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Does speed-sintering affect the optical and mechanical properties of yttria-stabilized zirconia? A systematic review and meta-analysis of *in-vitro* studies

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ABSTRACT

Zirconia restorations are increasingly popular in dental treatment. Yttria-stabilized zirconia (YSZ) needs to be sintered for clinical applications and novel speed-sintering protocols are being developed for chairside treatments. Whether the properties of speed-sintered YSZ meet clinical requirements, however, remains unclear. Therefore, we conducted a systematic review and meta-analysis on the influence of speed-sintering on the optical and mechanical properties of dental YSZ according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. A literature search was conducted using PubMed, Embase, and Web of Science databases for relevant articles published between January 1, 2010 and February 28, 2022 in English, Chinese, or Japanese. After full-text evaluation and quality assessment, 26 articles were selected. Meta-analysis revealed that speed-sintering does not significantly affect the CIEDE2000-based translucency parameter, contrast ratio, three-point flexural strength, biaxial flexural strength, or fracture toughness of YSZ ($p < 0.01$) compared to conventional sintering. However, the CIELab-based translucency parameter of conventionally sintered YSZ is higher than that of speed-sintered YSZ. The descriptive analysis indicated that speed-sintering does not affect the hardness of YSZ compared to that of conventionally sintered YSZ. The results indicate that speed-sintering is suitable for preparing YSZ for dental restorations.

1. Introduction

After having initially been used as a femoral head replacement material, 3-mol% yttria-stabilized zirconia (YSZ) was first applied in dentistry for crown-and-bridge prosthodontics in 2004 [1]. Compared to conventional metal and porcelain-fused-to-metal restorations, full-ceramic zirconia restorations have better aesthetic performance and eliminate the risk of complications due to metal allergies [2]. Furthermore, their mechanical properties are superior to those of other ceramic restorations such as lithium-disilicate glass-ceramics and hybrid ceramics [3].

Pure zirconia is a ceramic that exists in three polymorphs depending on the temperature: monoclinic (*m*), from room temperature to 1170 °C; tetragonal (*t*), from 1170 to 2370°C; and cubic (*c*), above 2370 °C [4,5]. However, monoclinic zirconia (*m*-ZrO_2) has inferior mechanical properties, which limits its clinical application. In order to stabilize tetragonal zirconia (*t*-ZrO_2) at room temperature, Y_2O_3, CaO, MgO, or CeO_2 stabilizers are incorporated in the zirconia-crystal structure during sintering. Among these stabilizers, yttria (Y_2O_3) is the most popular for dental zirconia. Depending on the Y_2O_3 content, YSZ is categorized as tetragonal zirconia polycrystals (TZP), containing 3-mol% Y_2O_3 and being referred to as 3Y-TZP, or partially stabilized zirconia (PSZ), containing 4–6 mol% Y_2O_3 and being referred to as 4–6Y-PSZ. YSZ has excellent mechanical properties because of the stress-induced $t \rightarrow m$ transformation, which increases the toughness of the material. Along with the fine-grained microstructure, YSZ exhibits much higher strength

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and toughness than other technical ceramics [6–8]. YSZ can slowly and spontaneously degrade in moist environments, such as in the oral cavity and even at room temperature. This process, known as low-temperature degradation, can cause micro- and macro-cracking on the YSZ surface, which may influence the aesthetics and mechanical properties of YSZ in clinical practice [9–11].

For clinical applications, YSZ needs to be sintered to full density. Conventional sintering procedures are time- and energy-consuming. For example, monolithic 3Y-TZP requires sintering times and temperatures of 4–12 h and 1350–1550 °C, respectively, depending on the manufacturer's instructions [12,13]. Recently, there has been a drive towards the chairside fabrication of dental restorations. To our knowledge, there is no clear definition of speed-sintering of dental zirconia. However, speed-sintering typically consists of a fast heating step, a short dwell time at the sintering temperature, and a fast cooling step, enabling sintering in less than 240 min. Speed-sintering of YSZ within only 10–30 min has even been reported [14]. Notably, speed-sintering facilitates the clinical preparation of zirconia restorations in a single visit. Dental restorations can be designed, shaped, and sintered chairside by taking digital impressions using an intraoral scanner, customizing the restoration using computer-aided design (CAD) and computer-aided manufacturing/milling (CAM), and rapidly sintering the restoration by speed-sintering. As well as being less energy- and time-intensive than conventional sintering processes, speed-sintering also saves dentists' time by eliminating the need for temporary restorations. Additionally, patients benefit from this one-visit approach since they do not have to return for another appointment to set the restoration [15]. Nevertheless, the physical and mechanical properties and the microstructure of speed-sintered YSZ may differ from those of conventionally sintered YSZ [16], which means it remains unclear whether speed-sintered YSZ is suitable for clinical use.

Conventional sintering furnaces are based on conduction, radiation, and convection heating [17]. Conventional sintering of YSZ usually involves indirect heating via resistive heating elements (including molybdenum disilicide), which heat up the air in the furnace that in turn heats up the material surface. Heat slowly transmits from the surface to the restoration to the interior due to the low thermal conductivity (2.5–2.8 W/m•°C) of zirconia-based materials [1]. Because cracking can occur during rapid heating and cooling [18,19], a low heating rate (5–10 °C/min) and long dwell time (2–4 h) are typically used to achieve uniform heat distribution and optimum sintering [16,20]. In contrast, techniques such as microwave sintering [18,21], induction heating [16,22], flash sintering [23–26], cold sintering [27–29], spark plasma sintering [30,31], hot-pressing [32], and selective laser sintering [33] can shorten the total sintering time and reduce the energy consumption. The application of some of these procedures to YSZ is currently being investigated.

Recently, a few manufacturers have synthesized YSZ via microwave sintering and induction heating. In both cases, electromagnetic energy is used to directly heat the material. Microwave sintering uses electromagnetic radiation transmitted from a magnetron. For ceramic materials, a frequency of 2.45 GHz and wavelength of 122 mm are typically used. Heat is generated by dipole oscillation or grain-boundary polarization within the ceramic, and some energy is transported by ionic conduction in the oscillating electric field [34,35]. During induction heating, energy is transmitted via an electric current produced by an electroconductive susceptor body under an alternating magnetic field. Zirconia-based restorations can be sintered in a fluctuating magnetic field when placed at the center of a susceptor body surrounded by a copper induction coil [16,22]. These novel speed-sintering methods enable zirconia-based restorations to be heated at rates of up to 342 °C/min, reducing the total sintering time to as low as 10 min [36,37]. Some studies have reported that speed-sintered YSZ demonstrates comparable optical and mechanical properties, such as flexural strength, fracture toughness, hardness, and Weibull modulus, to those of conventionally sintered YSZ [21,22,36–40]. However, other studies have indicated that speed-sintering can lower the flexural strength, light transmittance, and translucency parameter of YSZ [6,16,41–44]. Such contrasting reports make it difficult to predict the clinical performance of speed-sintered restorations.

As a prospective technique for producing YSZ dental restorations, speed-sintered YSZ needs to be examined comprehensively and the fundamental properties of speed-sintered YSZ should be documented sufficiently. Therefore, the objective of this systematic review and meta-analysis is to investigate the influence of speed-sintering on the optical and mechanical properties of YSZ. The null hypothesis is that there is no difference between the optical and mechanical properties of conventionally sintered and speed-sintered YSZ.

2. Materials and methods

The systematic review and meta-analysis were conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [45] and registered in the International Prospective Register of Systematic Reviews (PROSPERO) network under number CRD42022335235. The population, intervention, comparison, outcome, and study design (PICOS) were as follows:

P (population): Monolithic YSZ with regular shapes (for example, disc and bar).

I (intervention): Speed-sintering.

C (comparison): Conventional sintering.

O (outcome): Changes in the optical and mechanical properties.

S (study design): *In-vitro* studies.

The focus question of this study is as follows:

> "Does speed-sintering influence the optical and mechanical properties of YSZ?".

2.1. *Eligibility criteria*

The studies included in the systematic review and meta-analysis were identified through a search of three online databases and the reference lists of all identified articles, with the latter being peer-reviewed publications. The inclusion criteria were as follows: (1) *in-vitro* study; (2) monolithic YSZ in a regular shape (disc or bar); (3) at least one speed-sintering procedure; (4) conventionally sintered YSZ as a control; (5) comparison of the optical and mechanical properties of speed-sintered and conventionally sintered YSZ; and (6) measurement of the optical and mechanical properties of speed-sintered and conventionally sintered YSZ. Studies were excluded if they met one or more of the following exclusion criteria: (1) *in-vivo* study; (2) zirconia framework with other materials, such as porcelain, metal, or acrylic; (3) zirconia crown or veneer; (4) zirconia containing a stabilizer other than Y_2O_3 (like CeO_2 or MgO); (5) no proper control; (6) no evaluation of the optical or mechanical properties prior to property-influencing processes such as low-temperature degradation and sandblasting; (7) data not related to differences in properties between speed-sintered and conventionally sintered YSZ; (8) no details of sintering; and (9) reviews, case reports, protocols, and clinical guidelines.

2.2. *Search strategy*

The literature search was performed using the following databases: PubMed, Embase, and Web of Science. Articles published between January 1, 2010 and February 28, 2022 in English, Chinese, or Japanese were included. The following strategy was used in the PubMed search: (((((zirconium [MeSH Terms]) OR (zirconi*)) OR (zirconia)) OR (zirconium oxide)) OR (zirconium dioxide)) AND ((((((((((((((((((((((speed sinter*) OR (speed sintering)) OR (speed sintered)) OR (fast sinter*)) OR (fast sintering)) OR (fast sintered)) OR (rapid sinter*)) OR (rapid sintering)) OR (rapid sintered)) OR (microwave sinter*)) OR (microwave sintering)) OR (microwave sintered)) OR

