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Dental zirconia residuals recycling: processes, applications, and future perspectives: a scoping review

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Abstract

Background This review aimed to address the growing interest in recycling dental zirconia residues, which are a significant byproduct of the CAD/CAM milling process, contributing to environmental and economic concerns. Further, the review evaluates the potential applications of recycled zirconia in dentistry.

Methods This scoping review followed PRISMA-ScR guidelines. Eligible sources included peer-reviewed articles, theses, and conference papers, with no restrictions on time or language; unrelated studies and opinion pieces were excluded. A systematic search was conducted across PubMed, Scopus, and Web of Science databases, as well as relevant grey literature. Two independent reviewers handled study selection, data extraction, and qualitative synthesis. Findings are presented in a narrative format with tables and figures.

Results The search yielded 26 pertinent studies on recycled zirconia, concentrating on recycling methodologies, sintering parameters, and prospective applications. The findings revealed that sintering parameters, including temperature, time, and atmospheric conditions, significantly impacted recycled zirconia's mechanical, physical, and optical properties. The mechanical properties, such as flexural strength, are still lower than those of commercially available dental zirconia. However, the microstructure, density, and shrinkage ratio, alongside the clinically acceptable flexural strength, are encouraging for the clinical adoption of recycled dental zirconia, particularly for short-span bridges. Moreover, the recycled zirconia powder can be applied as fillers in polymethyl methacrylate (PMMA) and as powders for digital scanning.

Conclusion Recycling dental zirconia is both feasible and beneficial; the utilized recycled materials might be adoptable for clinical applications with optimized recycling processes and sintering parameters. Despite the promising findings, challenges remain, particularly in using mechanical behavior compared with commercially available zirconia.

Keywords Dental materials, Environmental sustainability, Recycling, Waste management, Zirconium oxide

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Introduction

Zirconia is highly valued in modern dentistry for its exceptional mechanical strength, biocompatibility, durability, aesthetic qualities, and predictable dimensional stability, making it a primary choice for crowns, bridges, and dental implants [1, 2]. The fabrication of such restorations from zirconia materials requires an automated production technology. Computer-aided design and computer-aided manufacturing (CAD-CAM) have been used to design and produce dental restorations and prostheses for 4 decades [3]. The most adopted production process employs subtractive manufacturing, which implies grinding or milling zirconia blocks or discs until the desired form is reached. Consequently, this manufacturing process generates approximately 30% powdered waste. Furthermore, each disc has consistently unmachined portions, increasing waste production to as much as 80% of the initial mass [4, 5].

These residual materials, if not appropriately managed, might exacerbate the mounting problem of material wastage and indeed would contribute to environmental pollution. Moreover, given the steep expenses associated with zirconia, developing effective recycling strategies to address waste issues and optimize material utilization is imperative [6]. Considering the economic and environmental implications, understanding the potential for recycling zirconia residuals is paramount.

Apart from recycling potentials, several challenges are associated with zirconia residuals, including the contamination of zirconia residues with milling debris and other impurities, difficulties in processing without impairing zirconia properties referring to its zirconia's high hardness and brittleness [7], and the difficulty in developing efficient and cost-effective techniques for collecting, cleaning, and reprocessing zirconia waste into a usable form [8]. Several methods have been investigated for the recycling of residual zirconia, including mechanical milling, heat treatment, and chemical processing [9–11]. Sintering is a crucial stage in recycling and entails careful control of parameters such as temperature, time, and atmosphere to obtain the desired mechanical and aesthetic properties [10, 11]. Nevertheless, recycled zirconia was associated with lower mechanical, physical, and optical properties than commercially available zirconia materials in several studies [12–14], which might be attributed to lower quality or impurity than commercially available zirconia [6].

Advancements in recycling technologies can facilitate sustainable dental practices, thereby fostering a circular economy within the dental industry [15]. This scoping review aimed to comprehensively explore the scope of existing literature on recycling dental zirconia residue, focusing on the types of zirconia residuals, recycling processes, sintering parameters, and applications of recycled zirconia.

Method

This scoping review was carried out following the preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR) guidelines [16].

Research question

"What is the scope of existing literature on the recycling of dental zirconia residue, specifically examining the types of zirconia residues, recycling processes, sintering parameters, and applications of recycled zirconia across published studies?"

Eligibility criteria

The review's objective was to encompass peer-reviewed articles, conference papers, theses, and dissertations that address the recycling of dental zirconia residuals, with a particular emphasis on recycling procedures, sintering parameters, and applications of recycled dental zirconia. No limitations were imposed on time or language. Studies not focused on dental zirconia, its recycling, and opinion pieces, editorials, and commentaries were excluded.

Chinese sources were analyzed by reviewers who are proficient in the Chinese language. When necessary, a machine translation tool (www.deepl.com) was employed to facilitate interpretation. Two reviewers verified all translated material to ensure accuracy and consistency.

Systematic search

A comprehensive search strategy was formulated in collaboration with a medical librarian. The strategy focused on electronic databases such as PubMed, Scopus, and Web of Science. Additionally, the search encompassed manual checks of reference lists from relevant studies and an examination of grey literature through ProQuest Dissertations & Theses Global and conference proceedings. The search terms (including both text words and indexing terms) employed in this strategy included keywords such as "dental zirconia," "zirconia recycling," "recycled zirconia," "zirconia residuals," "zirconia waste," and "zirconia applications." These terms were combined using appropriate Boolean operators (AND, OR). The keywords employed and the databases searched are detailed in Supplementary Table 1.

Screening and selection

The selection process involved two stages: screening titles and abstracts to find eligible articles and exclude irrelative ones, followed by screening the full text of the selected records. Two reviewers independently assessed the titles and abstracts of the retrieved articles to identify studies that potentially met the eligibility criteria. Subsequently, the same two reviewers evaluated the full texts of the studies that passed the initial screening to confirm their eligibility. A consensus was reached in case of disagreements, or a third reviewer was consulted for resolution.

Data extraction

The data were independently extracted by two reviewers using a pre-tested data charting form, capturing study characteristics such as author, year, country of publication, type of zirconia residuals, detailed descriptions of the recycling processes, critical sintering parameters (temperature, time, atmosphere), and applications of recycled zirconia in dental practices.

Data analysis

The extracted data was synthesized using a qualitative methodology, in which the principal components of the included studies were systematically summarized. Subsequently, a narrative approach was employed to articulate the findings, supplemented by tables and figures to augment clarity.

Results

Web search results

Database searches identified 6,096 records, and 81 were found through other sources, totaling 6,177. After removing 1,962 duplicates, 4,217 titles and abstracts were screened, excluding 4,172 records, and 45 full-text articles were left for further eligibility evaluation. A total of 26 studies [5, 6, 8–11, 13, 14, 17–34] were included in this scoping review (Fig. 1). While 19 records were excluded for reasons (Supplementary Table 2, available online).

A high level of concordance was observed between the two reviewers when selecting articles (Cohen kappa = 0.93, $P<.001$) and data extraction (Cohen kappa = 0.96, $P<.001$).

Characteristics of included studies

The detailed characteristics of the included studies are summarized in Table 1. All studies were conducted in an in vitro setting using 3 Mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal (3Y-TZP) zirconia residue, except for one study that recycled 4 Mol% Yttria Stabilized Zirconia (4YSZ) residue [26]. All studies were published in English except for 2 Chinese records [14, 28]. Regarding the zirconia residuals form, 12 studies (46%) [5, 6, 14, 17, 22, 25–28, 31, 32, 34] used the remaining block residue, and 14 studies (54%) [8–11, 13, 18–21, 23, 24, 29, 30, 33] used the powder collected from the milling machines. Regarding the application of zirconia waste, 20 studies [5, 6, 8–11, 13, 14, 17, 18, 20, 22, 23, 25, 27, 28, 31–34] made recycled ceramic materials through various processes. Among these, one study focused on producing an alumina-zirconia composite [17], and 2 studies [19, 21] produced recycled zirconia powder. Additionally, 3 studies used the powder collected from the milling machines as reinforcement fillers for polymethyl methacrylate (PMMA) [24, 26, 30]. One study used residual powder for digital scanning as a substitute for optical scanning spray [29]. Figure 2 provides a comprehensive overview of the various stages involved in the recycling process of zirconia residue. Figure 3 illustrates the distribution of recycled zirconia waste across different applications.

Most included studies assessed recycled zirconia properties, including microstructure and physical, mechanical, and optical properties. The detailed properties evaluated are summarized in Table 2. The bulk of the included records assessed the mechanical properties of recycled zirconia.

