DOES THE APPLICATION OF POLYWAVE LIGHT-CURING UNITS INFLUENCE PHYSICO-MECHANICAL PROPERTIES OF RESIN-BASED MATERIALS? A META-ANALYSIS OF IN-VITRO STUDIES

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Abstract: The objective of this study was to systematically review the existing literature and to assess the effect of the use of polywave light-curing units on the properties of resin-based materials. A thorough search was conducted across five electronic databases: PubMed (MedLine), ISI Web of Science, SciELO, Scopus, and EMBASE.
Inclusion criteria comprised in-vitro studies that compared the effects of polywave light-emitting diode (LED) curing units with monowave LED curing units on resin-based material properties. Two reviewers evaluated the methodological quality of the included studies, considering parameters from previous systematic reviews.
Meta-analyses were conducted using Review Manager version 5.3.5 (The Cochrane Collaboration, Copenhagen, Denmark). Overall, when the TPO photoinitiator was employed, the use of a polywave light-curing unit demonstrated statistically significant higher values solely for the degree of conversion ($p<0.001$) and hardness ($p<0.01$).
No statistically significant differences were observed between monowave and polywave light-curing units in the other evaluated properties.
Based on the findings of this review, the use of polywave light-curing can be useful for polymerizing materials that contain photoinitiators other than camphorquinone in their composition.

Keywords: light-curing; monowave LED; polywave LED; photoinititiator; resin-based materials.

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L'APPLICATION D'UNITÉS DE PHOTOPOLYMÉRISATION POLYWAVE INFLUENCE-T-ELLE LES PROPRIÉTÉS PHYSICO-MÉCANIQUES DES MATÉRIAUX À BASE DE RÉSINE? UNE MÉTA-ANALYSE D'ÉTUDES IN VITRO

Résumé: L'objectif de cette étude était de passer en revue systématiquement la littérature existante et d'évaluer l'effet de l'utilisation d'unités de photopolymérisation polyonde sur les propriétés des matériaux à base de résine. Une recherche approfondie a été menée dans cinq bases de données électroniques : PubMed (MedLine), ISI Web of Science, SciELO, Scopus et EMBASE.
Les critères d'inclusion comprenaient des études in vitro comparant les effets des unités de polymérisation à diodes électroluminescentes (DEL) poly-ondes avec les unités de polymérisation à LED mono-onde sur les propriétés des matériaux à base de résine.
Deux évaluateurs ont évalué la qualité méthodologique des études incluses, en tenant compte des paramètres des revues systématiques précédentes. Les méta-analyses ont été réalisées à l'aide de Review Manager version 5.3.5 (The Cochrane Collaboration, Copenhague, Danemark).
Dans l'ensemble, lorsque le photoinitiateur TPO a été utilisé, l'utilisation d'une unité de photopolymérisation polyonde a démontré des valeurs statistiquement significatives plus élevées uniquement pour le degré de conversion ($p < 0,001$) et la dureté ($p < 0,01$).
Aucune différence statistiquement significative n'a été observée entre les unités de photopolymérisation mono-onde et poly-onde dans les autres propriétés évaluées.
Sur la base des résultats de cette revue, l'utilisation de la photopolymérisation polyonde peut être utile pour polymériser des matériaux contenant des photoinitiateurs autres que la camphorquinone dans leur composition.

Mots clés: photopolymérisable ; LED mono-onde ; LED polyonde; photoinitiateur; matériaux à base de résine.

Introduction

In the 1960s, Bowen introduced dental composite, a material that has since undergone multiple transformations to enhance its physical and mechanical properties [1]. Resin-based composites (RBCs) are widely utilized in clinical dentistry and have a wide range of applications, such as direct restorations, sealants, inlays, onlays, crowns, luting agents, and orthodontic devices. The primary advantages of RBC restorations lie in their aesthetic appeal and favorable mechanical characteristics [2]. Literature shown high survival rates, with annual failure rates of 1.8% at 5 years and 2.4% after 10 years of use [3].

However, common clinical issues associated with RBCs include problems related to polymerization shrinkage stress, fractures, and color changes. Several factors contribute to the failure of RBCs, including material composition, operator technique, quality of polymerization, and stresses generated during cyclic loading [4].

Light activation is a common method for curing resin-based composites [5]. The polymerization process in RBCs is mediated by photoreactive systems that absorb specific wavelengths of light, commonly emitted by a light-curing unit [6]. Photoinitiators present in the RBCs absorb photons emitted by the light-curing unit, leading to the excitation of monomers in the molecular structure. In this active state, the monomers undergo a transformation into a polymer network, facilitated by the photopolymerization initiator system. Camphorquinone (CQ) is the most commonly used photoinitiator in dental materials.5 However, alternative photoinitiators such as 2,4,6-trimethylbenzoyldiphenylphosphine oxide (Lucirin TPO) and 1-phenyl-1,2-propanedione (PPD) have been introduced in certain RBCs. These photoinitiators exhibit higher sensitivity to shorter wavelengths (<420 nm) [7]. These alternative photoinitiators have been developed to address the color stability issues associated with CQ-based systems, which can be compromised by the presence of amines. With the introduction of new photoinitiators like Lucirin TPO and Ivocerin, both photosensitivity and color stability have improved in RBCs [8].

The light-curing unit is an essential part of the resin curing process to achieve long-term clinical success and manufacturer proposed properties [9]. The first- and second-generation LED lights are only monowave (single-LED) and had an intensity of approximately 400mW/cm^2, while the second-generation ones reached intensities of up to 1000mW/cm^2. Nowadays, third-generation LED features polywave (dual/multi-peak) technology, avoiding wavelength compatibility issues, as well as featuring higher light intensities and multiple cure modes [6].

Due to conflicting findings in the literature, there is a lack of consensus regarding the impact of different light-curing units on the properties of resin composites. Consequently, the objective of this study was to conduct a systematic review of the existing literature to assess the influence of polywave light-curing units on the properties of resin-based materials. The null hypothesis tested was that there would be no difference between the effect of monowave light-curing unit and polywave light-curing unit on properties of resin-based materials.

Materials and Methods

This systematic review and meta-analysis was conducted according to the PRISMA statement [10]. The PICOS framework used was: Population: Resin-based materials.; Intervention: Polywave light-curing unit.; Control: Monowave light-curing unit; Outcomes: laboratorial performance; and Study design: in-vitro studies. The research question was: Is there any difference in selected mechanical properties of resin-based materials when polymerized using a monowave or polywave light-curing unit?

Literature search

Two independent reviewers conducted the literature search up until September 8th, 2022. Five electronic databases were meticulously screened, including PubMed (MedLine), ISI Web of Science, SciELO, Scopus, and EMBASE. The search strategy was tailored to each specific database. The keywords and search strategy employed in PubMed were adapted accordingly for the other search engines and are detailed in Table 1.

In addition, the reference lists of the included articles were manually examined to identify any additional

Table 1. Keywords used in the search strategy.

#1	Composites OR bulk fill composites OR resin composite restorations OR resin-based composites OR resin cement OR flowable resin
#2	Polywave OR multiple peak Monowave curing light OR monowave LED units
#3	depth of cure OR Effectiveness OR Curing profile OR Degree of conversion OR Microhardness OR Stiffness OR Elastic modulus OR Marginal integrity OR mechanical properties OR color changes OR polymerization efficacy OR compressive strength OR marginal gap OR properties OR degree of cure OR hardness OR color stability OR photopolymerization OR nanohardness OR hardness OR photocuring OR micro-hardness OR photoactivation OR translucency parameter.
# 4	#1 AND #2 AND #3

relevant manuscripts. Following the initial screening process, all identified studies were imported into Endnote X9 software to eliminate any duplicates.

Study selection

The titles and abstracts of all manuscripts were evaluated by two independent reviewers using the Rayyan QCRI mobile app with Blind mode enabled [11]. This process was carried out in order to select the manuscripts for full-text review based on the predetermined eligibility criteria. The criteria included the following: (1) in-vitro studies that compared the use of a polywave light-curing unit with a monowave light-curing unit on the properties of resin-based materials; (2) studies providing mean and standard deviation data (SD); (3) studies published in English. Case reports, case series, pilot studies, and reviews were excluded from consideration. Full copies of potentially relevant studies were thoroughly examined. Studies that appeared to meet the inclusion criteria or lacked sufficient data in the title and abstract to make a clear determination were selected for a comprehensive analysis of the full text. The full-text papers were independently assessed by two reviewers (M.A.F.-B. and W.D.). Any discrepancies regarding the eligibility of the included studies were resolved through discussion and consensus involving a third reviewer (C.E.C.S.).

Data extraction

The relevant data extracted from the included manuscripts were organized and recorded in Microsoft Office Excel 2021 spreadsheets (Microsoft Corporation, Redmond, WA, USA). The recorded data encompassed the publication year, country of origin, type of resin-based material tested, photoinitiator composition in the material, brand names of the monowave and polywave light-curing units utilized, properties analyzed, and the primary findings. In cases where data were partially missing, attempts were made to contact the corresponding authors via email to retrieve the missing information. If no response was received within one month of the initial contact, the missing information was not included in the analysis. For articles where the information was presented graphically and the original data could not be obtained from the authors, mean and standard deviation values were calculated using WebPlotDigitizer 4.0 software (Austin, Texas, USA).

Quality assessment

Two reviewers evaluated the methodological quality of the included studies by considering parameters established in previous systematic reviews [12,13]. The risk of bias in each article was assessed based on the following criteria: randomization of specimens, implementation of a single-operator protocol, presence of a control group, blinded operator, standardization of sample preparation, adherence to manufacturer instructions for material use, use of the same radiant exposure, and description of sample size. If a study provided a description for a specific parameter, it was marked as "YES"(. If the data for a parameter were missing or not described, it was marked as "NO" (x). The risk of bias was then categorized based on the cumulative number of "YES" (responses: 1 or 3 indicated a high risk of bias, 3 to 5 indicated a medium risk of bias, and 6 or 8 indicated a low risk of bias.

Statistical analysis

The meta-analyses were conducted using Review Manager version 5.3.5 software, developed by The Cochrane Collaboration in Copenhagen, Denmark. A random-effects model was employed for the analyses, comparing the standardized mean difference of various properties (degree of conversion, hardness, flexural strength, compressive strength, and depth of cure) when using a monowave or polywave light-curing unit. Different types of resin-based materials, including conventional composites, bulk fill composites, resin cements, and experimental materials, were analyzed separately. Subgroup analyses were also performed for materials based on camphorquinone (CQ) or 2,4,6-trimethylbenzoyldiphenylphosphine oxide (TPO). A p-value less than 0.05 was considered statistically significant. Heterogeneity was assessed using the Cochran Q test, and the inconsistency I2 test was employed to evaluate inconsistency among the included studies.

Results

A total of 3143 papers were retrieved from all databases searched. A flowchart that summarizes the selection procedure according to the PRISMA statement is showed in Figure 1.

A total of 2847 papers were initially reviewed for the initial inspection after removing the duplicates. From these, 2778 were excluded after reviewing the titles and abstracts, leaving 69 articles to be assessed by full-text reading. After the full-text reading, fifteen studies were excluded due to the following reasons: in ten studies there was not compared a polywave light-curing unit against a monowave light-curing unit [14-23], three studies evaluated adhesive properties [24-26], one full-text could not be retrieved [27], and one study did not evaluate any mechanical property [28]. Then, a total of 54 studies were included in the qualitative analysis (Table 2), and from these, eight were excluded for the quantitative analysis because in five of them data was not presented in the form of mean and SD [29-33], and because in three of them the experimental conditions were not similar to others to allow the comparisons among studies [34-36]. The characteristics of the studies included in the qualitative analysis are depicted in Table 2.

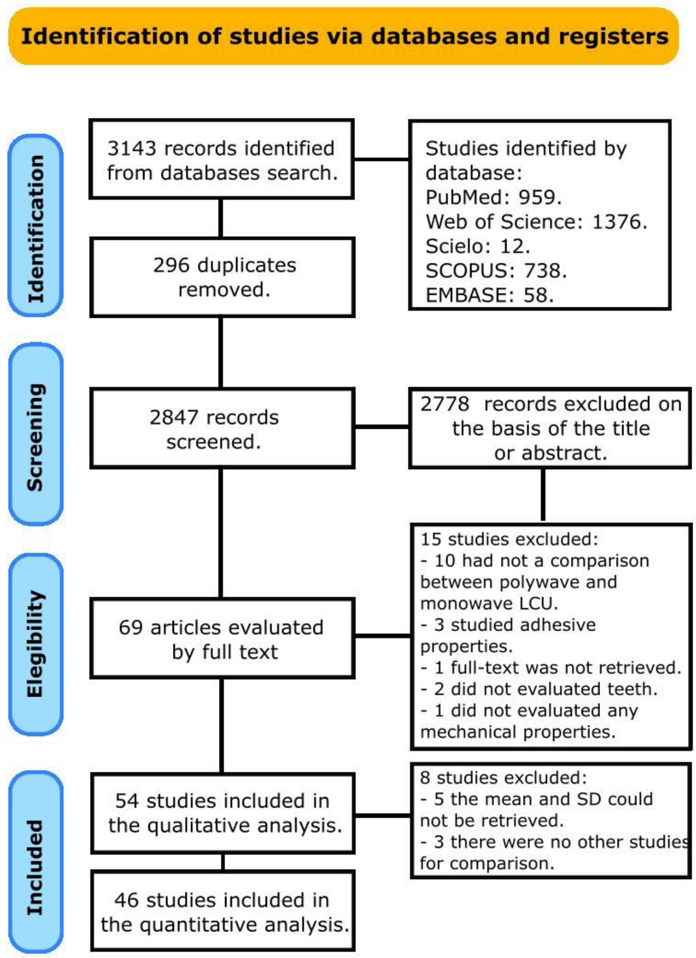


Figure 1. Flowchart according to PRISMA statement.

Table 2. Pairwise comparison of shear bond strength between Group I, II, III and IV.