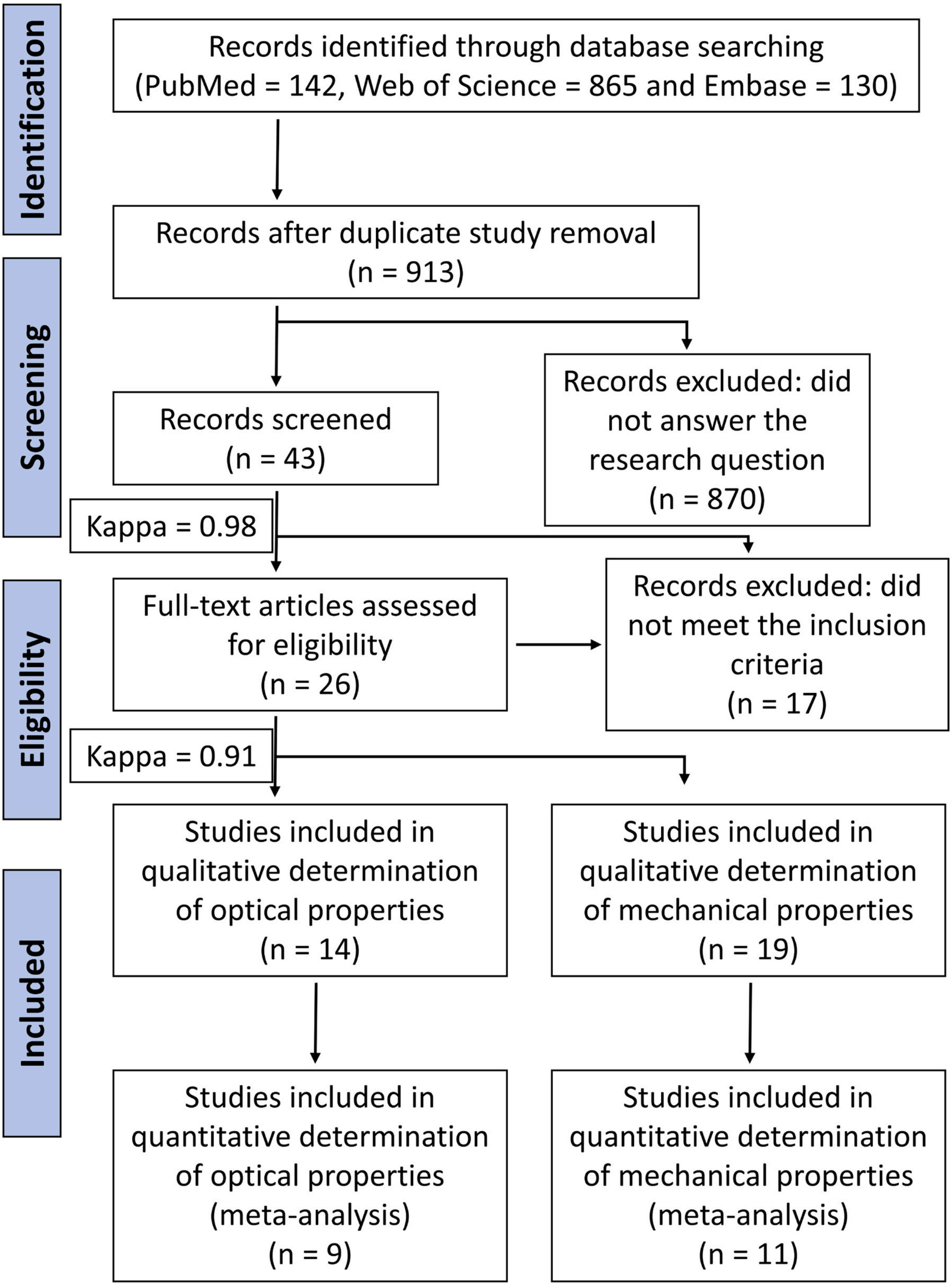


Fig. 1. Schematic of study selection according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.

(induction heat*)) OR (induction heating)) OR (induction heated)). Similar terms were employed in the Embase and Web of Science searches. The last database search was conducted on March 1, 2022.

2.3. Study screening and selection, and data extraction

Titles and abstracts were independently reviewed by two authors (H. L. and K.X.), and studies were selected for full-text screening if they met most of the inclusion criteria. After full-text evaluation, two shortlists of potentially appropriate studies were provided by both authors, and a third author (W.T.) was consulted if consensus was not reached. The final decision about the included studies was made based on the discussion between the two authors (H.L. and K.X.) with the suggestion of the third author (W.T.). The coefficient of inter-examiner agreement

Table 1
Characteristics of the included studies.

Ref.	Year	Material tested	Type of zirconia	Conventional sintering program	Heating rate of conventional sintering	Speed sintering program	Heating rate of speed sintering	Tested properties
Almazdi et al. [21]	2012	e-max ZirCAD[a]	3Y-TZP	1500 °C for 8 h	N/A	1500 °C for 30 min	N/A	Three-point flexural strength
Kim and Kim [42]	2017	Rainbow Shade A2[b]	3Y-TZP	1500 °C for 2 h (Total time: 8 h)	N/A	1500 °C for 30 min (Total time: 2 h)	N/A	Translucency parameter (CIEDE2000)
Jerman et al. [13]	2020	Ceramill ZI[c]	3Y-TZP	1450 °C for 120 min	N/A	1580 °C for 10 min	N/A	Three-point flexural strength
		Ceramill Zolid[c]	3Y-TZP	1450 °C for 120 min	N/A	1580 °C for 10 min	N/A	
		Ceramill Zolid HT+[c]	4Y-PSZ	1450 °C for 120 min	N/A	1580 °C for 10 min	N/A	
Presenda et al. [60]	2015	Lava[d]	3Y-TZP	1300/1400 °C for 120 min	10 °C/min to 1300/1400 °C	1200/1300 °C for 10 min	100 °C/min to 1200/1300 °C	Fracture toughness; Hardness
		Vita[e]	3Y-TZP	1300/1400 °C for 120 min	10 °C/min to 1300/1400 °C	1200/1300 °C for 10 min	100 °C/min to 1200/1300 °C	
		TZ3YS[f]	3Y-TZP	1300/1400 °C for 120 min	10 °C/min to 1300/1400 °C	1200/1300 °C for 10 min	100 °C/min to 1200/1300 °C	
Pekkan [84]	2021	CopranZri[h]	3Y-TZP	1500 °C for 90 min	10 °C/min to 950 °C, 6 °C/min to 1500 °C	1500 °C for 30 min	50 °C/min to 1100 °C, 20 °C/min to 1500 °C	Translucency parameter (CIELab)
		CopraSupreme[h]	4Y-PSZ	1500 °C for 90 min		1500 °C for 30 min		
		CopraSmile[h]	5Y-PSZ	1500 °C for 90 min		1500 °C for 30 min		
Presenda et al. [56]	2017	N/A[f]	3Y-TZP	1400 °C for 2 h	10 °C/min to 1400 °C	1200/1300 °C for 10 min	100 °C/min to 1200/1300 °C	Fracture toughness; Hardness
Yılmaz Savaş and Akın [53]	2022	InCoris TZI[g]	3Y-TZP	1500 °C for 120 min (Total time: 8 h)	N/A	1540 °C for 25 min/158 °C for 10 min (Total time: 130 min)	N/A	Translucency parameter (CIEDE2000);
Kim et al. [58]	2013	Lava Frame Zirconia[d]	3Y-TZP	1450 °C for 20 min to 40 h	10 °C/min to 1450 °C	1500 °C for 20 min	50 °C/min to 1500 °C	Contrast ratio light transmittance
		KaVo Everest ZS-blanks[i]	3Y-TZP	1450 °C for 20 min to 40 h	7 °C/min to 1450 °C	1500 °C for 20 min	50 °C/min to 1500 °C	
Marinis et al. [39]	2013	KaVo[i]	3Y-TZP	1450 °C for 2 h (Total time: 10 h)	N/A	1520 °C for 35 min (Total time: 2 h)	N/A	Fracture toughness
		Lava 3 M[d]	3Y-TZP	1500 °C for 2 h (Total time: 8.5 h)	N/A	1520 °C for 35 min (Total time: 2 h)	N/A	
		Crystal HS[j]	3Y-TZP	1510 °C for 2 h (Total time: 10 h)	N/A	1520 °C for 35 min (Total time: 2 h)	N/A	
Presenda et al. [59]	2017	Lava Zirconia[d]	3Y-TZP	1400 °C for 2 h (Total time: 380 min)	10 °C/min to 1400 °C	1200 °C for 10 min (Total time: 30 min)	100 °C/min to 1200 °C	Fracture toughness; Hardness
		TZ-3YSE[f]	3Y-TZP	1400 °C for 2 h (Total time: 380 min)	10 °C/min to 1400 °C	1200 °C for 10 min (Total time: 30 min)	100 °C/min to 1200 °C	
Presenda et al. [99]	2015	Lava Zirconia[d]	3Y-TZP	1400 °C for 2 h	10 °C/min to 1400 °C	1200 °C for 10 min	100 °C/min to 1200 °C	Hardness
		TZ-3YSE[f]	3Y-TZP	1400 °C for 2 h	10 °C/min to 1400 °C	1200 °C for 10 min	100 °C/min to 1200 °C	
Jansen et al. [41]	2019	Ceramill ZI[c]	3Y-TZP	1450 °C for 120 min	N/A	1570/1590 °C for 10 min	N/A	Light transmittance; Three-point flexural strength
		Ceramill Zolid[c]	3Y-TZP	1450 °C for 120 min	N/A	1570/1590 °C for 10 min	N/A	
		Ceramill Zolid HT+[c]	4Y-PSZ	1450 °C for 120 min	N/A	1570/1590 °C for 10 min	N/A	
Al-Zordk and Saker [85]	2020	DD Bio ZX2[k]	3Y-TZP	1450 °C for 120 min	8 °C/min to 900 °C, 3 °C/min to 1450 °C	1450 °C for 50 min	60 °C/min to 990 °C, 13 °C/min to 1450 °C	Translucency parameter (CIELab); Contrast ratio
		DD Cubex2[k]	5Y-PSZ	1450 °C for 120 min	8 °C/min to 900 °C, 3 °C/min to 1450 °C	1450 °C for 50 min	60 °C/min to 990 °C, 13 °C/min to 1450 °C	
		Zolid FX Preshaded[c]	5Y-PSZ	1450 °C for 120 min	20 °C/min to 900 °C, 10 °C/min to 1450 °C	1450 °C for 60 min	60 °C/min to 990 °C, 13 °C/min to 1450 °C	
		Zolid FX White[c]	5Y-PSZ	1450 °C for 120 min	20 °C/min to 900 °C, 10 °C/min to 1450 °C	1450 °C for 60 min	60 °C/min to 990 °C, 13 °C/min to 1450 °C	
Liu et al. [36]	2022	Katana HT[l]	4Y-PSZ	1500 °C for 120 min (Total time: ~7 h)	10 °C/min to 1500 °C	1515 °C for 30 min (Total time: ~90 min)	35 °C/min to 1515 °C	Translucency parameter (CIELab); Biaxial flexural strength
		Katana STML[l]	5Y-PSZ	1550 °C for 120 min (Total time: ~7 h)	10 °C/min to 1550 °C	1560 °C for 30 min/1560 °C for 6.9 min (Total time: ~90 min/18 min)	35 °C/min to to 1500 °C /342 °C/min to 1300 °C, 180 °C/min to 1450 °C, 24 °C/min to 1560 °C	

(*continued on next page*)

Table 1 (*continued*)

