and common beverages (including tea, coffee, and wine) 2. Provisional restorations showed the most significant discoloration with red wine 3. Discoloration by chromogenic beverages was reduced by the addition of a nanofilled light-polymerizing protective coating, being more effective against coffee

TABLE 3 (Continued)

Article	Publication year/country/journal	Objective	Type(s) of studied polymer(s)	Sample size	3D technology applied/printers	Evaluated properties and parameters	Measuring device	Conclusions
Kim JE. et al.[46]	2021 South Korea Materials	To examine and compare color and translucency stability of 3D printable dental materials for crown and bridge restorations	*Only 3D printing polymers* DT-1, shades A2 and A3 (HA2 and HA3; Hephzibah, Incheon, Korea), NextDent C&B MFH, shade N1 and NextDent C&B shade A3.5 (NN1 and NA3; NextDent, Soesterburg, The Netherlands), and DIOnavi C&B shade A3 (DA3; DIO Inc., Busan, Korea)	12	DLP -Printer: Veltz D2 3D (Hepsiba, Seoul, Korea)	*Color stability + translucency* -CIELAB color space -CIELAB metric (ΔE^*_{ab}) -Color difference -TP -Difference in TP (ΔTP)	Colorimeter (Spectrophotometer CM-2600d [Minolta, Osaka, Japan])	1. As time after post-curing increased, changes in the color of 3D printed resins were observed, and the differences varied with the materials used 2. In all materials, the changes in translucency were relatively minor 3. After six months of water storage, the 3D resins became darker, more yellowish and opaquer
Yao Q. et al.[47]	2021 USA J Prosthet Dent	To investigate whether different surface treatments could affect the color stability of milled and 3D printed IFDPs after simulated physiological aging	*3D printing polymers* NextDent Crown & Bridge NextDent B.V versus *CAD-CAM milled resin blocks* Temp Esthetic 98, Harvest Dental Products, LLC Shade A3,5	10	DLP -Printer: MAX; Asiga	*Color stability* -CIELAB color space -CIELAB metric (ΔE^*_{ab}) -Δa^*, Δb^*, ΔL^* -Color difference	Clinical spectrophotometer Vita EasyShade (Vita Zahnfabrik, Bad Sackingen, Germany)	1. For the milled IFDPs: lower color changes after thermocycling simulating 6 months of intraoral aging were observed only when a nano-filled protective coating was applied 2. For the 3D-printed IFDPs, lower color changes after thermocycling were observed when both surface polishing and light-polymerizing protective coating agents were applied. The protective effect of light-polymerizing coating agents was more substantial

Abbreviations: AM, additive manufacturing; CAD-CAM, computer-aided design and computer-aided manufacturing; CS, color stability; DLP, digital light processing; IFDPs, interim fixed dental prostheses; n, sample size (per experimental group); PMMA, poly(methylmethacrylate); RTP, relative translucency parameter; SLA, stereolithography apparatus; SR, surface roughness; TP, translucency parameter.

dentistry are still considered temporary constructs.[5] The sample size ranged from 7[42] to 60,[41] but the most popular was $n = 10$.[39,43–45,47]

Considering the applied 3D printers technology, five studies (55.5%) employed printers using Digital Light Processing (DLP) (Veltz D2, Zenith D, Rapid Shape D30 and Asiga printers),[40,41,45–47] one study used Stereolitography Apparatus (SLA) (Anycubic Photon),[39] and another study used both DLP (Nextdent ND5100) and SLA (Form 3 Formlabs) printers.[43] Two papers did not provide information about the 3D printer used.[42,44]

Regarding the evaluated materials properties and parameters, five studies (55.5%) focused on evaluating only color stability, measuring L*a*b* coordinates and color differences;[43–47] three articles (33.3%) assessed the color stability along with other materials properties (surface roughness, flexural strength, Vickers hardness, Knoop hardness, Weibull modulus, and biocompatibility)[40,42] and color masking ability;[39] and only one study (11.1%) compared color parameters of 3D printed to conventional polymers.[41] All studies used either a clinical spectrophotometer (VITA Easy-Shade®)[39,41,42,45,47] or a colorimeter to measure color.[40,43,44,46]

It was not found any study evaluating optical properties (scattering, absorption, and transmittance), and only two papers[39,46] evaluated translucency using the translucency parameter (TP)[46] or relative translucency parameter (RPT)[39] .