Study	Restorative material	Photoinitiator	Monowave LED	Polywave LED	Properties analyzed	Main results
Al Senan 2022 [34]	Bulk fill composite Tetric N-Ceram Bulk Fill (Ivoclar-Vivadent) Filtek Bulk Fill Posterior restorative (3M ESPE) Conventional composite Filtek Z350 XT (3M ESPE)	TPO CQ CQ	Elipar Deep cure-S (3M ESPE)	Blue phase G2 (Ivoclar-Vivadent)	Translucency parameter	Bulk-fill materials achieved higher translucent when polymerized with a polywave LED curing unit.
Al-Zain 2019 [29]	Conventional composite Tetric EvoCeram (Ivoclar Vivadent)	TPO	Demi (Kerr, Orange, CA) Demi Ultra (Kerr, Orange, CA)	Bluephase Style (Ivoclar Vivadent) SmartLite Max (Dentsply) Valo Cordless (Ultradent)	Degree of conversion Knoop microhardness Cross-link density	No significant differences were observed between the LED curing unit tested among the properties analyzed.

Al-Zain 2019b [37]	Conventional composite Tetric EvoCeram (Ivoclar Vivadent)	TPO	Demi (Kerr, Orange, CA) Demi Ultra (Kerr, Orange, CA)	Bluephase Style (Ivoclar Vivadent) SmartLite Max (Dentsply) Valo Cordless (Ultradent)	Degree of conversion	Degree of conversion was similar with all the photopolymerization units tested.
Al-Zain 2021 [38]	Conventional composite Tetric EvoCeram (Ivoclar Vivadent)	TPO	Demi (Kerr, Orange, CA) Demi Ultra (Kerr, Orange, CA)	Valo Cordless (Ultradent)	μ-flexural strength	Curing unit type has no significant influence on the flexural strength.
AlQhatani 2013 [39]	Resin cement Variolink II (Ivoclar-Vivadent)	TPO	Elipar-S10 (3M ESPE)	Blupehase-G2 (Ivoclar-Vivadent)	Degree of conversion Knoop microhardness	The type of curing light had no significant effect on the degree of conversion.
Amato 2016 [40]	Orthodontic resin Transbond XT (3M Unitek, Monrovia, CA) Opal Bond MV (Ultradent Products Inc, South Jordan, UT)	CQ CQ	Ortholux (3M/Unitek, Monrovia, CA)	Valo Cordless (Ultradent)	Degree of conversion	Type of LED light-curing unit had no influence on the DC of the orthodontic composites.
Araújo 2021 [41]	Conventional composite Tetric N-Ceram (Ivoclar-Vivadent)	TPO	Elipar™ FreeLight 2 (3M ESPE)	Bluephase (Ivoclar-Vivadent)	Knoop Microhardness Nanohardness	Monowave unit showed better effectiveness in curing nanohybrid composite resins.
Aung 2021 [42]	Conventional composite MI FIL Flow (GC) Estelite Flow Quick (Tokuyama Dental) Estilite Universal Flow (Tokuyama Dental) Estilite Universal Flow (Tokuyama Dental) Beautifil Flow Plus (Shofu) Clearfil Majesty ES Flow (Kuraray Noritake Dental) Filtek Supreme Ultra Flow (3M ESPE) Tetric Evoflow (Ivoclar Vivadent)	CQ CQ CQ CQ CQ CQ CQ TPO	ElipарTM DeepCure-L (3M ESPE)	Bluephase®20i (Ivoclar Vivadent)	Vickers hardness Degree of conversion	The monowave unit has poor performance on hardness and degree of conversion.
Bakhsh 2016 [43]	Bulk fill composite Tetric Evoceram BulkFill (Ivoclar-Vivadent) SonicFill composite (Kerr)	TPO CQ	Elipar S10 (3M ESPE)	Blue-phase N (Ivoclar vivadent)	Vickers Microhardness	The surface hardness of bulk-fill composite is not dependent on the type of light-cure used.

Barakah 2021 [44]	Conventional composite Tetric-N-Ceram (Ivoclar-Vivadent)	TPO	Elipar S10 (3M ESPE) Planmeca Lumion (Mectron)	Blue phase G2 (Ivoclar-Vivadent)	Vickers hardness	The use of polywave light-curing unit achieved higher values of hardness.
Bayindir 2016 [35]	Resin cement (Kuraray Japan)	CQ	Elipar S10 (3M ESPE)	Valo (Ultradent)	Color change	The different curing units have a significant effect on the final color of resin cement.
Boeira 2021[45]	Experimental resin-based material	CQ, TPO and BAPO	Radii-cal® (SDI) Emitter D® (Schuster)	Valo® Cordless (Ultradent) Bluephase N® (Ivoclar Vivadent)	Degree of conversion	Polywave light-curing units showed a higher degree of conversion.
Borges 2018 [46]	Experimental resin-based material	CQ, PPD and BAPO	Radii Cal (SDI)	Bluephase G2 (Ivoclar Vivadent)	Degree of conversion	A significantly higher degree of conversion was achieved following photoactivation with a polywave LED.
Brandt 2013 [47]	Experimental resin-based material	CQ and PPD	Ultra Blue IS (DMC)	Ultra Lume 5 (Ultradent)	Compression strength Diametral tensile strength Diametral modulus	No statistically significant differences were found among mechanical properties, regardless of the light-curing unit used.
Cardoso 2016 [48]	Experimental composite	TPO	Radii Plus (SDI)	Bluephase G2 (Ivoclar-Vivadent)	Degree of conversion	Polywave LED achieved higher degree of conversion.
Cardoso 2020 [49]	Conventional composite. Aura (SDI)	CQ	Optilight Color (GNATUS) Radii Plus (SDI) Radii Xpert (SD)	Bluephase (Ivoclar-Vivadent) Valo (Ultradent)	Degree of conversion Sorption and Solubility	No significant differences in the degree of conversion were observed between the polywave and monowave light-curing unit.
Cardoso 2021 [50]	Bulk fill composite Aura Bulk Fill (SDI) Tetric Bulk Fill (Ivoclar-Vivadent) Amaris (VOCO) Filtek One (3M)	CQ TPO CQ CQ	Radii Xpert (SDI)	Valo (Ultradent)	Degree of conversion, Knoop hardness	Polywave light-curing unit significantly increased the degree of conversion and Knoop hardness of a TPO-based bulk-fill resin composite.
Carvalho 2020 [36]	Conventional composite Filtek Z350XT (3M ESPE). Vit-l-escence (Ultradent)	CQ TPO	Poly Wireless (Kavo)	Valo (Ultradent)	Surface roughness Gloss	The type of LED device did not influence the roughness and surface gloss.
Chen 2018 [51]	Resin cement RelyX U200 (3M ESPE) SpeedCEM (Ivoclar- Vivadent)	CQ TPO	Elipar S10 (3M ESPE)	Bluephase Style (Ivoclar-Vivadent)	Degree of conversion	Polywave light-curing units significantly increase the degree of conversion.
Conte 2017 [52]	Conventional composite Tetric EvoCeram (Ivoclar Vivadent)	TPO	Smartlite IQ (Dentsply) Starlight Pro (Mcctron)	Valo (Ultradent)	Vickers Hardness	Curing a resin-based composite with a polywave led achieved higher hardness.

Contreras 2021 [53]	Bulk fill composite Tetric N-Ceram Bulk Fill (Ivoclar Vivadent) Admira fusion X-tra Bulk Fill (Voco)	TPO CQ	Elipar (3M ESPE, Sumare, Brazil)	Bluephase N (Ivoclar Vivadent)	Degree of conversion Marginal Adaptation	The type of LED curing unit had no significant influence on the degree of conversion.
de Oliveira 2016 [54]	Experimental resin-based materials	CQ and PPD	Radii (SDI)	Valo (Ultradent)	Degree of conversion Flexural strength Young's modulus Knoop hardness Crosslinking density Yellowing	The type of light-curing unit used had not significant effect on the properties evaluated.
Derchi 2018 [30]	Bulk fill composite Filtek Bulk Fill (3M ESPE) Surefil SDR (Dentsply) Tetric Evo Ceram Bulk Fill (Ivoclar-Vivadent)	CQ CQ TPO	Bluephase style M8 (Ivoclar Vivadent)	Bluephase style (Ivoclar Vivadent) Valo (Ultradent)	Elastic modulus Hardness Roughness parameter	The use of polywave LED significantly increased the degree of conversion of the tested materials.
dos Santos 2018 [55]	Conventional composite IPS Empress Direct resin (Ivoclar, Vivadent)	TPO	Coltolux (Coltene)	Bluephase style (Ivoclar Vivadent) Valo (Ultradent)	Degree of conversion	There was no statistical difference in the degree of conversion between curing units.
Farzad 2022 [56]	Conventional composites Point 4 (Kerr) G-aenial Anterior (GC Corporation) Estelite Sigma Quick (Tokuyama)	CQ CQ CQ	Woodpecker (IDS DenMed Private Limited)	Bluephase N (Ivoclar Vivadent)	Vickers microhardness Flexural strength	Light-curing with polywave LED yielded results similar to those monowave LED.
Gan 2018 [57]	Bulk-fill composites Tetric N-Ceram Bulk Fill (Ivoclar Vivadent) SDR Posterior Bulk Fill Flowable (Dentsply)	TPO CQ	Bluephase N Monowave (Ivoclar Vivadent)	Bluephase N Polywave (Ivoclar Vivadent)	Knoop Hardness	For camphorquinone-based materials, photopolymerization with a monowave light-curing unit may be more efficient.
Gonulol 2015 [58]	Conventional composite Filtek™ Z550 (3M ESPE)	CQ	Elipar S10 (3M ESPE)	Valo (Ultradent)	Vickers Microhardness	The type of light-curing unit did not influence the hardness of a conventional composite.
Haenel 2015 [59]	Conventional composite Arabesk (Voco)	CQ	Celalux® 2 (Voco)	Bluephase® 20i (Ivoclar-Vivadent)	Degree of conversion Knoop microhardness	The hardness was not affected by the type of LED curing unit used.
Kuguimiya 2015 [60]	Resin cements Rely X U-200 (3M ESPE) Rely X ARC (3M ESPE)	CQ CQ	Elipar Freelight 2 LED (3M ESPE)	Bluephase G2 (Ivoclar-Vivadent) Valo (Ultradent)	Knoop hardness	Hardness did not differ significantly among the light-curing units used.

Lancellotti 2018 [61]	Resin cement Vario Link II (Ivoclar-Vivadent)	TPO	Radii Cal (SDI)	Bluephase G2 (Ivoclar-Vivadent)	Crosslink density Flexural strength Flexural modulus	The light-curing units had no influence on the flexural strength of the resin cements.
Lima 2016 [62]	Resin cement RelyX ARC (3M ESPE) LuxaCore Dual (DMG) Variolink (Ivoclar Vivadent)	CQ TPO CQ	Bluephase 16i (Ivoclar Vivadent)	Bluephase G2 (Ivoclar Vivadent)	Degree of conversion Flexural strength Flexural modulus	They type of LED curing unit used did not affect the properties of the resin cements evaluated.
Lucey 2014 [63]	Conventional composite Vit-l-escence (Ultradent) Herculite XRV Ultra (Kerr) Fissure sealants Delton Clear Delton Opaque (Dentsply)	TPO CQ CQ CQ	Bluephase (Ivoclar-Vivadent)	Bluephase G2 (Ivoclar-Vivadent) Valo (Ultradent)	Degree of conversion	Polywave LED curing units performed better in TPO-containing materials.
Maghaireh 2019 [64]	Bulk fill composite TetricEvo Ceram Bulk Fill (Ivoclar-Vivadent). SDR Posterior Bulk Fill Flowable (Dentsply) X-tra Fill U (Voco) Filtek Bulk Fill Flowable Restorative (3M ESPE) Filtek Bulk Fill Posterior Restorative (3M ESPE)	TPO CQ CQ CQ CQ	Elipar S10 (3M ESPE)	Bluephase Style (Ivoclar-Vivadent)	Vickers microhardness	No differences in the Vickers hardness were observed between the LED curing units used.
Makhdoom 2020 [65]	Bulk fill composite Tetric EvoCeram Bulk Fill (Ivoclar-Vivadent) Filtek Bulk Fill (3M ESPE). Conventional composite Tetric EvoCeram (Ivoclar-Vivadent).	TPO CQ TPO	Satelec MiniLED Supercharged (SATELEC®)	Bluephase Style® (Ivoclar-Vivadent).	Depth of cure	Depth of cure was not affected by the type of LED used.
Mauricio 2021 [66]	Conventional composite FiltekTM Z550 (3M ESPE) Bulk fill composite Filtek Bulk Fill Posterior (3M ESPE)	CQ CQ	Non specified	Non specified	Compressive strength	Polywave LED curing unit promoted higher compressive strength values.