Ref.	Year	Material tested	Type of zirconia	Conventional sintering program	Heating rate of conventional sintering	Speed sintering program	Heating rate of speed sintering	Tested properties
		Katana UTML[l]	6Y-PSZ	1550 °C for 120 min (Total time: ~7 h)	10 °C/min to 1550 °C	1560 °C for 30 min (Total time: ~90 min)	35 °C/min to 1560 °C	
		Zpex 4 [f]	4Y-PSZ	1450 °C for 120 min (Total time: ~7 h)	10 °C/min to 1450 °C	1450 °C for 30 min (Total time: ~90 min)	35 °C/min to 1450 °C	
		Zpex Smile[f]	5Y-PSZ	1450 °C for 120 min (Total time: ~7 h)	10 °C/min to 1450 °C	1450 °C for 30 min (Total time: ~90 min)	35 °C/min to 1450 °C	
Yang et al. [86]	2020	Copran Zr-I[h]	3Y-TZP	1500 °C for 90 min	10 °C/min to 950 °C, 6 °C/min to 1500 °C	1500 °C for 30 min	50 °C/min to 1100 °C, 20 °C/min to 1500 °C	Translucency parameter (CIEDE); Biaxial flexural strength; Three-point flexural strength; Hardness
		Copran Zr-I Ultra-T white[h]	3Y-TZP	1500 °C for 90 min	10 °C/min to 950 °C, 6 °C/min to 1500 °C	1500 °C for 30 min	50 °C/min to 1100 °C, 20 °C/min to 1500 °C	
		Copran Zr-I Ultra-T A2[h]	3Y-TZP	1500 °C for 90 min	10 °C/min to 950 °C, 6 °C/min to 1500 °C	1500 °C for 30 min	50 °C/min to 1100 °C, 20 °C/min to 1500 °C	
		Cecron HT[g]	3Y-TZP	1520 °C for 130 min	22 °C/min to 880 °C, 11 °C/min to 1520 °C	1540 °C for 35 min	70 °C/min to 1540 °C	
		Cecron XT[g]	5Y-PSZ	1520 °C for 130 min	22 °C/min to 880 °C, 11 °C/min to 1520 °C	1540 °C for 35 min	70 °C/min to 1540 °C	
Cokic et al. [22]	2020	Katana STML[l]	5Y-PSZ	1550 °C for 2 h (Total time: 6.8 h)	10 °C/min to 1550 °C	1560 °C for 16 min (Total time: 28 min)	350 °C/min to 1300 °C, 150 °C/min to 1500 °C, 10 °C/min to 1560 °C	Translucency parameter (CIEDE); Contrast ratio; Biaxial flexural strength; Fracture toughness; Hardness
Ai et al. [61]	2015	N/A[m]	3Y-TZP	1350 °C for 2 h (the first sintering step: 900 °C for 30 min)	25 °C/min to 900 °C, 5 °C/min to 1350 °C	1350 °C for 30 min (First step: 900 °C for 30 min)	25 °C/min to 900 °C, 20 °C/min to 1350 °C; 25 °C/min to 1350 °C	Three-point flexural strength; Fracture toughness; Hardness
Borrell et al. [34]	2013	3Y-TZP-B[f]	3Y-TZP	1400 °C for 60 min	5 °C/min to 1400 °C	1100/1200/1300/1400 °C for 5/10/15 min	25 °C/min to 1100/1200/1300/1400 °C	Fracture toughness; Hardness
Luz et al. [18]	2021	Vipi Block[n]	3Y-TZP	1530 °C for 2 h (Total time: 600 min)	N/A	1450 °C for 15 min (Total time: 105 min)	30 °C/min	Translucency parameter (CIELab); Biaxial flexural strength
Liu et al. [87]	2022	Copran Zr-I Ultra-T[h]	3Y-TZP	~1500 °C for 60 min (Total time: 300 min)	N/A	~1500 °C for 15 min (Total time: 90 min)	N/A	Translucency parameter (CIELab)
		Cercon ht[g]	3Y-TZP	~1540 °C for 90 min (Total time: 270 min)	N/A	~1540 °C for 15 min (Total time: 60 min)	N/A	
		Cercon xt[g]	5Y-PSZ	~1540 °C for 90 min (Total time: 270 min)	N/A	~1540 °C for 15 min (Total time: 60 min)	N/A	
Li et al. [54]	2019	ST-3Y-TZP A2 preshaded Zirconia Blank[o]	3Y-TZP	1480 °C for 2 h (Total time: 15 h)	20 °C/min to 1480 °C	1580 °C for 2–20 min (Total time: 12–40 min)	400 °C/min to 1200 °C, 190 °C/min to 1480 or 1580 °C	Light transmittance; Three-point flexural strength; Fracture toughness; Hardness
Lawson and Maharishi [16]	2020	Katana STML[l]	5Y-PSZ	1550 °C for 2 h (Total time: 7 h)	N/A	N/A (Total time: 18/30 min)	N/A	Translucency parameter (CIElab); Three-point flexural strength
		Prettau Anterior[p]	5Y-PSZ	1550 °C for 2 h (Total time: 7 h)	N/A	N/A (Total time: 30 min)	N/A	
		Zpex Smile[f]	5Y-PSZ	1550 °C for 2 h (Total time: 7 h)	N/A	N/A (Total time: 30 min)	N/A	
Moratal et al. [19]	2021	3Y-TZP[f]	3Y-TZP	1400 °C for 60 min	10 °C/min to 1400 °C	1200/1300 °C for 10 min	30 °C/min to 1200/1300 °C	Contrast ratio; Fracture toughness; Hardness

(*continued on next page*)

Table 1 (*continued*)

Ref.	Year	Material tested	Type of zirconia	Conventional sintering program	Heating rate of conventional sintering	Speed sintering program	Heating rate of speed sintering	Tested properties
Jiang et al. [52]	2015	Lava Zirconia[d]	YSZ	1500 °C for 2 h	N/A	1420 °C for 30 min	15 °C/min to 1420 °C	Translucency parameter (CIElab)
		Zenostar Zirconia[n]	YSZ	1490 °C for 2 h	N/A	1420 °C for 30 min	15 °C/min to 1420 °C	
Han et al. [55]	2018	Domestic TZP[o]	YSZ	1530 °C for 8.2 h	N/A	1578 °C for 13.5 min	N/A	Biaxial flexural strength; Fracture toughness; Hardness
Ribeiro et al. [57]	2019	Experimental TZP	3Y-TZP	1530 °C for 2 h	10 °C/min to 800 °C, 5 °C/min to 1530 °C	1350/1450 °C for 15/30 min	25 °C/min to 1000 °C, 15 °C/min to 1300 °C, 5 °C/min to 1350/1450 °C	Fracture toughness; Hardness
		Vita In-Ceram 2000 YZ Cubes 4019[e]	3Y-TZP	1530 °C for 2 h	10 °C/min to 800 °C, 5 °C/min to 1530 °C	1350/1450 °C for 15/30 min		

[a] Ivoclar Vivadent, Schaan, Liechtenstein; [b]Genoss, Suwon, South Korea; [c]Amann Girrbach, Pforzheim, Germany; [d]3M Oral Care, St.Paul, MN,USA; [e]Vita Zahnfabrik, Bad Säckingen, Germany; [f]Tosoh, Tokyo, Japan; [h]Whitepeaks Dental Solutions, Hamminkeln, Germany; [g]Dentsply Sirona, Bensheim, Germany; [i]Kavo Dental, Biberach, Germany; [j]DLMS, Scottsdale, AZ, USA; [k]Dental Direct, Spenge, Germany; [l]Kuraray Noritake Dental, Tokyo, Japan; [m]Yixing ultrafine powder company, Yixing, China; [n]Vipi Wieland, Francisco Beltrão, Brazil; [o]Upcera, Shenzhen, China; [p]Zirconzahn, South Tyrol, Italy.

(kappa coefficient) was calculated for the two authors (H.L. and K.X.).

Data were extracted by two investigators (H.L. and K.X.). The following data were acquired from the included studies: author(s), publication year, title, publication journal, sample size, brand and commercial name of YSZ, type of material, sample shape (bar or disc), type of speed sintering, evaluation method, and numerical results of the study. For meta-analysis, the confidence intervals (CIs) were converted to means and standard deviations if the study provided CIs only, and the groups were combined into one if multiple conventional sintering or speed-sintering protocols were investigated in one study. The above-mentioned conversions were performed using spreadsheet software (Microsoft Office Excel 365 for Windows) according to the Cochrane Handbook for Systematic Reviews of Interventions [46]. One author (H. L.) contacted the corresponding author(s) of the studies via e-mail when some essential data, such as mean values, standard deviation, or sample size, were missing. Studies were excluded from the meta-analysis if the required information could not be obtained.

2.4. Risk of bias assessment

Risk of bias was assessed by two reviewers (H.L. and K.X.) based on the modified Consolidated Standards of Reporting Trials (CONSORT) checklist [47]. The following items were evaluated for quality assessment: (1) structured summary in the abstract; (2a) adequate information on scientific background and rationale; (2b) clear and well-formulated objectives and/or hypotheses; (3) specific information on the intervention enabling study replication; (4) pre-specified primary and secondary measures of outcome; (5) sample-size justification; (6) method of specimen randomization; (7) mechanism of specimen randomization; (8) person who performed specimen randomization; (9) person blinded before intervention practices; (10) statistical analysis used; (11) complete dataset; (12) description of the study limitations; (13) listed funding or other supports mentioned; and (14) study protocol available for potential readers. Each item was evaluated as reported or not reported according to the study description.

Another risk of bias evaluation was based on and adapted from previous studies [48–50]. The following parameters were utilized to evaluate the qualities of the included articles: (1) sample-size justification; (2) randomization; (3) sintering; (4) sample preparation; (5) adequate statistical analysis; (6) measuring procedures of each experiment; and (7) tests executed by a single-blinded operator. If the parameter was clearly reported, the study received a “0”; if the parameter was written but detailed information was missing, the study received a “1”; if a parameter was not mentioned at all, the study received a “2”. Studies were considered low-, medium-, and high-risk if they had a total sum of values in the range of 0–4, 5–9, and 10–14, respectively.

2.5. Data analyses

Meta-analysis was applied to a parameter if that parameter was included in at least three different studies and at least five different datasets were available, and the studies revealing comprehensive meta-analytic data of that parameter accounted for at least 50% of the studies. Therefore, the data for the CIELab-based translucency parameter, CIEDE2000-based translucency parameter, contrast ratio, three-point flexural strength, biaxial flexural strength, and fracture toughness were considered for meta-analysis. Other properties such as light transmittance and hardness were included in the systematic review, but are presented as descriptive data because some information for meta-analysis was lacking.

Mean values (mean), standard deviations (SD), and sample sizes (n) of each study were included in the meta-analysis. The data for the meta-analysis were combined in a random-effects model, and a heterogeneity study was conducted by Q and I^2 tests. $p < 0.1$ in the Q test and $I^2 > 50\%$ in the I^2 test indicated statistically high heterogeneity [51]. R statistical software (version 4.1.2, R Foundation for Statistical Computing, Vienna, Austria) was used in this study, and the significance level for the analyses was set as $\alpha = 0.05$.

3. Results

3.1. Search and selection

Fig. 1 shows a schematic of the study search and selection process according to the PRISMA statement. The initial electronic searches of PubMed, Web of Science, and Embase identified 142, 865, and 130 studies, respectively. A total of 224 studies were rejected because of duplications. After removing the duplicate studies, 870 studies were excluded based on the titles and abstracts reviewed, and the remaining 43 studies were selected for full-text analysis. Finally, 26 studies were included in the systematic review, among which 25 were written in English and one was written in Chinese [52]. The kappa coefficients for screening and eligibility were 0.98 and 0.91, respectively.

Detailed information on the included articles is provided in Table 1, where the authors, year, material tested, type of YSZ, and details of speed-sintering and conventional sintering for each article are presented.

Table 2
Parameters examined in the included studies for descriptive analysis and meta-analysis.

Ref.	CIELab-based translucency	CIEDE2000-based translucency	Contrast ratio	Light transmittance	Three-point flexural strength	Biaxial flexural strength	Fracture toughness	Hardness
Almazdi et al. [21]	-	-	-	-	○	-	-	-
Kim and Kim [42]	-	○	-	-	-	-	-	-
Jerman et al. [13]	-	-	-	-	○	-	-	-
Presenda et al. [60]	-	-	-	-	-	-	*	*
Pekkan (2021)[84]	○	-	-	-	-	-	-	-
Presenda et al. [56]	-	-	-	-	-	-	○	○
Yılmaz Savaş and Akın [53]	-	○	○	-	-	-	-	-
Kim et al. [58]	-	-	-	○	-	-	-	-
Marinis et al. [39]	-	-	-	-	-	-	○	-
Presenda et al. [59]	-	-	-	-	-	-	*	*
Presenda et al. [99]	-	-	-	-	-	-	-	*
Jansen et al. [41]	-	-	-	*	*	-	-	-
Al-Zordk and Saker (2020)[85]	○	-	○	-	-	-	-	-
Liu et al. [36]	○(+)	-	-	-	-	○	-	-
Yang et al. [86]	*	-	-	-	*	*	-	*
Cokic et al. [22]	○(+)	-	○	-	-	○	○(+)	○(+)
Ai et al. [61]	-	-	-	-	*	-	*	*
Borrell et al. [34]	-	-	-	-	-	-	*	*
Luz et al. [18]	○(+)	-	-	-	-	○(+)	-	-
Liu et al. [87]	*	-	-	-	-	-	-	-
Li et al. [54]	-	-	-	*	○	-	○	○
Lawson and Maharishi)[16]	-	○	-	-	○	-	-	-
Moratal et al. [19]	-	-	*	-	-	-	*	*
Jiang et al. [52]	○	-	-	-	-	-	-	-
Han et al. [55]	-	-	-	-	-	○	○	○
Ribeiro et al. (2019) [57]	-	-	-	-	-	-	○	○
Total	8	3	4	3	7	5	11	12
Numbers of full information articles	6	3	3	1	4	4	6	5
Percentage of full information articles	75%	100%	75%	33.3%	57.1%	80%	54.5%	41.7%
Number of datasets	22	7	6	1	9	7	8	6

○: With full information for meta-analysis; * : Lack of essential information for meta-analysis; ○(+): Information directly obtained from the author.

