Applied Physics A (2026) 132:215
https://doi.org/10.1007/s00339-026-09319-2

Applied Physics A
Materials Science & Processing

Effect of lithium oxide (Li_2O) on the development of ceramic materials: a systematic review

Mariana Caroline Andrade Silva[1] · **Tiago Mozart Gonçalves Leite**[1] · **Érica Linhares Reis**[1]

Received: 12 August 2025 / Accepted: 12 January 2026 / Published online: 25 February 2026
© The Author(s) 2026

Abstract
The presented review aims to evaluate the effect of lithium compounds on the development of ceramic materials. Based on a systematic review methodology, 17 publications were selected from databases provided by Scopus (Elsevier), Web of Science (Thomson Reuters), and Springer Link. The analysis of the selected articles is presented segmented into the following topics: bibliometric analysis and contextualization of the global scenario, evaluation of the lithium source used in each of the works, as well as the products and technological parameters evaluated (linear shrinkage and apparent density, water absorption and porosity, mechanical strength, thermal expansion, other properties, and microstructure). In general, authors attribute to lithium compounds a fluxing agent, being responsible for the formation of a vitrous phase due to the reduction of viscosity during heat treatment. Thus, products with lower porosity and water absorption are generated, parameters associated with higher density and mechanical strength. Further investigation is still needed on the influence of α and β-spodumene phases in a comparative manner, as well as more studies regarding the coefficient of thermal expansion.

Keywords Lithium compounds · Ceramic materials · Systematic review · B-spodumene

1 Introduction

In parallel with the increase in global demand, ores with increasingly lower grades have been observed, leading to greater environmental challenges due to the significant amounts of waste generated from extraction. The valorization of tailings from the mining industry aligns with the Sustainable Development Goals proposed by the United Nations [1], particularly those related to clean energy, sustainable industry, and responsible production and consumption, by promoting circularity and increasing the reliability of resource supply chains in strategic sectors [2]. This approach enables not only the recovery of residual valuable minerals but also the reuse of the mineral matrix for new technological applications. Integrated tailings management has thus emerged as a key pillar for improving environmental, social, and economic performance across mining operations, reinforcing the principles of a circular economy.

One of the segments of the mining industry that has stood out in recent years is lithium extraction. The growth of this consumer market is justified by the increasing demand for batteries and electronic devices, driving technological development in this sector. In 2023, global production of this element increased by 23% compared to the previous year, totaling 180,000 tons, with approximately 98,000 tons coming from pegmatite deposits [3, 4]. Among lithium-bearing deposits, pegmatites are characterized by a lithium oxide content ranging from 0.8% to 2%, typically crystallized in the form of the mineral spodumene [5]. Ores from lithium pegmatites can be concentrated by flotation, an effective method for removing silicate gangue, mainly consisting of quartz and feldspar [6]. In this processing route, the lithium ore concentrate has approximately 6% lithium oxide, generating about 80% of waste by mass [7].

Due to the predominant presence of aluminosilicates, as well as lithium as a trace element, tailings from this process

✉ Mariana Caroline Andrade Silva
mariana.andrade@ufop.edu.br

Tiago Mozart Gonçalves Leite
tiago.mozart@outlook.com

Érica Linhares Reis
erica@ufop.edu.br

[1] Mining Engineering Department, School of Mines, Federal University of Ouro Preto, Ouro Preto 35400-000, Brazil

have attracted interest in the ceramic production sector. This sector, in turn, has been receptive to developing materials using non-toxic tailings as raw materials, with only the mineralogical complexity of these materials posing a constraint [8]. Recent research indicates increasing interest in the use of multi-source solid waste–derived materials in the production of ceramic foams, structural ceramics, and functional materials, reflecting both technological potential and environmental benefits [9]. However, the mineralogical complexity of these tailings may impose constraints on processing, requiring careful control of phase evolution, interface behavior, and microstructure formation—factors that are especially relevant in ceramic–metal laminated systems [10].

Among the applications of lithium-containing materials in the ceramic sector, several stand out: gas turbines, due to their low thermal expansion coefficient and excellent thermal shock resistance, essential properties for regenerative components operating under fluctuating temperatures [11, 12]. Lithium-containing glass-ceramics with β-spodumene are renowned for their low coefficient of thermal expansion, high mechanical strength and hardness, as well as a low dielectric constant, enabling a wide range of applications in electronics, high-performance optics, and defense technologies [13–16]. Thermal shock resistance is an additional factor favoring the use of lithium-containing materials in the production of whiteware, sanitaryware, and porcelains [17].

In ceramic materials, microstructure refers to the nature, quantity, and distribution of structural elements within the phases constituting a given material. The sintering conditions imposed on a ceramic material directly influence the resulting microstructure: successful processes yield simple monophasic structures composed of crystalline grains and their interfaces; incomplete densification, however, results in residual phases with significant porosity between the grains [18]. The incorporation of lithium-based materials has a direct impact on the resulting microstructure of ceramic products, as well as on their properties.

This study presents a comprehensive literature review, grounded in a systematic review, focusing on the impact of lithium oxide on the properties of ceramic materials, primarily from a microstructural perspective. The objective is to discuss this topic and identify which aspects of lithium oxide's influence on microstructure have been explored in published research, along with their implications.

2 Methodology

To evaluate the effect of lithium oxide on the microstructure of ceramic materials, published studies up to 2024 were analyzed based on databases provided by Scopus (Elsevier), Web of Science (Thomson Reuters), and Springer Link, chosen due to the bibliometric relevance of these sources and their support of engineering-related research [19]. The research and evaluation methodology for the selected studies followed the scheme presented in Fig. 1:

- Initially, keywords were selected so that the databases would return as many studies as possible relevant to the topic. Thus, the search was conducted using the following terms: influence OR evaluation AND spodumene OR "lithium silicate" OR "lithium ore" OR "lithium oxide" AND "ceramic material" OR porcelain AND NOT dental OR oral OR restoration. The inclusion of the term "lithium silicate" returned many studies focused on the biochemical and dental industries. This work is limited to industrial applications in the ceramic materials sector and does not address the effect of lithium oxide in dental ceramics production. Therefore, terms related to the biochemical or dental sectors were added in the "AND NOT" search line to better define the target database.
- In the Scopus and Web of Science databases, the search was limited to the title, abstract, and keywords. For Springer Link, the search algorithm does not allow such restriction. In this case, the search was conducted throughout the full text, which explains the variation in the number of publications returned by each database.
- Based on the selected articles, duplicate publications were removed. Among the defined database, 15 publications appeared as duplicates across the analyzed databases.
- Subsequently, an analysis was conducted based on the titles and abstracts of the publications retrieved from the databases. Articles that, after reading the abstract, were found to be unrelated to the review were removed.
- Then, a full-text analysis of the selected articles was carried out. At this stage, publications that seemed not to contribute to the work were also removed, and another 4 were excluded due to difficulty in locating them. Despite being publications from the last 20 years, they could not be found in the databases' collection, possibly due to the difficulty of accessing journals with lower international impact. A qualitative synthesis of the selected publications was performed, gathering information about the proposed methodologies, as well as the techniques employed for microstructural analysis. Then, an analysis of the relevant results was made, identifying the main effects of introducing lithium-based compounds in the ceramic production sector. Furthermore, possible academic and scientific gaps were identified and pointed out based on current publications.

In order to assess the bibliometric data, information regarding the journal of publication, authors, country, and year of publication was analyzed from a statistical perspective,

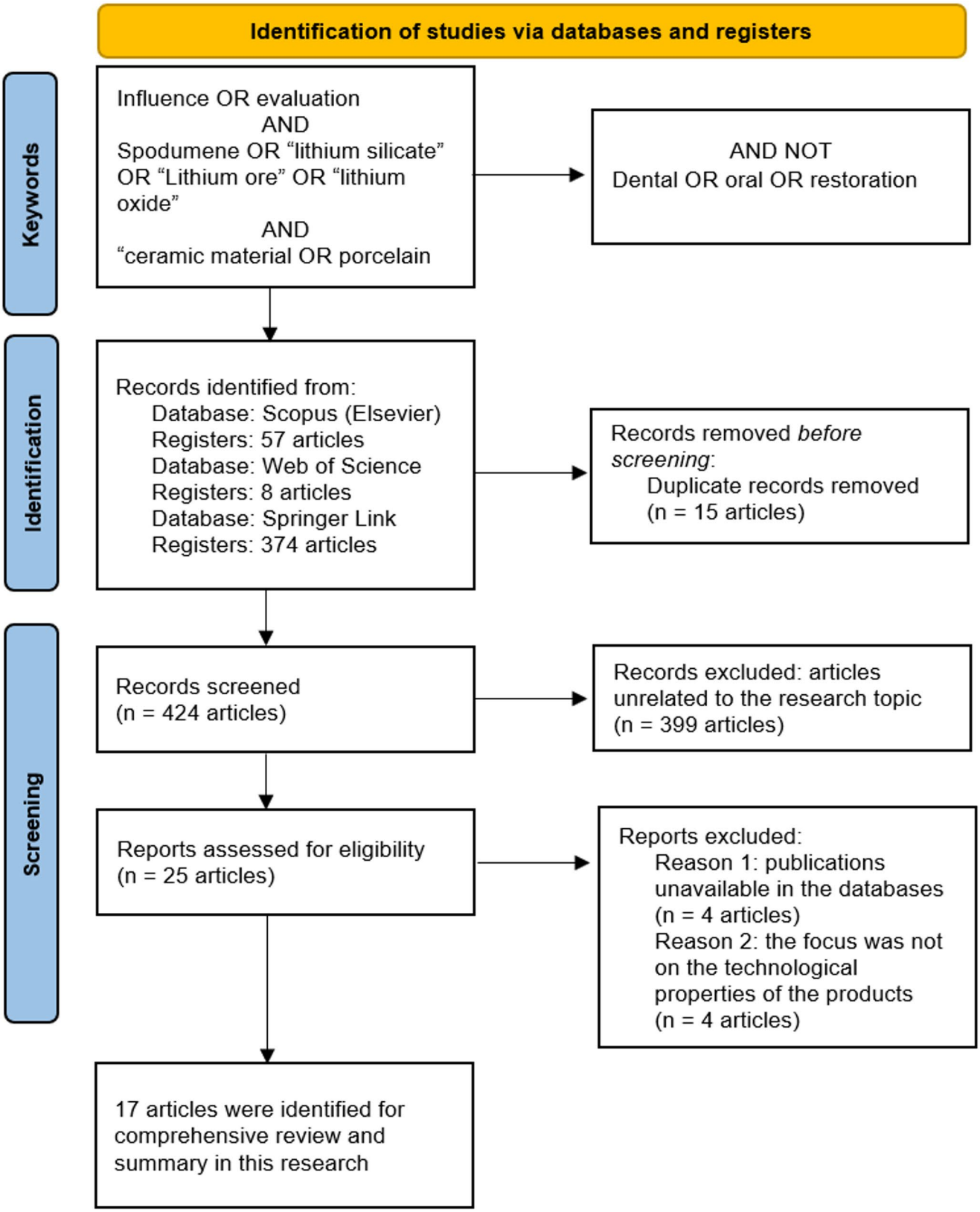


Fig. 1 PRISMA flow diagram of the steps involved in the systematic review

aiming to evaluate the impact of journals and countries on scientific production related to the topic.

3 Results and discussion

3.1 Bibliometric analysis and global context

The literature on the impact of lithium-based compounds on ceramic materials remains relatively limited and underdeveloped. However, a notable increase in research interest and activity can be observed from the 1960s to the present. Of the 17 relevant publications identified, 6% were published between 1964 and 1974, and no significant publications were found between 1975 and 1994. Between 1995 and 2004, 18% of relevant publications were identified, while the majority (76%) were published in the last 20 years, highlighting the growing interest in this field (Fig. 2). This surge in publications correlates with the significant increase in global lithium production over the past two decades. Production rose from 15.5 thousand tons in 2004 to 180 thousand tons in 2023. Global lithium production data was sourced from the Minerals Yearbooks (1964–1994) published by the Bureau of Mines [20–23] and the Mineral Commodity Summaries (2004–2023) provided by the United States Geological Survey (USGS) [3, 23, 24].

The publications used were authored by a total of 68 authors from 13 different countries. According to Fig. 3, the most cited work is the publication by [25], which sought to develop ceramics using aluminum nitride as a raw material, associated with a sintering aid that would volatilize after firing. The authors obtained ceramic products with high thermal conductivity and mechanical strength by using lithium oxide and yttrium as the sintering aids.

When relating the number of publications from each country to the impact of citations, it was observed that although the most cited publication originated from Japan, the country with the highest number of publications is Ukraine (Fig. 4). In this case, the author in question and collaborators evaluate the application of lithium-based compounds in the production of special glass-ceramics with military applications between the years 2016 and 2022.