4 | DISCUSSION

Color science in dentistry offers an objective way to measure and evaluate the appearance of teeth and dental materials in clinical practice and dental research.[9–11] Specifically, the Technical Report ISO/TR 28642[12] describes visual and instrumental methods to assess monochromatic and polychromatic tissues and materials related to dentistry. This standard proposes an interpretation of findings through color difference thresholds, and provides guidelines for future standardization related to dental shade conformity and interconvertibility.[12]

This review aimed to present a qualitative analysis of studies published on color and optical properties of 3D printing restorative resin-based materials with application in dentistry. The search showed that there are no studies evaluating optical properties, such as scattering, absorption and transmittance, and a limited number of studies addressing some aspects related to the chromaticity of the 3D printing polymers-based restorative materials.[39–47] Furthermore, most studies included in the present review do not report the color coordinates of 3D printing polymers or their agreement with a dental shade guide. In addition, the included studies do not report on the experimental conditions related to the printing process that could influence on the optical properties and final color of the constructs. Considering the last search was performed in mid of October, 2021, all the included studies are recent publications (2020 and 2021), which reveals a contemporary topic and the innovation status of such technology, with inherent limited scientific information scattered on several journals.

The challenge of performing and evaluating color measurements and color perception requires careful control of the factors that affect them. Thus, the applied devices and settings (illuminant, standard observers, geometric conditions, and background) should be reported in any color science study. As mentioned, all included studies used either a commercially available clinical spectrophotometer[39,41,42,45,47] or a colorimeter[40,43,44,46] to measure color, and the CIELAB color space and coordinates were used to evaluate color. However, these devices do not guarantee the accuracy needed to simulate visual conditions.[18] Therefore, a spectroradiometer should be used to measure the spectral reflectance and color coordinates, since it is considered the gold standard device to evaluate the optical and colorimetric properties of dental materials.[13,14] Furthermore, clinical spectrophotometers (VITA Easy-Shade®) are not calibrated as desired to measure polymers, as their primary using indication is for ceramics and natural teeth. In addition, the settings of these commercial devices are limited (D65 illuminant and 2° Standard Observers). Furthermore, it is well known that the color of the background significantly influences on color measurements[15] and on the perceptibility and acceptability thresholds (PT and AT) in dentistry.[19] However, only some studies[39,41,47] indicated the achromatic backgrounds used in their studies, even though, in general, it was not reported the used background chromatic coordinates.

Most studies included in the present review examined color changes and color stability before and after thermocycling,[39] after storage in various discoloration media and for different time,[43,44,46,47] and using different surface treatments[42,45,47] and post-curing time.[40] The greater the storage time, the greater the discoloration of the polymers. In addition, the color stability of 3D printing polymers was lower than CAD/CAM materials either after storage in staining solutions or after thermocycling. A CIELAB color difference (ΔE^*_{ab}) from 1.4 to 3.8 was found after polishing procedures[47] and a significant influence of surface treatment on color differences was observed with a 6-month storage in various staining solutions and beverages.[45]

The included studies show great variability of data for materials properties and parameters, which is mostly associated to the evaluation of different polymers manufactured by different stereolithography technology and printers. Regarding the post-curing procedure, some studies reported the use a UV device[39,40,43,46,47] or an association of UV and visible spectrum range device,[45] but other studies did not report[41,44] this information or stated that post-curing was not used.[42] Finally, but not least, it has been shown that polishing and finishing 3D printed constructs influences color stability and most material properties. While some studies surface finished the printed samples after post-curing using a sequence of polishing discs,[39,41–44,47] another study used only one polishing disc to surface finish the construct[40] and other studies evaluated the influence of such variable (surface finishing) on color stability applying different surface finishing techniques.[45,46]