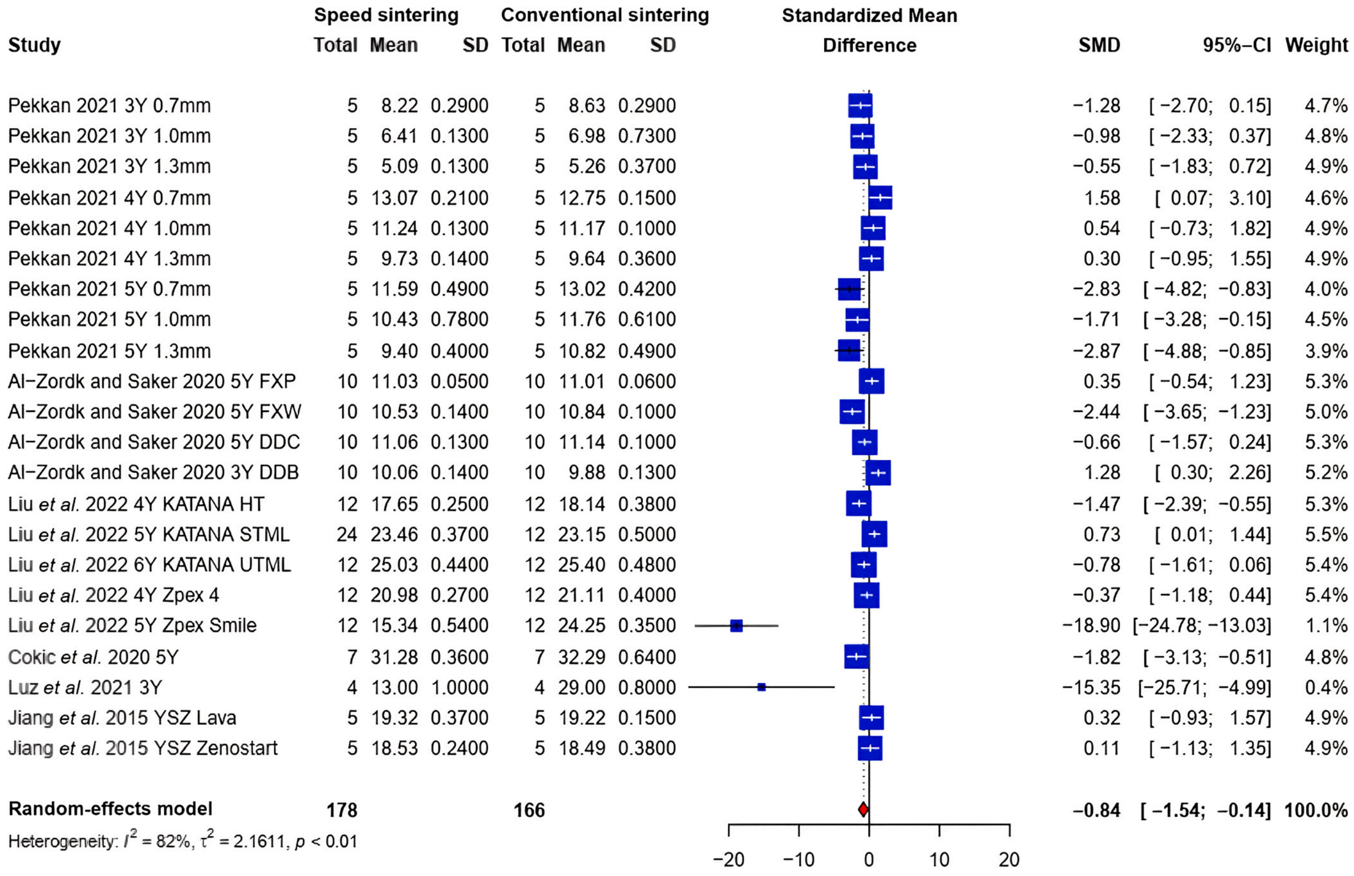
Table 3
Risk of bias in the included studies according to the modified Consolidated Standards of Reporting Trials (CONSORT) checklist. Each item is marked as reported (*) or not (empty box) according to the description of each study.

Ref.	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14
Almazdi et al. [21]	*	*	*	*	*						*	*	*		
Kim and Kim [42]	*	*	*	*	*						*	*	*	*	
Jerman et al. [13]	*	*	*	*	*						*	*	*	*	
Presenda et al. [60]	*	*	*	*	*									*	
Pekkan [84]	*	*	*	*	*						*	*	*	*	
Presenda et al. [56]	*	*	*	*	*							*		*	
Yılmaz Savaş and Akın [53]	*	*	*	*	*	*	*	*			*	*	*		
Kim et al. [58]	*	*	*	*	*						*	*	*	*	
Marinis et al. [39]	*	*	*	*	*	*					*	*		*	
Presenda et al. [59]	*	*	*	*	*							*		*	
Presenda et al. [99]	*	*	*	*	*							*		*	
Jansen et al. [41]	*	*	*	*	*						*	*	*	*	
Al-Zordk and Saker [85]	*	*	*	*	*						*	*	*		
Liu et al. [36]	*	*	*	*	*	*					*	*	*	*	
Yang et al. [86]	*	*	*	*	*						*			*	
Cokic et al. [22]	*	*	*	*	*						*	*		*	
Ai et al. [61]	*	*	*	*	*									*	
Borrell et al. [34]	*	*	*	*	*									*	
Luz et al. [18]	*	*		*	*						*	*		*	
Liu et al. [87]	*	*	*	*	*						*		*	*	
Li et al. [54]	*	*	*	*	*						*	*			
Lawson and Maharishi [16]	*	*	*	*	*						*	*	*	*	
Moratal et al. [19]	*	*	*	*	*									*	
Jiang et al. [52]	*	*	*	*	*						*	*			
Han et al. [55]	*	*	*	*	*						*	*		*	
Ribeiro et al. [57]	*	*	*	*	*							*		*	

Table 4
Risk of bias in the included studies adapted and modified from previous studies.

Ref.	Sample size	Random	Sintering	Sample preparation	Statistical analysis	Measuring procedures	Operator	Total	Risk of bias
Almazdi et al. [21]	2	2	1	0	0	0	2	7	Medium
Kim and Kim [42]	2	2	1	0	0	0	2	7	Medium
Jerman et al. [13]	2	2	1	0	0	0	2	7	Medium
Presenda et al. [60]	2	2	1	0	2	0	2	9	Medium
Pekkan [84]	2	2	0	0	0	0	2	6	Medium
Presenda et al. [56]	2	2	1	1	2	0	2	10	High
Yılmaz Savaş and Akın [53]	0	0	1	0	0	0	2	3	Low
Kim et al. [58]	2	2	1	0	0	0	2	7	Medium
Marinis et al. [39]	0	2	1	0	0	0	2	5	Medium
Presenda et al. [59]	2	2	1	0	2	0	2	9	Medium
Presenda et al. [99]	2	2	1	0	2	0	2	9	Medium
Jansen et al. [41]	2	2	1	0	0	0	2	7	Medium
Al-Zordk and Saker [85]	2	2	0	0	0	0	2	6	Medium
Liu et al. [36]	0	2	0	0	0	0	2	4	Low
Yang et al. [86]	2	2	0	0	0	0	2	6	Medium
Cokic et al. [22]	2	2	0	0	0	0	2	6	Medium
Ai et al. [61]	2	2	1	0	2	1	2	10	High
Borrell et al. [34]	2	2	1	0	2	0	2	9	Medium
Luz et al. [18]	2	2	0	1	0	0	2	7	Medium
Liu et al. [87]	2	2	0	1	0	0	2	7	Medium
Li et al. [54]	2	2	0	1	2	0	2	9	Medium
Lawson and Maharishi [16]	2	2	1	0	0	0	2	7	Medium
Moratal et al. [19]	2	2	1	0	2	1	2	10	High
Jiang et al. [52]	2	2	1	0	0	0	2	7	Medium
Han et al. [55]	2	2	1	0	0	0	2	7	Medium
Ribeiro et al. [57]	2	2	0	0	2	0	2	8	Medium

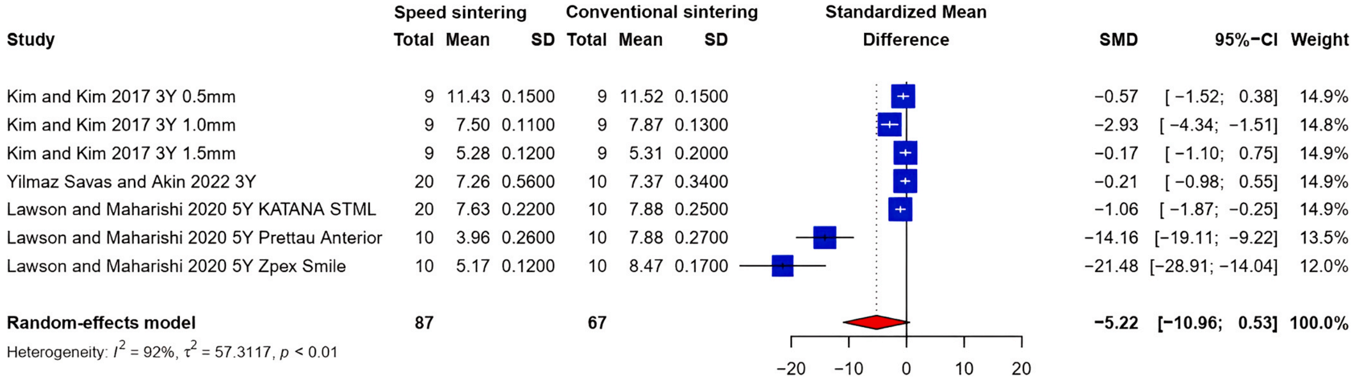
The main focus of this review is to investigate the effect of speed-sintering on the optical and mechanical properties of YSZ (Table 2). The optical properties comprise the CIELab-based translucency parameter, CIEDE2000-based translucency parameter, contrast ratio, and light transmittance, and the mechanical properties include three-point flexural strength, biaxial flexural strength (piston-on-three-ball