A complete analysis and documentation of the countries involved in these investigations can provide invaluable

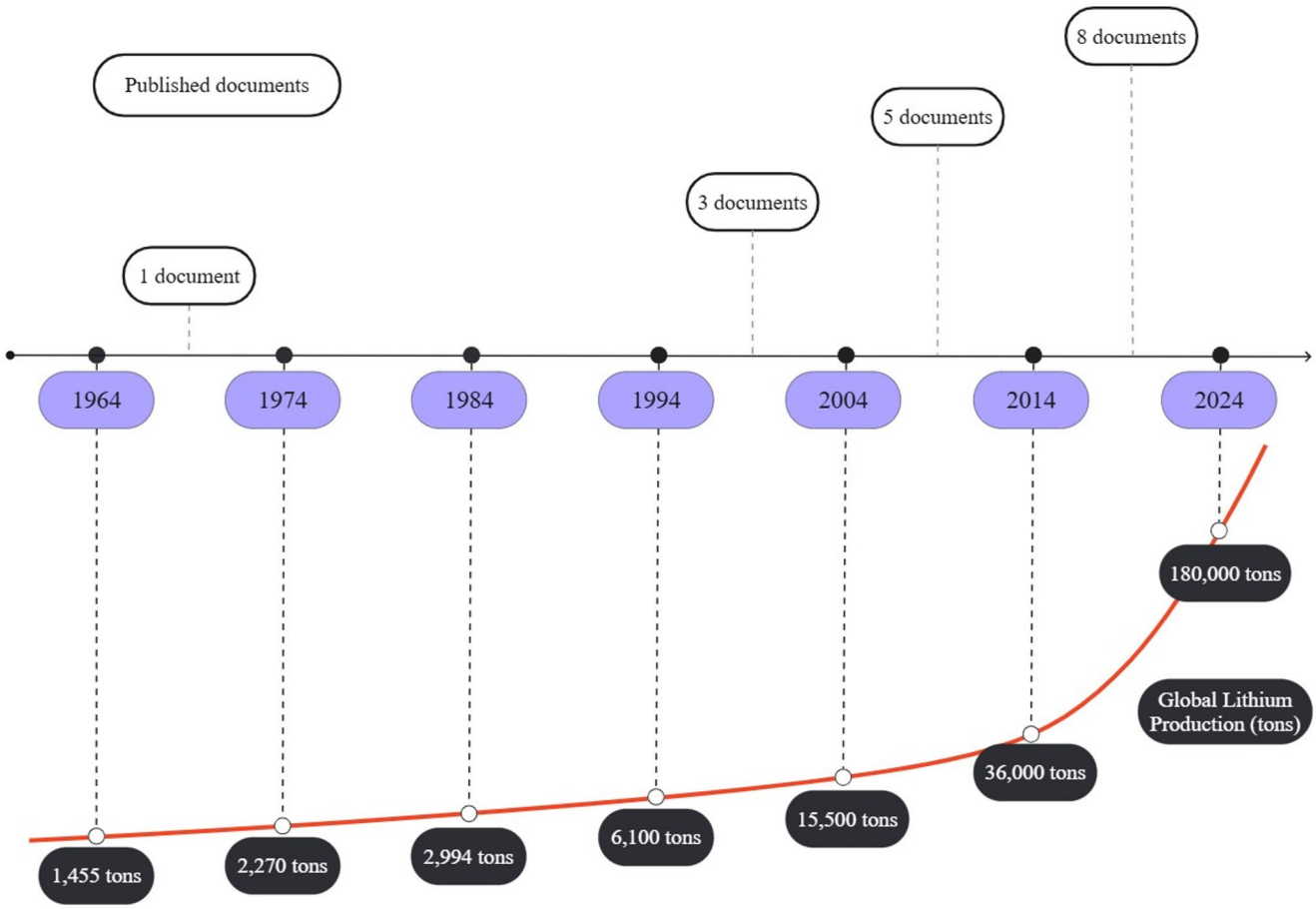


Fig. 2 Comparative infographic between the number of published articles and the production of lithium equivalent in each decade

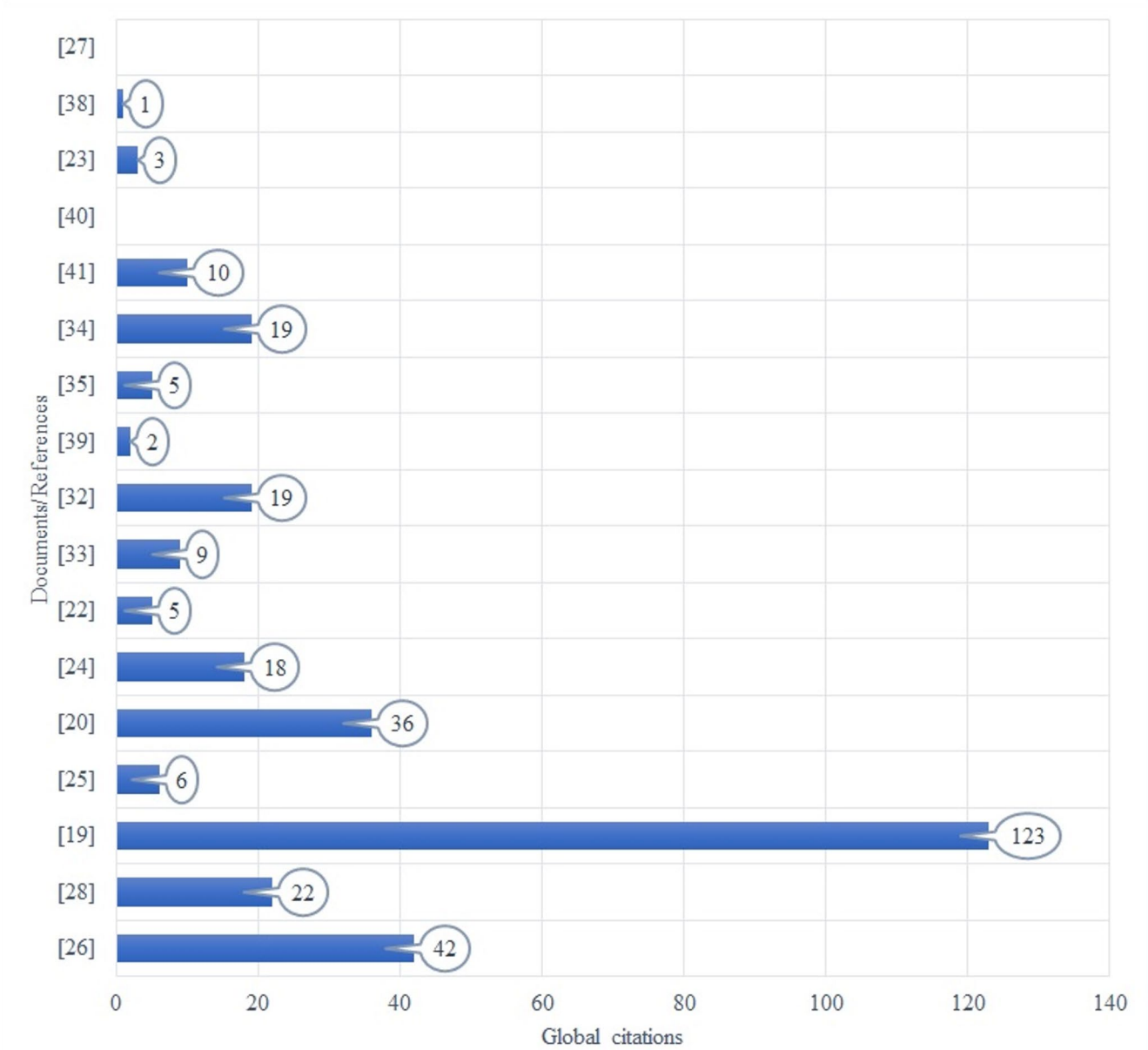


Fig. 3 Correlation between the number of publications on the microstructure of lithium-containing ceramic materials and the number of citations received by these publications

support to young scientists. It can help them forge scientific alliances, initiate collaborative projects, and exchange innovative methods and concepts.

3.2 Use of lithium oxide in different ceramic materials

3.2.1 Lithium source

Among the analyzed articles, a diversity was observed regarding the source of lithium added to the production of ceramic materials. Table 1 presents a summary of which material was incorporated as a lithium source, the size of these particles, as well as the chemical and mineralogical analysis of the raw materials. In general, lithium oxide is associated with other alkali oxides (Na and K), as well as alumina (Al_2O_3) and silica (SiO_2). The main lithium-bearing mineral is spodumene ($LiAl(SiO_3)_2$), but [26] incorporated a pegmatitic rock containing petalite ($LiAlSi_4O_{10}$) into the ceramic composition, both minerals being classified as lithium aluminosilicates.

Due to the high value associated with lithium carbonate, the application of this material in the production of ceramics has not always been economically viable, making it possible

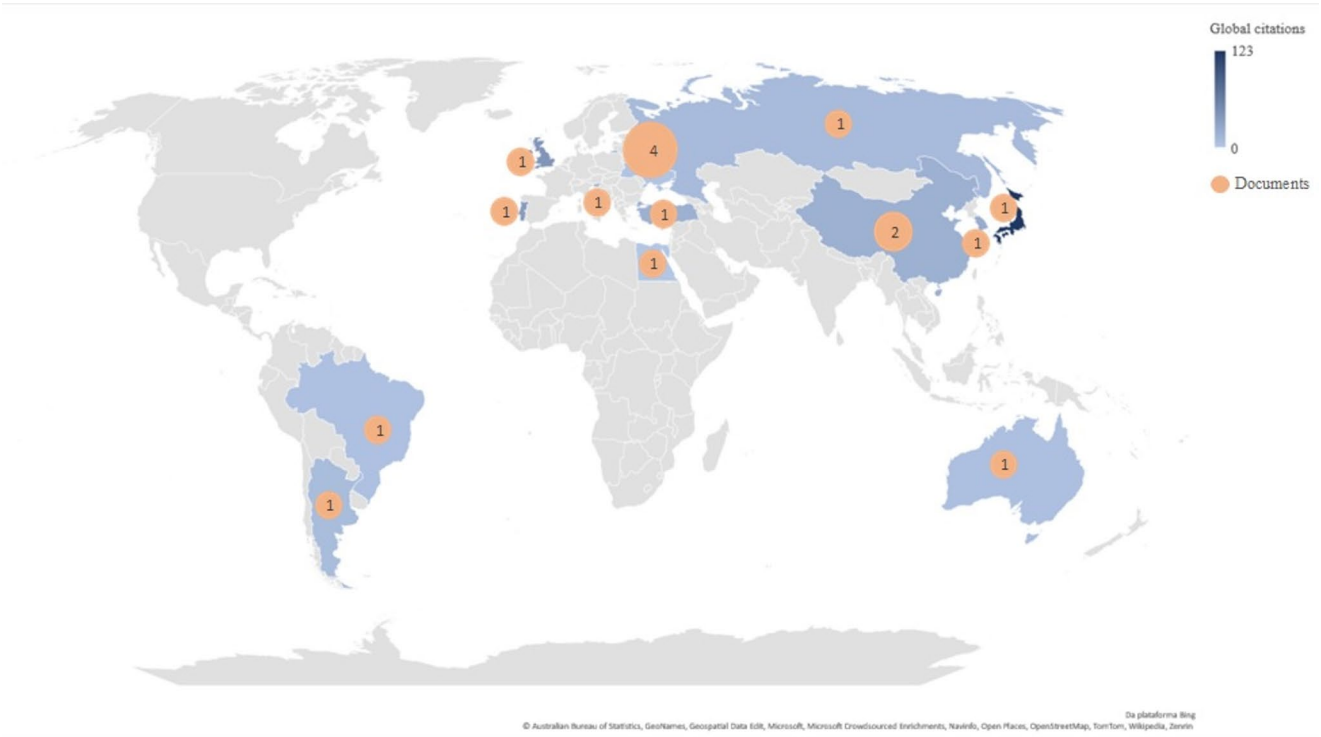


Fig. 4 Relationship between publications on the microstructure of lithium-containing ceramic materials and their respective citations

Table 1 Chemical, mineralogical, and granulometric characterization of lithium-bearing raw materials