CIELAB color difference formula has been considered as the reference for the evaluation of color differences in dentistry for many years. However, in the last decade CIEDE2000 formula has gained more interest since it has proven to fit more accurately the visual perception[20,21] Its improvements to the calculation of total color difference for color difference evaluation are based on corrections for the effects of lightness, chroma, and hue dependence and hue-chroma interaction on perceived color difference.[22,26] Several studies[20,21,24] supported the CIE recommendation to use CIEDE2000 formula to evaluate color differences in dentistry and, in particular, for dental resin composites.[25] However, only two of the included studies[39,43] used solely this recommended formula to evaluate color differences. Other studies used both CIELAB and CIEDE2000 metrics[40,41] or used only the CIELAB color difference formula.[42,44–47]

Furthermore, the ISO/TR 28642:2016 standard[12] suggests an interpretation of findings through color difference thresholds. These thresholds for tooth colored restorative materials were established in a prospective multi-center research study[23] (50:50% $PT_{ab} = 1.2$ and $AT_{ab} = 2.7$ CIELAB units; and 50:50% $PT_{00} = 0.8$ and $AT_{00} = 1.8$) and they can be applied to evaluate quality of color matching in dentistry. Yet, the color difference thresholds recommended by the ISO were not used to assess color changes and color stability in the included studies of the present review. Further, a study[41] incorrectly stated that the color differences thresholds using CIEDE2000 were not established.

Translucency describes the ability of a material to transmit light. Translucency and changes in translucency were evaluated in two papers[39,46] using the translucency parameters RPT[39] and TP.[46] The RTP difference values of four different provisional materials (acrylic resin, bis-acryl resin, polymethyl methacrylate [PMMA] CAD/CAM resin blocks, and 3D printed resin) before and after thermocycling ranged from −0.036 to 2.66 for 1.3 mm thick samples, and from 0.52 to 2.57 for 0.6 mm thick samples. It was concluded that RTP varied among different materials and according to sample thicknesses and that the overall performance of the 3D printed resin was inferior than other materials.[39] The translucency stability of five different 3D printed polymers for crowns and partial fixed dental prosthesis was evaluated after different storage time.[46] A value of $\Delta TP > 2.0$ was used as perceptibility threshold.[16] The TP value after 6 months of storage showed significant differences, and translucency differences were higher than the perceptibility threshold. It has been reported that thickness, staining and thermocycling influence on the TP of resin-based composite materials.[17] These factors also influenced on the translucency of 3D printing restorative polymer-based materials.[39,46]

Thus, the present scoping review showed that 3D printing polymers for restorative dentistry are not adequately evaluated with regards to their optical and chromatic characteristics. Finally, future studies on the influence of experimental printing conditions, such as layer orientation and thickness, on color and optical properties of 3D printing dental polymers should benefit the understanding and assist to improve esthetic features of these materials.

Although this study has been performed within the context of a scoping review, one limitation is that the nine studies included are heterogeneous in terms of objective of study and several aspects of the methodology. Despite a rigorous and transparent methodology, some studies meeting the inclusion criteria may have been missed due to the authors' choice of key-words and terms included in the title.

5 | CONCLUSIONS

The present review on color and optical properties of 3D printed polymers for restorative dentistry showed the current materials are not adequately evaluated and characterized. It is understandable that new technologies, such as 3D printing, take time and need scientific development before translate to clinics. In addition, from the innovative concept to the commercial product, industry follows development and research priorities, which may explain the incipient and often scientific deficient literature on color and optical properties of 3D printing polymers for restorative dentistry. Future studies on the influence of experimental printing conditions should include these physical properties to assist on improving the esthetic features of 3D printing restorative polymer-based materials.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are included in it. The documents are available on request from the corresponding author.

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