Study	Speed sintering Total	Speed sintering Mean	Speed sintering SD	Conventional sintering Total	Conventional sintering Mean	Conventional sintering SD	SMD	95%−CI	Weight
Pekkan 2021 3Y 0.7mm	5	8.22	0.2900	5	8.63	0.2900	−1.28	[−2.70; 0.15]	4.7%
Pekkan 2021 3Y 1.0mm	5	6.41	0.1300	5	6.98	0.7300	−0.98	[−2.33; 0.37]	4.8%
Pekkan 2021 3Y 1.3mm	5	5.09	0.1300	5	5.26	0.3700	−0.55	[−1.83; 0.72]	4.9%
Pekkan 2021 4Y 0.7mm	5	13.07	0.2100	5	12.75	0.1500	1.58	[0.07; 3.10]	4.6%
Pekkan 2021 4Y 1.0mm	5	11.24	0.1300	5	11.17	0.1000	0.54	[−0.73; 1.82]	4.9%
Pekkan 2021 4Y 1.3mm	5	9.73	0.1400	5	9.64	0.3600	0.30	[−0.95; 1.55]	4.9%
Pekkan 2021 5Y 0.7mm	5	11.59	0.4900	5	13.02	0.4200	−2.83	[−4.82; −0.83]	4.0%
Pekkan 2021 5Y 1.0mm	5	10.43	0.7800	5	11.76	0.6100	−1.71	[−3.28; −0.15]	4.5%
Pekkan 2021 5Y 1.3mm	5	9.40	0.4000	5	10.82	0.4900	−2.87	[−4.88; −0.85]	3.9%
Al−Zordk and Saker 2020 5Y FXP	10	11.03	0.0500	10	11.01	0.0600	0.35	[−0.54; 1.23]	5.3%
Al−Zordk and Saker 2020 5Y FXW	10	10.53	0.1400	10	10.84	0.1000	−2.44	[−3.65; −1.23]	5.0%
Al−Zordk and Saker 2020 5Y DDC	10	11.06	0.1300	10	11.14	0.1000	−0.66	[−1.57; 0.24]	5.3%
Al−Zordk and Saker 2020 3Y DDB	10	10.06	0.1400	10	9.88	0.1300	1.28	[0.30; 2.26]	5.2%
Liu *et al.* 2022 4Y KATANA HT	12	17.65	0.2500	12	18.14	0.3800	−1.47	[−2.39; −0.55]	5.3%
Liu *et al.* 2022 5Y KATANA STML	24	23.46	0.3700	12	23.15	0.5000	0.73	[0.01; 1.44]	5.5%
Liu *et al.* 2022 6Y KATANA UTML	12	25.03	0.4400	12	25.40	0.4800	−0.78	[−1.61; 0.06]	5.4%
Liu *et al.* 2022 4Y Zpex 4	12	20.98	0.2700	12	21.11	0.4000	−0.37	[−1.18; 0.44]	5.4%
Liu *et al.* 2022 5Y Zpex Smile	12	15.34	0.5400	12	24.25	0.3500	−18.90	[−24.78; −13.03]	1.1%
Cokic *et al.* 2020 5Y	7	31.28	0.3600	7	32.29	0.6400	−1.82	[−3.13; −0.51]	4.8%
Luz *et al.* 2021 3Y	4	13.00	1.0000	4	29.00	0.8000	−15.35	[−25.71; −4.99]	0.4%
Jiang *et al.* 2015 YSZ Lava	5	19.32	0.3700	5	19.22	0.1500	0.32	[−0.93; 1.57]	4.9%
Jiang *et al.* 2015 YSZ Zenostart	5	18.53	0.2400	5	18.49	0.3800	0.11	[−1.13; 1.35]	4.9%
Random-effects model	**178**			**166**			**−0.84**	**[−1.54; −0.14]**	**100.0%**

Heterogeneity: $I^2 = 82\%$, $\tau^2 = 2.1611$, $p < 0.01$

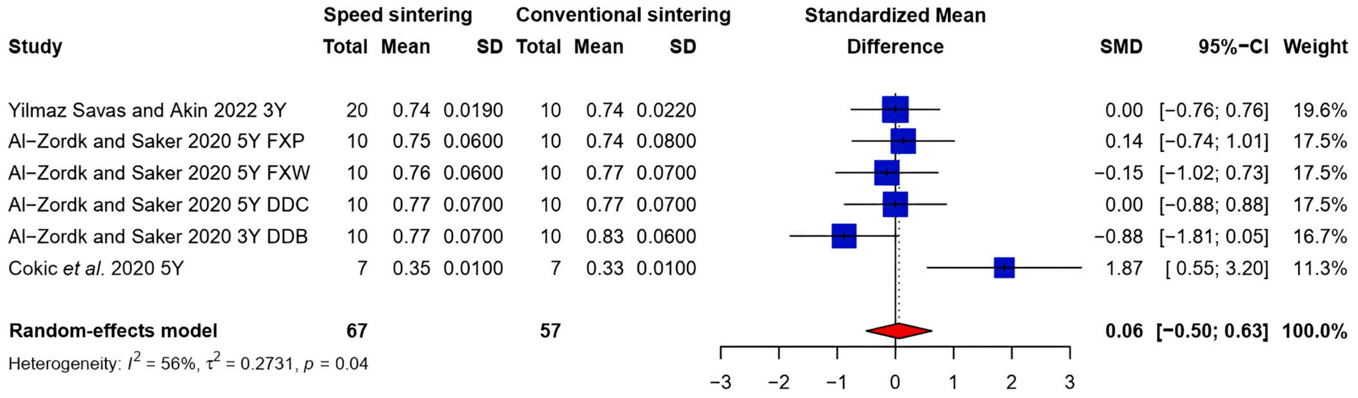
Fig. 2. Forest for CIELab-based translucency based on the meta-analysis (SD, standard deviation; CI, confidence interval; SMD, standardized mean difference).



Study	Speed sintering Total	Mean	SD	Conventional sintering Total	Mean	SD	SMD	95%−CI	Weight
Kim and Kim 2017 3Y 0.5mm	9	11.43	0.1500	9	11.52	0.1500	−0.57	[−1.52; 0.38]	14.9%
Kim and Kim 2017 3Y 1.0mm	9	7.50	0.1100	9	7.87	0.1300	−2.93	[−4.34; −1.51]	14.8%
Kim and Kim 2017 3Y 1.5mm	9	5.28	0.1200	9	5.31	0.2000	−0.17	[−1.10; 0.75]	14.9%
Yilmaz Savas and Akin 2022 3Y	20	7.26	0.5600	10	7.37	0.3400	−0.21	[−0.98; 0.55]	14.9%
Lawson and Maharishi 2020 5Y KATANA STML	20	7.63	0.2200	10	7.88	0.2500	−1.06	[−1.87; −0.25]	14.9%
Lawson and Maharishi 2020 5Y Prettau Anterior	10	3.96	0.2600	10	7.88	0.2700	−14.16	[−19.11; −9.22]	13.5%
Lawson and Maharishi 2020 5Y Zpex Smile	10	5.17	0.1200	10	8.47	0.1700	−21.48	[−28.91; −14.04]	12.0%
Random-effects model	**87**			**67**			**−5.22**	**[−10.96; 0.53]**	**100.0%**

Heterogeneity: $I^2 = 92\%$, $\tau^2 = 57.3117$, $p < 0.01$

Fig. 3. Forest for CIEDE2000-based translucency according to the meta-analysis (SD, standard deviation; CI, confidence interval; SMD, standardized mean difference).



Study	Speed sintering Total	Mean	SD	Conventional sintering Total	Mean	SD	SMD	95%−CI	Weight
Yilmaz Savas and Akin 2022 3Y	20	0.74	0.0190	10	0.74	0.0220	0.00	[−0.76; 0.76]	19.6%
Al−Zordk and Saker 2020 5Y FXP	10	0.75	0.0600	10	0.74	0.0800	0.14	[−0.74; 1.01]	17.5%
Al−Zordk and Saker 2020 5Y FXW	10	0.76	0.0600	10	0.77	0.0700	−0.15	[−1.02; 0.73]	17.5%
Al−Zordk and Saker 2020 5Y DDC	10	0.77	0.0700	10	0.77	0.0700	0.00	[−0.88; 0.88]	17.5%
Al−Zordk and Saker 2020 3Y DDB	10	0.77	0.0700	10	0.83	0.0600	−0.88	[−1.81; 0.05]	16.7%
Cokic *et al.* 2020 5Y	7	0.35	0.0100	7	0.33	0.0100	1.87	[0.55; 3.20]	11.3%
Random-effects model	**67**			**57**			**0.06**	**[−0.50; 0.63]**	**100.0%**

Heterogeneity: $I^2 = 56\%$, $\tau^2 = 0.2731$, $p = 0.04$

Fig. 4. Forest for contrast ratio based on the meta-analysis (SD, standard deviation; CI, confidence interval; SMD, standardized mean difference).

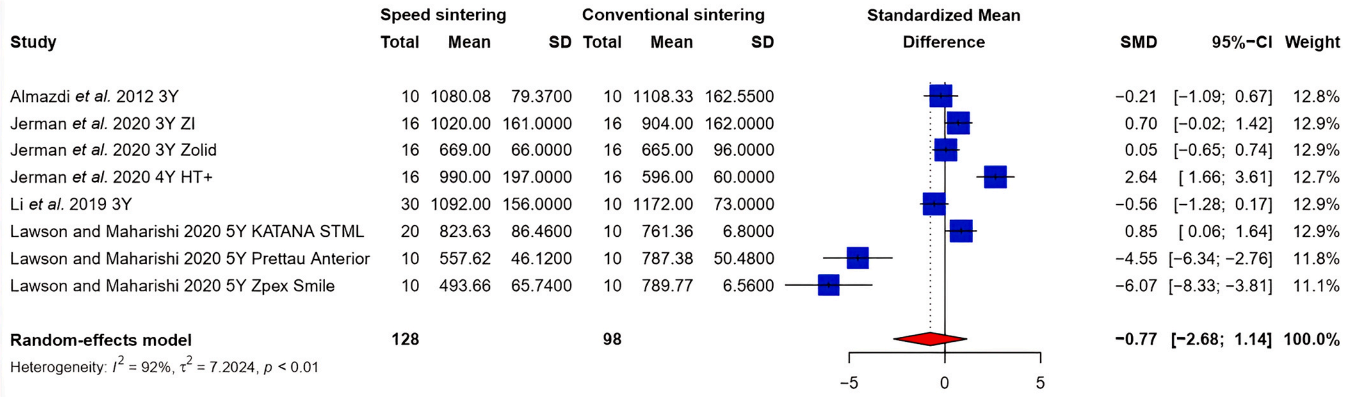
method), fracture toughness, and hardness.

3.2. Risk of bias

The risk of bias in the evaluated studies is presented in Tables 3 and 4. The modified CONSORT scale demonstrated that all the articles had sufficient information on the structured summary, scientific background, intervention, and pre-specified measures of outcome, and most of the included studies contained information on the specific objectives, statistical methods, limitations, and sources of funding or other support. However, only Yılmaz Savaş and Akın [53], Marinis et al. [39], and Liu et al. [36] reported how the sample size was determined. Only Yılmaz Savaş and Akın [53] reported the method used to implement the random-allocation sequence and the author who conducted the randomization. The remaining items were not noted in any of the included studies. Regarding the evaluation of risk of bias, as adapted and modified from previous studies, most of the studies exhibited a medium risk of bias, two studies demonstrated a low risk of bias, and three studies presented a high risk of bias.

3.3. Meta-analysis

Six meta-analyses were conducted for the CIELab-based translucency parameter, CIEDE2000-based translucency parameter, contrast ratio, three-point flexural strength, biaxial flexural strength (piston-on-three-ball method), and fracture toughness. Some studies were included in the



Study	Speed sintering Total	Mean	SD	Conventional sintering Total	Mean	SD	SMD	95%−CI	Weight
Almazdi *et al.* 2012 3Y	10	1080.08	79.3700	10	1108.33	162.5500	−0.21	[−1.09; 0.67]	12.8%
Jerman *et al.* 2020 3Y ZI	16	1020.00	161.0000	16	904.00	162.0000	0.70	[−0.02; 1.42]	12.9%
Jerman *et al.* 2020 3Y Zolid	16	669.00	66.0000	16	665.00	96.0000	0.05	[−0.65; 0.74]	12.9%
Jerman *et al.* 2020 4Y HT+	16	990.00	197.0000	16	596.00	60.0000	2.64	[1.66; 3.61]	12.7%
Li *et al.* 2019 3Y	30	1092.00	156.0000	10	1172.00	73.0000	−0.56	[−1.28; 0.17]	12.9%
Lawson and Maharishi 2020 5Y KATANA STML	20	823.63	86.4600	10	761.36	6.8000	0.85	[0.06; 1.64]	12.9%
Lawson and Maharishi 2020 5Y Prettau Anterior	10	557.62	46.1200	10	787.38	50.4800	−4.55	[−6.34; −2.76]	11.8%
Lawson and Maharishi 2020 5Y Zpex Smile	10	493.66	65.7400	10	789.77	6.5600	−6.07	[−8.33; −3.81]	11.1%
Random-effects model	**128**			**98**			**−0.77**	**[−2.68; 1.14]**	**100.0%**

Heterogeneity: $I^2 = 92\%$, $\tau^2 = 7.2024$, $p < 0.01$

Fig. 5. Forest for three-point flexural strength according to the meta-analysis (SD, standard deviation; CI, confidence interval; SMD, standardized mean difference).