Reference	Li source	Chemical composition					Mineralogical composition	Particle size	Company, manufacturer, or synthesis method of the lithium source used
		Li_2O	SiO_2	Al_2O_3	Na_2O	K_2O			
[22]	Spodumene-bearing pegmatite	2.18%	77%	15.3%	3.2%	1.2%	Quartz, albite, spodumene and aluminosilicate	115µm	Colorminas Company (Minas Gerais – Brazil)
[23]	Spodumene flotation waste	-	80%	12%	1%	5.4%	Quartz, albite, muscovite	62µm	Ganzi Prefecture (Sichuan Province – China)
[20]	Pegmatite A	2.36%	72.8%	16.9%	1.2%	4.7%	Albite, microcline, muscovite, spodumene, quartz	6 - 7µm	-
	Pegmatite B	1.76%	71%	17.7%	2.6%	3.6%	Albite, microcline, muscovite, petalite, quartz		-
	Lithium carbonate	44%	-	-	-	-	-	-	Aldrich
[32]	α-spodumene	7.5%	65%	25.2%	0.3%	0.6%	Spodumene	-	-
[33]	α-spodumene	-	-	-	-	-	Spodumene	-	-
[34]	β-spodumene (artificial)	-	-	-	-	-	-	2.7µm	Li_2CO_3:Al_2O_3:SiO_2 (1:1:4) pre-sintering (1050°C) sintering (1200°C)
[35]	Spodumene (artificial)	-	-	-	-	-	-	-	R_2O–RO–RO_2–R_2O_3–LiF–CaF_2–P_2O_5–SiO_2 R_2O à Na_2O, Li_2O, K_2O;RO à CaO, MgO, ZnO;RO_2 à ZrO_2, TiO2;R_2O_3 à Al_2O_3, B_2O_3
[24]	Calcined spodumene concentrate	-	-	-	-	-	-	Bimodal distribution with a mode at 0.6 µm	Gwalia Consolidated Ltd
[25]	Calcined spodumene concentrate	8.1%	64%	27%	0.2%	0.05%	-	23µm	Gwalia Consolidated Ltd

to use low-grade pegmatites for this purpose [27]. Due to the growing demand for batteries and medicines, such lithium-bearing pegmatites, previously considered low-grade, have become economically exploitable. The works of Bragança et al. [28] and Tulyaganov et al. [26] used lithium-bearing pegmatites as a source of lithium minerals (whose Li2O contents vary between 1.76 and 2.36%) with the same purpose, the production of triaxial ceramics. Despite the similarity in terms of lithium source and the product obtained, the average diameter of the particles used in these works differs: 115 µm for [28] and 6 to 7 µm for [26]. Possibly this discrepancy is associated with the process that generated this material: in the first work, a sample from gravity concentration processes was used to remove dense minerals, while in the second work, comminution of the pegmatitic rock was carried out exclusively for ceramic production.

Like the authors Bragança et al. [28], the study done by Yang et al. [29] also used as a lithium-bearing source a reject from a physical concentration process. However, the two works present materials with different granulometries: particles with average diameters equivalent to 115 and 62 µm, respectively. Once again, this discrepancy is justified by the concentration process that generated this reject: [28] used a reject from dense medium concentration, while [29] used a reject from flotation concentration, processes that occur efficiently in distinct granulometric ranges.

Another lithium source used is the product obtained from the calcination process of spodumene concentrate. Despite targeting different applications (high-alumina porcelain and aluminum titanate-based ceramics, respectively) and working in different countries (Slovenia and Australia), Oberzan et al. [30] and Low and Shi [31] both utilized calcined products from the same manufacturer, Gwalia Consolidated Ltd. For this reason, although chemical analysis data is absent in [30], it is likely that the raw materials exhibit some degree of similarity. The difference in particle sizes is attributed to the comminution stage used by [30].

Studies that introduced lithium in the form of carbonate are not shown in Table 1. In such cases, analytical-grade purity compounds, readily available on the market, are generally used, and thus the authors typically do not detail the characterization of this raw material. Manufacturers cited include TU (Shakhove et al., 2019), Aldrich [26], Johnson Matthey Grade II reagents [32], BDH – England [33], and Kanto Chemical [25]. The work by [34] did not provide the characterization of the compound used and did not mention the supplier.

From a mineralogical perspective, only the studies by [28, 29], and [26] utilized polymineral samples as sources of lithium minerals. In all three cases, the sample used underwent no prior thermal treatment, preserving the crystalline structure of the minerals present. In these cases, lithium minerals (spodumene or petalite) are associated with the following phases: quartz (SiO_2), feldspars (such as albite – $NaAlSi_3O_8$ and microcline – $KAlSi_3O_8$), and muscovite ($KAl_2O_{10}(OH, F)_2$). The authors of [28] and [29] provided mineralogical characterization data obtained via X-ray diffraction, as shown in Fig. 5.

Among the identified minerals, the relevance of each for the ceramics sector is notable: quartz contributes to reducing plasticity and deformation during thermal treatment; feldspars in general, including albite, serve as densifying agents, promoting the formation of a vitreous phase and resulting in ceramic products with lower porosity; muscovite enhances mechanical strength due to recrystallization into more stable phases [35–37]. This highlights the potential application of these industrial by-products as co-products that can serve as raw materials in the ceramics industry.

3.2.2 Products and technological parameters analyzed

Lithium-based compounds have significant applications in the ceramic materials industry, acting as flux agents and fillers with low expansion rates, yielding products with high physical, chemical, and thermal resistance [42, 43]. Table 2 provides an overview of the ceramic products studied in the analyzed articles, the tests and analyses conducted, associated raw materials, and the evaluated conditions.

Most studies on white and structural ceramics predominantly cite quartz, kaolinite, feldspars, and alumina as the main associated raw materials. The content of Li_2O incorporated into the ceramic matrix ranges from 0 to 5.5%, with thermal treatment temperatures between 550 and 1350 °C.

Another important application of lithium oxide is in the development of glass-ceramics, with uses ranging from military applications, such as personal protective equipment, to the production of microelectronic devices, like large-scale chips. The reviewed articles in this segment assessed Li_2O contents of up to 19.55%. In these cases, the use of polymineral raw materials becomes unfeasible, and lithium carbonate is typically employed. Sintering temperatures for glass-ceramic materials appear to be lower compared to structural ceramic materials, as shown in Table 2. However, there is a high-temperature melting step for raw materials to form the initial glass phase prior to glass-ceramic production. The works by [40] and [33] used melting temperatures around 1200 °C; [32] and [44] produced the required glass phase at temperatures near 1400 °C; and [41, 45], and [46] utilized temperatures as high as 1600 °C.

Lithium also plays a critical role in developing aluminum titanate-based ceramics [31] and aluminum nitride ceramics [25], in addition to stabilizing solid electrolytes

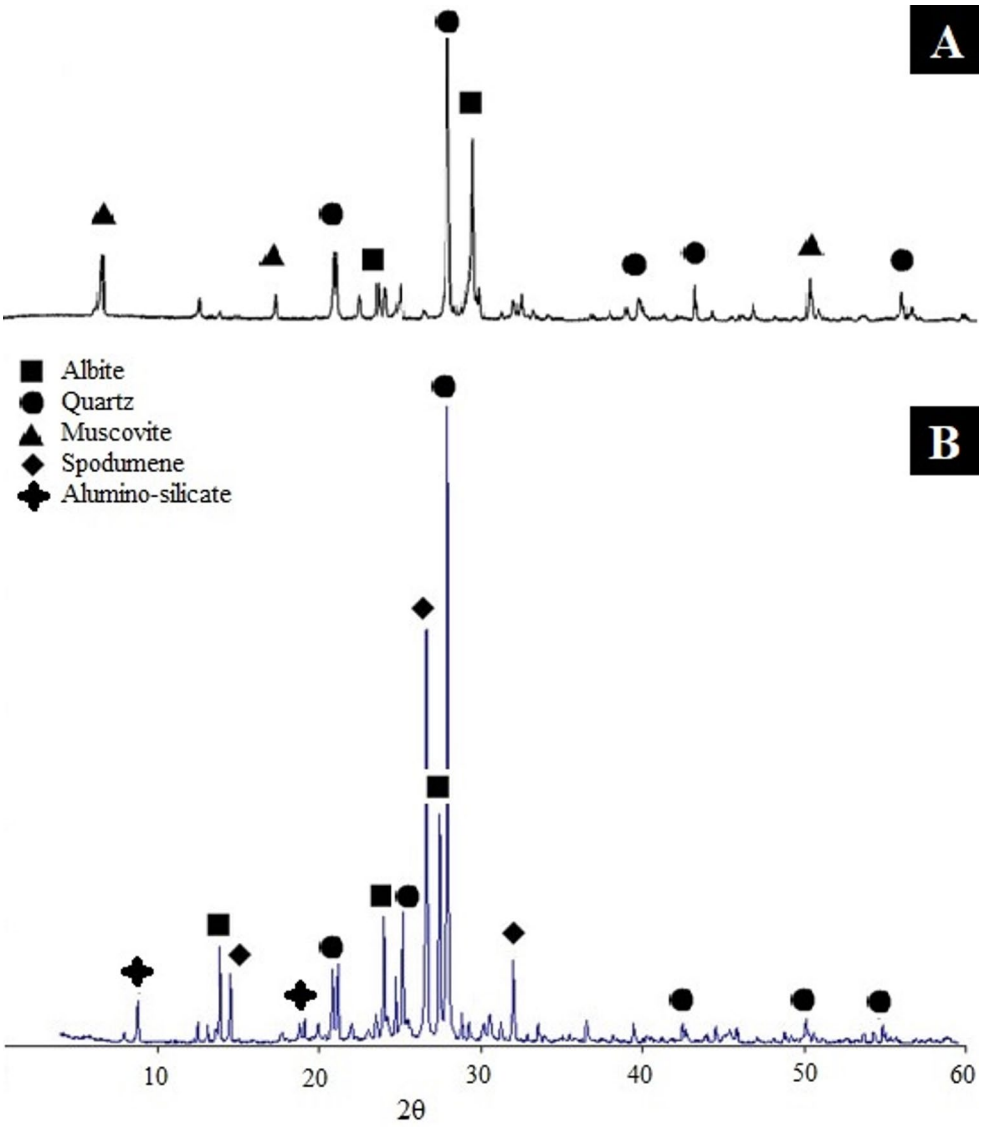


Fig. 5 Diffractograms of mineral samples used as by-products in the ceramic segment. A- Spodumeme flotation tailings [29]; B- Spodumeme-bearing pegmatite rock [28]

for secondary batteries [34]. These three studies reported sintering temperatures reaching up to 1600 °C.

From the tests and analyses conducted in each study, the authors drew several conclusions regarding the effects of lithium compounds on the production of the aforementioned ceramic materials.

Linear shrinkage and apparent density Among the studies that evaluated linear shrinkage (LS) as a physical index [28, 29], , and [39] made common observations: higher sintering temperatures resulted in ceramic products with greater linear shrinkage. The authors of [28] evaluated temperatures between 1140 and 1240 °C, obtaining shrinkage rates between 3.5 and 8.5% (for materials with 0.54% Li_2O); [29] worked with low-temperature ceramics (between 550 and 650 °C) and obtained shrinkage rates between 2.29 and 2.38%; while [39] used temperatures between 900 and 1200 °C and observed a shrinkage of up to -5%.

On the other hand, the studies by [31, 38], and [40] investigated how the lithium content impacts the shrinkage of the obtained products. The authors of [31] and [40] observed that higher Li_2O contents (up to 4.13%) implied greater shrinkages (up to 19%). In these cases, the authors attribute the increased shrinkage to the greater formation of liquid phase in the presence of Li_2O. While [38] obtained different results, indicating that oxide contents of up to 0.3% did not significantly impact the results of the physical index investigated.