Menees 2015 [67]	Bulk fill composite Tetric Evoceram Bulk Fill (Ivoclar-Vivadent) Filtek Bulk Fill Posterior (3M ESPE)	TPO CQ	Elipar S10 (3M ESPE)	Bluephase G2 (Ivoclar-Vivadent)	Depth of cure	No significant difference was noted between the monowave and polywave light-curing unit.
Miletic 2012 [68]	Experimental composites	CQ and TPO	Bluephase (Ivoclar-Vivadent)	Bluephase G2 (Ivoclar Vivadent)	Degree of conversion	Polywave LED curing units promoted higher degree of conversion only for TPO-based materials.
Modena 2021 [69]	Conventional composite Siriuz-Z (DFL) Bulk fill composite Filtek Bulk Fill (3M) Opus Bulk-fll APS (FGM) Tetric N-Ceram Bulk Fill (Ivoclar Vivadent) Filtek Bulk Fill Flow (3M) Opus Bulk-fll Flow APS (FGM) SureFil SDR Flow (Dentsply)	CQ CQ CQ TPO CQ CQ CQ	Poly wireless (Kavo Kerr) Radii-cal (SDI)	Bluephase G2 (Ivoclar Vivadent) Valo Cordless (Ultradent)	Degree of conversion	The type of curing unit has not any significant effect on the degree of conversion of the tested materials.
Price 2010 [31]	Conventional composite Filtek Supreme (3M ESPE) Vit-l-escence (Ultradent) Aelite LS Posterior (Bisco) Tetric EvoCeram (Ivoclar-Vivadent)	CQ TPO CQ TPO	Bluephase 16i (Ivoclar Vivadent) LEDemetron II (Kerr)	UltraLume 5 (Ultradent) Bluephase G2 (Ivoclar Vivadent)	Knoop microhardness	Polywave LED curing lights should be used in preference to single-peak led curing lights.
Price 2010b [70]	Conventional composite Tetric EvoCeram (Ivoclar-Vivadent) 4 seasons (Ivoclar-Vivadent) Filtek Z250 (3M ESPE) Vit-l-esence (Ultradent) Solitaire 2 (Hereaus Kulzer)	TPO TPO CQ TPO CQ	Bluephase 16i (Ivoclar-Vivadent) LEDMetron II (Kerr) Allegro (Denn-Mat) SmartLite IQ (Dentsply)	UltraLume 5 (Ultradent)	Knoop Hardness	The use of a polywave curing unit did not enhance the Knoop hardness of the materials.
Rocha 2017 [71]	Bulk fill composite Sonic Fill 2 (Kerr) Tetric EvoCeram (Ivoclar-Vivadent)	CQ TPO	Smartlite Focus (Dentsply)	Valo Cordless (Ultradent)	Degree of conversion	Polywave LED promoted a higher degree of conversion for TPO-based materials.

Rocha 2022 [72]	Conventional composite Admira fusion (Voco) Estelite Quick (Tokuyama) Filtek Supreme (3M ESPE) Herculite (Kerr) Mosaic (Ultradent) Tetric Evoceram (Ivoclar-Vivadent) Bulk fill composite Surefil SDR flow+ (Dentsply) Tetric Powerflow (Ivoclar-Vivadent) X-tra fil (Voco)	CQ CQ CQ CQ CQ TPO CQ TPO CQ	SmartLite Pro (Dentsply Sirona)	Valo Grand (Ultradent)	Depth of cure	Both monowave and polywave LED were successful for the polymerization of resin-based composites
Sahadi 2018 [73]	Bulk fill composite Filtek bulk fill (3M Oral Care) Surefil SDR flow (Dentsply Sirona) Tetric EvoCeram Bulk Fill (Ivoclar Vivadent)	CQ CQ TPO	Demi Ultra (Kerr)	Valo Cordless (Ultradent)	Surface roughness Knoop Microhardness	The choice of light-curing unit did not affect the roughness, but, depending on the composite, it affected the microhardness.
Santini 2014 [74]	Orthodontic resin APCPlus (3M ESPE) OpalH BondH (Opal Bond Orthodontics) LightBond™ (Reliance Orthodontic Products)	CQ CQ CQ	Bluephase (Ivoclar-Vivadent)	Bluephase G2 (Ivoclar-Vivadent) Valo (Ultradent)	Degree of conversion	All light-curing units performed similarly with the orthodontic adhesives.
Santini 2012 [75]	Conventional composite Tetric EvoCeram (Ivoclar Vivadent) Vit-l-escence (Ultradent) Herculite XRV Ultra (Kerr)	TPO TPO CQ	Bluephase (Ivoclar Vivadent)	Bluephase G2 (Ivoclar Vivadent) Valo (Ultradent)	Degree of conversion and Knoop microhardness	The use of polywave LED significantly improves both the degree of conversion and hardness of materials.
Shimokawa 2018 [76]	Bulk fill composite Filtek bulk fill (3M Oral Care) Tetric EvoCeram Bulk Fill (Ivoclar Vivadent)	CQ TPO	Celalux 3 (VOCO) Elipar DeepCure-S (3M Oral Care)	Bluephase 20i (Ivoclar-Vivadent) Valo Grand (Ultradent)	Knoop microhardness	No significant differences were found between the LED curing units used.
Shimokawa 2020 [77]	Bulk fill composite Filtek bulk fill (3M Oral Care) Tetric EvoCeram Bulk Fill (Ivoclar Vivadent)	CQ TPO	Celalux 3 (VOCO) Elipar DeepCure-S (3M Oral Care)	Bluephase 20i (Ivoclar-Vivadent) Valo Grand (Ultradent)	Knoop microhardness	The multiple-peak light-curing units produced higher hardness values.

Sim 2012 [78]	Conventional composite Grandio (Voco) Filtek Z350 (3M ESPE) Aelite LS Posterior (Bisco) Tetric N-Ceram (Ivoclar Vivadent) Vit-l-escence (Ultradent)	CQ CQ TPO TPO TPO	L.E. Demetron (Kerr)	G-light (GC Corp) Bluephase G2 (Ivoclar-Vivadent)	Microhardness, polymerization shrinkage, flexural, and compressive strength	The LED light-curing units tested achieve a similar degree of polymerization.
Souza 2019 [79]	Conventional composite Tetric N-Ceram (Ivoclar Vivadent) Vit-l-escence (Ultradent) Filtek Z350XT (3M ESPE)	TPO TPO CQ	Radii-Cal (SDI)	Valo (Ultradent),	Knoop microhardness	Polywave LED influenced the microhardness of materials containing Lucirin-TPO.
Souza 2019b [80]	Conventional composite Tetric N-Ceram (Ivoclar-Vivadent) Vit-l-escence (Ultradent) Filtek Z350 (3M ESPE)	TPO TPO CQ	Radii-Cal (SDI)	Valo (Ultradent),	Knoop microhardness	LED curing units did not affected the Knoop microhardness.
Strazzi-Sahyon 2020 [81]	Conventional composite TPH Spectrum (Dentsply)	CQ	EC 450 (ECEL)	Valo (Ultradent)	Knoop microhardness	Polywave LED promoted better mechanical properties.
Sword 2016 [82]	Conventional composite Premise Body (Kerr)	CQ	Elipar S10 (3M ESPE) FLASHlite Magna (DenMat)	Bluephase 20i (Ivoclar Vivadent) VALO (Ultradent)	Degree of conversion	No significant differences were found in the degree of conversion among the light-curing units tested.
Wang 2021 [83]	Bulk fill composites Beautiful Bulk Flow GIOMER (Shofu Dental Cooperation) Tetric PowerFill (Ivoclar Vivadent) Admira Fusion X-tra (Voco GmbH) FiltekV R One Bulk Fill (3M ESPE)	CQ TPO CQ CQ	Elipar DeepCure-L (3M)	Bluephase PowerCure (Ivoclar Vivadent)	Nanohardness Degree of conversion	The use of the monowave light-curing unit resulted in higher microhardness.
Yilmaz 2020 [33]	Orthodontic resin Transbond XT (3M ESPE) Gr□ngloo™ Adhesive (Ormco) Light Bond Paste (Reliance Orthodontic products-Inc)	CQ CQ CQ	Demi Ultra (Kerr) Optima 10 (B.A. International)	Valo (Ultradent)	Degree of conversion Vickers hardness	No differences were found in the properties analyzed among the different LED curing units used.

Several types of resin-based materials were evaluated, including conventional resin composites, bulk-fill composites, and resin cements. Most of the materials evaluated were based on the CQ photoinitiator, while only the Tetric ® family products (Ivoclar-Vivadent), Vit-l-escence (Ultradent), and Aelite LS Posterior (Bisco) claimed to have used TPO photoinitiator in their compositions. The mechanical properties evaluated included degree of conversion, hardness, translucency parameter, cross-linking density, flexural strength, elastic modulus, color stability, diametral tensile strength, compressive strength, sorption and solubility, surface roughness, depth of cure, and polymerization shrinkage. Table 3 shows the analysis of the risk of bias of the included articles.

Table 3. Risk of bias analysis.

Study	Specimens' randomization	Single Operator	Control group	Operator blinded	Standardized specimens	Manufacturer's instruction	Sample size calculation	Used equivalent radiant exposure	Risk of bias
Al-Senan 2022	x	x	√	x	√	√	√	x	Medium
Al-Zain 2019	x	x	√	x	√	√	x	√	Medium
Al-Zain 2019b	x	x	√	x	√	√	x	√	Medium
Al-Zain 2021	x	x	√	x	√	√	x	√	Medium
AlQahtani 2013	x	x	√	x	√	√	x	x	High
Amato 2016	x	x	√	x	√	√	x	x	High
Araujo 2021	x	x	√	x	√	√	x	x	High
Aung 2021	x	x	x	x	√	√	x	√	High
Bakhsh 2016	x	x	x	x	x	√	x	x	High
Barakah 2021	x	x	x	x	√	√	x	x	High
Bayindir 2016	x	x	√	x	√	√	x	x	High
Boeira 2021	x	x	√	x	√	√	x	x	High
Borges 2018	x	x	√	x	√	√	x	x	High
Brandt 2013	x	x	x	x	√	√	x	√	High
Cardoso 2016	x	x	x	x	√	√	x	√	High
Cardoso 2020	x	√	x	x	√	√	x	√	Medium
Cardoso 2021	x	x	√	x	√	√	x	√	Medium
Carvalho 2019	x	x	x	x	√	√	x	x	High
Chen 2019	√	x	x	x	√	√	√	x	Medium
Conte 2017	x	x	x	x	√	√	√	x	High
Contreras 2021	√	x	x	x	√	√	x	√	Medium
de Oliveira 2016	x	x	x	x	√	√	x	√	High
Derchi 2018	√	x	√	x	√	√	x	x	Medium
dos Santos 2018	x	x	√	x	√	√	x	x	High
Farzad 2022	x	√	x	x	√	√	x	x	High
Gan 2018	x	x	x	x	√	√	x	x	High
Gonulol 2015	√	x	√	x	√	√	x	x	Medium
Haenel 2015	x	x	x	x	√	√	x	√	High
Kuguimilla 2015	√	x	√	x	√	√	x	x	Medium
Lancellotti 2018	√	x	√	x	√	√	x	x	Medium
Lima 2016	x	x	√	x	√	√	x	√	Medium
Lucey 2014	√	x	√	x	√	√	√	x	Medium
Maghaireh 2019	√	x	x	x	√	√	x	√	Medium
Makhdoom 2020	x	x	√	x	√	√	x	x	High
Mauricio 2021	x	x	√	x	√	√	√	x	Medium
Menees 2015	x	x	x	x	√	√	x	x	High
Miletic 2012	x	x	√	x	√	√	x	x	High
Modena 2021	x	x	√	x	√	√	x	x	High
Price 2010	√	x	x	x	√	√	x	x	High
Price 2010b	√	x	√	x	√	√	x	x	High

Rocha 2017	x	x	x	x	√	√	x	√	High
Rocha 2022	√	√	x	√	√	√	√	√	Low
Sahadi 2018	x	x	√	x	x	√	√	x	High
Santini 2012	√	x	√	x	√	√	x	x	Medium
Santini 2014	√	x	√	x	√	√	x	x	Medium
Shimokawa 2018	x	x	x	x	√	√	x	√	High
Shimokawa 2020	x	√	x	x	√	√	x	√	High
Sim 2012	x	x	x	x	√	√	x	x	High
Souza 2019b	x	x	√	x	√	√	x	x	High
Souza 2019	x	x	√	x	√	√	x	√	High
Strazzi-Sahyon 2020	x	x	x	x	√	√	x	x	High
Sword 2016	√	x	√	x	√	√	x	√	Medium
Wang 2021	x	√	x	√	√	√	√	√	Low
Yilmaz 2020	√	x	x	x	√	√	x	x	High

√:Yes and x:NO

According to this analysis, most of the studies were cataloged as medium to high risk of bias. Most of the studies did not show the specimen randomization, single operator, sample size calculation, and use of equivalent radiant exposure values.

A meta-analysis was performed to analyze the effect of the type of light-curing used on the degree of conversion, hardness, flexural strength, compressive strength, and depth of cure of different resin-based restorative materials. Figure 2 shows the meta-analysis for the compressive strength. Both TPO and CQ based materials were evaluated for this property. For conventional resin composites and experimental materials, the use of different light-curing units was not statistically significant ($p=0.32$, and $p=0.86$, respectively). On the other hand, for bulk-fill materials, the use of a monowave light-curing unit achieved statistically significant higher values ($p=0.004$).

Figure 3 shows the results of the analysis of the DC of conventional resin composites according to the photoinitiator system used. According to the analysis, when the TPO is incorporated as photoinitiator, the DC is higher when a polywave LED curing unit is used ($p<0.001$); on the other hand, when only the CQ is used as photoinitiator, the differences between the light-curing unit are not statistically significant ($p=0.07$).

Figure 4 shows the meta-analysis of the DC of bulk-fill composites. The global analysis showed that a polywave light-curing unit achieved statistically significant higher values ($p=0.0008$).

Figure 5 shows the analysis of the DC of resin cements and experimental materials. For these types of the materials, the differences between the monowave and polywave light-curing units were not statistically significant, irrespectively of the type of photoinitiator used ($p>0.07$).

In figure 6 the analysis of the depth of cure for conventional (A) and bulk-fill resin composites (B) is shown. According to the analysis, this property is favored in conventional composites when a monowave light-curing unit is used ($p<0.0001$). However, the depth of cure of bulk-fill composites was statistically significant similar between the polywave and the monowave light-curing unit ($p=0.27$).

In figure 7 the analysis of the flexural strength of the conventional resin composites is shown. The global differences within this property were not statistically significant ($p= 0.08$).

Regarding resin cements, the flexural strength was higher when a monowave light-curing unit was used (Figure 8, $p<0.001$). In contrast, for experimental materials, differences were not statistically significant ($p=0.18$).