The findings of the included studies

Recycled zirconia is associated with lower mechanical-physical properties than commercially available zirconia in most studies [12, 22, 29, 30, 32, 34]. Blending zirconia residue powder with commercial zirconia powder at a concentration of 5%, 10%, and 50% ratios showed no difference in the end product with different integrated ratios, and all products containing residue powder reported half the flexural strength values of the products manufactured from the commercially available powder [20].

Sintering parameters played a crucial role in determining the quality and performance of recycled zirconia. Across the studies, sintering temperatures typically ranged between 1400 °C and 1600 °C, with most researchers reporting optimal results around 1550 °C. For instance, de Assis et al. 2014 [9] and Kayalar et al. 2022 [27] highlighted the benefits of higher sintering temperatures in achieving densification and mechanical stability. Pre-sintering at lower temperatures, commonly around 1000 °C, was frequently employed to reduce surface defects and improve particle packing [33]. Heating and cooling rates were meticulously controlled, with gradual rates such as 4 °C/min [31], ensuring uniform phase transformations and densification. Holding times of approximately 2 h at the peak sintering temperature were standard across studies, facilitating full material densification and minimizing structural inconsistencies [32].

Higher sintering temperatures might enhance fracture toughness and dense microstructures [18]. Kim et al. 2012 [14] reported a flexural strength of 680 MPa for recycled zirconia compared to 800 MPa for commercial materials, while Hovakhti et al. 2018) [22] noted a reduction to 250 MPa but observed improvements with optimized methods. Hardness values for

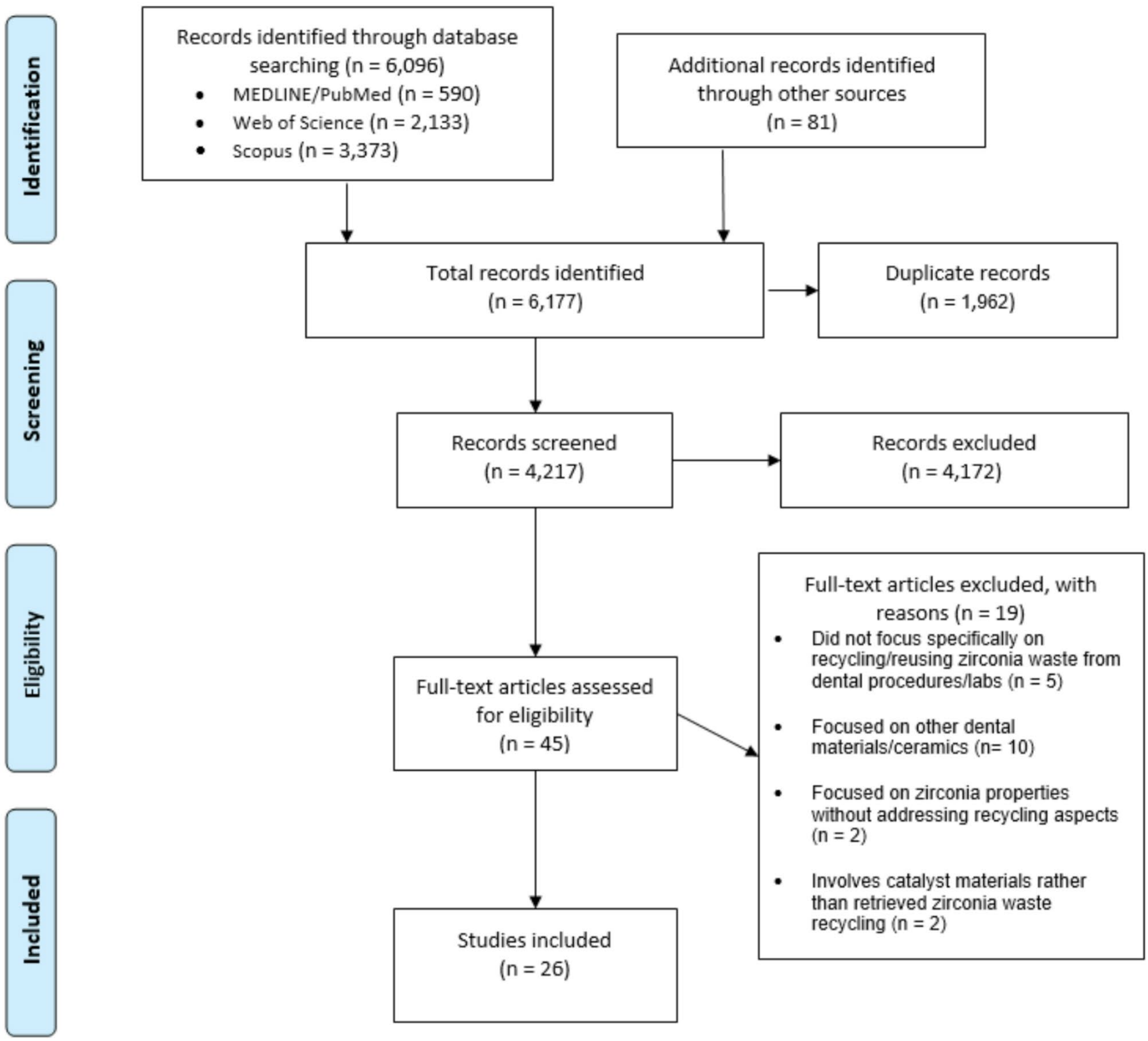

Fig. 1 Preferred Reporting Items for scoping review (PRISMA-ScR) flow indicating number of studies at different review stages

composites with 3–15% recycled zirconia ranged from 1300 HV to 1400 HV, with fracture toughness between 3.3 and 3.7 MPa·m$^{1/2}$ [17]. Elzahar et al. 2022 [26] found that adding 0.3% ZrO_2 nanoparticles improved flexural strength, elasticity, and hardness. Temperature significantly affects outcomes; a study reported that higher sintering temperatures (up to 1250 °C) improve densification and mechanical performance [13]. More details are available in Table 3.

The optical properties of recycled zirconia were evaluated by four studies [8, 20, 31, 32], which collectively reported reduced translucency and aesthetic appearance compared to commercially available zirconia. Specifically, Su et al. 2024 [32] concluded that recycled zirconia exhibited lower translucency and opalescence, with the color differences exceeding acceptable thresholds even when using the same staining procedure, and these effects were more pronounced with increasing thickness. These findings highlight the need for further research to optimize processing techniques and enhance the aesthetic properties of recycled zirconia for dental applications.

The particle size of recycled zirconia powder, a crucial factor impacting the material properties, is associated with improving the physical-mechanical properties when fine particles are produced compared with coarse particle products [25, 28]. The molding process significantly influences the properties of recycled material, with cold isostatic pressing typically yielding denser recycled zirconia compared to uniaxial pressing [10, 11]. For further