The authors of [26] observed that the introduction of lithium in the form of carbonate reduced the shrinkage of the products obtained at temperatures between 1200 and 1300

Table 2 Evaluated ceramic products, tests performed, and evaluated conditions according to the articles reviewed in this study

Reference	Product	Tests and analyses carried out	Raw materials employed	Experimental conditions			
				$\%Li_2O$	Conformation	Drying	Sintering
[28]	Triaxial ceramics	XRF, XRD, AA, SEM, PM, PDI, BET, FC, LS, WA,	Quartz, kaolinite, albite and feldspar	0–1.09%	20 MPa	110 °C (24 h)	1140–1240 °C
[29]	Low-temperature ceramics	LS, AD, FS, CS, WA, AP, XRF, XRD, SEM, TGA e DSC, FT-IR	Kaolinite and glass powder	-	-	60 °C (48 h)	550–650 °C
[30]	High-alumina porcelain	AP, AD, DTA, TGA, CTE, FS, XRD, SEM	Alumina	0–1.56%	Extrusion	105 °C (4 h)	950–1350 °C
[38]	Porcelain stoneware	AD, AP, XRF, XRD, CTE, FS, LS, WA, PDI	Kaolinite, soil, quartz and sodium feldspar	0–0.3%	15 MPa	-	1210 °C
[39]	Triaxial ceramics	AP, LS, AD, FS, TGA, E	Kaolinite, quartz and feldspar	1.13%	-	100 °C (72 h)	800–1200 °C
[26]	Triaxial ceramics	LS, AD, WA, FS, WS, XRD, SEM	Kaolinite, quartz and potassium feldspar	0–3.16%	80 MPa	50–110 °C	1100–1350 °C
[47]	Facing ceramics	AD, AP, WA, FS, F, SC, TC, XRD, SEM	Soil, titanium dioxide and boric acid	0–5%	15 MPa	130 °C	1000 °C
[32]	Glass-ceramic	TGA, XRD, SEM, AD, ESR	Al_2O_3, SiO_2 and TiO_2	17.5–19.5%	-	-	520–900 °C
[40]	LTCC glass-ceramic	LS, FS, AD, CTE, XRD, DSC, SEM, FS, DI	H_3BO_3, SiO_2 (amorphous), MgO and Na_2CO_3	0–4.13%	20 MPa	100 °C	450 °C (1 h), 875 °C (2 h)
[33]	Glass-ceramic	TGA, XRD, SEM, BDS.	SiO_2, TiO_2	20%	-	-	650 °C (2 h)
[41]	Glass-ceramic (armor elements)	XRD, PM, TGA, E, H, HV, K	SiO_2, Al_2O_3, B_2O_3, P_2O_5	5.2–15%	-	-	450–950 °C (single stage or successive heating)
[45]	Glass-ceramic (armor elements)	XRD, TGA, PM, V, H, K	SiO_2, Al_2O_3	5–11%	-	-	450–950 °C (single stage or successive heating)
[46]	Glass-ceramic (armor elements)	AD, E, K, PM, DI	SiO_2, Al_2O_3	-	-	450 °C	600–900 °C (single stage or successive heating)
[44]	Glass-ceramic (armor elements)	XRD, PM, SEM, H, HV, E, V, FT-IR, BT, K	SiO_2, Al_2O_3, ZnO, SnO_2	7–8%	3 stages: 7.36–11.78–14.71 MPa	120–150 °C	530–850 °C (successive heating)
[31]	Aluminum titanate (AT) cermic	XRD, TGA, SEM, CTE, AD, AP, HV, TSR, LS	TiO_2, Al_2O_3, Al_2TiO_5 and ZrO_2 (monoclinic)	0–2.43%	150 MPa	450 °C (30 min)	1600 °C (3 h)
[34]	Solid-state electrolyte for secondary batteries	XRD (for the quantification of the phases formed as a function of varying temperature)	Al_2O_3, Na_2O	0.8–1.5%	-	-	1000–1600 °C
[25]	Aluminum nitride (AlN) cermic	XRD, TGA, ICP, AD, SEM, ON, FS, TC,	AlN, Y_2O_3, $CaCO_3$	0–0.47%	20 MPa	-	800–1600 °C

LS linear shrinkage, *WA* water absorption, *SEM* scanning electron microscopy, *TGA* thermogravimetric analysis, *FT-IR* Fourier transform infrared spectroscopy, *AD* apparent density, *AP* apparent porosity, *FS* flexural strength, *CS* compressive strength, *XRF* X-ray fluorescence, *XRD* X-ray diffraction, *AA* atomic absorption, *PM* petrographic microscope, *BET* Brunauer–Emmett–Teller (specific surface area), *FC* fusion cone, *CTE* coefficient of thermal expansion, *PDI* pyroplastic deformation index; *E* modulus of elasticity, *WS* whiteness, *F* frost resistance, *SC* compressive strength, *TC* thermal conductivity, *ESR* electron spin resonance, *LTCC* low-temperature co-fired ceramic, *DSC* differential scanning calorimetry, *DI* dielectric impedance, *BDS* broadband dielectric spectroscopy, *H* microhardness, *HV* Vickers hardness, *K* fracture toughness, *V* viscosity measurements as a function of temperature, *BT* ballistic tests, *TSR* thermal shock resistance, *ON* oxygen content in sintered materials

°C, showing similar behavior in cases with Li_2O content between 0.44 and 1.32%. By replacing lithium carbonate with lithium-bearing pegmatite containing spodumene or petalite, the authors observed that these natural conditions achieved maximum shrinkage at temperatures 100–120 °C lower compared to the conventional formulation.

In general, the authors attribute higher shrinkage rates to greater densification. This observation is confirmed by the data presented in Fig. 6: according to [25, 30, 39], and [29], higher sintering temperatures resulted in greater densification of the generated ceramic. According to discussions raised by [25], bodies sintered at 1600 °C (for 2 h) presented

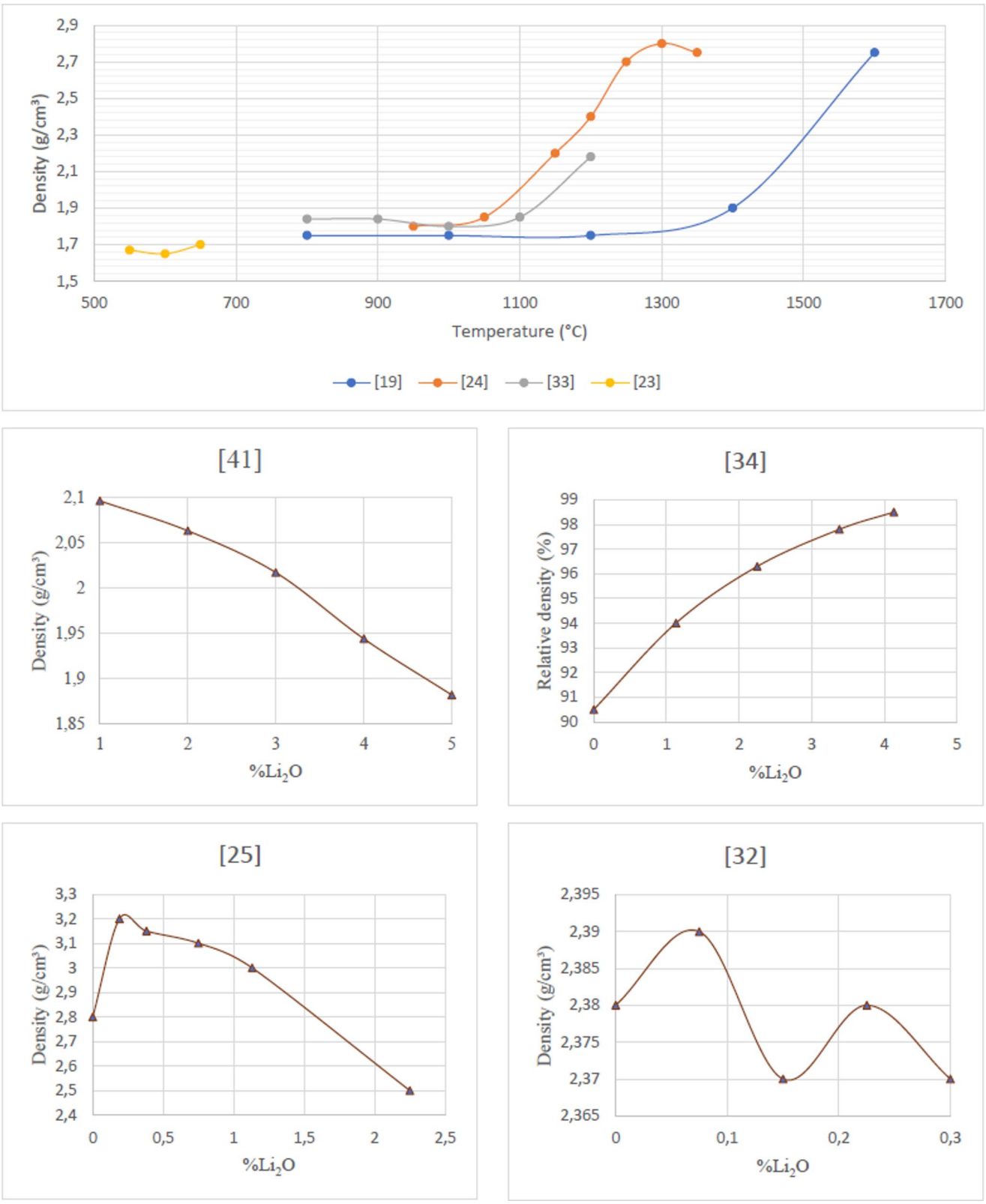


Fig. 6 Relationship between density and sintering temperature or lithium oxide content based on articles reviewed

densities of 3.3 and 2.4 g/cm³ in the conditions with and without the addition of Li_2O, respectively. According to the authors, the results of thermogravimetric decomposition of the compositions with and without the incorporation of lithium justify the increase in apparent density: endothermic peaks were observed attributed to partial reactions between metal oxide - metal oxide and metal oxide - metal nitride, forming a macroscopically observed liquid phase in conditions with the addition of Li_2O sintered from 1350 °C. This fact possibly also justifies the difference in density presented between the works of [25], indicating that the introduction of this alkaline oxide reduces the formation temperature of the liquid phase, promoting greater densification consequently.

The studies by [30] and [39] evaluated the temperature range between 950 and 1100 °C in a coincident manner. Although they aimed to produce high-alumina porcelain and triaxial ceramics, respectively, both studies identified the optimal Li_2O content as between 1 and 1.2%, reaching similar density values, as shown in Fig. 6. Conversely, the study by [25] reported lower density values compared to these two studies, despite evaluating the same sintering temperature range. The lower values observed are likely due to differences in the raw materials used. At temperatures above 1350 °C [25], reported an increase in density, attributed to partial melting of the raw materials, as indicated by thermogravimetric decomposition analysis. The subsequent tempering process likely produced ceramics with higher density.

Other studies evaluated the influence of lithium oxide content on the densification of ceramic products. Generally, higher oxide content resulted in reduced density of the final product. The authors of [38] and [47] attribute this phenomenon to the effectiveness of aluminosilicate as a fluxing agent, which facilitates a more homogeneous distribution of the vitreous phase by reducing fluid-phase viscosity, resulting in greater quartz dissolution and, consequently, lower density. This density reduction was also observed by [31], consistent with findings by [48]: additions exceeding 20% spodumene lead to ceramic products with reduced density, likely due to pore formation caused by the excess liquid phase.

On the other hand, Wang et al. [40] found that higher levels of β-spodumene resulted in greater densification of the composites and, consequently, higher shrinkage rates. This observation may contrast with others due to the distinct nature of the raw materials used in their study. Additionally, this was the only study focused on the production of glass-ceramics that evaluated this physical index.

Furthermore, in a comparative investigation of artificial compositions (introducing lithium in the form of carbonate) and natural compositions (introducing lithium in the form of spodumene or petalite) [26], observed that natural pegmatite formulations densified earlier than artificial ones, with density values of 2.5 g/cm³ at 1150 °C and 2.3 g/cm³ at 1300 °C, respectively.

Water absorption and porosity When evaluating the water absorption index [26], observed that artificial products sintered at 1250 °C exhibited lower water absorption indices compared to lower or higher sintering temperatures. Compositions with Li_2O content above 2.2% showed water absorption values that differed from the others in the range between 1300 and 1350 °C, possibly due to the effect of overfiring and rapid vitrification. The authors confirmed this hypothesis based on the rounding of the edges of the test specimens, confirming that the sintering interval was not adequate for the indicated formulations. Among the natural compositions, the authors observed that formulations with petalite and higher lithium content presented lower water absorption values compared to those with spodumene and, consequently, lower lithium contente.

The authors of [28] associated higher Li_2O contents and higher sintering temperatures with lower water absorption indices. When comparing the lithium compound with traditional fluxing agents, the authors point out the evident potential of the rock containing spodumene as a fluxing agent in the production of ceramic materials, with the higher densification due to the formation of a vitreous phase from 1000 °C, resulting in lower water absorption indices. According to the authors, the rock containing 0.51% Li_2O presented a higher fluxing action compared to albite and feldspar, despite containing a lower content of alkali oxides. This finding is justified by the higher diffusion coefficient of lithium ions, due to the smaller ionic radius of this element, compared to K^+ and Na^+.

In general, water absorption results are directly related to porosity indices. The studies by [30] and [39] indicated that higher sintering temperatures generated products with lower porosity indices, and both studies obtained products with porosities between 10 and 15% (at 1200 °C). The author of [31] also quantified the porosity index, associating lower indices with higher spodumene contents, due to the higher sintering and densification promoted by the presence of a liquid phase in the presence of the fluxing agent. However, contents of lithium aluminosilicate above 30% implied an increase in porosity, possibly due to the formation of pores due to the excess of liquid phase.