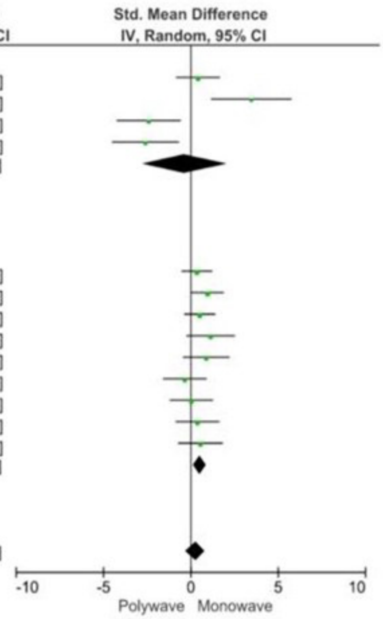
Figure 9 shows the results of the hardness property. For conventional resin composites, this property was favored when a polywave light-curing unit was used ($p=0.006$). And this effect occurred when TPO was used within the formulation of the material ($p<0.001$).

The same effect was observed for the bulk fill materials (Figure 10, $p=0.002$).

The figure 10 shows the meta-analysis for the hardness of bulk fill resin composites. The use of a polywave light-curing unit achieved statistically significant higher values ($p=0.0002$). Figure 11 shows the meta-analysis of the hardness for resin cements (C) and experimental materials (D). According to this, differences between the monowave and polywave light-curing units were not statistically significant ($p=0.98$ and $p=0.47$, respectively).

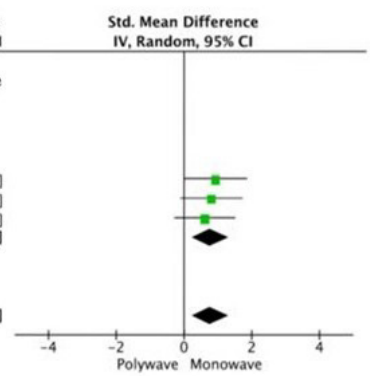
A. Conventional resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 TPO containing								
Sim 2012	229.5	18.6	5	223.4	4.7	5	8.0%	0.41 [-0.85, 1.67]
Sim 2012	246	6.9	5	223.4	4.7	5	4.1%	3.46 [1.15, 5.77]
Sim 2012	278.3	8.4	5	296.4	4.6	5	5.5%	-2.41 [-4.25, -0.57]
Sim 2012	272.3	10.9	5	296.4	4.6	5	5.2%	-2.60 [-4.52, -0.68]
Subtotal (95% CI)			**20**			**20**	**22.8%**	**-0.34 [-2.75, 2.07]**
Heterogeneity: Tau² = 5.16; Chi² = 21.96, df = 3 (P < 0.0001); I² = 86%								
Test for overall effect: Z = 0.28 (P = 0.78)								
1.1.2 Only CQ								
Mauricio 2021	238.36	34.69	10	222.33	53.09	10	10.1%	0.34 [-0.54, 1.23]
Mauricio 2021	238.36	34.69	10	209.21	22.52	10	9.8%	0.95 [0.02, 1.89]
Mauricio 2021	238.36	34.69	10	215.76	49.11	10	10.1%	0.51 [-0.38, 1.40]
Sim 2012	273.4	21.4	5	251.8	11.5	5	7.3%	1.14 [-0.26, 2.53]
Sim 2012	271.1	25.5	5	251.8	11.5	5	7.6%	0.88 [-0.45, 2.22]
Sim 2012	272.4	13.5	5	278.8	19.4	5	8.1%	-0.35 [-1.60, 0.91]
Sim 2012	279.3	4.7	5	278.8	19.4	5	8.1%	0.03 [-1.21, 1.27]
Sim 2012	284	15.4	5	275.7	23.5	5	8.0%	0.38 [-0.88, 1.64]
Sim 2012	292.7	32	5	275.7	23.5	5	7.9%	0.55 [-0.73, 1.82]
Subtotal (95% CI)			**60**			**60**	**77.2%**	**0.50 [0.13, 0.87]**
Heterogeneity: Tau² = 0.00; Chi² = 4.47, df = 8 (P = 0.81); I² = 0%								
Test for overall effect: Z = 2.63 (P = 0.009)								
Total (95% CI)			**80**			**80**	**100.0%**	**0.29 [-0.27, 0.84]**
Heterogeneity: Tau² = 0.59; Chi² = 29.81, df = 12 (P = 0.003); I² = 60%								
Test for overall effect: Z = 1.00 (P = 0.32)								
Test for subgroup differences: Chi² = 0.45, df = 1 (P = 0.50), I² = 0%								



B. Bulk-fill resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 TPO containing								
Subtotal (95% CI)			**0**			**0**		**Not estimable**
Heterogeneity: Not applicable								
Test for overall effect: Not applicable								
1.2.2 Only CQ								
Mauricio 2021	126.34	34.82	10	97.71	22.95	10	32.2%	0.93 [-0.00, 1.86]
Mauricio 2021	126.34	34.82	10	101.43	23.12	10	33.2%	0.81 [-0.11, 1.73]
Mauricio 2021	126.34	34.82	10	105.6	29.49	10	34.5%	0.62 [-0.29, 1.52]
Subtotal (95% CI)			**30**			**30**	**100.0%**	**0.78 [0.25, 1.31]**
Heterogeneity: Tau² = 0.00; Chi² = 0.23, df = 2 (P = 0.89); I² = 0%								
Test for overall effect: Z = 2.89 (P = 0.004)								
Total (95% CI)			**30**			**30**	**100.0%**	**0.78 [0.25, 1.31]**
Heterogeneity: Tau² = 0.00; Chi² = 0.23, df = 2 (P = 0.89); I² = 0%								
Test for overall effect: Z = 2.89 (P = 0.004)								
Test for subgroup differences: Not applicable								



C. Experimental material

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.3.1 TPO containing								
Subtotal (95% CI)			**0**			**0**		**Not estimable**
Heterogeneity: Not applicable								
Test for overall effect: Not applicable								
1.3.2 Only CQ								
Brandt 2013	287	47	7	281	71	7	100.0%	0.09 [-0.96, 1.14]
Subtotal (95% CI)			**7**			**7**	**100.0%**	**0.09 [-0.96, 1.14]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.17 (P = 0.86)								
Total (95% CI)			**7**			**7**	**100.0%**	**0.09 [-0.96, 1.14]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.17 (P = 0.86)								
Test for subgroup differences: Not applicable								

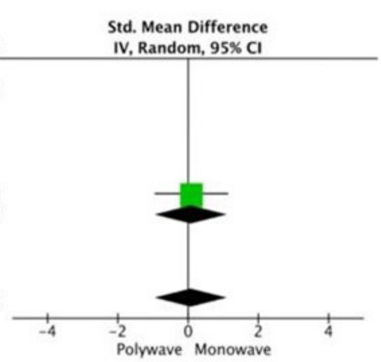


Figure 2. Meta-analysis for the compressive strength of conventional resin composites (A), bulk-fill resin composites (B), and experimental materials (C). For conventional and bulk fill resin composites, the compressive strength was higher when used monowave LED curing unit.

A. Conventional resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.1.1 TPO containing								
Al-Zain 2019 b	65.3	0.7	3	70.23	0.09	3	0.2%	-7.90 [-15.70, -0.11]
Al-Zain 2019 b	65.3	0.7	3	70.05	0.7	3	0.5%	-5.43 [-10.91, 0.05]
Al-Zain 2019 b	65.72	0.88	3	68.33	0.51	3	1.1%	-2.90 [-6.13, 0.32]
Al-Zain 2019 b	65.72	0.88	3	70.23	0.09	3	0.4%	-5.77 [-11.56, 0.03]
Al-Zain 2019 b	65.72	0.88	3	70.05	0.7	3	0.7%	-4.36 [-8.86, 0.14]
Al-Zain 2019 b	65.3	0.7	3	68.33	0.51	3	0.8%	-3.96 [-8.10, 0.19]
Aung 2021	59.4	0.8	8	64.6	0.8	8	1.5%	-6.15 [-8.79, -3.50]
dos Santos 2018	40.1	14.3	10	40.8	12.6	10	3.6%	-0.05 [-0.93, 0.83]
Lucey 2014	60.52	4.41	3	64.24	3.32	3	2.4%	-0.76 [-2.52, 1.00]
Lucey 2014	60.52	4.41	3	63.31	4.72	3	2.5%	-0.49 [-2.16, 1.18]
Santini 2012	48.6	6.3	5	59.5	7.6	5	2.7%	-1.41 [-2.88, 0.06]
Santini 2012	48.6	6.3	5	63.9	5.5	5	2.3%	-2.34 [-4.14, -0.53]
Santini 2012	64.8	4.4	5	70.1	2.8	5	2.8%	-1.30 [-2.74, 0.14]
Santini 2012	64.8	4.4	5	72.5	3.1	5	2.5%	-1.83 [-3.44, -0.22]
Subtotal (95% CI)			**62**			**62**	**24.0%**	**-2.11 [-3.08, -1.14]**
Heterogeneity: Tau² = 1.71; Chi² = 35.22, df = 13 (P = 0.0008); I² = 63%								
Test for overall effect: Z = 4.27 (P < 0.0001)								
2.1.2 Only CQ								
Amato 2016	65.8	8	5	65.6	2.2	5	3.1%	0.03 [-1.21, 1.27]
Amato 2016	80.7	3.8	5	83	1.2	5	3.0%	-0.74 [-2.04, 0.57]
Aung 2021	58.8	0.8	8	59.4	0.8	8	3.4%	-0.71 [-1.73, 0.31]
Aung 2021	50.1	0.8	8	50.1	0.8	8	3.4%	0.00 [-0.98, 0.98]
Aung 2021	61.7	0.6	8	61.7	0.8	8	3.4%	0.00 [-0.98, 0.98]
Aung 2021	59.4	0.8	8	59.8	0.8	8	3.4%	-0.47 [-1.47, 0.53]
Aung 2021	65.7	0.6	8	65.5	0.8	8	3.4%	0.27 [-0.72, 1.25]
Aung 2021	55.9	0.8	8	59.2	0.8	8	2.3%	-3.90 [-5.74, -2.06]
Aung 2021	59	1	8	58.4	0.8	8	3.4%	0.63 [-0.38, 1.64]
Cardoso 2020	57.93	2.98	10	52.92	3.17	10	3.4%	1.56 [0.53, 2.59]
Cardoso 2020	53.23	2.8	10	52.92	3.17	10	3.6%	0.10 [-0.78, 0.98]
Cardoso 2020	52.89	3.81	10	52.92	3.17	10	3.6%	-0.01 [-0.88, 0.87]
Cardoso 2020	57.93	2.98	10	51.39	3.75	10	3.3%	1.85 [0.76, 2.93]
Cardoso 2020	53.23	2.8	10	51.39	3.75	10	3.6%	0.53 [-0.36, 1.43]
Cardoso 2020	52.89	3.81	10	51.39	3.75	10	3.6%	0.38 [-0.51, 1.27]
Contreras 2021	56.5	4.4	5	53.6	2	5	3.0%	0.77 [-0.55, 2.08]
Lucey 2014	67.26	3.76	3	62.34	2.61	3	2.1%	1.22 [-0.77, 3.20]
Lucey 2014	67.26	3.76	3	62.81	2.08	3	2.1%	1.17 [-0.79, 3.13]
Santini 2012	65	3.1	5	61.2	3.3	5	2.9%	1.07 [-0.31, 2.45]
Santini 2012	65	3.1	5	61.03	2.4	5	2.8%	1.29 [-0.14, 2.73]
Santini 2014	45.8	2.7	3	45.9	3.2	3	2.6%	-0.03 [-1.63, 1.57]
Santini 2014	63.3	5.9	3	59.8	4.2	3	2.5%	0.55 [-1.14, 2.23]
Santini 2014	61.5	5.3	3	59.6	5.2	3	2.5%	0.29 [-1.34, 1.91]
Sword 2016	53	1.2	5	50	4	5	2.9%	0.92 [-0.43, 2.26]
Sword 2016	51.1	2.7	5	48.5	3.6	5	3.0%	0.74 [-0.57, 2.05]
Subtotal (95% CI)			**166**			**166**	**76.0%**	**0.32 [-0.03, 0.66]**
Heterogeneity: Tau² = 0.39; Chi² = 50.94, df = 24 (P = 0.001); I² = 53%								
Test for overall effect: Z = 1.81 (P = 0.07)								
Total (95% CI)			**228**			**228**	**100.0%**	**-0.22 [-0.62, 0.18]**
Heterogeneity: Tau² = 0.96; Chi² = 119.70, df = 38 (P < 0.00001); I² = 68%								
Test for overall effect: Z = 1.09 (P = 0.27)								
Test for subgroup differences: Chi² = 21.42, df = 1 (P < 0.00001), I² = 95.3%								

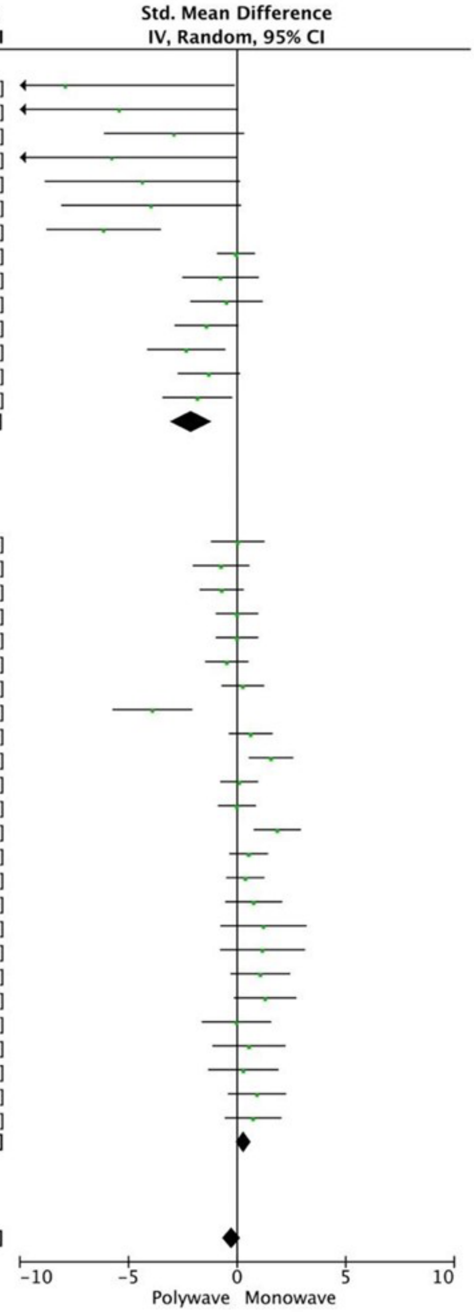


Figure 3. Meta-analysis for the DC of conventional resin composites (A). Global differences between the type of LED curing unit were not statistically significant (p=0.27).