Table 1 Characteristics of included studies

Study ID	zirconia structure	zirconia residuals	Recycling process	Sintering parameters	Application of recycled product
Kojima et al. 2007	3Y-TZP	Zirconia Powder	Zirconia powder pressed into disc, sintered, then disintegrated into small fragments by hydrothermal treatment and milled into recycled zirconia powder.	Room temperature to 1500–1600 °C with holding time of 2 h.	To produce recycled zirconia powder
Kamiya et al. 2007	3Y-TZP	Zirconia Powder	Zirconia powder was pressed into a disc and sintered, then disintegrated into small fragments by hydrothermal treatment, milled into recycled zirconia powder, sieved, pressed into a disc by uniaxial pressing, and finally sintered.	Room temperature to 1450°–1550 °C for 2 h	To produce recycled zirconia ceramic
Kim et al. 2012	3Y-TZP	Zirconia residual waste blocks	Residual zirconia blocks were crushed into 1.5–2 cm pieces using a zirconia mortar, milled for 10 min at 1000 rpm with a vibrating disc mill, and sieved through a 180-mesh sieve for uniform particle size distribution.	The ceramic material underwent preliminary sintering at 1000 °C for 1 h, followed by full sintering in a conventional furnace with 100 °C increments (1200–1600 °C), each held for 1 h. The heating rate was not specified but likely slow, and the atmosphere was inferred to be air.	To produce recycled zirconia ceramic
de Assis et al. 2014	3Y-TZP	Zirconia powder	Zirconia residue powder was collected and calcined, then pressed into a disc with pressures of either 70 or 100 MPa, and finally sintered.	The sintering of the compacts was performed at 1550 °C for 60 min with a heating and cooling rate fixed at 5 °C/min in a MAITEC F1650 oven to obtain sintered samples.	To produce recycled zirconia ceramic
Silva et al. 2016	3Y-TZP	Zirconia powder	Zirconia powder was collected and sieved, then pressed into a disc using uniaxial (50 MPa) isostatically pressed(200 MPa), and finally sintered.	The final sintering process involved subjecting the samples to a temperature of 1500 °C for 1 h to achieve full densification of the material, without any information on pre-sintering steps.	To produce recycled zirconia ceramic
Sriboonpeng et al. 2017	3Y-TZP	Zirconia powder	Zirconia residue powder was collected, purified, and then milled to produce nanopowder.	NR	To produce nano-recycled zirconia powder
Sliva et al. 2017	3Y-TZP	Zirconia powder	The recycled zirconia powder was collected and pressed into a disc using both a uniaxial dry press (30 MPa) and then an isostatic press (100 MPa)., and then finally sintered.	The samples were heated to 1500, 1550, and 1600 °C at the heating and cooling rate of 10 °C / min for 1 h. This was done to test the densification over a range of temperatures.	To produce recycled zirconia ceramic
Gouveia et al. 2017	3Y-TZP	Zirconia powder	Zirconia residue powder was collected, sieved to achieve uniform particles, and dried at 100 °C. Mixed with commercial zirconia powder in varying proportions (5%, 10%, and 50%) using a Turbula Shaker Mixer for 10 h at 80 rpm, pressed into disc shapes at 100 MPa.	A gradual increase in temperature to 1500 °C at a rate of 5 °C per minute, followed by a 2-hour holding period, effectively achieved complete densification of the material in a one-step procedure.	To produce recycled zirconia ceramic
Hovakhti et al. 2018	3Y-TZP	unused remnants of abrasion zirconia blocks	Zirconia remnants were ground into powder, separated to 1 micrometer or smaller, and pressed into 18 mm molds under 50 bar, forming 1.6 mm thick discs.	The discs were sintered in a furnace at 1360 °C for 2 h.	To produce recycled zirconia ceramic
Cossu et al. 2018	3Y-TZP	zirconia residue block	The zirconia, recycled from pre-sintered blocks, was fragmented into powder, mixed with alumina powders in varying proportions (3-15wt%), and uniaxially pressed at 80 MPa into specific shapes.	Sintering in a MAITEC™ F1650 oven involves heating at 1 °C/min to 900 °C for 2 h to remove the binder, followed by 5 °C/min to 1600 °C for 2 h, and cooling at 10 °C/min.	To produce alumina-zirconia composite
Sriboonpeng et al. 2019	3Y-TZP	zirconia powder	Zirconia residue powder was collected, purified, milled to produce nano-powder, and pressed into pellets using a uniaxial die press at 100 MPa, forming discs approximately 15 mm in diameter and 7 mm thick.	Each pellet was placed in an alumina plate and sintered in air at temperatures ranging from 950 to 1250 °C with a dwell time of 2 h and heating/cooling rates of 5 °C min.	To produce presinteredrecycled zirconia ceramic

Table 1 (continued)

Study ID	zirconia structure	zirconia residuals	Recycling process	Sintering parameters	Application of recycled product
Su et al. 2020	3Y-TZP	zirconia powder	A slurry was prepared using commercially available zirconia powder, methyl alcohol, dispersant, and photopolymer resin. The zirconia powder obtained from this slurry was recycled by collecting it, adding it to methyl alcohol, ball milling it, and then preparing a new slurry for 3D printing. This process resulted in the production of recycled zirconia through 3D printing.	The samples were sintered in a tube furnace by heating from room temperature to 310 °C at a rate of 2 °C/min and holding for 30 min, then increasing the temperature to 590 °C at the same rate and holding for 1 h. Finally, the temperature was raised to 1500 °C at 4 °C/min and held for 2 h.	To produce recycled zirconia ceramic
Ding et al. 2020	3Y-TZP	zirconia residue block	Zirconia waste was pulverized, sieved, and treated with 0.5 mol/L nitric acid to remove impurities. The processed powder was hydraulically pressed into green blanks and dried.	Pre-sintering involved gradual heating to 600 °C, then rapid increases to 800–1100 °C in 50 °C increments, with 2-hour holds at each step. Final sintering involved a quick heat-up to 800 °C, followed by heating to 1450 °C at 10 °C/min, with 2-hour holds at each stage. Both processes ended with natural cooling, evaluating various temperature parameters.	To produce recycled zirconia ceramic
Ozdogan et al. 2021	3Y-TZP	zirconia powder	The zirconia residue powder was mixed with acrylic resin powder. Next, MMA liquid was added to create a dough. The dough was poured into a mold and left to cure, forming samples.	NR	As reinforcing fillers for PMMA
Cordeiro et al. 2022	3Y-TZP	Zirconia Waste Powder	Zirconia Waste Powder (ZWP), sourced from dental prosthesis production using CAD/CAM zirconia discs, was calcined at 500 °C to remove impurities, de-agglomerated for fine particle size, humidified, and uniaxially pressed into disc-shaped samples.	The pressed specimens were sintered at 1300 °C, 1400 °C, and 1500 °C with a heating rate of 10 °C/min, held at the target temperature for 2 h, and then cooled naturally.	To produce recycled zirconia ceramic
Elzahar et al. 2022	4Y-PSZ	Remaining zircon particles	Zircon powder was milled into nanoparticles via ball milling, dispersed in methyl methacrylate (MMA) at concentrations of 0.01%, 0.1%, 0.3%, and 0.5%, and polymerized to form a composite. Recycled zirconia nanoparticles were incorporated into PMMA using the sprinkle technique, and polymerized at 41 °C under 2.4 bar for 15 min, ensuring uniform bonding and distribution.	NR	As reinforcing fillers for PMMA
Yang et al. 2022	3Y-TZP	zirconia residue block	Zirconia residue was pulverized into coarse and fine powders, pressed into discs via uniaxial and isostatic pressing, respectively, then subjected to presintering and final sintering.	Presintering involved slow heating to 600 °C, followed by varied rates to 1050 °C with a 2-hour hold. Final sintering included rapid heating to 800 °C, then to 1450 °C at 10 °C/min with a 2-hour hold. Controlled cooling from 1450 °C to 800 °C and 800 °C to 250 °C preceded natural cooling, enabling a multi-step densification cycle.	To produce recycled zirconia ceramic
Kayalar, et al. 2022	3Y-TZP	zirconia residual waste blocks	Residual zirconia blocks were crushed into 1.5–2 cm pieces, milled for 10 min at 1000 rpm using a vibrating disc mill, and sieved through a 45 μm screen for uniform particle size. The recycled powder was analyzed via particle size analysis, XRD, and SEM, then mixed with 3Y-TZP powder (3–100% by weight) to form test mixtures. These were uniaxially cold pressed and CIPed at 250 MPa to create green pellets.	Samples were pre-sintered at 1000 °C for 4 h, then sintered at 1450 °C, 1500 °C, and 1550 °C for 2 h each with varied heating rates and cooling at 10 °C/min. A Protherm furnace facilitated densification through multi-step heating from room temperature to final sintering in air.	To produce recycled zirconia ceramic
Campos, et al. 2024	3Y-TZP	Residual zirconia powder	The recycling process for 3Y-TZP involves collecting powder from CAD/CAM milling equipment, calcining at 900 °C to remove impurities, sieving to isolate particles < 75 μm, compacting into discs, pre-sintering at 1000 °C, and optionally glass-infiltrating before sintering at 1450–1550 °C to enhance mechanical properties for dental reuse.	Sintering was conducted at 1450–1550 °C for 2 h following pre-sintering at 1000 °C for 1 h, with heating and cooling rates of 5 °C/min. Glass-infiltrated and non-infiltrated specimens were compared at each sintering temperature.	To produce recycled ceramic

Table 1 (continued)