Complementarily [38, 47], , and [29] evaluated and associated porosity and water absorption indices, as shown in Fig. 7. It is noted that the study by [29] presented higher porosity values and, consequently, higher water absorption. In this case, the authors attribute this phenomenon to the accumulation of large particles, the formation of bubbles during the sintering process, and internal porosity within

the particles. Although the study by [28] used particles with an even larger diameter, the discrepancy in water absorption values is justified by the sintering temperatures: [28] used temperatures between 1140 and 1240 °C (achieving products with up to 0% water absorption), while [29] used temperatures between 550 and 650 °C (obtaining products with water absorption between 15.5 and 14%).

The work by Aydin and Kara [38] obtained lower porosity and water absorption values for compositions with up to 0.15% lithium oxide. The authors related the obtained values to the viscosity of the fluid phase generated during sintering: for the condition with 0.15% Li_2O, a viscosity of 0.872 GPa·s and 0% water absorption was achieved, while in the formulation with 0.23% Li_2O, a viscosity of 0.688 GPa·s and 0.17% water absorption was obtained. This observation is consistent with other authors who also indicated that the introduction of lithium compounds reduces the viscosity of the fluid phase.

The study by [47] showed a trend of increased porosity and water absorption as the lithium oxide content increased. The authors attribute this to the role of lithium carbonate as a flux and pore-forming agent, lowering the sintering temperature of the liquid phase, increasing the amount of vitreous phase, and acting as a binder for the ceramic grains, creating a self-glazing effect on the surface of ceramic products.

Mechanical strength Generally, studies aimed at producing structural ceramics and whiteware evaluate flexural strength as the main mechanical strength index. Therefore, the data on this index were organized: some authors evaluated flexural strength as a function of sintering temperature, while others associated this physical parameter with the lithium oxide content (Fig. 8).

The authors of [29] found that higher contents of glass powder and higher sintering temperatures resulted in higher mechanical strength indices. The sintering temperatures used in this work differ from the others, due to the material being intended for the production of low-temperature ceramics. The condition whose raw material was composed of 60% waste, 10% kaolin, and 30% glass powder, sintered at 650 °C, presented a flexural strength equivalent to 42 MPa.

The authors of [39] evaluated different fluxing agents and observed that the mechanical strengths of all compositions sintered up to 1000 °C were not significantly different, assuming values between 10 and 23 MPa. Although the flexural strength index remained constant for the conditions sintered at 1100 and 1200 °C (60 MPa), the authors related this physical index to the modulus of elasticity, obtaining values equal to 30 GPa (1100 °C) and 60 GPa (1200 °C).

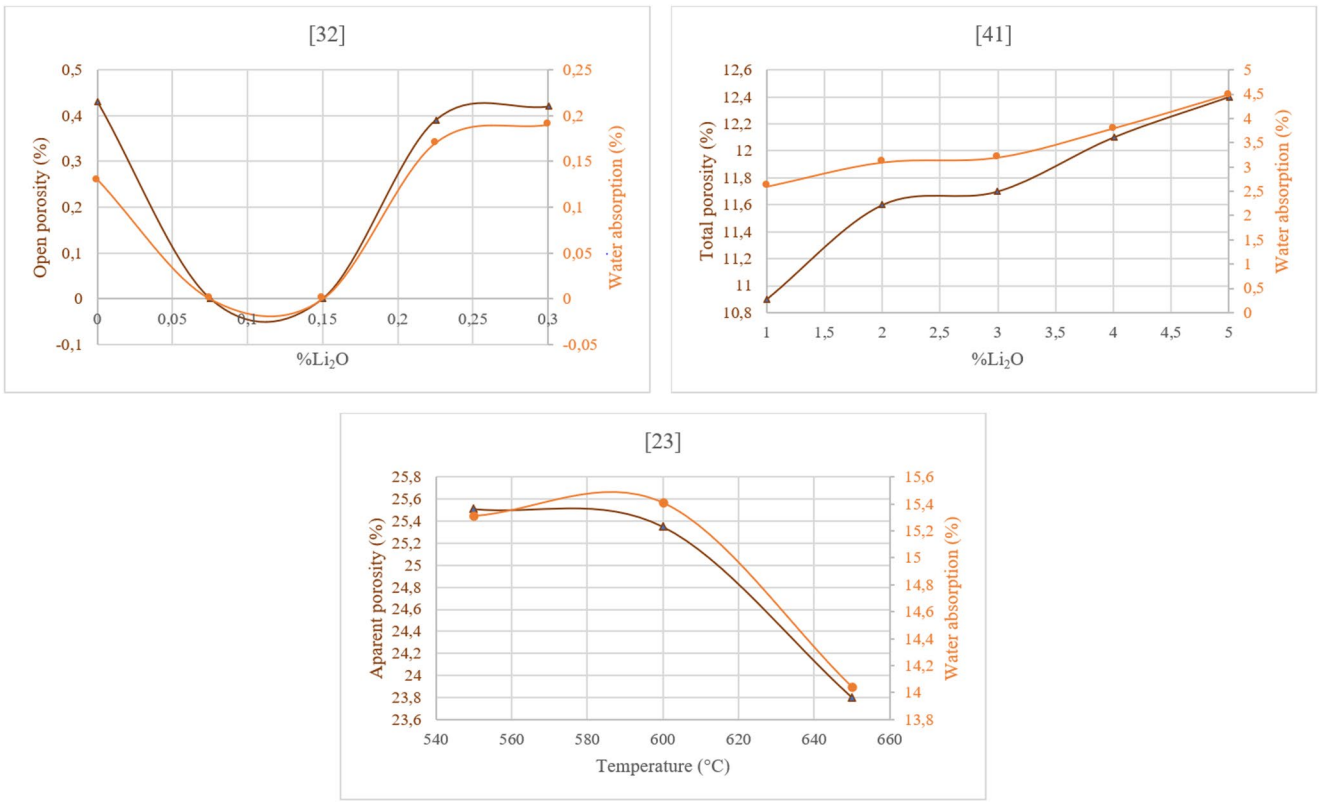


Fig. 7 Relationship between porosity and water absorption as a function of sintering temperature or lithium oxide content based on the reviewed articles

Such a change in the modulus of elasticity can lead to an improvement in thermal shock behavior, indicating the potential of the application of this secondary fluxing agent in the production of these materials.

Among the compositions evaluated by [30], the authors observed that the highest flexural strength was obtained when the material was sintered at 1300 °C (204 MPa). The authors attribute this to the reduction in thermal expansion of the mixture with the incorporation of Li_2O, with values on the order of 5.8×10^{-6} K^{-1}. When the firing temperature was raised to 1350 °C, a decrease in mechanical strength was observed (160 MPa). In this case, the authors associate this reduction with the linear shrinkage phenomenon and density variations at the analyzed temperature.

The studies by [30] and [39] evaluated the 950–1100 °C temperature range coincidentally. Although they aimed at producing high-alumina porcelain and triaxial ceramics, respectively, both studies identified an optimal Li_2O content between 1 and 1.2%, achieving similar flexural strength values, as shown in Fig. 8.

The authors of [26] investigated lithium introduction from pegmatites. It was observed that mechanical strength values were not significantly different across temperatures, presenting average values of 86 and 81 MPa at 1250 and 1350 °C, respectively. The authors also varied the Li_2O contents to 0.55% and 0.83%, achieving higher strength indices when sintered at 1250 °C: 93 and 80 MPa. This study differs from the others, as it was the only one to evaluate petalite as a lithium source, which resulted in higher mechanical strength indices compared to conditions where spodumene was used.

The authors of [38] evaluated mechanical strength as a function of Li_2O content, achieving a maximum flexural strength of 66 MPa at an Li_2O content of 0.15%. The authors attribute the increase in flexural strength to the fluxing action of lithium aluminosilicate, which acts by reducing the viscosity of the liquid phase and enhancing the dissolution of quartz and albite. However, Li_2O contents above 0.15% reduced the mechanical strength of the products obtained. Similar to [30], the authors associate this reduction with variations in the apparent density of the samples.

The authors of [40] observed an increase in flexural strength in compositions with higher β-spodumene contents. However, Li_2O contents above 2.25% proved detrimental to mechanical strength. The authors attribute this fact to the low flexural strength (145 MPa) of the added mineral, and also associate the reduction of this parameter possibly to the existence of porous structures. This work presents substantially higher mechanical strength values than the others presented in this topic. Possibly, such a discrepancy is due to the application: [40] was the only work directed to the production of glass-ceramics that evaluated flexural strength.

The study by [47] individually evaluated the action of lithium carbonate in the composition of structural ceramic coatings: this carbonate showed interesting due to the more homogeneous distribution of the vitreous phase (due to the reduction of the viscosity of the liquid phase), as well as acting as a pore-forming agent (generating products with lower density and thermal conductivity); however, the amount of vitreous phase generated was small and there was a large reduction in flexural strength. The association of lithium carbonate with boric acid proved to be a better option, since both act as fluxing agents, reducing the sintering temperature and increasing the amount of vitreous phase. The decomposition of titanium dioxide formed compounds in both the vitreous phase and the crystalline phase, thus increasing the mechanical strength of the product obtained.

In works directed to the production of glass-ceramics and special ceramics, mechanical strength is usually quantified from parameters such as Vickers hardness. The authors of [31] evaluated lithium oxide contents of up to 2.25% in the composition of aluminum titanate ceramics, reaching a maximum Vickers hardness value in the condition with 0.19% lithium oxide (15 GPa). The authors attribute this improvement to the greater densification resulting from the introduction of the lithium compound. Higher oxide contents resulted in a reduction in mechanical strength, but the authors consider that contents of up to 0.75% Li_2O would provide considerable improvements in fracture resistance. The works of [41, 45] and [44] obtained glass-ceramics with Vickers hardness values of the order of 7.9 GPa (for compositions with 6% Li_2O sintered in a single stage) to 8.7 GPa (for compositions with 8% Li_2O sintered in a staged manner). The authors attribute the success of the staged sintering process to the formation of a ceramized structure with the presence of β-spodumene under low-temperature heat treatment. Thus, this material becomes promising for application in the military segment, directed to the production of armor plates.

Thermal expansion Among the studies that evaluated the coefficient of thermal expansion, a certain unanimity was noted among the discussions raised: in all cases, higher lithium oxide contents resulted in a reduction in the coefficient of thermal expansion. The work by [40] obtained values of the coefficient of thermal expansion between 5.79 and 1 ppm/°C for compositions containing between 0 and 55% β-spodumene, respectively. In turn [38], also observed the same trend and related the reduction in the coefficient of thermal expansion to the dissolution of quartz in the vitreous phase due to the presence of the lithium compound. In addition to evaluating the effect of lithium oxide content on thermal expansion [30], also observed that higher sintering

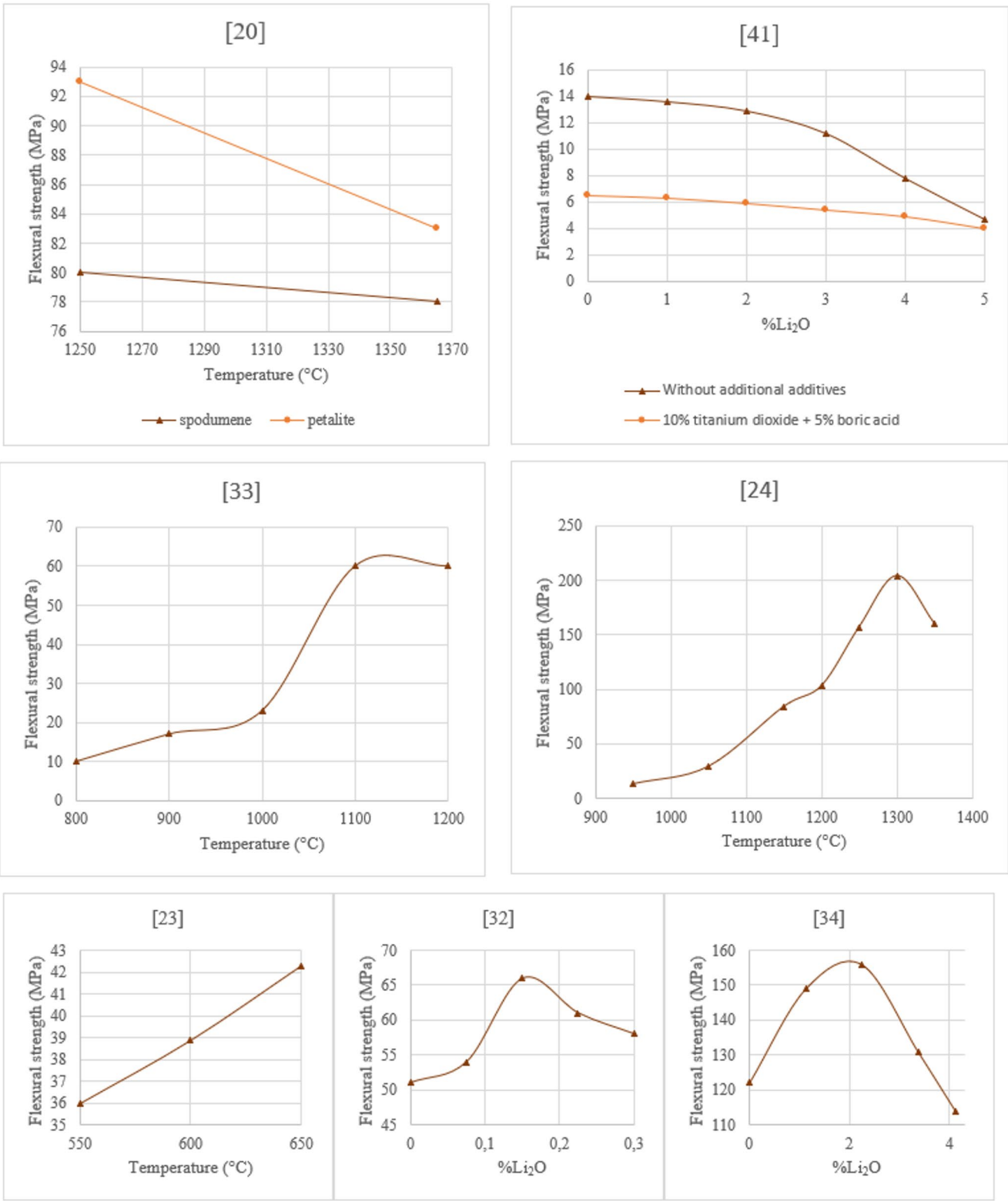


Fig. 8 Relationship between flexural strength and sintering temperature or lithium oxide content based on the reviewed articles

temperatures generate products with a higher coefficient of thermal expansion.