B. Bulk-fill resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.2.1 TPO containing								
Cardoso 2021	52.1	3.1	10	54.8	1.7	10	6.2%	-1.03 [-1.98, -0.09]
Contreras 2021	49.2	1.2	5	45.5	2.2	5	3.8%	1.89 [0.25, 3.52]
Modena 2021	58.1	0.5	5	58.3	1.2	5	5.1%	-0.20 [-1.44, 1.05]
Modena 2021	58.2	1.5	5	62.6	0.6	5	2.4%	-3.48 [-5.80, -1.16]
Rocha 2017	52.8	7.2	3	60	5.87	3	3.4%	-0.88 [-2.69, 0.93]
Subtotal (95% CI)			**28**			**28**	**21.0%**	**-0.61 [-1.95, 0.72]**
Heterogeneity: $Tau^2 = 1.67$; $Chi^2 = 16.13$, df = 4 (P = 0.003); $I^2 = 75\%$								
Test for overall effect: Z = 0.90 (P = 0.37)								
2.2.2 Only CQ								
Cardoso 2021	45.9	3.4	10	47.2	3.6	10	6.5%	-0.36 [-1.24, 0.53]
Cardoso 2021	51.7	3	10	51.2	1.9	10	6.5%	0.19 [-0.69, 1.07]
Cardoso 2021	47	2	10	49.7	2.7	10	6.2%	-1.09 [-2.04, -0.13]
Contreras 2021	59.9	4.9	5	59.4	6.1	5	5.1%	0.08 [-1.16, 1.32]
Modena 2021	64.9	1	5	66.3	0.2	5	4.0%	-1.75 [-3.34, -0.17]
Modena 2021	64.7	0.7	5	66.9	1.2	5	3.7%	-2.02 [-3.71, -0.34]
Modena 2021	71	2.1	5	73	2.6	5	4.8%	-0.76 [-2.08, 0.55]
Modena 2021	68.1	4.7	5	72.8	2.7	5	4.6%	-1.11 [-2.50, 0.28]
Modena 2021	67.4	1.2	5	67	2.4	5	5.1%	0.19 [-1.05, 1.43]
Modena 2021	64.9	0.6	5	67.5	0.9	5	2.7%	-3.07 [-5.20, -0.94]
Modena 2021	65.9	2.8	5	70.5	1.9	5	4.0%	-1.74 [-3.32, -0.16]
Modena 2021	64.6	0.5	5	68	1	5	2.1%	-3.88 [-6.40, -1.37]
Modena 2021	62.7	1.6	5	64.1	2.7	5	4.9%	-0.57 [-1.85, 0.71]
Modena 2021	61.8	14	5	63.2	2.2	5	5.1%	-0.13 [-1.37, 1.12]
Modena 2021	61.9	1.8	5	61.3	2.5	5	5.1%	0.25 [-1.00, 1.50]
Modena 2021	61.7	1	5	62.5	0.7	5	4.8%	-0.84 [-2.16, 0.49]
Rocha 2017	69.6	3.2	3	70.67	2.13	3	3.9%	-0.31 [-1.94, 1.31]
Subtotal (95% CI)			**98**			**98**	**79.0%**	**-0.74 [-1.17, -0.31]**
Heterogeneity: $Tau^2 = 0.34$; $Chi^2 = 28.76$, df = 16 (P = 0.03); $I^2 = 44\%$								
Test for overall effect: Z = 3.37 (P = 0.0008)								
Total (95% CI)			**126**			**126**	**100.0%**	**-0.72 [-1.14, -0.30]**
Heterogeneity: $Tau^2 = 0.51$; $Chi^2 = 44.92$, df = 21 (P = 0.002); $I^2 = 53\%$								
Test for overall effect: Z = 3.37 (P = 0.0008)								
Test for subgroup differences: $Chi^2 = 0.03$, df = 1 (P = 0.86), $I^2 = 0\%$								

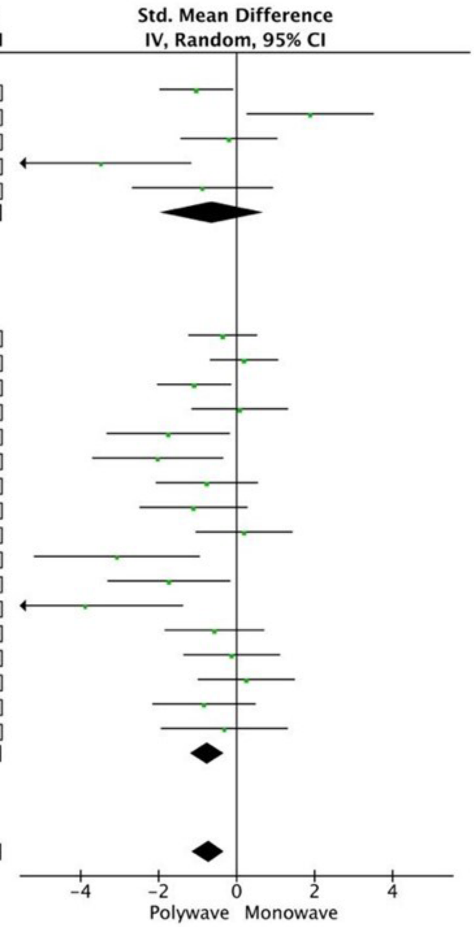
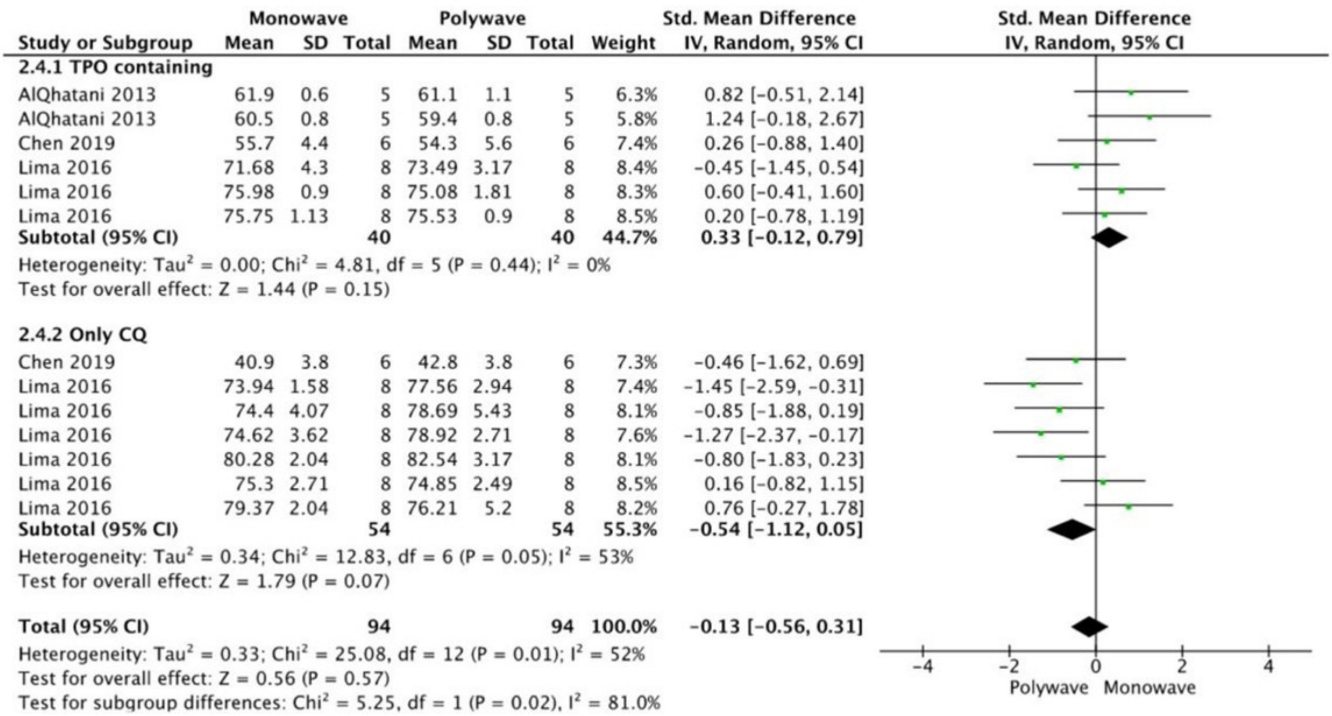


Figure 4. Meta-analysis for the DC of bulk-fill resin composites (B). Global differences between the type of LED curing unit were statistically significant, favoring the use of polywave LED curing units (p=0.0008).

C. Resin cements



D. Experimental materials

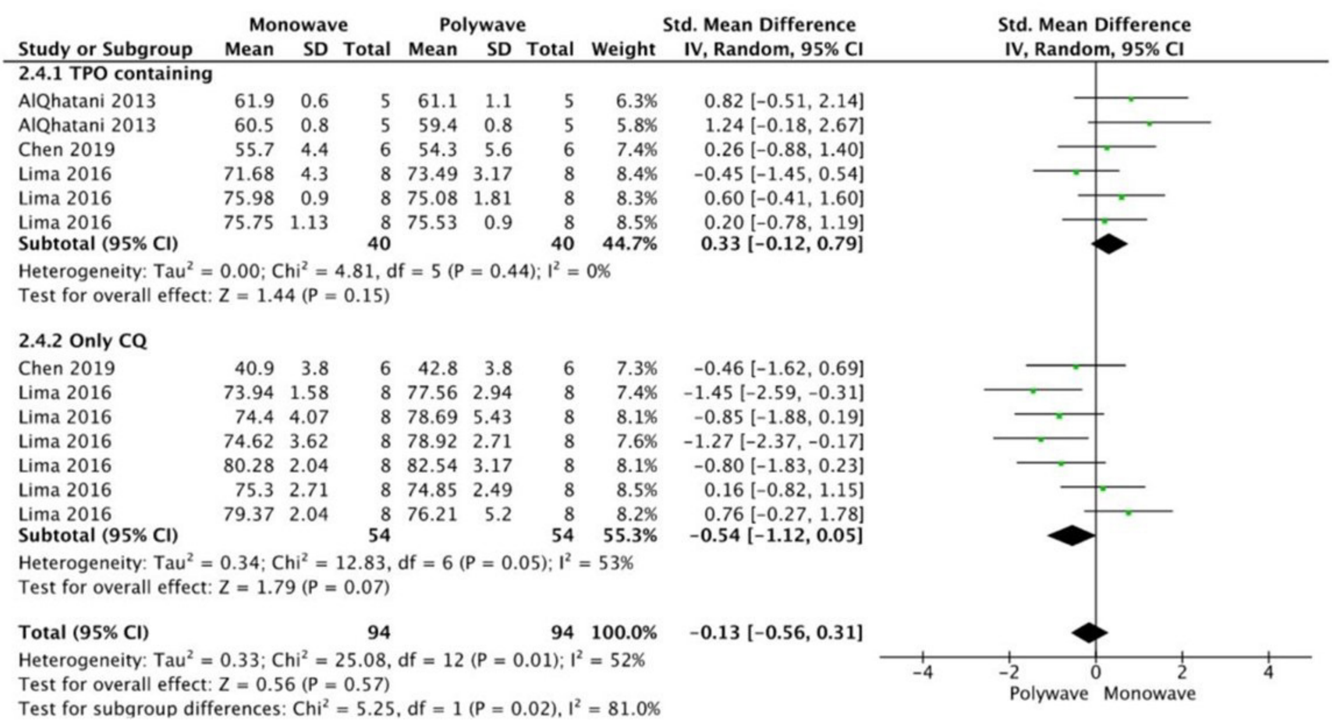
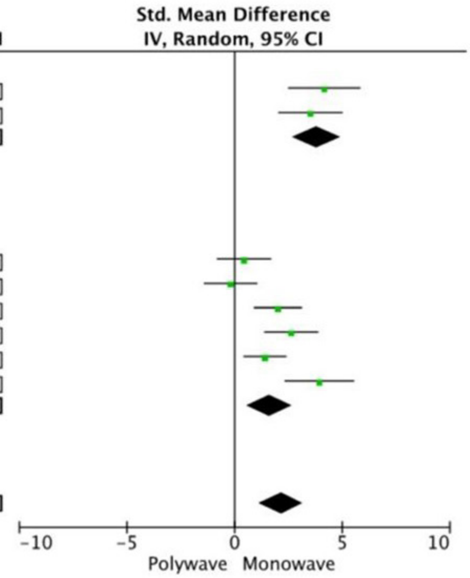


Figure 5. Meta-analysis for the DC of resin cements (C) and experimental materials (D). Global differences between the type of LED curing unit were not statistically significant (p=0.57).