Study ID	zirconia structure	zirconia residuals	Recycling process	Sintering parameters	Application of recycled product
Su et al. 2024	3Y-TZP	zirconia residual waste blocks	specimens were made from commercial 3Y-TZP blocks and 60 specimens were made from residual zirconia waste from the same blocks. Residual zirconia blocks are pulverized into a fine powder, then heated to 900 °C at 10 °C per minute, held for 30 min, and cooled to remove organic additives. The powder is compacted into a rectangular mold using a high-pressure powder tablet press machine and a cold isostatic press. The compacted blocks are presintered at 1050 °C for 2 h, cooled to room temperature, and subsequently cut into specimens using a low-speed precision cutter.	Recycled zirconia powder was heated to 900 °C at 10 °C/min and held for 30 min to remove organic additives. Blocks were presintered at 1050 °C for 2 h, followed by cooling to room temperature.	To produce recycled zirconia ceramic
Sahyon, et al. 2024	3Y-TZP	Non-milled zirconia remnants	The 3Y-TZP zirconia recycling process involves collecting non-milled remnants, fragmenting, ball-milling to < 5 μm particle size, sieving, optional calcination at 900 °C, uniaxial pressing, and sintering. Calcination enhances the microstructure, optical, and mechanical properties, improving suitability for dental applications.	Zirconia specimens, both commercial and recycled, were sintered at 1550 °C for 2 h with a controlled heating and cooling rate of 4 °C/min. The process ensured uniform densification and maintained the tetragonal phase, adhering to ISO 6872:2015 dental material standards.	To produce recycled zirconia ceramic
Lu et al. 2024	3Y-TZP	zirconia residual waste blocks	Residual zirconia blocks were ground into powder, sieved through a 300-mesh screen, and heat-treated at 900 °C with a 10 °C/min ramp and a 30-minute hold. The powders were compacted into green bodies via hydraulic pressing at 70 kN and isostatically pressed at 300 MPa. Sectioning was done with a low-speed diamond saw under water cooling, followed by sintering per manufacturer instructions to produce recycled zirconia blocks.	Gradual heating process to 900 °C with a 10 °C/minute ramp,	To produce recycled zirconia ceramic
Echhpal II et al. 2024	3Y-TZP	Zirconia powder	The zirconia powder was collected in a sterile bowl left over from the milling machine.	NA	To reuse for extraoral scanning instead of an optical scanning spray:
Naina et al. 2024	3Y-TZP	Zirconia powder	The zirconia powder was collected from the milling machine.	NA	Residual zirconia incorporated into acrylic resin to improve mechanical properties for use in provisional restorations.
Abi et al. 2024	3Y-TZP	Zirconia powder	Dental zirconia waste powders were collected, calcined to remove wax, and milled to reduce size. Slip-casting suspensions were prepared to contain the powder, water, dispersant, and binder. These were used to cast samples that were dried and pre-sintered. Final sintering occurred at 1400–1450 C. Density, strength, and microstructure analysis determined the waste powders could be recycled through this process to produce usable ceramic samples.	Pre-sintering samples at 1000 °C after casting and drying to remove surface defects. Final stage, sintering then occurred at either 1400–1450 °C, using a 5 °C/min heating rate and two hours at the peak temperature. Natural furnace cooling was followed without forced cooling to evaluate the effect of the final sintering temperature on density, strength, and microstructure.	To produce recycled zirconia ceramic

Table 1 (continued)

Study ID	zirconia structure	zirconia residuals	Recycling process	Sintering parameters	Application of recycled product
Valian et al., 2024	3Y-TZP	zirconia residual waste blocks	. Hydrothermal treatment of residual zirconia blank margins at 275 °C and 10.5 MPa for 24 h. This was followed by ball milling to produce nano-powders. Samples were then fabricated and analyzed via uniaxial and isostatic pressing from the milled powders.	Sintering was done at 600 °C for 30 min and 1000 °C for 2 h, while full sintering was conducted at 1450 °C for 2 h with the given heating and cooling rates.	To produce recycled zirconia ceramic

details, the main findings of the included studies are summarized in Table 3.

Discussion

The rationale for this scoping review stems from the growing interest and emerging research in the recycling of dental zirconia. While previous reviews [35] have provided valuable insights, an updated exploration is warranted, given the increased number of relevant studies and the expanding range of investigated applications and properties. This review incorporates a broader and more recent body of literature, including studies published up to 2024, and aims to map key themes such as recycling procedures, sintering parameters, and the physical and mechanical characteristics of recycled zirconia. It also identifies underexplored aspects—such as optical properties [8, 31, 32, 34], bonding affinity [5], and novel applications like scanning powders—that have received limited attention in earlier reviews. By taking a more inclusive and exploratory approach, this review seeks to provide a comprehensive overview of the current landscape and highlight areas for future research.

The grinding of zirconia residues

Early research [18, 19] laid the groundwork by exploring recycled 3Y-TZP zirconia powder and ceramics through pressing, sintering, hydrothermal treatment, and milling, focusing on particle size, microstructure, and crystalline structure. The reviewed studies demonstrated a diverse range of approaches to recycling. Generally, recycling processes primarily focused on transforming zirconia waste into usable powders, employing various techniques tailored to optimize purity and particle size. Disintegration and milling were widely utilized, with hydrothermal treatment and mechanical milling ensuring uniform particle size distribution [18, 19]. Mechanical crushing, often followed by ball milling, was another common approach to generating fine powders [14, 27].

The pulverization process was well described by Valian et al. 2024 [34]. The process started by crushing the residuals from zirconia discs in a zirconia mortar grinder into millimeter and micrometer size fragments at 100 rpm for 10 min. The ground fragments were rinsed with distilled water to remove the dust particles. Finally, the fragments were dried at 120 ∘C for 24 h in an oven to remove any remaining moisture content. This process was followed by ball milling, which was conducted at 450 rpm for 8 h using a zirconia jar and ball with distilled water as the grinding medium. Other additives, including dispersants and binders, were also added to the zirconia slurry. This process was followed by a gradual drying process to achieve a moist mass with approximately 3–5% humidity, which was granulated by passing through a 20 stainless steel mesh screen via sieving. The granules

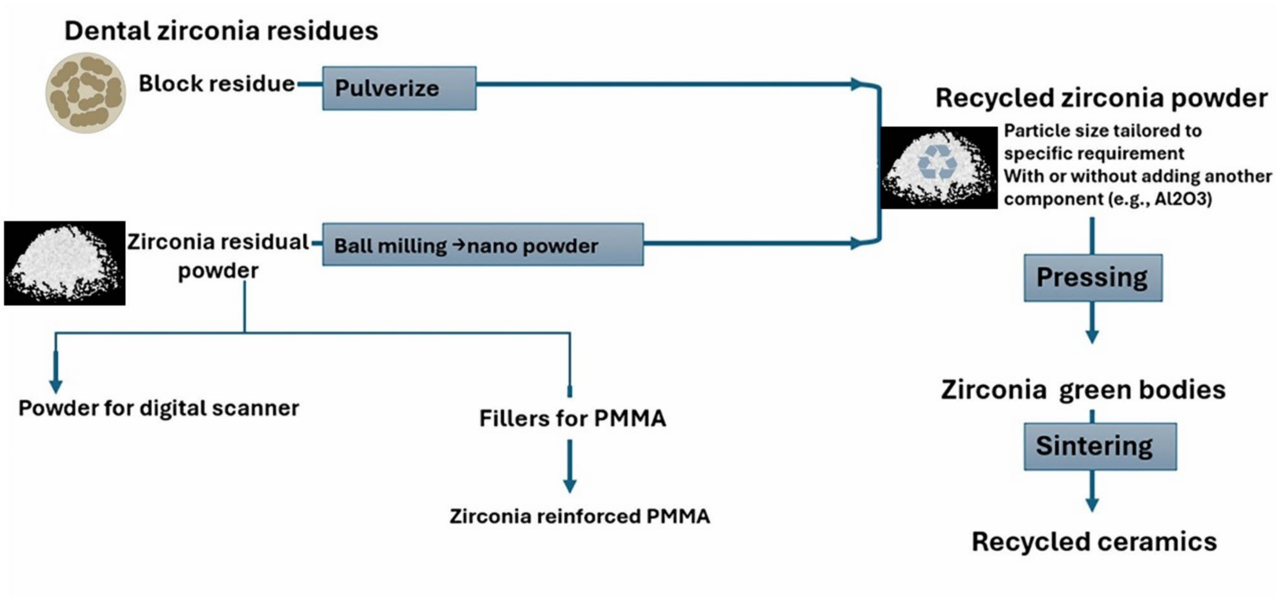

Fig. 2 Overview of the different stages involved in the recycling of zirconia residue