In the composition with the presence of lithium [31], observed a negative thermal expansion during heating (20 to 1000 °C) and, during cooling, some expansion was initially noted, followed by contraction possibly due to the presence of the vitreous phase, according to the authors. Once again, the authors compare the observations pointed out with the work of [48]: the same behavior was observed for mullite obtained from a composition containing 20% β-spodumene. From thermal shock resistance tests, it was possible to observe that ceramic bodies containing 5% lithium aluminosilicate and sintered at 800 °C showed a 75% increase in the mechanical strength index (from 12 to 21 GPa), demonstrating that the introduction of the lithium fluxing agent resulted in higher thermal shock resistances.

Other physical properties The production of glass-ceramics and special ceramics meets a variety of industrial needs, from the manufacture of microelectronic devices to the development of personal protective equipment in the military segment. For this reason, the technological parameters indicative of the quality of the products generated differ according to the desired final product.

A physical index little explored by the selected articles is the pyrolastic deformation index, which refers to the bending caused by the action of gravity during sintering. From this index, it is possible to elucidate assumptions about the formation of the vitreous phase and the viscosity of this phase. The work [28] observed an increase in pyrolastic deformation as a function of the increase in sintering temperature. From this analysis, it was noted that the temperature of liquid phase formation, where the viscosity is low enough to generate deformations, occurred from 1215 °C, reaching the maximum pyrolastic deformation at 1200 °C ($3.5 \times 10^{-3} cm^{-1}$). The authors attribute this fact to the low eutectic temperature of the rock containing spodumene, possibly due to the reaction of fluxing oxides with silica and alumina, thus reducing the viscosity of the vitreous phase.

In parallel, the work of [38] pointed out that higher contents of lithium oxide generated products with lower pyrolastic deformations, reaching the optimal value in the composition with 2% Li_2O (pyrolastic index equal to $5.6 \times 10^{-5} cm^{-1}$). The authors attribute this fact to the greater dissolution of quartz, causing a higher viscosity of the vitreous phase and greater resistance to deformation in the presence of lithium aluminosilicate.

In an extraordinary way, there are works that quantify thermal conductivity as a physical index [25]. observed higher thermal conductivity and mechanical strength indices resulting from the introduction of Li_2O associated with yttrium and calcium ($LiYO_2$-CaO), obtaining thermal conductivity values of up to 175 $Wm^{-1}K^{-1}$ for compositions sintered at 1600 °C (6 h). The authors related high thermal conductivity values to the removal of defects related to the presence of oxygen in the evolution of the precipitation of a large amount of grain boundary phases. Complementarily [47], observed that higher contents of lithium oxide are normally associated with lower thermal conductivities, obtaining values between 0.87 and 0.62 $Wm^{-1}K^{-1}$ for products with Li_2O contents between 1 and 5%, respectively. Once again, the authors attribute this fact to the pore-forming action of lithium carbonate, as well as acting as a modifier of the vitreous phase, reducing its viscosity during heat treatment.

Another fundamental physical index for quantifying the performance of special ceramics with electrical applications is dielectric impedance. The authors of [40] observed that higher β-spodumene contents and, consequently, lower alumina contents reduced the dielectric constant of the obtained products. The authors attribute this fact to the higher dielectric constant of Al_2O_3 compared to the other raw materials used. This behavior is coherent with the markedly high intrinsic permittivity of α-Al_2O_3 compared with lithium aluminosilicates, as discussed in the classical work of Kingery et al. [49]. Complementarily [46], pointed out that compositions sintered at higher temperatures generated products with lower dielectric constant values - in line with studies on glass-ceramics conducted by Holland and Beall [50], which indicated that sintering at higher temperatures promotes the crystallization of low-polarizability phases and reduces the residual glassy phase, both contributing to a decrease in the dielectric constant.

Still on electrical properties [33], pointed out that the condition free of titanium dioxide proved to be highly conductive, confirming the impact of free Li^+ ions on the electrical characteristics of the material. The introduction of the nucleating agent made the structure heterogeneous, possibly this microstructural characteristic resulted in the reduction of electrical conductivity, making the glass-ceramic insulating. The addition of TiO_2 as a nucleating agent, however, promotes the formation of a heterogeneous microstructure with increased crystallinity, which restricts ion mobility. This mechanism is consistent with observations by Shelby [51] and Scholze [52], who report that crystallization decreases alkali diffusivity and consequently reduces electrical conductivity, effectively shifting the material behavior from conductive toward insulating.

The works of [41, 46], and [44] evaluated the effect of lithium carbonate and sintering temperatures on the production of glass-ceramics aimed at the military segment. For this reason, the three works evaluated the modulus of elasticity as a physical index due to its implication in the quality of ceramic-based armor elements. According to [41]

and [44], the composition with 8% Li_2O presented a better value for the modulus of elasticity (100 GPa) and the staged heat treatment generated products of better quality, due to the formation of a ceramized structure with the formation of β-spodumene at low temperatures. In addition, the work of [46] pointed out that, in addition to the Li_2O content, the sintering temperature also interferes with the modulus of elasticity of the glass-ceramics, presenting higher values (350 GPa) for products sintered at higher temperatures (1150 °C).

Microstructure Most of the analyzed works presented microstructural analysis information that, in turn, was used to justify data obtained for various physical indices. The authors of [26] and [30] related the formation of the vitreous phase to the reduction of porosity based on microstructural analyses. In the work of [26], the authors observed the crystallization of mullite at 1250 °C (in compositions with the introduction of lithiferous pegmatite, presenting an acicular habit, as shown in Fig. 9) and at 1365 °C (in the composition without the introduction of lithium). Under all conditions, mullite and quartz phases were identified after firing, evidencing that the lithium was dissolved in the vitreous phase. Due to its small ionic radius, lithium was diffused into the metakaolinite particles, which exhibit a high surface area and pore volume distribution after metakaolinization [53]. Possibly, the presence of lithium reduces the eutectic point at the feldspar/metakaolinite interface, promoting the formation of a vitreous phase at this interface. The diffusion of lithium and early melting, together with the diffusion of potassium and sodium ions from feldspar and muscovite into kaolinite residues, should favor the densification and crystallization of primary mullite. Secondary mullite originates from the nucleation of primary mullite seeds and its crystals are generated on the surface of kaolinite and grow in the less viscous residues of feldspar [54].

Additionally [30], pointed out that compositions with the addition of lithium presented lower coefficients of thermal expansion and more homogeneous porosity from a microstructural standpoint, however, contents close to 1.6% of this oxide generated products with excessive porosity. Figure 10 shows the microstructure generated in products incorporating Li_2O contents ranging from 1.02 to 1.56%. The authors pointed out that contents close to 1.6% of this oxide generated products with excessive porosity. In this case, the authors attribute the larger size and greater sphericity of the pores to the overheating process and excess lithium oxide.

In the work of [28], the authors observed smaller pores in the condition with the association of rock containing spodumene, quartz, and kaolinite. Such porosity is justified based on the dissolution of quartz due to the high alumina content in the vitreous phase, resulting from the thermal decomposition of kaolinite. From a microstructural standpoint, the

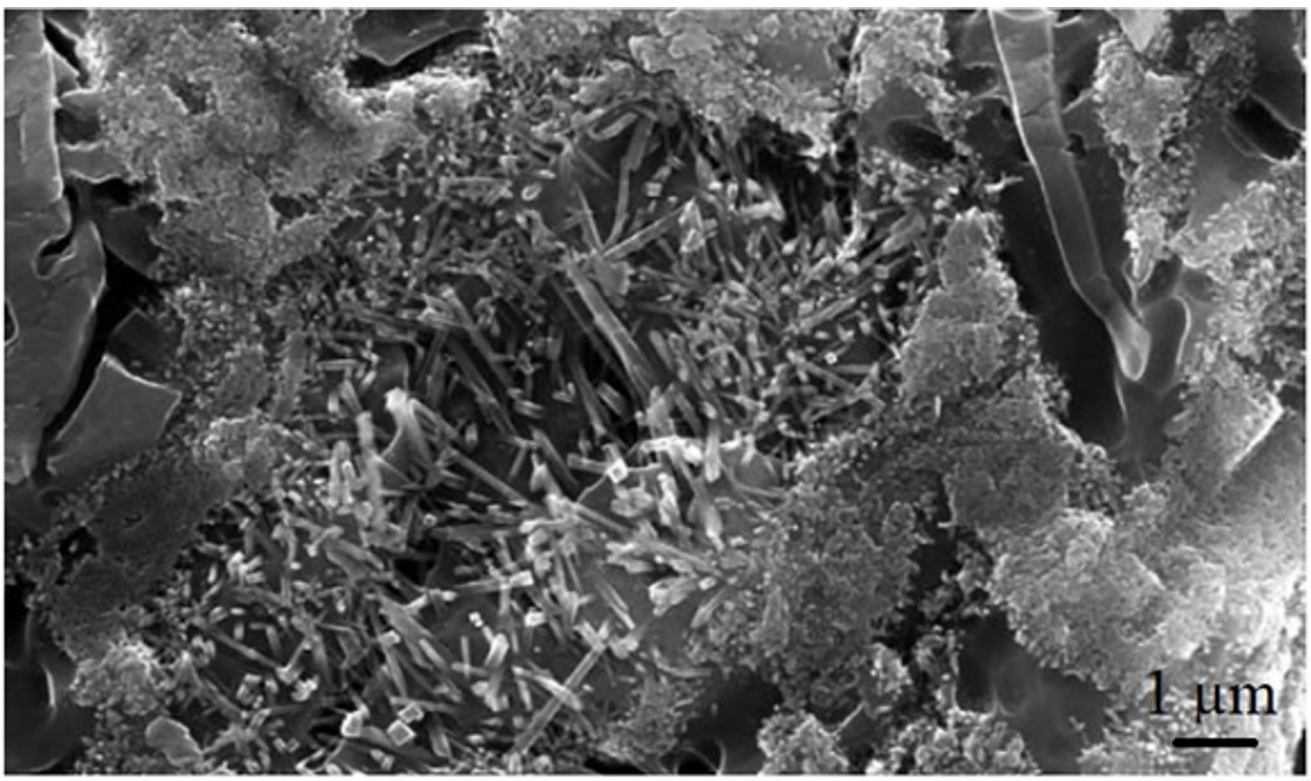


Fig. 9 Microstructure of a triaxial porcelain sintered at 1250 °C containing 1.76% Li_2O obtained from natural pegmatite [26]

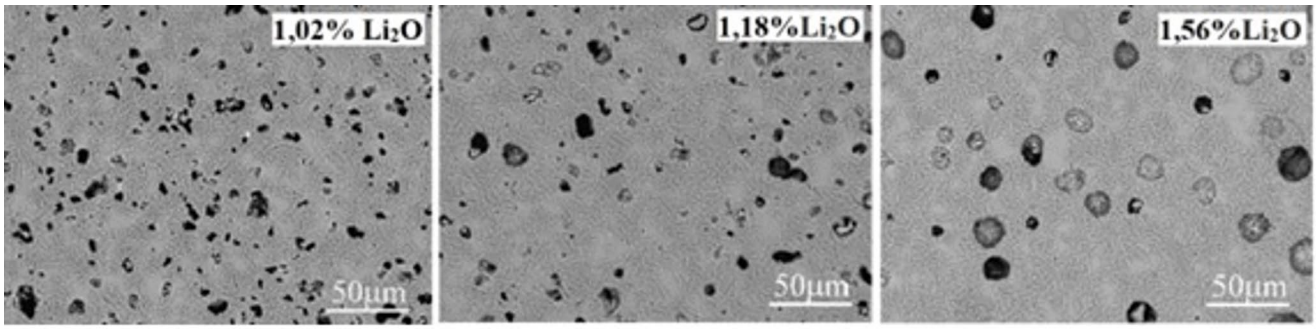


Fig. 10 Microstructure of porcelains sintered at 1300 °C containing 1.02%, 1.18%, and 1.56% Li2O [30]

quartz crystals presented a reduced size and rounded shape, confirming the hypothesis raised earlier. Cracks were also observed, possibly due to the difference between the coefficient of thermal expansion of quartz and the vitreous phase. The occurrence of cracks from the anisotropy between the coefficients of thermal expansion was previously pointed out in the work of [31]. In this work, the authors also attributed the formation of the vitreous phase to the thermal decomposition of lithium aluminosilicate.