A. Conventional resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.1.1 TPO containing								
Rocha 2017	2.39	0.05	10	2.15	0.06	10	11.2%	4.16 [2.48, 5.85]
Rocha 2017	3.15	0.04	10	3.02	0.03	10	11.9%	3.52 [2.02, 5.02]
Subtotal (95% CI)			**20**			**20**	**23.0%**	**3.80 [2.68, 4.93]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.31$, df = 1 (P = 0.58); $I^2 = 0\%$								
Test for overall effect: Z = 6.65 (P < 0.00001)								
3.1.2 Only CQ								
Makhdoom 2022	2.33	0.08	5	2.25	0.22	5	12.8%	0.44 [−0.83, 1.70]
Makhdoom 2022	2.72	0.08	5	2.74	0.11	5	12.9%	−0.19 [−1.43, 1.06]
Rocha 2022	3.42	0.1	10	3.21	0.1	10	13.3%	2.01 [0.89, 3.13]
Rocha 2022	3.86	0.09	10	3.65	0.06	10	12.8%	2.63 [1.37, 3.89]
Rocha 2022	3.05	0.09	10	2.91	0.1	10	13.8%	1.41 [0.41, 2.41]
Rocha 2022	2.7	0.08	10	2.44	0.04	10	11.4%	3.94 [2.32, 5.56]
Subtotal (95% CI)			**50**			**50**	**77.0%**	**1.65 [0.59, 2.71]**
Heterogeneity: $Tau^2 = 1.35$; $Chi^2 = 22.36$, df = 5 (P = 0.0004); $I^2 = 78\%$								
Test for overall effect: Z = 3.05 (P = 0.002)								
Total (95% CI)			**70**			**70**	**100.0%**	**2.16 [1.12, 3.20]**
Heterogeneity: $Tau^2 = 1.78$; $Chi^2 = 35.69$, df = 7 (P < 0.00001); $I^2 = 80\%$								
Test for overall effect: Z = 4.08 (P < 0.0001)								
Test for subgroup differences: $Chi^2 = 7.46$, df = 1 (P = 0.006), $I^2 = 86.6\%$								



B. Bulk-fill composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.2.1 TPO containing								
Makhdoom 2022	2.84	0.19	5	3.02	0.07	5	13.5%	−1.14 [−2.53, 0.26]
Makhdoom 2022	3.54	0.06	5	3.63	0.18	5	14.0%	−0.61 [−1.89, 0.68]
Rocha 2022	4.99	0.02	10	4.93	0.03	10	14.6%	2.25 [1.08, 3.43]
Subtotal (95% CI)			**20**			**20**	**42.1%**	**0.19 [−1.94, 2.33]**
Heterogeneity: $Tau^2 = 3.12$; $Chi^2 = 16.60$, df = 2 (P = 0.0002); $I^2 = 88\%$								
Test for overall effect: Z = 0.18 (P = 0.86)								
3.2.2 Only CQ								
Makhdoom 2022	2.88	0.05	5	2.78	0.12	5	13.7%	0.98 [−0.37, 2.34]
Makhdoom 2022	3.44	0.21	5	3.53	0.25	5	14.2%	−0.35 [−1.61, 0.90]
Rocha 2022	4.36	0.08	10	4.08	0.12	10	14.1%	2.63 [1.37, 3.89]
Rocha 2022	5.04	0.05	10	5.03	0.04	10	15.9%	0.21 [−0.67, 1.09]
Subtotal (95% CI)			**30**			**30**	**57.9%**	**0.84 [−0.38, 2.06]**
Heterogeneity: $Tau^2 = 1.18$; $Chi^2 = 13.01$, df = 3 (P = 0.005); $I^2 = 77\%$								
Test for overall effect: Z = 1.35 (P = 0.18)								
Total (95% CI)			**50**			**50**	**100.0%**	**0.58 [−0.44, 1.60]**
Heterogeneity: $Tau^2 = 1.51$; $Chi^2 = 30.15$, df = 6 (P < 0.0001); $I^2 = 80\%$								
Test for overall effect: Z = 1.11 (P = 0.27)								
Test for subgroup differences: $Chi^2 = 0.27$, df = 1 (P = 0.61), $I^2 = 0\%$								

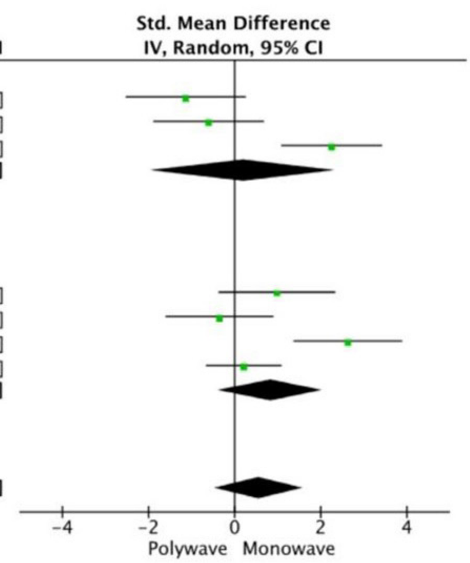
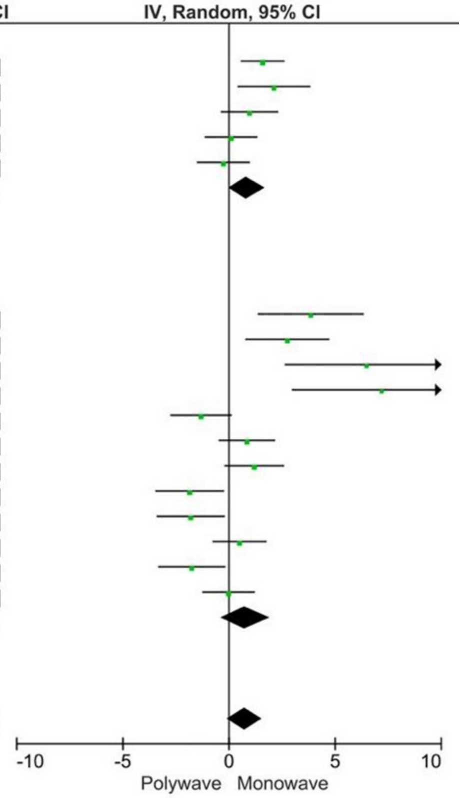


Figure 6. Meta-analysis for the depth of cure of conventional (A) and bulk-fill composites (B). Global differences between the type of LED curing unit were not statistically significant for the bulk-fill materials (p=0.27)



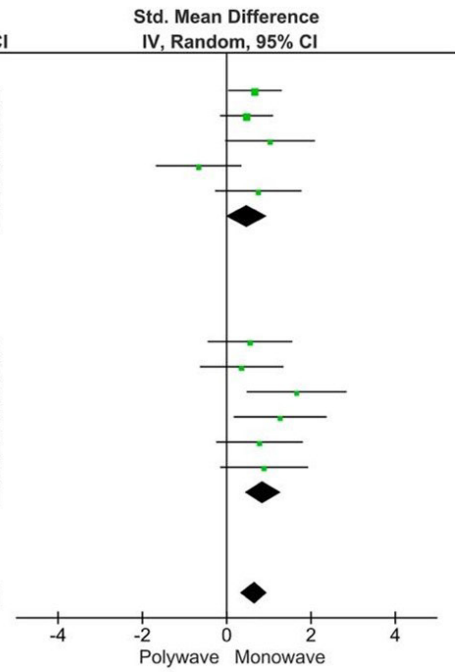
A. Conventional resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
4.1.1 TPO containing								
Al-Zain 2021	512.3	37.1	10	442.3	46.9	10	7.1%	1.59 [0.55, 2.62]
Sim 2012	142.7	9.7	5	124.5	5.2	5	5.9%	2.11 [0.39, 3.83]
Sim 2012	142.7	9.7	5	134.7	4.2	5	6.6%	0.97 [-0.39, 2.32]
Sim 2012	96.7	9.3	5	95.9	5.1	5	6.8%	0.10 [-1.14, 1.34]
Sim 2012	96.7	9.3	5	99	5.9	5	6.8%	-0.27 [-1.52, 0.98]
Subtotal (95% CI)			**30**			**30**	**33.2%**	**0.85 [0.00, 1.69]**
Heterogeneity: Tau² = 0.49; Chi² = 8.54, df = 4 (P = 0.07); I² = 53%								
Test for overall effect: Z = 1.97 (P = 0.05)								
4.1.2 Only CQ								
Farzad 2022	76.54	1.94	5	63.81	3.75	5	4.5%	3.85 [1.35, 6.35]
Farzad 2022	79.74	5.42	5	66.39	3.01	5	5.4%	2.75 [0.77, 4.73]
Farzad 2022	88.98	3.64	5	56.74	5.21	5	2.8%	6.48 [2.63, 10.33]
Farzad 2022	111.65	6.53	5	68.54	4	5	2.5%	7.19 [2.96, 11.42]
Farzad 2022	108.52	6.73	5	118.69	7.21	5	6.4%	-1.32 [-2.76, 0.13]
Farzad 2022	115.41	4.9	5	107.67	10.64	5	6.6%	0.84 [-0.48, 2.17]
Sim 2012	151.9	12.7	5	136.5	10.6	5	6.5%	1.19 [-0.22, 2.60]
Sim 2012	126.7	5.4	5	140.1	7.5	5	6.1%	-1.85 [-3.47, -0.23]
Sim 2012	106.4	11.6	5	124.2	4.9	5	6.1%	-1.81 [-3.41, -0.20]
Sim 2012	106.4	11.6	5	100.7	9	5	6.7%	0.50 [-0.77, 1.77]
Sim 2012	126.7	5.4	5	143.8	11.2	5	6.2%	-1.76 [-3.34, -0.17]
Sim 2012	151.9	12.7	5	152.2	12.2	5	6.8%	-0.02 [-1.26, 1.22]
Subtotal (95% CI)			**60**			**60**	**66.8%**	**0.77 [-0.38, 1.93]**
Heterogeneity: Tau² = 3.19; Chi² = 60.62, df = 11 (P < 0.00001); I² = 82%								
Test for overall effect: Z = 1.31 (P = 0.19)								
Total (95% CI)			**90**			**90**	**100.0%**	**0.73 [-0.08, 1.53]**
Heterogeneity: Tau² = 2.07; Chi² = 72.32, df = 16 (P < 0.00001); I² = 78%								
Test for overall effect: Z = 1.77 (P = 0.08)								
Test for subgroup differences: Chi² = 0.01, df = 1 (P = 0.92), I² = 0%								

Figure 7. Meta-analysis for the flexural strength of conventional (A) resin composite (B). Global differences between the type of LED curing unit were not statistically significant (p=0.08).

B. Resin cement

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
4.4.1 TPO containing								
Lancellotti 2018	123.76	19.15	20	111.47	16.74	20	16.4%	0.67 [0.03, 1.31]
Lancellotti 2018	128.83	20.74	20	118.01	24.07	20	16.7%	0.47 [-0.16, 1.10]
Lima 2016	149.21	10.05	8	134.39	16.4	8	7.2%	1.03 [-0.03, 2.09]
Lima 2016	140.21	15.34	8	150.79	14.81	8	7.8%	-0.66 [-1.68, 0.35]
Lima 2016	151.85	17.99	8	139.68	12.17	8	7.7%	0.75 [-0.28, 1.77]
Subtotal (95% CI)			**64**			**64**	**55.9%**	**0.47 [-0.00, 0.95]**
Heterogeneity: Tau² = 0.11; Chi² = 6.51, df = 4 (P = 0.16); I² = 39%								
Test for overall effect: Z = 1.95 (P = 0.05)								
4.4.2 Only CQ								
Lima 2016	162.43	21.16	8	150.79	18.52	8	8.0%	0.55 [-0.45, 1.56]
Lima 2016	151.32	9.52	8	146.03	17.46	8	8.2%	0.36 [-0.63, 1.35]
Lima 2016	170.37	16.4	8	143.39	14.29	8	6.0%	1.66 [0.48, 2.84]
Lima 2016	160.85	25.4	8	134.92	10.05	8	6.8%	1.27 [0.17, 2.37]
Lima 2016	158.2	23.81	8	142.86	11.11	8	7.7%	0.78 [-0.25, 1.81]
Lima 2016	154.5	11.64	8	139.68	19.05	8	7.5%	0.89 [-0.15, 1.93]
Subtotal (95% CI)			**48**			**48**	**44.1%**	**0.87 [0.44, 1.30]**
Heterogeneity: Tau² = 0.00; Chi² = 3.66, df = 5 (P = 0.60); I² = 0%								
Test for overall effect: Z = 3.96 (P < 0.0001)								
Total (95% CI)			**112**			**112**	**100.0%**	**0.65 [0.35, 0.96]**
Heterogeneity: Tau² = 0.04; Chi² = 11.91, df = 10 (P = 0.29); I² = 16%								
Test for overall effect: Z = 4.19 (P < 0.0001)								
Test for subgroup differences: Chi² = 1.45, df = 1 (P = 0.23), I² = 31.2%								



C. Experimental material

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
4.3.1 TPO containing								
Subtotal (95% CI)			**0**			**0**		**Not estimable**
Heterogeneity: Not applicable								
Test for overall effect: Not applicable								
4.3.2 Only CQ								
de Oliveira 2016	165.2	30.6	10	158.4	13.4	10	33.7%	0.28 [-0.61, 1.16]
de Oliveira 2016	126.7	13.4	10	158.4	13.4	10	29.6%	-2.27 [-3.44, -1.09]
Lancellotti 2018	95.92	5.19	20	103.43	14.53	20	36.7%	-0.67 [-1.31, -0.04]
Subtotal (95% CI)			**40**			**40**	**100.0%**	**-0.83 [-2.04, 0.39]**
Heterogeneity: Tau² = 0.94; Chi² = 11.49, df = 2 (P = 0.003); I² = 83%								
Test for overall effect: Z = 1.33 (P = 0.18)								
Total (95% CI)			**40**			**40**	**100.0%**	**-0.83 [-2.04, 0.39]**
Heterogeneity: Tau² = 0.94; Chi² = 11.49, df = 2 (P = 0.003); I² = 83%								
Test for overall effect: Z = 1.33 (P = 0.18)								
Test for subgroup differences: Not applicable								

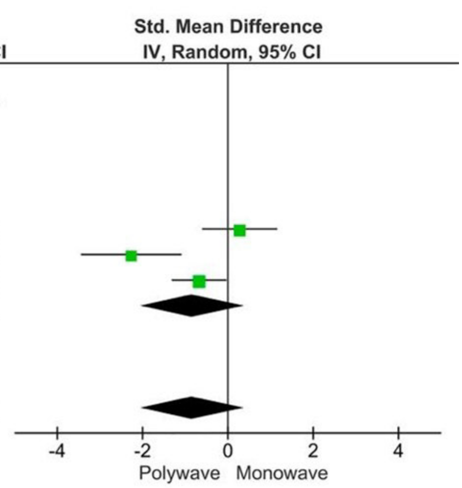


Figure 8. Meta-analysis for the flexural strength of resin cements (B) and experimental materials (C).