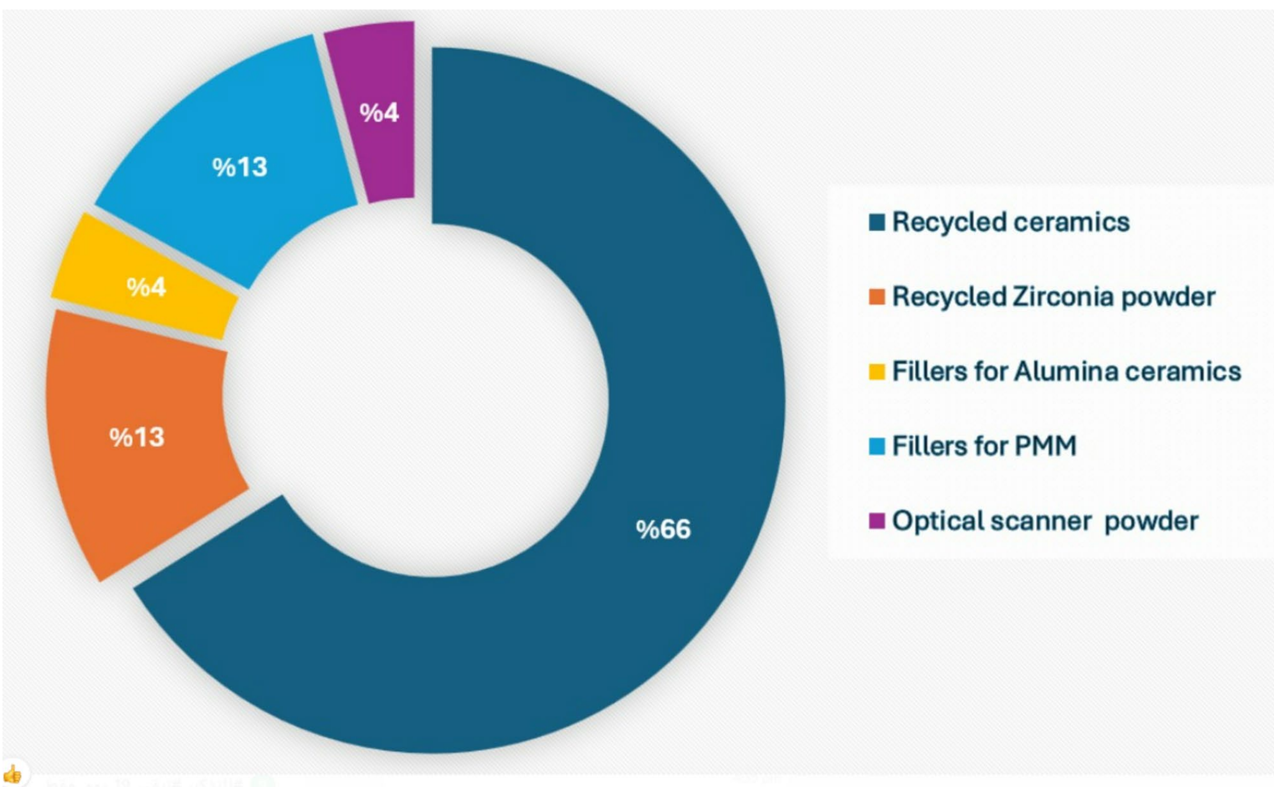

Fig. 3 Distribution of various applications of recycled zirconia waste

were stored in moisture-proof containers for 24 h, allowing for the homogenization of moisture throughout the granulated material. Additionally, advanced techniques such as hydrothermal treatment followed by ball milling showcased the potential to produce nano-powders with superior properties for applications like dental ceramics [34].

Another study [33] grinds the residual zirconia powder to simulate the commercially available powder (20 and 120 µm particle size [20] with 0.1 to 2000 µm residue [20,

Table 2 Tested properties of recycled zirconia in included studies

Category	Tested properties
Mechanical properties	• Bending/Flexural Strength, (Kim et al., 2012, Gouveia et al., 2017, Silva et al., 2017, Hovakhti et al., 2018, Sriboonpeng et al., 2019, Su et al., 2020, Ding et al., 2021, Cordeiro et al., 2022, Elzahar et al., 2022, Yang et al., 2022, Valian et al., 2024) • Shear Bond Strength, (Lu et al., 2024) • Bonding Durability, (Lu et al., 2024) • Fractography, (Campos et al., 2024, Strazzi-Sahyon et al., 2024, Valian et al., 2024) • Fracture Toughness, (Cossu et al.,, Kamiya et al., 2007, Kayalar 2022, Silva et al., 2017, Sriboonpeng et al., 2019, Ding et al., 2021) • Impact Strength, (Elzahar et al., 2022) • Flexure strength, (Campos et al., 2024, Strazzi-Sahyon et al., 2024) • biaxial flexural strength (Campos et al., 2024, Strazzi-Sahyon et al., 2024) • Young's Modulus, (Gouveia et al., 2017, Su et al., 2020) • Modulus of Elasticity, (Elzahar et al., 2022)
Physical and chemical properties	• Porosity, (Abi et al.,, Kim et al., 2012, Gouveia et al., 2017, Silva et al., 2017, Sriboonpeng et al., 2019, Cordeiro et al., 2022, Kayalar 2022) • Bonding Affinity, (Lu et al., 2024) • Density, (Cossu et al.,, de Assis et al.,, Kamiya et al., 2007, Gouveia et al., 2017, Silva et al., 2017, Sriboonpeng et al., 2019, Su et al., 2020, Ding et al., 2021, OZDOGAN and Karslıoğlu 2021, Cordeiro et al., 2022, Kayalar 2022, Yang et al., 2022, Campos et al., 2024, Strazzi-Sahyon et al., 2024, Valian et al., 2024) • Chemical Composition, (Gouveia et al., 2017, Ding et al., 2021, OZDOGAN and Karslıoğlu 2021, Cordeiro et al., 2022, Lu et al., 2024) • Cutting Surface Morphologies, (Ding et al., 2021) • Grain Size, (Kamiya et al., 2007, Gouveia et al., 2017, Silva et al., 2017, Silva et al., 2017, Sriboonpeng et al., 2019, Lu et al., 2024, Strazzi-Sahyon et al., 2024, Valian et al., 2024) • Hardness, (Cossu et al.,, Kamiya et al., 2007, Silva et al., 2017, Sriboonpeng et al., 2019, Ding et al., 2021, OZDOGAN and Karslıoğlu 2021, Cordeiro et al., 2022, Elzahar et al., 2022, Kayalar 2022, Strazzi-Sahyon et al., 2024, Valian et al., 2024) • Microhardness, (Naina et al., 2024) • Microstructure, (Abi et al.,, Cossu et al.,, de Assis et al.,, Kamiya et al., 2007, Kojima et al., 2007, Kim et al., 2012, Gouveia et al., 2017, Silva et al., 2017, Silva et al., 2017, Sriboonpeng et al., 2017, Sriboonpeng et al., 2019, Su et al., 2020, Ding et al., 2021, OZDOGAN and Karslıoğlu 2021, Cordeiro et al., 2022, Kayalar 2022, Yang et al., 2022, Campos et al., 2024, Strazzi-Sahyon et al., 2024, Valian et al., 2024) • Crystalline Structure, (Cossu et al.,, de Assis et al.,, Kamiya et al., 2007, Kojima et al., 2007, Gouveia et al., 2017, Silva et al., 2017, Silva et al., 2017, Sriboonpeng et al., 2017, Hovakhti et al., 2018, Sriboonpeng et al., 2019, Ding et al., 2021, Cordeiro et al., 2022, Yang et al., 2022, Campos et al., 2024, Strazzi-Sahyon et al., 2024) (Lu et al., 2024, Valian et al., 2024) • Particle Size, (de Assis et al.,, Kamiya et al., 2007, Kojima et al., 2007, Kim et al., 2012, Silva et al., 2017, Sriboonpeng et al., 2017, Cordeiro et al., 2022) • Phase Evolution, (Abi et al.,, Kayalar 2022) • Roughness, (OZDOGAN and Karslıoğlu 2021, Lu et al., 2024) • Solubility (Elzahar et al., 2022) • Specific gravity (Kim et al., 2012) • Surface Morphology (Elzahar et al., 2022) • Water Absorption (Abi et al., Kim et al., 2012, Cordeiro et al., 2022, Elzahar et al., 2022) • Wettability(Lu et al., 2024). • Volume fraction of monoclinic phase. (Kojima et al., 2007)
Optical properties	• Color, (Gouveia et al., 2017, Campos et al., 2024, Strazzi-Sahyon et al., 2024, Valian et al., 2024) • Contrast Ratio(Campos et al., 2024, Strazzi-Sahyon et al., 2024, Su et al., 2024) • Opalescence(Su et al., 2024) • Translucency(Campos et al., 2024, Strazzi-Sahyon et al., 2024, Su et al., 2024)
Accuracy and other properties	• Accuracy, (Echhpal II et al., 2024) • Trueness, (Echhpal II et al., 2024) • Dimensional Stability, (Kayalar 2022) • Linear Shrinkage, (Kim et al., 2012, Silva et al., 2017, Su et al., 2020, Ding et al., 2021, Yang et al., 2022, Valian et al., 2024) • Polymerization Shrinkage, (Naina et al., 2024) • Precision, (Echhpal II et al., 2024)

33]) applying attritor milling for 2 h in isopropyl alcohol [33]. The slurry was prepared to be used for slip casting so it was further treated to be 65% solid and 35% water. Moreover, 6% by weight of selected dispersant and 2% by weight of binder were added and mixed in a magnetic stirrer for 2 h. Strazzi-Sahyon et al. 2024 [31] described the pulverization process by initial fragmentation to nearly 5 mm fragments, followed directly by ball milling with a distilled water medium. Sieving was a crucial step in the grinding protocol, ensuring homogenous particles with a granulometric range of less than 5 µm, resulting in a small fraction (5 to 7%) that did not reach this granulometric range.