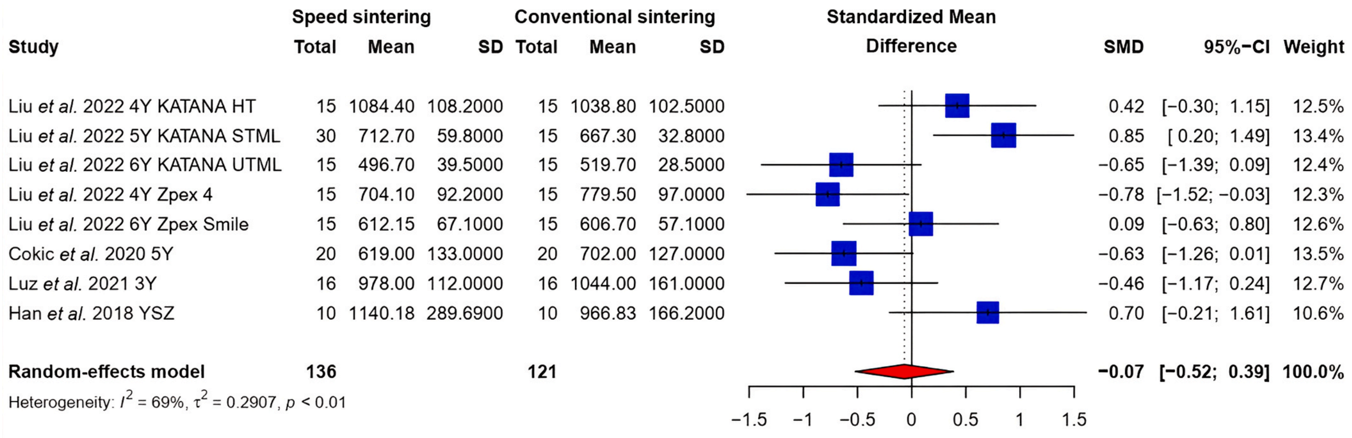


Fig. 6. Forest for biaxial flexural strength based on the meta-analysis (SD, standard deviation; CI, confidence interval; SMD, standardized mean difference).

meta-analysis more than once, because two or more different types of YSZ or specimen thicknesses were evaluated.

For CIELab-based translucency, three articles involving 22 comparisons were analyzed using a random-effects model. The results indicated that the CIELab-based translucency parameter of conventionally sintered samples was higher than that of speed-sintered samples (mean difference (MD) $= -0.84$; 95% CI $= -1.54$ to -0.14; $p = 0.0183$) (Fig. 2). The meta-analysis exhibited high heterogeneity: $I^2 = 82\%$ and $Q = 119.5$ ($p < 0.0001$).

For CIEDE2000-based translucency, three articles combining seven datasets were included in the meta-analysis and subsequently evaluated using a random-effects model. The results indicated that there is no significant difference in CIEDE2000-based translucency between speed-sintered and conventionally sintered samples (MD $= -5.22$; 95% CI $= -10.96$ to 0.53; $p = 0.0750$) (Fig. 3). The heterogeneity was high: $I^2 = 92\%$ and $Q = 70.98$ ($p < 0.0001$).

For contrast ratio, six datasets from three studies were analyzed using a random-effects model. The results demonstrated that the contrast ratio of speed-sintered samples was comparable to that of conventionally sintered samples (MD $= 0.06$; 95% CI $= -0.50$ to 0.63; $p = 0.8250$) (Fig. 4). The heterogeneity was intermediate: $I^2 = 56\%$ and $Q = 11.35$ ($p = 0.0449$).

For three-point flexural strength, four articles with eight datasets were included in the meta-analysis. The specimen sizes were 25 × 4.5 × 2.5 mm [21], 25 × 4 × 1 mm [13], 20 × 4 × 1.2 mm [54], and 16 × 4 × 1.2 mm [16]. One study followed ISO 2006 [21] and one study followed ISO 6872 [16]. Jerman et al. [13] reported that ISO 6872:2019 was not strictly followed because the increased material thickness might hide the influence of phase transformation on the flexural strength. A random-effects model was utilized to assess the three-point flexural strength of different samples. The results indicated that the three-point flexural strength of speed-sintered YSZ bars was comparable to that of conventionally sintered YSZ bars (MD $= -0.77$; 95% CI $= -2.68$ to 1.14; $p = 0.4302$) (Fig. 5). The heterogeneity was high: $I^2 = 92\%$ and $Q = 89.99$ ($p < 0.0001$).

For biaxial flexural strength (piston-on-three-ball method), data from four studies combining eight estimations were examined using a random-effects model. The specimen sizes were Φ14.5 × 1.2 mm [36], 12 × 12 × 1.2 mm [22], and Φ12 × 1.2 mm [18,55]. Three studies followed ISO 6872:2015 [18,22,36] and one study followed ISO 6872:2008 [55]. The results demonstrated that the biaxial flexural strength of speed-sintered YSZ discs was similar to that of conventionally sintered YSZ discs (MD $= -0.07$; 95% CI $= -0.52$ to 0.39; $p = 0.7691$) (Fig. 6). The heterogeneity was intermediate: $I^2 = 69\%$ and $Q = 22.42$ ($p = 0.0021$).

For fracture toughness, six studies with eight datasets were included in the meta-analysis. The indentation method was employed to measure the fracture toughness in five studies [22,54–57], whereas one study [39] used the single edge V-notch beam method. The datasets were analyzed using a random-effects model. The results implied that speed-sintered YSZ has a similar fracture toughness to conventionally sintered YSZ (MD $= -0.85$; 95% CI $= -1.80$ to 0.00; $p = 0.0502$) (Fig. 7). The heterogeneity was intermediate: $I^2 = 70\%$ and $Q = 23.40$ ($p = 0.0015$).

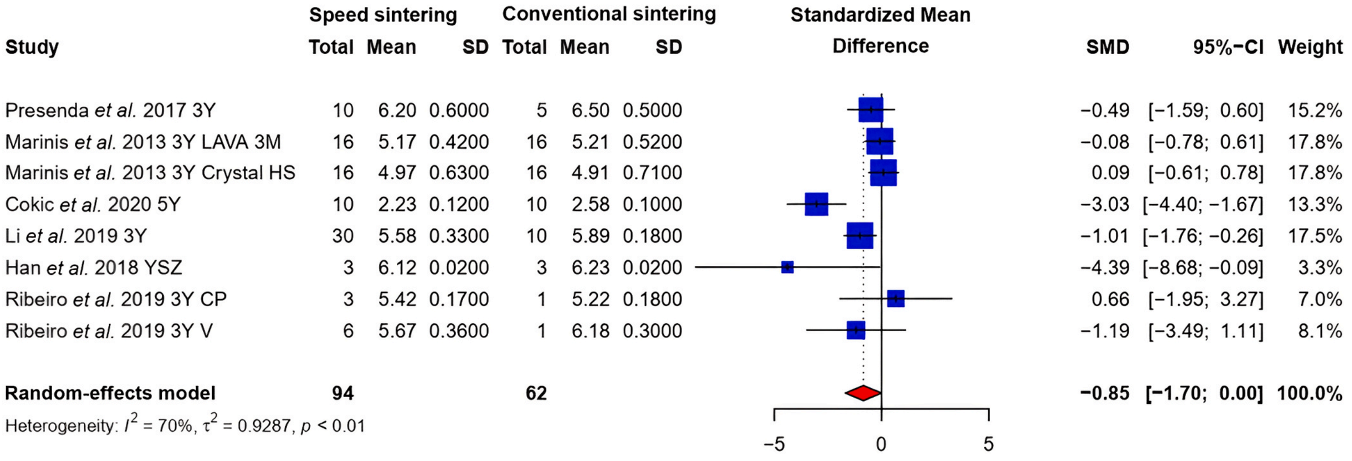


Fig. 7. Forest for fracture toughness according to the meta-analysis (SD, standard deviation; CI, confidence interval; SMD, standardized mean difference).

Table 5
Outcomes of the parameters investigated in the included studies for descriptive analysis.

Parameter investigated	Ref.	Year	Outcome
Translucency parameter (CIELab)	Yang et al. [86]	2020	Translucency parameters of conventionally sintered ZW and XT higher than those of other conventionally sintered materials; No significant differences between the translucency parameters of conventionally sintered and rapid-sintered UW, UT, and HT.
	Liu et al. [87]	2022	Translucency parameters of conventionally sintered samples comparable to those of corresponding speed-sintered samples, except XT, whose translucency parameter was calculated using the colorimeter “DD.”
Contrast ratio	Moratal et al. [19]	2021	Contrast ratio of conventionally sintered NK00 similar to that of microwave-sintered NK00.
Light transmittance	Kim et al. [58]	2013	Light transmittances of microwave-sintered Lava and KaVo higher than those of conventionally sintered Lava and KaVo.
	Jansen et al. [41]	2019	Light transmittances of conventionally sintered ZD and HT+ (all thicknesses) and ZI (thickness of 2.5–3 mm) higher than those of corresponding speed-sintered samples.
	Li et al. [54]	2019	Light transmittance of rapid-sintered sample (R-1) lower than those of conventionally sintered and rapid-sintered samples (R-2 and R-3, respectively).
Three-point flexural strength	Jansen et al. [41]	2019	No significant differences between three-point flexural strengths of conventionally sintered and speed-sintered samples for a given type of zirconia.
	Yang et al. [86]	2020	No significant differences between three-point flexural strengths of conventionally sintered and speed-sintered samples for a given type of zirconia.
	Ai et al. [61]	2015	Three-point flexural strength of microwave-sintered sample higher than that of conventionally sintered sample.
Biaxial flexural strength	Yang et al. [86]	2020	No significant differences between biaxial flexural strengths of conventionally sintered and speed-sintered samples for a given type of zirconia.
Fracture toughness	Presenda et al. [60]	2015	No significant differences between biaxial flexural strengths of conventionally sintered and microwave-sintered LAVA and TOSOH. Fracture toughness of microwave-sintered VITA lower than that of conventionally sintered VITA.
	Presenda et al. [59]	2017	No considerable differences between fracture toughnesses of conventionally sintered and speed-sintered samples.
	Ai et al. [61]	2015	Flexural toughness of microwave-sintered sample higher than that of conventionally sintered sample.
	Borrell et al. [34]	2013	At 1400 °C, flexural toughness of conventionally sintered and microwave (5 min)-sintered samples higher than those of microwave (10 and 15 min)-sintered samples.
	Moratal et al. [19]	2021	Fracture toughness of microwave (1200 °C)-sintered NK00 higher than those of conventionally sintered and microwave (1300 °C)-sintered NK00 samples.
Hardness	Presenda et al. [60]	2015	No statistical differences between the hardnesses of conventionally sintered and microwave-sintered LAVA and VITA. Hardness of microwave-sintered TOSOH higher than those of other microwave-sintered samples.
	Presenda et al. [56]	2017	3Y-TZP hardness values: conventionally sintered, 13.9 ± 0.4 GPa; microwave-sintered, 13.9 ± 0.8 GPa (1200 °C) and 14.7 ± 0.6 GPa (1300 °C).
	Presenda et al. [59]	2017	LAVA hardness values: conventionally sintered, 12.9 ± 0.2 GPa; microwave-sintered, 13.6 ± 0.3 GPa. LAB zirconia hardness values: conventionally sintered, 13.0 ± 0.1 GPa; microwave-sintered, 13.4 ± 0.4 GPa.
	Presenda et al. [99]	2015	LAVA hardness values: conventionally sintered, 15.9 ± 0.5 GPa, whereas that of microwave-sintered LAVA was 15.8 ± 0.6 GPa. LAB zirconia hardness values: conventionally sintered, 17.0 ± 0.4 GPa; microwave-sintered, 16.8 ± 0.6 GPa.
	Yang et al. [86]	2020	No significant differences between hardness values of conventionally sintered and speed-sintered samples.
	Cokic et al. [22]	2020	Hardness of speed-sintered sample higher than that of conventionally sintered sample.
	Ai et al. [61]	2015	Hardness of microwave-sintered sample higher than that of conventionally sintered sample.
	Borrell et al. [34]	2013	At 1400 °C, hardness of conventionally sintered sample lower than that of microwave-sintered sample.
	Li et al. [54]	2019	Hardness values: conventionally sintered sample, 13.4 ± 0.2 GPa; rapid-sintered samples, 13.6 ± 0.2 (R-1), 13.4 ± 0.3 (R-2), and 13.3 ± 0.1 GPa (R-3).
	Moratal et al. [19]	2021	Hardness of microwave (1300 °C)-sintered sample higher than those of conventionally sintered and microwave (1200 °C)-sintered samples.
	Han et al. [55]	2018	Hardness of rapid-sintered sample higher than that of conventionally sintered sample.
	Ribeiro et al. [57]	2019	Hardness of microwave-sintered coprecipitated powder-made zirconia lower than that of conventionally sintered sample. No statistical differences between hardness values of conventionally sintered and microwave-sintered pre-sintered zirconia samples.