A. Conventional resin composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
5.1.1 TPO containing								
Araujo 2021	60.9	7.8	5	52.7	5	5	2.8%	1.13 [-0.26, 2.52]
Araujo 2021	77	3.6	5	55.7	2.8	5	1.4%	5.97 [2.39, 9.55]
Barakah 2021	55.8	2.2	5	61.3	1.6	5	2.4%	-2.58 [-4.49, -0.67]
Barakah 2021	45.8	1.1	5	61.3	1.6	5	0.7%	-10.20 [-16.07, -4.32]
Sim 2012	41.9	1.8	12	50.2	1.7	12	2.6%	-4.58 [-6.20, -2.95]
Sim 2012	41.9	1.8	12	50.4	1.5	12	2.6%	-4.95 [-6.68, -3.22]
Sim 2012	57.9	1.6	12	67.1	0.8	12	2.1%	-7.02 [-9.34, -4.71]
Sim 2012	57.9	1.6	12	63.9	1.7	12	2.8%	-3.51 [-4.86, -2.16]
Souza 2019b	71.66	3.1	20	68.89	4.8	20	3.3%	0.67 [0.03, 1.31]
Subtotal (95% CI)			**88**			**88**	**20.8%**	**-2.55 [-4.79, -0.31]**
Heterogeneity: Tau² = 10.25; Chi² = 139.81, df = 8 (P < 0.00001); I² = 94%								
Test for overall effect: Z = 2.23 (P = 0.03)								
5.1.2 Only CQ								
Aung 2021	70	2	8	66.5	1.4	8	2.9%	1.92 [0.67, 3.16]
Aung 2021	52.6	1.8	8	53	3.5	8	3.1%	-0.14 [-1.12, 0.85]
Aung 2021	53	1.8	8	49.7	1.8	8	2.9%	1.73 [0.53, 2.93]
Aung 2021	50.5	1.4	8	52.2	1.4	8	3.0%	-1.15 [-2.23, -0.07]
Aung 2021	44.8	1.6	8	57.9	2.3	8	1.9%	-6.25 [-8.93, -3.57]
Aung 2021	52.6	1.6	8	49.7	1.6	8	2.9%	1.71 [0.52, 2.91]
Aung 2021	58.3	0.6	8	56.3	2	8	3.0%	1.28 [0.18, 2.39]
Farzad 2022	51.64	0.98	5	53.48	1.1	5	2.7%	-1.60 [-3.13, -0.06]
Farzad 2022	51.64	0.98	5	53.48	1.1	5	2.7%	-1.60 [-3.13, -0.06]
Farzad 2022	51.32	2.1	5	53.52	2.01	5	2.8%	-0.97 [-2.32, 0.39]
Farzad 2022	28.72	0.83	5	32.74	2.43	5	2.6%	-2.00 [-3.67, -0.33]
Farzad 2022	30.62	2.29	5	30.52	1.55	5	2.9%	0.05 [-1.19, 1.29]
Farzad 2022	45.58	2.63	5	46.32	1.77	5	2.9%	-0.30 [-1.55, 0.95]
Gonulol 2015	86.7	2.06	10	85.8	5.28	10	3.1%	0.22 [-0.66, 1.09]
Haenel 2015	22.6	1.6	5	26.2	1.6	5	2.6%	-2.03 [-3.72, -0.35]
Santini 2012	59.7	1.6	5	57.2	4.3	5	2.9%	0.70 [-0.60, 2.00]
Santini 2012	59.7	1.6	5	59	3	5	2.9%	0.26 [-0.99, 1.51]
Sim 2012	91.2	4.5	12	107.4	3.6	12	2.8%	-3.84 [-5.27, -2.41]
Sim 2012	91.2	4.5	12	105.4	3.9	12	2.9%	-3.26 [-4.54, -1.97]
Sim 2012	102	4.1	12	96.3	4.8	12	3.1%	1.23 [0.35, 2.12]
Sim 2012	102	4.1	12	105.2	3.6	12	3.2%	-0.80 [-1.64, 0.04]
Sim 2012	73.6	3.4	12	68.9	3.9	12	3.1%	1.24 [0.35, 2.13]
Sim 2012	73.6	3.4	12	75.5	3.2	12	3.2%	-0.56 [-1.37, 0.26]
Souza 2019	83.8	5.6	10	82.68	6.66	10	3.1%	0.17 [-0.70, 1.05]
Souza 2019b	73.24	6.9	20	72.54	3.9	20	3.3%	0.12 [-0.50, 0.74]
Strazzi-Sahyon 2020	3.1	3	20	3.3	1.1	20	3.3%	-0.09 [-0.71, 0.53]
Strazzi-Sahyon 2020	4.3	2.2	20	3.1	2.1	20	3.3%	0.55 [-0.09, 1.18]
Subtotal (95% CI)			**253**			**253**	**79.2%**	**-0.32 [-0.81, 0.17]**
Heterogeneity: Tau² = 1.34; Chi² = 154.14, df = 26 (P < 0.00001); I² = 83%								
Test for overall effect: Z = 1.28 (P = 0.20)								
Total (95% CI)			**341**			**341**	**100.0%**	**-0.79 [-1.35, -0.23]**
Heterogeneity: Tau² = 2.40; Chi² = 309.38, df = 35 (P < 0.00001); I² = 89%								
Test for overall effect: Z = 2.77 (P = 0.006)								
Test for subgroup differences: Chi² = 3.61, df = 1 (P = 0.06), I² = 72.3%								

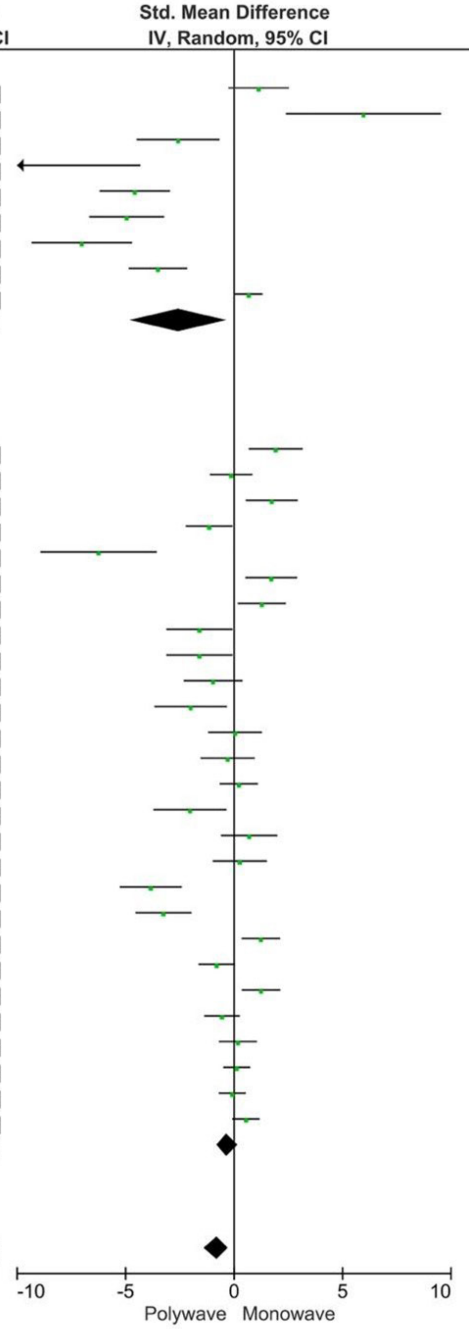


Figure 9. Meta-analysis for the hardness of conventional resin composites (A). The use of a polywave LED curing unit achieved higher hardness values (p=0.006).

B. Bulk-fill composite

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
5.2.1 TPO containing								
Bakhsh 2016	35.3	2.61	4	41.8	5.03	4	2.1%	-1.41 [-3.10, 0.28]
Cardoso 2021	59.7	1.7	10	62.1	0.9	10	2.7%	-1.69 [-2.74, -0.64]
Conte 2017	72.5	3.3	5	76.5	8.5	5	2.5%	-0.56 [-1.84, 0.72]
Conte 2017	50.4	2.2	5	55	2.98	5	2.2%	-1.59 [-3.11, -0.06]
Conte 2017	67	5.4	5	72.03	4.7	5	2.4%	-0.90 [-2.24, 0.44]
Conte 2017	64.3	2.4	5	76.5	8.5	5	2.2%	-1.76 [-3.35, -0.18]
Conte 2017	70.3	3.6	5	55	2.98	5	1.3%	4.18 [1.52, 6.84]
Conte 2017	69.1	2.4	5	72.03	4.7	5	2.5%	-0.71 [-2.01, 0.59]
Gan 2018	22.8	1.9	6	25.8	3.6	6	2.5%	-0.96 [-2.19, 0.26]
Gan 2018	22.8	1.9	6	30.1	4.1	6	2.2%	-2.11 [-3.64, -0.58]
Gan 2018	22.8	1.9	6	29.1	4.7	6	2.4%	-1.62 [-3.00, -0.24]
Maghaireh 2019	41.11	1.73	5	49.57	2.42	5	1.5%	-3.63 [-6.02, -1.24]
Menees 2015	41.32	1.89	5	48.9	2.84	5	1.7%	-2.84 [-4.86, -0.82]
Sahadi 2018	48.6	4.7	10	56.5	5.4	10	2.8%	-1.49 [-2.51, -0.48]
Shimokawa 2018	59.6	1.7	5	61	1.7	5	2.5%	-0.74 [-2.05, 0.56]
Shimokawa 2018	60.6	2.2	5	62.4	0.3	5	2.4%	-1.04 [-2.41, 0.33]
Shimokawa 2020	40.2	0.6	5	45.5	0.5	5	0.5%	-8.67 [-13.70, -3.63]
Shimokawa 2020	44.4	0.7	5	49.8	0.7	5	0.7%	-6.97 [-11.08, -2.85]
Wang 2021	0.64	0.23	25	0.6	0.17	25	3.2%	0.19 [-0.36, 0.75]
Subtotal (95% CI)			**127**			**127**	**40.2%**	**-1.33 [-1.95, -0.71]**
Heterogeneity: Tau² = 1.20; Chi² = 64.60, df = 18 (P < 0.00001); I² = 72%								
Test for overall effect: Z = 4.19 (P < 0.0001)								
5.2.2 Only CQ								
Bakhsh 2016	72.73	3.1	4	69.47	1.73	4	2.2%	1.13 [-0.46, 2.72]
Cardoso 2021	58.8	2.3	10	57.6	2.5	10	2.9%	0.48 [-0.41, 1.37]
Cardoso 2021	69.9	1.7	10	70.5	0.8	10	2.9%	-0.43 [-1.32, 0.46]
Cardoso 2021	51.3	1	10	53	4.4	10	2.9%	-0.51 [-1.40, 0.38]
Gan 2018	16.2	1.5	6	15.2	2.4	6	2.6%	0.46 [-0.69, 1.62]
Gan 2018	16.2	1.5	6	16.4	1.4	6	2.6%	-0.13 [-1.26, 1.01]
Gan 2018	16.2	1.5	6	17.2	1.7	6	2.6%	-0.58 [-1.74, 0.59]
Maghaireh 2019	30.4	1.04	5	35.58	2.25	5	1.8%	-2.67 [-4.62, -0.72]
Maghaireh 2019	33.51	3.11	5	35.75	1.9	5	2.4%	-0.79 [-2.10, 0.53]
Maghaireh 2019	96.89	3.63	5	93.26	5.53	5	2.5%	0.70 [-0.60, 2.00]
Maghaireh 2019	65.46	1.9	5	74.61	2.59	5	1.5%	-3.64 [-6.03, -1.24]
Menees 2015	96.85	4.1	5	93.38	5.36	5	2.5%	0.66 [-0.64, 1.95]
Menees 2015	65.62	2.52	5	74.45	2.84	5	1.7%	-2.97 [-5.05, -0.89]
Menees 2015	29.65	1.58	5	36.28	1.26	5	1.3%	-4.19 [-6.86, -1.53]
Menees 2015	33.44	3.15	5	35.65	2.21	5	2.5%	-0.73 [-2.04, 0.57]
Sahadi 2018	62.6	3.2	10	68.3	5.4	10	2.8%	-1.23 [-2.20, -0.26]
Sahadi 2018	37.2	3.9	10	36.7	2.1	10	2.9%	0.15 [-0.73, 1.03]
Shimokawa 2018	67.3	1.7	5	69.4	4.2	5	2.5%	-0.59 [-1.88, 0.69]
Shimokawa 2018	68.9	3.1	5	67.3	1.2	5	2.5%	0.61 [-0.67, 1.90]
Shimokawa 2020	56.5	0.5	5	57.3	0.4	5	2.2%	-1.60 [-3.13, -0.06]
Shimokawa 2020	54.3	0.3	5	54	0.4	5	2.5%	0.77 [-0.55, 2.08]
Wang 2021	0.94	0.47	25	0.42	0.2	25	3.2%	1.42 [0.79, 2.04]
Wang 2021	0.75	0.41	25	0.88	0.26	25	3.2%	-0.37 [-0.93, 0.19]
Wang 2021	0.93	0.38	25	0.65	0.25	25	3.2%	0.86 [0.28, 1.44]
Subtotal (95% CI)			**207**			**207**	**59.8%**	**-0.28 [-0.72, 0.16]**
Heterogeneity: Tau² = 0.80; Chi² = 88.02, df = 23 (P < 0.00001); I² = 74%								
Test for overall effect: Z = 1.26 (P = 0.21)								
Total (95% CI)			**334**			**334**	**100.0%**	**-0.72 [-1.10, -0.34]**
Heterogeneity: Tau² = 1.08; Chi² = 178.09, df = 42 (P < 0.00001); I² = 76%								
Test for overall effect: Z = 3.71 (P = 0.0002)								
Test for subgroup differences: Chi² = 7.24, df = 1 (P = 0.007), I² = 86.2%								