Purification of fragments and fine powder

Purification started by removing the dust particles in distilled water [34], or deionized water, then drying at 120 °C for 24 h in an oven to remove water, dust, and some impurities [10, 13, 21], although Silva et al. applied only thermal treatment to remove dust [10]. In Ding et al. 's study [6], the powders were soaked, mixed, and appropriately pickled in 0.5 mol/L nitric acid for 5 min at 55°C, then cleaned thoroughly with distilled water and stored in a drying oven. Other cleaning methods involve picking zirconia fragments in acidic solutions (such as hydrogen fluoride and nitric acid) to remove fragments' surface contaminants [36].

To remove all impurities, including the organic remnants and wastes that occur during CAD/CAM production, calcination is regularly applied. The process involves raising the temperature gradually until reaching the calcination temperature and holding it for 2 h. The calcination temperature was set at 500 °C in one study [25] and 900 °C in most reviewed original studies [8, 17, 31, 32]. Calcination was reported as a vital step, effectively removing impurities and enhancing the quality of recycled powders [8, 9], adhering to the reported calcination temperature to ensure purification without compromising the powder reactivity through the formation of sintering necks and initial densification.

The role of sintering of recycled zirconia

Sintering is an integral part of zirconia fabrication; it happens during the manufacturing of zirconia parts or in the densification process of subtractive and additive-manufactured zirconia parts. Increasing sintering temperature and holding time are associated with improvement in physical-mechanical properties to a certain limit [2, 8, 13, 37]. Increasing sintering temperature over 1600 °C and increasing holding time more than 3 h were found to have detrimental impacts on the final product [2].

For recycled zirconia, Kim et al. [14] optimized sintering temperatures and times for pre-sintered dental zirconia block residue, using processes like crushing, milling, sieving, and slip casting to enhance bending strength, linear shrinkage, and specific gravity. Subsequent studies [9–11, 13, 20, 21] expanded on these methods, incorporating calcination and sintering at varied temperatures and pressures to improve microstructures, hence mechanical, physical, and optical properties.

Fine particles of recycled zirconia powders exhibit better densification due to higher surface activity and lower activation energy required during sintering. Conversely, coarse particles hinder grain boundary formation, increasing porosity and weakening the material. These findings highlight the need for careful control of particle size and sintering conditions to optimize the properties of recycled zirconia [28].

The use of two-step sintering was advocated by several studies [6, 28, 32] as the pre-sintering yielding improves structural integrity and mechanical, physical, and optical properties of recycled zirconia. A pre-sintering up to 950 °C and 1,000–1,050 °C was found appropriate, resulting in a zirconia product with 897 Mpa flexural strength comparable to the commercially available zirconia (904 Mpa) [6, 28].

The rate of increasing the pre-sintering heat might not impact the quality of the product [28]. Compared with a non-calcined group, the uniaxial pressing and sintering at 1550 °C for 2 h of recycled powder showed improved characteristic strength, hardness, and fracture toughness, particularly with calcination. Confirming the deteriorative impact of impurities within the recycled zirconia and underscores the importance of purification, particularly calcination steps. However, the commercial zirconia exhibited overall superior mechanical performance [31].

The mostly applied sintering temperature of dental zirconia ceramic is 1450 °C, 1500 °C, 1550 °C, and 1600 °C; increasing sintering temperature allows for crystalline growth, which increases the grain size and increases relative density [11]. A most recent study found increased relative density from $86.7 \pm 1.5\%$ to $92.2 \pm 1.7\%$ when applying 1450 to 1550 °C respectively, although the mechanical behavior is still very low relative to the commercial zirconia. However, another study showed a significant increase in flexural strength, reaching up to 700 MPa when applying 1550 °C for 2 h as a sintering temperature and a cooling rate of 4 °C/min in a one-step sintering protocol [14]. This method ensured optimal thermal conditions, resulting in 0 apparent porosities, 200–300 nm grain size, and 20% linear shrinkage after sintering. These properties are comparable and slightly better than commercially available zirconia. Moreover, a study applied a one-step sintering process, increasing the temperature at 10 °C/min rate to 1300, 1400, and 1500 °C with a 2-hour hold at each temperature. These sintering protocols aimed to optimize densification and mechanical properties, resulting in comparable strength

Table 3 Main findings of the included studies

Study ID	Main finding
Kojima et al. 2007	The yttria-stabilized zirconia 3Y-TZP ceramics sintered at 1,500 °C and 1,600 °C could be effectively disintegrated into small fragments using hydrothermal treatment at 200 °C to 400 °C, and these fragments could be further pulverized into primary particles through ball milling.
Kamiya et al. 2007	The recycled 3Y-TZP sintered at higher temperatures showed improved fracture toughness compared to the original 3Y-TZP, while maintaining a dense microstructure.
Kim et al. 2012	The study found that recycled zirconia from CAD/CAM milling waste had similar bulk density and microstructure to commercial zirconia. SEM revealed homogeneous, well-densified grains in both materials sintered at 1500 °C, with densities matching standard 3Y-TZP values. While the flexural strength of recycled zirconia (680 MPa) was slightly lower than commercial zirconia (800 MPa).
de Assis et al. 2014	The study demonstrated the feasibility of recycling $ZrO_2(Y_2O_3)$ waste from dental prosthesis fabrication. After processing, the material achieved a green density of ~ 40% and relative densities of 87–91% upon sintering at 1550ºC, retaining only the tetragonal phase. This suggests recycled $ZrO_2(Y_2O_3)$ is a cost-effective option for less demanding dental applications
Silva et al. 2016	The study confirmed that zirconia powder waste from dental prosthesis machining can be recycled. Isostatically pressed samples, sintered at 1500 °C, showed fracture strengths of ~ 356 MPa, comparable to commercial zirconia.
Sriboonpeng et al. 2017	The study showed that vibro-milling time significantly influences the phase transformation and particle size of zirconia nano-powders from dental debris. Milling for 2 h produced minimally agglomerated powders with a dominant tetragonal phase and minor monoclinic phase. Extended milling increased monoclinic content and reduced particle size to ~ 35 nm.
Sliva et al. 2017	Compacted and sintered at 1500–1600 °C, the zirconia waste achieved > 93% densification, comparable grain sizes, and similar mechanical properties to commercial zirconia. Flexural strength improved with temperature, reaching 461 MPa at 1600 °C for isostatically pressed waste, confirming its suitability for reuse while reducing costs and environmental impact.
Gouveia et al. 2017	The study found that incorporating 5–10% recycled zirconia maintained mechanical properties like flexural strength and Weibull modulus comparable to commercial zirconia, while 50% reduced performance. Recycled zirconia is suitable for dental, jewelry, pigments, and refractory applications, providing an eco-friendly, cost-effective recycling solution.
Hovakhti et al. 2018	Zirconia waste recovery was successful, but the flexural strength of recycled samples was about one-third that of the commercial samples (250 MPa vs. 650 MPa). Using a zirconia-specific bur for dry grinding, especially with heat treatment, improved flexural strength compared to a diamond bur. However, there was no significant difference in flexural strength between dry and wet grinding with the zirconia bur, regardless of heat treatment. The zirconia-specific bur performed better than the diamond bur, but heat treatment did not significantly affect flexural strength when using the diamond bur.
Cossu et al. 2018	The composites, with 3wt% to 15wt% recycled zirconia, were sintered at 1600 °C, achieving over 95% relative density. They exhibited hardness values between 1300HV and 1400HV and fracture toughness from 3.3 to 3.7 $MPa{\cdot}m^{1/2}$. The study concluded that while the recycled zirconia effectively reinforced the composites, enhancing the mixing process could improve the uniformity of zirconia distribution and further optimize the material's properties.
Sriboon-peng et al. 2019	The study findings showed that sintering temperature greatly influences recycled zirconia ceramics. At 1100 °C, properties matched commercial dental zirconia, while higher temperatures (up to 1250 °C) enhanced densification, reduced porosity, and increased grain size, confirming its potential for cost-effective, high-quality dental materials.
Su et al. 2020	Recycled zirconia powder exhibited agglomeration, increasing slurry viscosity. Pristine powder achieved > 99% density with a 20 µm layer, while recycled powder reached ~ 90% density with a 40 µm layer. Both showed similar Vickers hardness, but flexural strength differed significantly (1057 MPa for pristine vs. 389 MPa for recycled). This suggests pristine zirconia suits dental prostheses, while recycled zirconia is better for less demanding uses.
Ding et al. 2020	Recycled zirconia blocks had similar elemental compositions and uniformly distributed particles with smooth surfaces. Pre-sintering at 950–1000 °C was optimal, yielding comparable flexural strength, microhardness, density, and shrinkage to control blocks. The study supports a simple pre-sintering method at 950 °C as an effective recycling solution for dental CAD/CAM materials.
Ozdogan et al. 2021	Reinforcing PMMA with up to 60% YSZ enhances microhardness, density, and durability without significantly impacting surface roughness. Beyond 60%, agglomeration reduces mechanical properties, making 60% YSZ the optimal balance for performance and the sustainable use of zirconia waste.
Cordeiro et al. 2022	The study investigated recycling zirconia waste powder (ZWP) from CAD/CAM-milled Y-TZP dental ceramics as a cost-effective dental material. Optimal de-agglomeration (13 grinding medium-to-powder ratio, 90-minute milling) reduced particle size to 0.4 µm while preserving the tetragonal phase. Sintered ZWP achieved high bulk density (5.8 g/cm^3), microhardness (1523 HV), and flexural strength (342.8 MPa), comparable to commercial zirconia and superior to porcelain and glass-ceramics, highlighting its potential for dental applications.
Elzahar et al. 2022	The study enhanced cold-cure acrylic denture base material by adding recycled zirconia (ZrO_2) nanoparticles functionalized with HEMA. Testing various concentrations, 0.3% ZrO_2 showed the best results, significantly improving flexural strength, elasticity, and hardness without reducing impact strength. This approach offers a cost-effective, eco-friendly solution for improving denture base materials.
Yang et al. 2022	The study revealed that pre-sintering heating rates (2 ℃/min, 5 ℃/min, 8 ℃/min) had minimal effect on the relative density and porosity of recycled zirconia but influenced flexural strength based on particle size. Smaller particles achieved higher flexural strength (746.7–777.2 MPa) compared to larger ones (421.2–444.2 MPa), highlighting the mechanical advantages of finer particles.