3.4. Descriptive analysis

A descriptive analysis of the evaluated studies is presented in Table 5. The studies included in the descriptive analysis suggest that the translucency parameters (CIELab) and contrast ratios of most of the speed-sintered samples were similar to those of conventionally sintered samples. Kim et al. [58] reported that the light transmittance of microwave-sintered YSZ was higher than that of conventionally sintered YSZ. In contrast, Jansen et al. [41] demonstrated that the light transmittance of conventionally sintered YSZ was higher than that of speed-sintered YSZ. Li et al. [54] reported that the light transmittance of a sample prepared using a 12-min rapid-sintering protocol was inferior to those prepared with conventional sintering, 25-min rapid-sintering, and 40-min rapid-sintering protocols.

Most of the studies included in the descriptive analysis indicated that the three-point or biaxial flexural strengths of the speed-sintered samples were comparable to those of conventionally sintered samples. Presenda and colleagues [59,60] and Borrell et al. [34] reported that the fracture toughness of microwave-sintered samples was comparable to or lower than that of conventionally sintered samples. In contrast, Ai et al. [61] and Moratal et al. [19] reported that microwave-sintered samples presented a higher fracture toughness than conventionally sintered samples. Almost all included studies revealed that speed-sintered samples had similar or higher hardness than the corresponding conventionally sintered samples, except for Ribeiro et al. [57], who reported that the hardness of microwave-sintered samples using a co-precipitated powder was lower than that of conventionally sintered samples.

4. Discussion

This systematic review and meta-analysis disclosed specific differences in the optical and mechanical properties between speed-sintered and conventionally sintered YSZ. The meta-analysis revealed that the investigated properties of speed-sintered YSZ are comparable to those of conventionally sintered YSZ, except for the CIELab-based translucency parameter. The descriptive analysis indicated that the hardness of speed-sintered samples is similar or higher than that of conventionally sintered samples, except in one study [19], which showed that conventionally sintered samples had a lower hardness than microwave-sintered samples. Overall, the null hypothesis was partially accepted.

In this study, optical properties were compared for four parameters, namely, CIELab-based translucency, CIEDE2000-based translucency, contrast ratio, and light transmittance. These parameters are determined based on spectral transmittance and reflectance data in a certain wavelength range, as acquired using a spectrophotometer or colorimeter, as well as color coordinates, such as lightness (L*), red/green coordinates (a*), yellow/blue coordinates (b*), chroma (C*), and hue angle (H*) [62]. CIELab-based translucency ranges from 0 for a totally opaque material to 100 for a totally transparent material; that is, a higher CIELab-based translucency parameter indicates higher translucency. Alp et al. [63] demonstrated that CIEDE2000-based translucency is suitable for non-uniform optical materials, whereas CIELab-based translucency can only be applied to optically uniform materials. In addition, the color difference on black versus white backgrounds can be evaluated when an extremely translucent material is investigated using the CIEDE2000-based translucency parameter; instead, the CIELab-based translucency parameter would be 100 for a transparent material. The contrast ratio ranges from 0 for an absolutely transparent sample to 1 for a completely opaque sample [64]. Light transmittance always ranges from 0% (totally opaque) to 100% (totally transparent) [65].

Generally, the translucency of YSZ increases with an increase in sintering temperature and time [66–70], because larger grained microstructures with fewer grain boundaries and a higher volume fraction of c-ZrO_2 are formed. The birefringence effect, which occurs in non-symmetric crystal structured materials, will result in reflection and refraction at the grain boundaries if adjacent grains have different crystallographic orientations. t-ZrO_2 has high birefringence, which reduces light transmittance, whereas c-ZrO_2 is isotropic, which reduces light scattering [71,72]. Therefore, zirconia ceramics with fewer grain boundaries cause less light reflection, and c-ZrO_2-containing ceramics transmit more light. As a consequence, fewer grain boundaries or larger grains and a high fraction of c-ZrO_2 are conducive to the translucency of YSZ. Recent studies, however, have shown that the translucency of YSZ sintered at 1450 °C is higher than that of YSZ sintered at 1350 and 1550 °C [73,74]. In contrast, the translucency of YSZ sintered at 1600 °C is similar to that of YSZ sintered at 1450 °C [66,67,72]. Theoretically, the optical properties of YSZ sintered at 1550 °C should be superior or at least not inferior to those of YSZ sintered at 1450 °C [75,76]. Nevertheless, some studies have reported the opposite results [73,74]. This might be due to microcrack formation during $t \rightarrow m$ phase transformations above a critical t-ZrO_2 grain size with higher sintering temperatures and longer sintering times, which could negatively affect light transmittance [73,74,77,78]. Inokoshi et al. [79] reported that a significant fraction of m-ZrO_2 was obtained when 3Y-TZP was sintered at higher temperatures for longer times, and the translucency of 3Y-TZP might be affected by the increase in m-ZrO_2 fraction. Meanwhile, the phase composition has a considerable impact on the translucency of zirconia [80]; Cho Too et al. [75] reported that zirconia with a higher fraction of c-ZrO_2 had higher translucency, and Pekkan et al. [71] suggested that m-ZrO_2 itself could lower translucency because of the difference in refractive index between t-ZrO_2 and c-ZrO_2. Another hypothesis is that the amount of light scattering increases with an increase in grain size when the grain size is similar to the light wavelength. In contrast, the amount of light scattering decreases with an increase in grain size when the grain size is substantially larger than the light wavelength [58,81–83]. Moreover, some studies have reported that longer sintering times (up to 2 h) can lead to YSZ with better optical properties [70,73,74]. However, no difference was noticed between the optical properties of the YSZ samples when sintered longer than 2 h [70,74]. Therefore, short-time sintered YSZ with optical properties similar to those of long-time sintered YSZ can be achieved by increasing the sintering temperature within reasonable limits. Although some studies have reported that the optical properties of some speed-sintered YSZ materials are similar to those of the corresponding conventionally sintered samples, contradictory results have also been reported [16,22,36,42,52,53,84–87]. This indicates that speed-sintering should not be used to sinter commercial YSZ without testing or approval from the respective manufacturer.

Compared to other dental ceramics, YSZ has become popular in the field of dentistry because of its superior mechanical properties. Among the different types of YSZ, 3Y-TZP exhibits the highest flexural strength, typically ranging from 850 to 1500 MPa [66,75,88–90]; 4Y-PSZ tends to show similar flexural strength to 3Y-TZP, ranging from 900 to 1450 MPa [36,75,88–91]; 5Y-PSZ demonstrates significantly lower flexural strength at 650–1000 MPa [36,66,75,88–91]; and 6Y-PSZ has the lowest flexural strength at 500–700 MPa [36,90,91]. In this study, the mechanical properties of YSZ were characterized in terms of four different parameters, namely, three-point flexural strength, biaxial flexural strength (piston-on-three-ball method), fracture toughness, and hardness.

Stawarczyk et al. [69] reported that YSZ with a higher fracture strength (>1100 MPa) was obtained when sintered at 1400–1550 °C, whereas YSZ with a lower flexural strength (<1000 MPa) was obtained when sintered at ≤ 1350 or ≥ 1600 °C. Some other studies have partially agreed with this conclusion, while some comparisons of these studies have revealed that the flexural strength of YSZ sintered at 1350 or 1600 °C is comparable to that of those sintered at 1400–1550 °C [66,70,72,92]. Theoretically, higher sintering temperatures result in larger grains with higher transformability/toughness and possibly fewer internal defects, which would enhance the mechanical properties of YSZ [93]. Nevertheless, increasing the grain size above a critical size causes a

Table 6
Speed sintering protocols recently reported by manufacturers.

Manufacturer	Product	Recommended furnaces for speed sintering	Conventional sintering	Speed sintering	Limitations of speed sintering program	Reference
Ivoclar Vivadent, Schaan, Liechtenstein	IPS e-max ZirCAD prime; IPS e-max ZirCAD MT Muti; IPS e-max ZirCAD MT; IPS e-max ZirCAD LT; IPS e-max ZirCAD MO; IPS e-max ZirCAD prime Esthetic (only applies to third-party furnaces).	Programat S1 1600 (Except IPS e-max ZirCAD Prime Esthetic); Third-party furnaces.	440–590 min (Programat S1 1600); 550 min (third-party furnaces)	Programat S1 1600: 90–265 min (up to 3 units); 75–175 min (single crown); 165–270 min (14 units, For IPS e-max ZirCAD MO/LT) Third-party furnaces: ~290 min	For single units or 3-unit bridges (except IPS e-max ZirCAD MO/LT)	https://www.ivoclar.com/en_gb/products/a-products/ips-e.max-zircad-prime
Dentsply Sirona, Charlotte, NC, USA	Cercon ht; Cercon xt; Cercon Base; Cecron ht ML; Cecron xt ML.	Multimat2Sinter; heat DUO; Sirona HTC-speed sintering furnace; Third-party furnaces	~280 min (Multimat2Sinter, heat DUO, Sirona HTC-speed sintering furnace) 240–560 min + slow cooling to 200 °C (third-party furnaces)	Multimat2Sinter, heat DUO, Sirona HTC-speed sintering furnace: ~175 min (Cercon ht/ht ML/Base: up to 6 units; Cercon xt/xt ML: up to 3 units). Third-party furnaces: ~3 h. (Cercon ht/ht ML/Base: up to 6 units; Cerconxt/xt ML: up to 3 units).	Up to 6 units for Cercon ht/ht ML/Base; Up to 3 units for Cercon xt/xt ML	https://www.dentsplysirona.com/en-us/categories/lab/zirconia.html#zirconia-materials
Dentsply Sirona	inCoris Zi meso; inCoris TZI; inCoris TZI C; CEREC Zirconia; CEREC Zirconia Meso; CEREC Zirconia Plus	inFire HTC; inFire HTC Speed; CEREC SpeedFire	4–8 h	Speed: 1–3 h Superspeed: 10–15 min	3 single crowns or one 3-unit bridge.	https://www.dentsplysirona.com/en/service-contact/download-center.html; https://www.dentsplysirona.com/en-us/categories/cerec/sinter-with-cerec.html; https://www.dentsplysirona.com/ja-jp/explore/cerec/sinter-with-cerec.html.
Dental Direkt, Spenge, Germany	DDBioZ; DDBioZX2; DDcubeONE; DDcubeX2.	Dekema Austromat 664; Dekema Austromat 674	564–660 min (T_{max}: 1450 °C)	~2 h + rapid cooling (T_{max}: 1450 °C, Austromat 664); ~2.5 h + rapid cooling (T_{max}: 1450 °C, Austromat 674)	One plane, maximum 3 crowns per sintering process (Austromat 664); One plane, maximum 6 crowns per sintering process (Austromat 674) Only single crowns with maximum 4 mm wall thickness can be used for speed sintering programs.	https://www.dentaldirekt.de/en/products/materials/zirconium-dioxide
3 M Oral Care, St.Paul, MN, USA	3 M Chairside Zirconia	CEREC speedfire; Programat CS4.	~2.5 h (T_{max}: 1500 °C, Programat CS4 only)	20–40 min (T_{max}: 1565 °C for Programat CS4)	Only single crowns can be used for Programat CS4 furnace; 3 single crowns or 3-unit bridges can be used for CEREC speedfire.	https://www.3 m.com/3 M/en_US/p/d/b5005087087/
Zirkonzahn, South Tyrol, Italy	ICE Translucent; Prettau 4 Anterior; Prettau 4 Anterior Dispersive; Prettau; Prettau 2; Prettau 2 Dispersive; Anatomic Coloured	Zirkonofen 600/V2; Zirkonofen 600/V3; Zirkonofen 700; Zirkonofen 700 Ultra-Vakuum; Zirkonofen Turbo;	8–12 h (1500–1600 °C)	Speed sintering[†]: ~4.5 h (1500 °C) Fast sintering[‡]: ~1.5 h (1500–1600 °C) Ultra-fast sintering[§]: ~1 h (1500 °C)	[†]For ICE Translucent (single crowns and thin-walled bridges), Prettau 4 Anterior (single crowns only), Prettau 4 Anterior Dispersive (Single crowns only), Anatomic Coloured; [‡]For Prettau 4 Anterior, Prettau 4 Anterior Dispersive, Prettau, Prettau 2 and Prettau 2 Dispersive; [§]For Prettau 4 Anterior, Prettau 4 Anterior Dispersive.	https://zirkonzahn.com/us/download-section