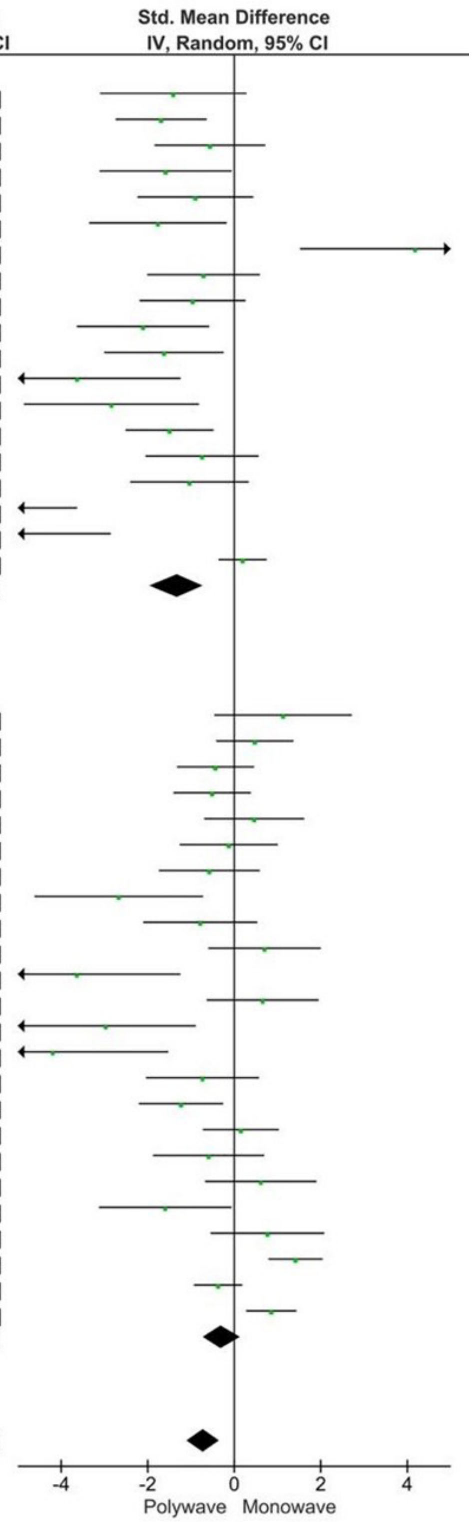
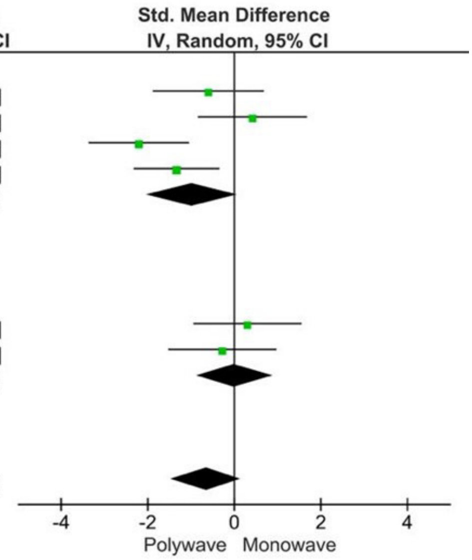


Figure 10. Meta-analysis for the hardness of bulk fill resin composites (B). The use of a polywave LED curing unit achieved higher hardness values (p=0.0002).

C. Resin cement

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
5.4.1 TPO containing								
AlQhatani 2013	8.77	0.44	5	9.09	0.52	5	15.8%	-0.60 [-1.88, 0.68]
AlQhatani 2013	8.3	0.43	5	8.1	0.43	5	16.0%	0.42 [-0.84, 1.68]
Lancellotti 2018	37.35	2.49	10	43.26	2.64	10	17.0%	-2.21 [-3.37, -1.04]
Lancellotti 2018	59.04	2.64	10	62.37	2.11	10	18.8%	-1.33 [-2.33, -0.34]
Subtotal (95% CI)			**30**			**30**	**67.7%**	**-0.96 [-2.02, 0.09]**
Heterogeneity: Tau² = 0.80; Chi² = 9.80, df = 3 (P = 0.02); I² = 69%								
Test for overall effect: Z = 1.79 (P = 0.07)								
5.4.2 Only CQ								
Kugimiya 2015	37.57	5.6	5	36.09	2.71	5	16.1%	0.30 [-0.95, 1.56]
Kugimiya 2015	40.42	2.41	5	41.2	2.68	5	16.2%	-0.28 [-1.53, 0.97]
Subtotal (95% CI)			**10**			**10**	**32.3%**	**0.01 [-0.87, 0.90]**
Heterogeneity: Tau² = 0.00; Chi² = 0.41, df = 1 (P = 0.52); I² = 0%								
Test for overall effect: Z = 0.03 (P = 0.98)								
Total (95% CI)			**40**			**40**	**100.0%**	**-0.65 [-1.46, 0.16]**
Heterogeneity: Tau² = 0.66; Chi² = 13.98, df = 5 (P = 0.02); I² = 64%								
Test for overall effect: Z = 1.56 (P = 0.12)								
Test for subgroup differences: Chi² = 1.93, df = 1 (P = 0.16), I² = 48.1%								



D. Experimental material

Study or Subgroup	Monowave Mean	Monowave SD	Monowave Total	Polywave Mean	Polywave SD	Polywave Total	Weight	Std. Mean Difference IV, Random, 95% CI
5.3.1 TPO containing								
Subtotal (95% CI)			**0**			**0**		**Not estimable**
Heterogeneity: Not applicable								
Test for overall effect: Not applicable								
5.3.2 Only CQ								
de Oliveira 2016	19.9	4.1	10	23.5	7.7	10	34.2%	-0.56 [-1.46, 0.34]
de Oliveira 2016	23.6	6.9	10	23.5	7.7	10	34.4%	0.01 [-0.86, 0.89]
Lancellotti 2018	14.21	0.96	10	11.79	0.88	10	31.3%	2.52 [1.28, 3.75]
Subtotal (95% CI)			**30**			**30**	**100.0%**	**0.60 [-1.03, 2.23]**
Heterogeneity: Tau² = 1.81; Chi² = 16.30, df = 2 (P = 0.0003); I² = 88%								
Test for overall effect: Z = 0.72 (P = 0.47)								
Total (95% CI)			**30**			**30**	**100.0%**	**0.60 [-1.03, 2.23]**
Heterogeneity: Tau² = 1.81; Chi² = 16.30, df = 2 (P = 0.0003); I² = 88%								
Test for overall effect: Z = 0.72 (P = 0.47)								
Test for subgroup differences: Not applicable								

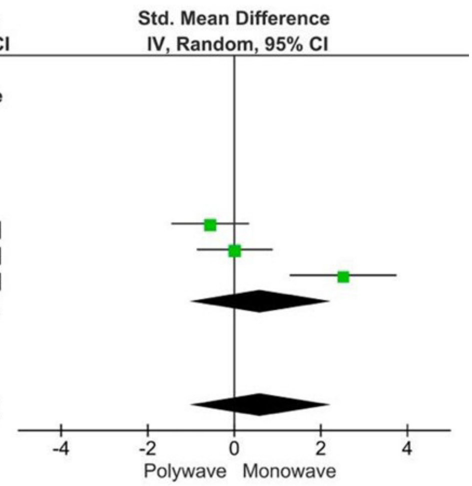


Figure 11. Meta-analysis for the hardness of resin cements (C) and experimental materials (D). The difference between the polywave and monowave LED curing units were not statistically significant.

Discussion

This systematic review and meta-analysis were conducted to evaluate the effect of monowave and polywave light-curing units on different properties of resin-based materials. In order to keep the clinical relevance of the present study, it is important to point out that the light-curing unit type impacted on the polymerization DC, hardness, flexural strength, compressive strength, and depth of cure. The meta-analyses indicated that differences in the use of a polywave and monowave light-curing units were partially significant in the evaluated mechanical properties. Considering this, the null hypothesis tested in this study was partially accepted.

Despite resin-based materials are widely used, it has been reported that some of them do not last as long as they should [84,85]. The fact that dentists are not aware of the photoinitiators present in the different composite resins available, end up selecting an unsuitable light-curing unit for the correct polymerization of the material, leading to clinically unsatisfactory results [85]. The properties evaluated in this study have an impact on the clinical performance of resin-based restorations. RBCs materials included in this study were conventional composite, experimental composite, cement resin-based and bulk-fill composites.

Three studies evaluated the compressive strength of conventional, bulk-fill or experimental resin composites. The compressive strength is a measure of the material ability to resist sustained heavy loads during mastication [86]. In the present study, the global analysis showed that there were no statistically significant differences in this property for conventional resin-based composites between a polywave or a monowave light-curing unit. These results are consistent with previous literature where polywave light-curing units had no influence on the compressive strength values of several composites [78]. Also, other explanations could be found since it has been demonstrated that other properties, like the degree of conversion, are not affected by the type of light-curing unit used, especially when the material have CQ as photoinitiator [40,42].

According to the results of this study, the degree of conversion was significantly improved when a polywave light-curing unit was used for the photoactivation of bulk-fill composites. This behavior was not observed for conventional composites, resin cements or experimental materials. Bulk-fill composites are typically formulated using CQ as photoinitiator; besides this, manufacturers add another other photoinitiators with the objective to produce less yellowish [87]. Alternatives photoinitiators like Lucirin or TPO (diphenyl(2,4,6-trimethylben-zoyl)phosphin oxide) are more effective due to its ability to produce two free radicals [88]. Despite these advantages, the range of absorption of Lucirin and TPO is 380–425 nm, and the maximum absorbance is 400 nm [89], actually, monowave light-curing units cannot emit light of this absorbance, and therefore, they have a limited efficacy to polymerize adequately this type of materials [90].

The depth of cure was assessed as part of this review. Regarding bulk-fill composites, the influence of the light-curing unit type was not found to be significant ($p=0.27$). This outcome was unexpected considering the anticipation that a polywave light-curing unit would be necessary to activate the TPO initiator present in some of these materials [67]. The inefficiency of the polywave light-curing unit to achieve a greater depth of cure could be attributed to the absorption of light in the violet range (~410nm) by the top layers of the composite. It was hypothesized that the high absorbance of a photoinitiator with similar properties to TPO resulted in the depletion of most light photons in the upper layers of the composite, hindering their penetration into the material depth and potentially reducing the initiation of the polymerization process in deeper regions [91]. Another explanation for the limited effectiveness of polywave light is based on the relationship between the wavelength of the light emitted by the light-curing unit and the dimensions of the filler particles in the resin composite, as described by the Rayleigh effect. According to this phenomenon, shorter wavelengths of light are more likely to be scattered by filler particles. Consequently, the violet spectrum of the polywave light-curing unit could be significantly attenuated within the composite, resulting in a predominant delivery of radiation in the blue light spectrum to the depth of the specimen [92]. This means that, in deeper areas, short wavelengths are inefficient and only longer wavelengths (as blue light) would penetrate enough, consequently in this case only CQ would be excited [92].

The present review showed no consistent effect on the flexural strength according to the light-curing unit used. As stated by Miletic and Santini [68], even though polywave light-curing units are better suited for composites that use initiators other than CQ, monowave light-curing units can still show optimal performance. This is attributed to the wavelength of monowave light-curing units not differing significantly from the absorbance peak of the photoinitiator. The reason behind this outcome is the high intensity of light and photon production achieved by monowave light-curing unit devices. Also, some research has found a higher compatibility in wavelength of the light-curing unit device with the photoinitiator (mainly CQ) [93].

Hardness is related to mechanical strength, rigidity, and resistance to intraoral softening [94]. The results of the present study confirm that the polywave light-curing unit achieved statistically higher hardness values than monowave light-curing units. The resin composite's hardness after polymerization depends on factors such as the types of filler, matrix, photoinitiator, and light-curing unit, as well as the intensity and wavelength of light [95], and this property is related to material wear resistance and the ability to maintain its anatomical form. In order to recognize the benefit of polywave curing units, it should emphasize that these units are only effective for composites with a TPO initiator integrated into their formulation. This finding results important since only polywave curing units have the ability to excite the TPO initiator, and therefore, to leverage the advantages that this photoinitiator could offer to the overall performance of the material [96].

It is crucial to exercise caution when interpreting the findings of this review due to several limitations that should be acknowledged. Firstly, the analysis focused on the photoinitiator used in the resin-based material, while some composite resins may contain undisclosed initiators. The exact identities of these initiators are often not discernible, as manufacturers tend to protect this information. Consequently, a more comprehensive discussion on the properties of the materials becomes impractical due to limited knowledge of their exact composition regarding the photoinitiator systems. Therefore, it is important to emphasize the necessity of including information in the instructions for use of these materials regarding the wavelength spectrum and minimum radiant exposure required to achieve optimal performance. This serves to alert users about potential procedural issues if the recommended guidelines are not followed. Additionally, it is worth noting that no clinical studies investigating this variable were identified in this review. Therefore, further research is encouraged to design clinical trials that explore the clinical performance of resin-based materials in relation to the generation of LED light-curing unit utilized. Further, novel LED curing unit like the polywave Curing Pen and Curing Pen E (Eighteeth, Changzhou, China) could be tested to expand the results of this study by im-plementing a boarder LED curing unit.

Conclusions

According to the results of this review, the use of polywave light-curing can be useful for polymerizing materials that contain photoinitiators other than camphorquinone in their composition.

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