Table 3 (continued)

Study ID	Main finding
Kayalar, et al. 2022	The recycled zirconia specimens showed physical and mechanical properties comparable to commercial dental zirconia, even with 10–30% recycled content. Key attributes like density, grain size, phase stability, hardness, and flexural strength remained consistent when sintered at optimal temperatures, supporting the reuse of zirconia waste in restorative dentistry.
Campos, et al. 2024	Recycled 3Y-TZP zirconia powder from CAD/CAM vacuum cleaners demonstrated high purity and recycling potential, especially with thermally compatible glass infiltration. After calcination and sieving (< 75 µm), samples sintered at 1450 °C and 1550 °C achieved relative densities of 88 ± 2% and 92 ± 2%, respectively, with residual porosity and strength limitations. Glass infiltration significantly enhanced strength, making the material suitable for reconstructive dentistry. Higher sintering temperatures further improved flexural strength through microstructural changes and stronger glass-zirconia interactions.
Su, et al. 2024	Recycled zirconia followed a bonding protocol similar to commercial zirconia, both showing reduced bonding strength after thermocycling. While recycling preserved the crystalline phase and elemental composition, it altered surface roughness.
Sahyon, et al. 2024	The study examined the effects of calcination on recycled 3Y-TZP from non-milled CAD/CAM remnants, comparing it to commercial zirconia. Calcination improved strength (855 MPa) and fracture toughness compared to non-calcined material (646 MPa) but remained inferior to commercial zirconia in strength, toughness, and translucency. Both recycled materials retained densities above 98.15% and unchanged crystalline structure. While suitable for specific dental applications, further optimization is needed for long-span restorations.
Lu et al. 2024	Recycled zirconia from CAD/CAM milling waste exhibited similar bulk density and microstructure to commercial zirconia. Both showed homogeneous, well-densified grains when sintered at 1500 °C, with densities matching standard 3Y-TZP. Although recycled zirconia had slightly lower flexural strength (680 MPa vs. 800 MPa), the 15% difference was statistically insignificant.
Echhpal II et al. 2024	Waste zirconia dust proved an effective, sustainable, and cost-efficient alternative to commercial optical scanning sprays for extraoral implant abutment scans. It delivered comparable accuracy in trueness and precision, with minimal impact from operator technique. This approach is especially beneficial for dental practices in developing regions, supporting hybrid digital-conventional workflows.
Naina et al. 2024	Incorporating zirconia dust into PMMA resin enhances microhardness and reduces polymerization shrinkage in provisional restorations. Heat-polymerized resins with zirconia dust outperformed other resins, positioning recycled zirconia as a sustainable solution to improve dental resin performance and minimize waste.
Abi et al. 2024	The recycling of dental zirconia waste powders through slip casting and sintering yielded zirconia with properties comparable to commercial specimens. Sintering at 1450 °C resulted in recycled zirconia with relative densities of 98%, bending strengths of 350 MPa, and porosity below 2%, demonstrating that waste powders can be effectively reused to produce high-quality zirconia ceramics for dental applications.
Valian et al. 2024	The study investigated recycling residual zirconia blanks using a hydrothermal process followed by milling. All samples maintained a tetragonal crystalline structure and density over 95%. While mechanical strength was lower than controls, hardness remained unchanged. Recycled zirconia shows promise for low-stress dental restorations, such as veneers, inlays, and single crowns, offering a viable and cost-effective alternative.

and toughness to commercially available zirconia materials [26].

Furthermore, a significant increase in flexural strength was observed after glass infiltration of zirconia recycled parts, reporting flexural strength of 778 MPa and 862 MPa for specimens sintered at 1450 °C and 1550 °C, respectively [8]. Fulfilling the ISO criteria for prosthetic applications for more than 4-units fixed partial dentures, including molar region (Flexural strength ≥ 800 Mpa) [2, 38]. Another study applied 1,360 °C as a sintering temperature and reported very low flexural strength (mean: 254.24 MPa) that might not be suitable for dental clinical applications [22].

Physical-mechanical properties of recycled zirconia

There is a consensus in all included studies that recycled zirconia possesses lower physical-mechanical properties compared with commercially available zirconia [12, 22, 23, 25, 29, 30, 32, 34]. This is true for recycled presintered green zirconia bodies, which exhibit lower density and lower linear shrinkage compared with commercially available zirconia. The phase distribution, grain size, and microstructure were comparable for both materials [11, 34]. However, a study found difficulties in the full densification of recycled zirconia during sintering due to the agglomerates' formation in the grain boundaries [17]. The studies attempted to enhance these properties by conducting several experiments on the pulverized particles' size, purification, the calcination process, and the sintering parameters.

Some studies succeeded in utilizing the final recycled product with as high flexural strength as commercial zirconia [6, 28, 31], high relative density with fine grain size, and lower apparent porosities that are even better than the commercially available zirconia materials [14, 17, 26, 33]. Moreover, recycled zirconia in some studies exhibited relatively high hardness, fracture toughness, and characteristic strength [10, 31], with controlled linear shrinkage between 20 and 24% [14].

The experimental studies conducted to enhance recycled zirconia properties underscore the importance of controlling the recycling process, starting with the utilization of fine powder after pulverization, as it revealed better properties than the coarse one [28]. Purification and calcination should have a great impact on the final product, as the process aids significantly in removing all impurities, resulting in enhanced mechanical strength [31]. Furthermore, the proper sintering parameters were found to be significantly important for the production of recycled zirconia with desirable physical-mechanical properties [8, 11, 13]. However, sintering alone can not guarantee recycled product quality; the impurities and microstructure are important factors to be considered. This was evident in studies with ultimate sintering parameters; however, it resulted in a product with flexural strength lower than some glass-ceramic materials, rendering the produced zirconia suitable for single restorations that should be used with caution, giving preference for glass ceramic regarding their esthetic appeal [25].