The formation of the vitreous phase is directly related to the good performance of the physical indices, acting as a binder between the ceramic particles, promoting the sintering of the liquid phase and reducing the number of ceramic particles that are in direct contact with each other, with the formation of agglomerates. Although it acts in the formation of the vitreous phase [47], point out that the introduction of lithium carbonate individually results in the formation of a very small amount of vitreous phase, being necessary to use it in combination with other additives that additionally increase the amount of the vitreous phase. The authors indicate that the association of lithium carbonate with boric acid proved to be a better option, since both act as fluxing agents, reducing the sintering temperature and increasing the amount of vitreous phase. The decomposition of titanium dioxide formed compounds in both the vitreous and crystalline phases, thus increasing the mechanical strength of the obtained product.

Complementarily, the work of [33] evaluated the association of the fluxing agent (Li_2CO_3) with a nucleating agent (TiO_2). The authors observed the presence of spherules (between 40 and 100 nm) as shown in Fig. 11, possibly due to the introduction of titanium dioxide which, accompanied by the presence of lithium oxide, favored the mobility of silicon oxide and the crystallization of lithium silicate compounds. The introduction of the nucleating agent made the structure heterogeneous, possibly this microstructural characteristic resulted in the reduction of electrical conductivity, making the glass-ceramic insulating. Previously [32], had already studied the association between lithium carbonate and titanium dioxide, but directed to the production of glass-ceramics. The authors pointed out that titanium dioxide influenced the morphology, quantity, and growth rate of the crystals, as well as increasing the proportion of slower-growing biconic crystals in compositions sintered from 580 °C. Despite this, no relationship was established between TiO_2 and nucleation events, with this dioxide being pointed out only as a surfactant. In the composition without TiO_2 sintered up to 700 °C, the β-eucryptite and lithium

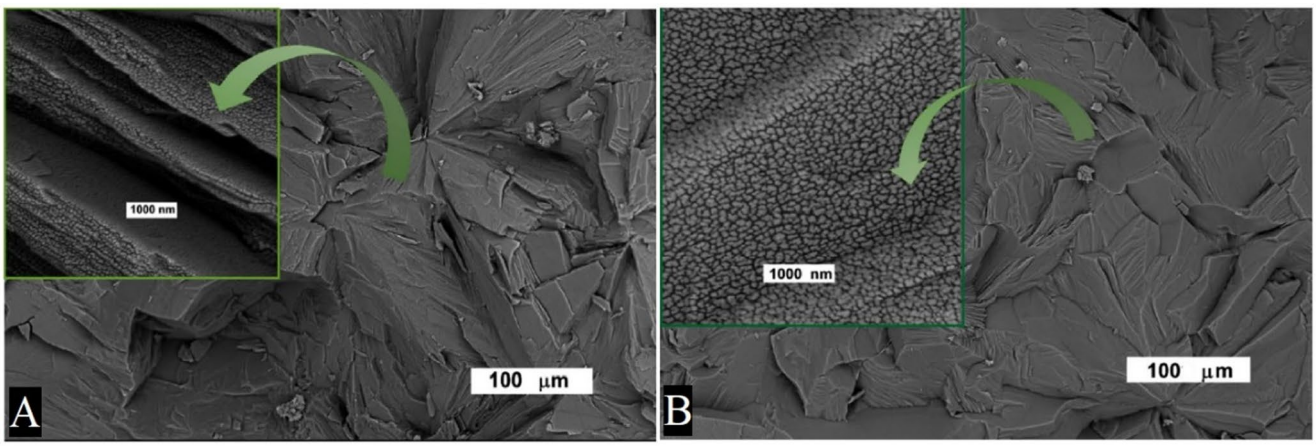


Fig. 11 Microstructure of glass-ceramic samples sintered at 650 °C for 2 h with compositions A (80% SiO2 + 20% Li2O) and B (60% SiO2 + 20% TiO2 + 20% Li2O), adapted from [33]

metasilicate phases were identified. When titanium dioxide was added to the composition, lithium metasilicate was only identified in conditions sintered above 700 °C.

Aimed at the production of special ceramics constituted of aluminum nitride, the work of [25] also evaluated the association of lithium with other sintering aids, CaO and $LiYO_2$. From microstructural analysis, the authors observed that the generated product was homogeneous and had finer grains than the conventional one (less than 2 μm). According to the authors, smaller particle sizes are related to better mechanical strength indices, evidencing the potential of using the association of sintering aids.

On the other hand, the works of [29, 40], and [44] associated mechanical strength indices with the development of microstructural structures. In study by [40], was observed an increase in flexural strength as the content of β-spodumene increased up to 30%, with a decrease in mechanical strength being noted with higher contents of the aluminosilicate. In this case, the authors indicated that better flexural strength indices were associated with lower porosity of the ceramic product (Fig. 12).

While [29] justified the increase in mechanical strength associated with the reduction in porosity for samples sintered from 600 °C (Fig. 13) due to the crystallization of glass powder, triggering chemical reactions such as the formation of P-O and Si-O bonds, based on results from scanning electron microscopy, thermogravimetric analysis, and Fourier transform infrared spectroscopy. In study by [44], also associated scanning electron microscopy and infrared spectroscopy results, evidencing some relevant microstructural events such as the fine crystallization of glass in the form of spherulites due to the nucleation of lithium metasilicate (550 °C), crystallization of β-eucryptite (650 °C), and its recrystallization into β-spodumene (850 °C). The authors also pointed out that the presence of β-eucryptite negatively affects the mechanical properties of glass-ceramics, and it is possible to produce materials with mechanical properties satisfactory for the military industry from 850 °C.

4 Conclusions

A literature review revealed that the application of lithium compounds is a widely discussed topic from an academic-scientific perspective in various countries. Regarding the number of publications, a significant increase in the

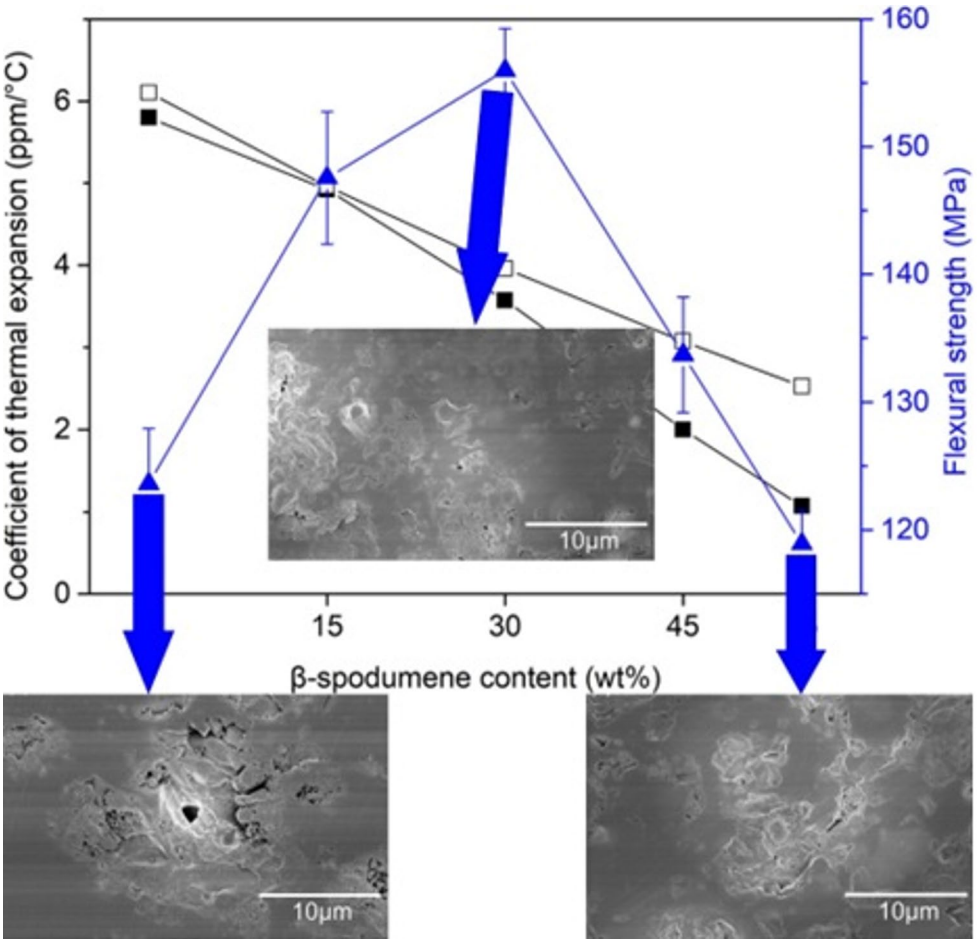


Fig. 12 Correlation between flexural strength, thermal expansion coefficient, and microstructure of glass-ceramics containing up to 55% β-spodumene, sintered at 875 °C. (Adapted from [40]).

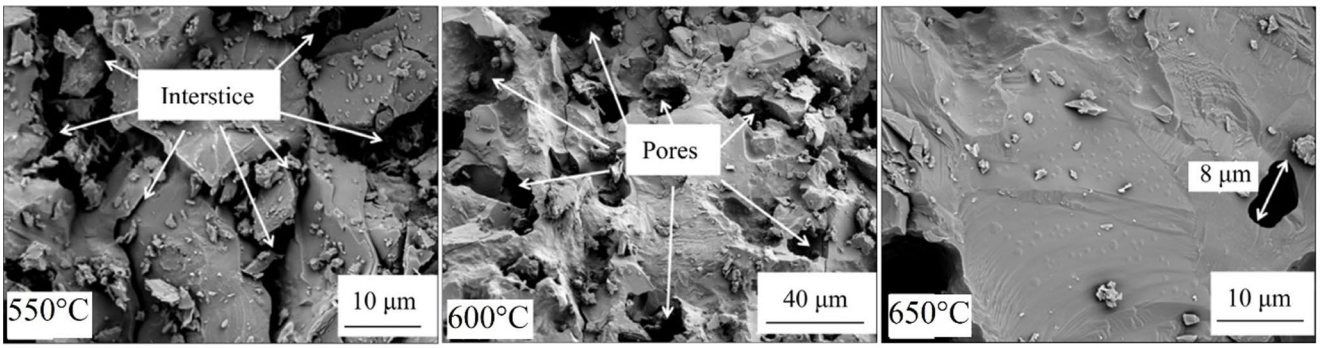


Fig. 13 Microstructure of ceramic products sintered at 550, 600, and 650 °C. (Adapted from [29]).

production of works on the subject has been observed in the last 20 years (76% of the analyzed articles were published in this period), a phenomenon associated with the increase in global lithium production (starting from 15.5 thousand tons in 2004 reaching 180 thousand tons in 2023).

Among the products developed containing lithium among the raw materials, triaxial ceramics, structural coating ceramics, porcelains, glass-ceramics, and special ceramics are the main products investigated in the analyzed works. In general, the authors attribute the improvements in the technological parameters of the obtained products to the action of lithium as a fluxing and melting agent, being responsible for reducing the viscosity of the vitreous phase, causing greater dissolution of the other mineral phases and, consequently, better mechanical and thermal quality.