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Table 6 (*continued*)

Manufacturer	Product	Recommended furnaces for speed sintering	Conventional sintering	Speed sintering	Limitations of speed sintering program	Reference
Kuraray Noritake, Tokyo, Japan	KATANA HT/LT; KATANA ML; KATANA HTML; KATANA STML; KATANA UTML; KATANA YML; KATANA Zirconia Block	Noritake KATANA F-2 N; CEREC speedfire†; Third-party furnaces	7 h (1550 °C)	Speed sintering 1: ~90 min (1515–1560 °C); Speed sintering 2: ~54 min (T_{max}: 1600 °C, excluding KATANA HT/LT and KATANA Zirconia Block) Super speed sintering†: ~18 min	Up to 3 crowns or 3 units bridges. †For KATANA Zirconia Block only.	https://www.kuraraynoritake.eu/en/labside/zirconia; https://www.kuraraynoritake.com/world/product/cad_materials/katana_zirconia.html
Metoxit, Thayngen, Switzerland	Z-CAD HD; Z-CAD HTL; Z-CAD ONE4ALL; Z-CAD ONE4ALL MULTI; Z-CAD SMILE.	N/A	~400–700 min (T_{max}: 1450 °C)	~105 min (T_{max}: 1530 °C)	Single crowns or bridges up to 3 units.	https://metoxit.com/dental-en/cad-cam-en/
Pritidenta, Leinfelden-Echterdingen, Germany	priti multidisc ZrO_2 multicolor (Multi Translucent/High Translucent/Extra Translucent/Translucent); priti multidisc ZrO_2 monochrome (High Translucent/Extra Translucent/Translucent/Opaque); priti multibloc ZrO_2 multicolor (High Translucent/Extra Translucent)	N/A	~7 h (T_{max}: 1450 °C)	Speed sintering $1^{\dagger}$: ~4 h (T_{max}: 1500 °C, except priti multibloc ZrO_2 multicolor Extra Translucent) Speed sintering $2^{\ddagger}$: ~1 h (only for priti multibloc ZrO_2 multicolor Extra Translucent)	†Suitable for single crowns or bridges up to 3 units; ‡Suitable for single crowns only.	https://pritidenta.com/en/products/cadcam-materials/
Whitepeaks Dental Solutions, Hamminkeln, Germany	Copran Zri; CopraSupreme; CopraSmile; CopraSupreme Hyperion; CopraClassic HS	N/A	~275 min (T_{max}: 1500 °C) + cooling time (unregulated in the closed furnace)	~70 min (1500 °C) + cooling time (unregulated in the closed furnace)	Speed program not recommended to achieve maximum translucency.	https://www.white-peaks-dental.com/en/downloads/
Sagemax, Federal Way, WA, USA	NexxZr T Multi; NexxZr+ Multi	Programat* S1, Programat* S1 1600 Programat* S2	~9.6 h (T_{max}: 1500 °C)	~4.8 h (T_{max}: 1530 °C)	Up to 5 units	https://eifu.sagemax.com/en

spontaneous $t \rightarrow m$ transformation during cooling [94], and may enhance crack propagation due to internal stresses [95]. Additionally, at high sintering temperatures (for example, 1650 °C for 3Y-TZP), the grain size and amounts of c-ZrO_2 and m-ZrO_2 increase owing to partial $t \rightarrow c$ and $t \rightarrow m$ transformations [79]. Consequently, the flexural strength of the sintered YSZ may be lower than that sintered at lower temperatures (1400–1550 °C) because of the lower proportion of t-ZrO_2 [69]. Prolonged sintering times can also contribute to better mechanical properties [54,93]. Recent studies have not provided compelling evidence for a positive influence of speed-sintering on fracture strength, which indicates that the strength of YSZ may be affected by CAD/CAM fabrication [40,96]. However, the yttrium distribution is affected by the sintering temperature, which might be another effect causing a difference in the mechanical and optical properties of YSZ [97].

Recent studies have revealed that the fracture toughness of 3Y-TZP is approximately 3.7–4.5 $MPa \cdot m^{1/2}$; that of 4Y-PSZ is approximately 3.5–4.0 $MPa \cdot m^{1/2}$; that of 5Y-PSZ is lower at 2.4–3.2 $MPa \cdot m^{1/2}$; and that of 6Y-PSZ is just 2.2 $MPa \cdot m^{1/2}$ [88–90]. Positive correlations have been reported between the fracture toughness and sintering temperature [79], sintering time [54,79], and cooling rate [88]. However, speed-sintering cannot guarantee a higher fracture toughness than conventional sintering, which indicates that a high sintering rate may have a strong negative influence on fracture toughness [30]. YSZ with lower hardness can occasionally be obtained at higher sintering temperatures [79], which suggests that a larger grain size decreases the hardness of YSZ [98]. In addition, the increased fraction of m-ZrO_2 on the outer surface of YSZ may affect the hardness of YSZ because the $t \rightarrow m$ transformation at the YSZ surface would produce compressive stresses, leading to higher hardness [70]. However, the $t \rightarrow m$ transformation could also reduce the hardness because of the presence of microcracks. Nevertheless, our meta-analysis did not find significant differences in the fracture toughness and hardness of conventionally sintered and speed-sintered YSZ.

Some studies have investigated "superspeed" sintering, which is characterized by an extremely short sintering time, i.e., a total sintering time of 10–30 min, with an initial heating rate of 100–400 °C/min [16,22,36,37,53,54,59]. Most of these studies demonstrated that the optical properties of superspeed-sintered YSZ are comparable to those of conventionally sintered YSZ. Nevertheless, the mechanical properties of superspeed-sintered YSZ are different from those of conventionally sintered YSZ. Lawson and Maharishi [16] and Liu et al. [36] reported that the flexural strength of superspeed-sintered 5Y-PSZ was higher than that of conventionally sintered 5Y-PSZ due to the smaller grain size. Other studies revealed that the hardness and fracture toughness of superspeed-sintered YSZ were higher and lower than those of conventionally sintered YSZ, respectively [22,54,59]. Few studies have focused on the differences in the optical and mechanical properties of superspeed- and speed-sintered YSZ samples. Yılmaz Savaş and Akın [53] reported that the translucency parameter and contrast ratio of superspeed-sintered 3Y-TZP were similar to those of speed-sintered

3Y-TZP in a group of samples processed without dipping in coloring liquid. Liu et al. [36] demonstrated that the translucency parameter of superspeed-sintered Katana STML (5Y-PSZ; Kuraray Noritake Dental, Tokyo Japan) was comparable to that of speed-sintered Katana STML. However, the biaxial flexural strength of superspeed-sintered Katana STML was considerably higher than that of speed-sintered Katana STML. The current study showed that superspeed-sintered YSZ can be a viable material for dental treatment, which may facilitate one-day or chairside restorative treatment.

Recently, some manufacturers have reported speed-sintering protocols with total sintering times that are significantly shorter than those of their conventional sintering protocols (Table 6). However, most speed-sintering protocols have two main limitations. The first is that only a few furnaces can be used for speed-sintering. Some manufacturers have suggested the use of specific speed-sintering furnaces. Another limitation is that speed-sintering cannot be used for the fabrication of long bridge restorations. According to the manufacturers, speed-sintering is only suitable for single crowns or bridges of up to three units. Although manufacturers have not explicitly stated the reasons for this, there are several possible reasons why speed-sintering programs may not be suitable for long-span restorations. For example, the limited chamber size of the designated furnaces and zirconia blocks used in speed-sintering may mean that they are not able to accommodate long bridges. Additionally, the rapid sintering and cooling processes inherent to speed-sintering could lead to increased shrinkage and cracking in long bridges compared to that in single crowns or shorter bridges. The presence of such cracks might adversely affect the overall quality and structural integrity of long-span restorations. Nevertheless, further research is crucial to fully comprehend the feasibility and limitations of using speed-sintering protocols with long-span dental restorations, and a comprehensive investigation is warranted to thoroughly examine how speed-sintering protocols affect long-span restorations.

Our study has some limitations since detailed data could not fully be obtained. Another notable concern is that a considerable proportion of the selected studies did not specify the method employed for sample size calculation. Consequently, it is challenging to ascertain whether the sample sizes in each study were adequate to draw reliable conclusions. Some studies had suboptimal study designs, which could have introduced bias into the overall findings of this review. In addition, only three databases were searched. Some relevant studies in other databases were unavailable. Some studies have proposed a manual search of the related studies on websites such as Google Scholar; however, herein, a manual search was not conducted. Our review suggests that speed-sintered YSZ could be a viable and acceptable option for restorative dental treatments. Once *in-vitro* experimental studies yield appropriate results for speed-sintered YSZ, clinical or *in-vivo* studies are needed to assess the clinical behavior of this material.

5. Conclusion

A systematic review and meta-analysis of the effects of speed-sintering on the optical and mechanical properties of YSZ are reported. The meta-analysis revealed that speed-sintering does not considerably influence the CIEDE2000-based translucency, contrast ratio, three-point flexural strength, biaxial flexural strength, or fracture toughness of YSZ compared to those of conventionally sintered YSZ. However, the CIELab-based translucency of conventionally sintered YSZ is higher than that of speed-sintered YSZ. The descriptive analysis indicated that speed-sintering does not affect the hardness of YSZ compared to that of conventionally sintered YSZ. The abovementioned results suggest that speed-sintered YSZ could be a feasible material for crowns and short-span restorations. It is important to note that most of the papers selected for this study did not provide a clear explanation of their sample size determination method. Given this limitation, a cautious interpretation of the findings is warranted, along with more well-designed studies on the influence of speed-sintering on YSZ. However, based on the available evidence, speed-sintered YSZ demonstrates potential as a choice for restorative dental procedures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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