The point here is that the recycling procedure should be well-controlled, without focusing on a single aspect of the process, to utilize recycled products with high and desirable quality. Moreover, all the included studies focused on manipulating specific recycling steps and resulted in enhancing certain aspects of the physical-mechanical properties. It could be highly advocated to take the recycling procedure under comprehensive laboratory work of productive companies, covering all aspects of recycled raw material and processing parameters to guarantee a recycled product with excellent physical-mechanical properties and draw the guidelines for a successful recycling process.

Optical properties of recycled zirconia

The evaluation of the optical properties of recycled zirconia, as indicated by multiple studies, consistently demonstrates challenges in achieving translucency and aesthetic quality comparable to commercial zirconia. Several studies [8, 20, 31, 32] highlighted that recycled zirconia exhibits lower translucency and opalescence, with color discrepancies exceeding acceptable thresholds, even when identical staining procedures are employed. These optical deficiencies become increasingly remarkable as the material's thickness increases. Such findings underscore the critical need to enhance processing techniques to mitigate the adverse effects of recycling on zirconia's aesthetic properties, thereby ensuring its broader applicability in dental restorations where appearance is paramount.

The careful processing of recycled zirconia material, in addition to the calcination additional procedure, was reported to be crucial for optimizing the optical properties, specifically translucency, and opalescence, confirming that pre-sintering conditions directly impact the aesthetic quality of recycled zirconia restorations [32].

In an advanced improvement, Su et al. [23] applied recycled zirconia powder in 3D printing, making a printable zirconia slurry for stereolithography technology. Laboratory specimens printed at 40 µm layer thickness resulted in crowns with acceptable form, color, and texture. However, confirming the feasible and applicable 3D printing of recycled zirconia powder showed weaker mechanical behavior than pristine printed materials, rendering 3D printing of the recycled zirconia suitable for anterior crowns and 3-unite prostheses, not including molar regions.

Applications of recycled zirconia

The application of recycled zirconia depends on the composition/purity of the residue and the treatment and sintering protocols employed; those factors showed great influence on the properties of the end product, where some included records might utilize the recycled zirconia for industrial or engineering purposes, which was obvious by the sintering protocol applied 1100–1350 °C and the weak mechanical properties of the product [11, 13, 21].

Regarding applications in the dental field, the flexural strength is generally lower than that of dental zirconia, particularly 3Y-TZP; however, referring to other properties and the durability of the material, it could be promising for clinical dentistry, specifically for short-span bridges. Moreover, recycled zirconia's bonding affinity and durability compared to commercially available zirconia showed no significant difference in shear bond strength, indicating that recycled zirconia can achieve similar bonding performance. However, both types exhibited reduced bond strength after thermocycling, highlighting the importance of surface treatment for optimal adhesive properties in dental applications [14].

Moreover, one study reported the extraordinary microstructure of recycled zirconia for dental implants, where grain size reached values bigger than 260 µm [9] compared with the typical high-strength tetragonal zirconia grains (100–400 nm) reported in other studies [2, 9, 25].

Several challenges might interfere with the efficacy of recycling dental zirconia. First, in the irregular shape of recycled zirconia powders retrieved from the milling process during CAD/CAM production. These irregular shapes pose substantial challenges during pressing and sintering, as they can lead to uneven density distribution and increased porosity [20, 28]. To address this issue, cold isostatic pressing has been identified as an effective method for improving recycled zirconia's uniformity and relative density compared to uniaxial pressing [10, 11]. Nevertheless, these technologies must be carefully weighed before adoption regarding their practicality and cost-effectiveness in dental laboratories.

The applications of recycled zirconia powders are not limited to pressing into discs and blocks for reuse in restorative and prosthetic purposes, although, with proper treatment, the recycled materials might be suitable for such practices; however, other applications could found recycled powders very useful regardless of the limited mechanical properties, such as scanning powder for digital laboratory scanners [29], powder for air-particle abrasion of zirconia restoration [11], and as filler materials for reinforcement of other resinous and ceramic low properties materials. Studies have shown that integrating recycled zirconia powder into PMMA can enhance its mechanical strength [24, 26]. Nevertheless, increasing the zirconia fillers beyond the resin saturation limit would interrupt the resin matrix's continuity, reducing the mechanical properties [39]. For these reasons, precise calculations of the filler-resin matrix ratio must be undertaken to optimize the benefits of the filler while also considering the material's properties. Fine-tuning these parameters is essential for advancing the practical applications of recycled zirconia in dental materials.

In summary, while the recycling of dental zirconia presents several challenges, the potential benefits in terms of sustainability and material performance are significant. Continued research and development are necessary to overcome existing obstacles and fully realize the value of recycled zirconia in dentistry and other fields.

Limitations

This scoping review offers a comprehensive overview of the literature on recycling dental zirconia residues, but several limitations must be noted. Most studies were conducted in vitro, which may not accurately reflect clinical conditions, limiting the generalizability of the findings. Additionally, variations in methodologies, such as sintering parameters, recycling processes, and forms of zirconia residues, could contribute to inconsistencies in outcomes. The lack of long-term studies and clinical trials also restricts conclusions about the performance of recycled zirconia in real-world settings. Although a broad search strategy was employed, including electronic databases and grey literature, relevant studies not indexed in the selected databases may have been missed. The qualitative synthesis of data is subject to interpretation bias, and variations in study designs, sample sizes, and methodologies limit the generalizability of the conclusions.

Future perspectives

Recycling dental zirconia offers a promising path toward sustainability in dentistry and materials science, yet it poses technical challenges that demand further investigation. Studies indicate that favorable properties can be achieved when specific protocols—such as optimized sintering, particle size control [5, 27, 33], and calcination treatments—are applied [31]. However, recycled zirconia continues to exhibit inferior mechanical properties compared to its commercial counterparts, likely due to residual impurities and compromised material purity [40]. This highlights the importance of clean processing and proper waste handling to improve the quality of recycled outputs.

A key area of innovation involves refining particle size and morphology. Irregular particles have been linked to poor densification during sintering, resulting in increased porosity and diminished flexural strength [20, 28], as well as reduced esthetic performance. Techniques like cold isostatic pressing [11] and precise grinding of waste blocks [12] show the potential to enhance uniformity and packing density. Beyond direct reuse in prostheses, recycled zirconia powder has shown promise as a filler in resin-based materials like PMMA, improving mechanical strength [24]. However, optimizing the filler-matrix ratio remains crucial to maintaining durability and esthetics. Additionally, non-dental applications—including engineering, jewelry, and industrial components—could benefit from the material's optical qualities and luster.

Preserving or restoring optical properties is another vital frontier. Changes in translucency and color stability following recycling may be mitigated by novel sintering techniques, advanced additives, or surface coatings [12, 41]. Research into the effects of multiple reuse cycles and exposure to staining agents could further inform best practices. Establishing standardized protocols and predictive models would greatly support the integration of recycled zirconia in esthetic dentistry.

Finally, additive manufacturing using recycled zirconia is an emerging field with significant potential [23]. Developing printable slurries for anterior restorations could support more personalized care. However, enhancing the mechanical properties of 3D-printed forms remains essential, particularly for load-bearing posterior applications.

Conclusions

Based on the findings of this scoping review, the following conclusions were drawn:

1. Recycling dental zirconia is a feasible process influenced by the recycling process's effectiveness in terms of particle size, sintering parameters, and molding methods.
2. Most of the literature showed modest mechanical properties and esthetic values of recycled zirconia, rendering the material more suitable for short-span bridges or single restorations. High sintering temperatures and optimized protocols revealed a significant increase in strength.
3. Recycled zirconia shows reduced optical properties compared to commercial zirconia, necessitating advancements in recycling techniques to enhance its translucency and aesthetic appeal for dental applications.
4. Recycled zirconia powder can be used as fillers for resin materials such as PMMA, which is utilized for provisional restorations, or as scanning powder for old models of dental scanners.
5. Further research is needed to enhance the physical-mechanical and optical properties and, hence, the applications of recycled zirconia and its environmental benefits.

Abbreviations

3Y-TZP	3 Mol% Yttria-stabilized tetragonal zirconia
4Y-TZP	4 Mol% Yttria-stabilized tetragonal zirconia
°C	Degrees celsius
CAD/CAM	Computer-aided design/computer-aided manufacturing
HV	Vickers hardness
MPa	Megapascal
PRISMA-ScR	Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews
PMMA	Polymethyl methacrylate
ZrO_2	Zirconium dioxide

Supplementary Information

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Supplementary Material 1

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