However, the effect of α and β-spodumene phases is little explored in a comparative manner; moreover, few works were identified that address experimental tests to determine the coefficient of thermal expansion and thermal shock resistance, relevant parameters for the development of ceramics with special applications.

Acknowledgements The authors thank the support and encouragement of the Federal University of Ouro Preto, including the Department of Mining Engineering and the Graduate Program in Mineral Engineering, as well as the funding agencies CNPq, Fapemig, FINEP, and Capes.

Author Contribution We hereby declare, for all due purposes, that all listed authors actively participated in the preparation of the aforementioned article and are responsible for significant contributions, as described below:
Silva, M. C. A.: Conception and design of the study; drafting of the initial version of the manuscript; critical review of the intellectual content; data analysis and interpretation; critical revision of the manuscript.
Leite, T. M. G.: Methodological support; preparation of figures/tables; contribution to the discussion of the results.
Reis, E. L.: Overall supervision of the project; final revision of the manuscript; approval of the submitted version.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

Data Availability We declare that the data used and/or analyzed in the development of the aforementioned article are available or accessible in the following repositories of the databases used: Scopus, Web of Science, and Springer Link.

Declarations

Conflict of 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.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. United Nations, *The Sustainable Development Goals Report 2016* (United Nations, New York, 2016)
2. J. Xu, D. Li, J. Song, D. Du, X. Zhang, (2025). Hydrolysis behavior and mechanism of AlON powders. Materials & Design, 256, 114338, 2025. https://doi.org/10.1016/j.matdes.2025.114338
3. B.W. Jaskula, Lithium. In: Mineral commodity summaries 2024: U.S. Geological Survey, 110–111 p., Reston, 2024, https://doi.org/10.3133/mcs2024
4. International Lithium Association - ILiA, https://lithium.org/lithium/
5. J. Colton, W. Recovery of lithium from complex silicates. 1957
6. R. Xie, Y. Zhu, J. Liu, Y. LI, X. Wang, Z. Shumin, Research status of spodumene flotation: A review. Mineral. Process. Extractive Metall. Rev. V. **42**(5), 321–334 (2021)
7. F. Meng, J. Mcneice, S.S. Zadeh, A. Ghahreman, Review of lithium production and recovery from minerals, brines, and

lithium-ion batteries. Mineral. Process. Extractive Metall. Rev. V. **42**(2), 123–141 (2021)
8. P. Kinnunen, A. Ismailov, S. Solismaa, H. Sreenivasan, M. Räisänen, L. Levänen, Illikainen, M. Recycling mine tailings in chemically bonded ceramics–A review. J. Clean. Prod. **174**, 634–649 (2018)
9. T. Li, G. He, Z. Jiang, Y. Duan, M. Liu, Research advances and new insights into multi-source solid waste-derived ceramic foams. Sustainable Materials and Technologies, 45, e1535, 2025. https://doi.org/10.1016/j.susmat.2025.e01535
10. Y. Zhao, J. Jing, L. Chen, F. Xu, H. Hou, Current research status of interface of ceramic-metal laminated composite material for armor protection. Acta Metall. Sin. **57**(9), 1107–1125 (2021). https://doi.org/10.11900/0412.1961.2021.00051
11. Van L.H. Vlack, Automotive materials, in *Concise Encyclopedia of Advanced Ceramic Materials*, ed. by R.J. BROOK (MIT Press, Cambridge, 1991), pp. 25–30
12. Jiang, Z., He, G., Duan, Y., Jiang, Y., Lin, Y., Zhu, Y.,… Wang, J. Contrasting effects of various factors upon the properties of foam ceramics and the mechanisms of crystalline phase reconstruction and microstructure regulation. Ceramics International, 50(12), 21645–21657, 2024. doi: https://doi.org/10.1016/j.ceramint.2024.03.277
13. D.G. Grossman, Glass ceramics In: BROOK, R. J. (Ed.). Concise Encyclopedia of Advanced Ceramic Materials. Cambridge: MIT Press, 1991. pp. 170–176
14. K. Manu, M.T. Sebastian, Tape casting of low permittivity Wesselsite–Glass composite for LTCC based microwave applications. Ceram. Int. V. **42**(1), 1210–1216 (2016)
15. Jiang, Z., He, G., Jiang, Y., Zhao, H., Duan, Y., Yuan, G.,… FU, H. Synergistic preparation and properties of ceramic foams from wolframite tailings and high-borosilicate waste glass. Construction and Building Materials, 457, 139367, 2024. doi: https://doi.org/10.1016/j.conbuildmat.2024.139367
16. Wang, C., Hao, J., Duan, L., Zhao, D., Ma, Y., Zhang, J.,… Meng, F. Energy storage performance with ultrahigh energy density and power density of Ba0.85Ca0.15Zr0.1Ti0.9O3-based lead-free ceramics through synergistic optimization. Ceramics International, 51(21, Part B), 35133–35143, 2025. doi: https://doi.org/10.1016/j.ceramint.2025.05.237
17. W. Baumgart, A.C. Dunham, G.C. Amstutz, Lithium aluminosilicates. *Process Mineralogy of Ceramic Materials*, ed. by F. Enke (Stuttgart, Germany, 1984), pp. 9–10
18. R.J. Brook, Advanced ceramic materials: an overview, in *Concise Encyclopedia of Advanced Ceramic Materials*, ed. by R.J. BROOK (MIT Press, Cambridge, 1991), pp. 1–8
19. P. Mongeon, A. Paul-Hus, The journal coverage of web of science and scopus: a comparative analysis. Scientometrics V. **106**, 213–228 (2016)
20. D.E. Eilertsen, Lithium. In: Mineral commodity summaries 1965: U.S. Bureau of Mines, 607–610 p., Washington, 1966
21. R.H. Singleton, Lithium. In: Mineral commodity summaries 1975: U.S. Bureau of Mines, 851–859 p., Washington, 1977
22. J.P. Searls, Lithium. In: Mineral commodity summaries 1985: U.S. Bureau of Mines, 645–651 p., Washington, 1987
23. J.A. Ober, Lithium. In: Mineral commodity summaries 1996: U.S. Geological Survey, 96–97 p., Reston, 1996
24. B.W. Jaskula, Lithium. In: Mineral commodity summaries 2015: U.S. Geological Survey, 94–95 p., Reston, 2015, https://doi.org/10.3133/70140094
25. K. Watari, H.J. Hwang, M. Toriyama, S. Kanzaki, Effective sintering aids for low-temperature sintering of AlN ceramics. J. Mater. Res. V. **14**(4), 1409–1417 (1999)
26. D.U. Tulyaganov, A.G.A.T.H.O.P.O.U.L.O.S.S. Fernandes, H.R. FERREIRA, Influence of lithium oxide as auxiliary flux on the properties of triaxial porcelain bodies. J. Eur. Ceramic Soc. V. **26**, 1131–1139 (2006)
27. C. Sinton, *W. Raw Materials for Glass and Ceramics: sources, processes, and Quality Control* (Wiley, 2006)
28. S.R. Bragança, H.C.M. LENGLER, C.P. Bergmann, Spodumene-bearing rock as flux for triaxial ceramic bodies. Advances in Applied Ceramics, v. 110, n. 5, pp. 293–300, 2011
29. J. Yang, L.H. Xu, H.Q. Wu, Z.J. Wang, S.H.U.K.Q. XU, Y.B. Luo, L.P. Tang, Sintering behavior and mechanical properties of sintered ceramics based on spodumene tailings. J. Cent. South. Univ. **28**(6), 1637–1651 (2021)
30. M. Oberžan, H.O.L.C.J. Buh, M. Kuscer, High-alumina porcelain with the addition of a Li2O-bearing fluxing agent. J. Eur. Ceramic Soc. V. **29**(11), 2143–2152 (2009)
31. I.M. Low, Physical and thermal characteristics of aluminium titanate dispersed with β-spodumene and zirconia. J. Mater. Sci. V. **35**, 6293–6300 (2000)
32. T.I. Barry, D. Clinton, Lay, L. A., Mercer, R. A., Miller, R. P. The crystallisation of glasses based on eutectic compositions in the system Li 2 O-Al 2 O 3-SiO 2: part 1 lithium metasilicate—β-spodumene. J. Mater. Sci. **4**, 596–612 (1969)
33. E.M.A. Hamzawy, G.T. El-Bassyouni, M.A. Azooz, G.M. TURKY, Electrical properties of lithium silicate-based glasses and their Glass-ceramics. J. Mater. Science: Mater. Electron. V. **35**(3), 253 (2024)
34. J.H. Park, K.H. Kim, S.K. Lim, Influence of stabilizers on Na-β″-Al2O3 phase formation in Li2O (MgO)-Na2O-Al2O3 ternary systems. J. Mater. Sci. V. **33**, 5671–5675 (1998)
35. M. Dondi, M. Marsigli, Recycling of industrial and urban wastes in brick production-a review. Tile Brick Int. V. **13**, 218–225 (1997)
36. A. Bernasconi, N. Marinoni, P.A.V.E.S.E.A. Francescon, Feldspar and firing cycle effects on the evolution of sanitary-ware vitreous body. Ceram. Int. V. **40**(5), 6389–6398 (2014)
37. M. Földvári, *Handbook of Thermogravimetric System of Minerals and its Use in Geological Practice* (Geological Institute of Hungary, Budapest, 2011), p. 213
38. T. Aydin, Effect of spodumene addition on pyroplastic deformation of porcelain stoneware. J. Ceramic Process. Res. V. **15**(6), 486–491 (2014)
39. M.F. Serra, M. Picicco, E. Moyas, G. Suárez, E.F. Aglietti, Rendtorff, N. M. Talc, spodumene and calcium carbonate effect as secondary fluxes in triaxial ceramic properties. Procedia Mater. Sci. **1**, 397–402 (2012)
40. F. Wang, C.H.E.N.X. Zhang, Synthesis and characterization of borosilicate glass/β-spodumene/Al_2O_3 composites with low CTE value for LTCC applications. J. Mater. Science: Mater. Electron. V. **29**, 9038–9044 (2018)
41. O.V. Savvova, B.A.B.I.C.H.O.V.V.O.R.O.N.O.V.G.K. Ryabinin, S. O. High-strength spodumene glass-ceramic materials. Strength of materials, v. 49, pp. 479–486, 2017
42. C.A. Cowan, G.A. Bole, R.I. Stone, Spodumene as a flux component in sanitary Chinaware bodies. J. Am. Ceramic Soc. V. **33**(6), 193–197 (1950)
43. J.H. Fishwick, *Applications of Lithium in Ceramics* (Cahners Books, 1974)
44. O. Savvova, H. Voronov, F.E.S.E.N.K.O.O. Riabinin, Tymofieiev, V. High-strength glass-ceramic material with low temperature formation. Chem. Chem. Technol. V. **16**(2), 337–344 (2022)
45. O. Savvova, O. Babich, G. Shadrina, M. Kuriakin, A. Grivtsova, Investigation of effect of viscosity on crystallization ability of spodumene glass-ceramic materials. Funct. Mater. **23**(3), 414–419 (2016)
46. O.V. Savvova, L.Y.A.H.O.V.S.K.I.Y.A.F.B.L.I.N.O.V.A.N. K.V.O.R.O.N.O.V.G.K. RYABININ, S. A., TOPCHYI, V. L. Development of impact-resistant glass-ceramic materials for

radio-transparent armor elements. Voprosy Khimii i Khimicheskoi Tekhnologii, nº 3, pp. 151–157, 2019
47. V.N. Shakhova, B.E.R.E.Z.O.V.S.K.A.Y.A.A.V. Pikalov, Sysoev, E. P. Development of self-glazing ceramic facing material based on low-plasticity clay. Glass Ceram. **76**, 11–15 (2019)
48. I.M. Low, E. Mathews, T. Garrod, D. Zhou, D.N. Phillips, X.M. Pillai, Processing of spodumene-modified mullite ceramics. J. Mater. Sci. V. **32**, 3807–3812 (1997)
49. W.D. Kingery, H.K. Bowen, D.R. Uhlmann, *Introduction To Ceramics*, 2nd edn. (Wiley, 1995)
50. W. Holand, BEALL, G. H. *Glass-ceramic Technology*, 2nd edn. (Wiley, 2012)
51. J.E. Shelby, *Introduction To Glass Science and Technology* (Royal society of chemistry, 2020)
52. H. Scholze, *Glass: nature, structure, and Properties* (Springer Science & Business Media, 2012)
53. A. Yamuna, S. Devanarayanan, M. Lalithambika, Mullite–β-spodumene composites from aluminosilicates. J. Am. Ceramic Soc. V. **84**, 1703–1709 (2001)
54. Y. Iqbal, W.E. Lee, Fired porcelain microstructures revisited. J. Am. Ceramic Soc. V. **82**(12), 3584–3590 (1999)

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.