INTRODUCTION

The planet is facing a serious environmental crisis, including problems such as pollution, global warming, waste generation, and depletion of natural resources [1]. In the 21st century, the exacerbated population growth, accompanied by consumerism and industrialization, resulted in a rapid increase in waste generation [2-4]. Thus, it is necessary to formulate urban, industrial, agricultural, and transport development strategies and policies that are linked to environmental protection [5]. Conventional solid waste management methods, such as incineration, landfill, and composting, are widely used around the world. However, the emergence of stricter regulations in order to slow down the exploitation of non-renewable natural resources has motivated the use of waste materials as high-quality raw materials [4, 6]. The use of wastes, after detecting their potential, contributes to product diversification, energy savings, and improvement in population health [7-11].

In recent years, several studies have demonstrated the feasibility of using industrial waste in the manufacture of ceramic products, especially porous ceramic products. Among the studied waste materials, organic [12-32] and inorganic [33-51] ones have shown promising results.

In general, ceramics are produced from natural raw materials with very heterogeneous chemical and mineralogical compositions [52], which are similar to the compositions of many types of waste. This similarity makes them very suitable to be used as alternative raw materials in the production of various ceramic materials, especially porous ceramic materials. In the last decade, porous ceramics have stood out due to their wide possibilities for use in various fields of engineering, ranging from filtration and water treatment to thermal/acoustic insulation and catalytic support [53, 54]. Traditionally, porous ceramics are classified according to the pore size: macroporosity (diameter >50 nm), mesoporosity (2 nm < diameter <50 nm) and microporosity (diameter <2 nm). However, commonly used structures present a combination of pores of different sizes in a single monolithic matrix [55, 56]. Porous ceramics can also be classified according to the way in which their basic structure is composed: open cells (or reticulated) or closed cells. This characteristic plays a key role in determining the functionalities of these materials [56, 57]. A ceramic structure composed of open cells and interconnected pores is favorable for applications where fluid transport is required, such as in filtration processes. On the other hand, isolated pores in a continuous ceramic matrix composed of closed cells offer advantages for applications where fluid flow must be restricted, such as in thermal and acoustic insulation [56, 58-61].

In recent years, an intense effort around the world has aimed at more sustainable and technically differentiated reuse for waste. In this sense, a large volume of studies has been devoted to the development of porous ceramics using different types of industrial waste. However, there is no systematic analysis of the results and a current review of the state of the art in this technology. Thus, the present work aimed to provide a review on the use of organic and inorganic industrial waste as alternative raw materials in the production of porous ceramics, highlighting the technological innovations and potential of the studies developed.
ORGANIC WASTE

The wastes used as alternative raw materials in the production of porous ceramics can present in their composition inorganic and organic components [4], which can act in different ways, contributing to the consolidation of the ceramic matrix and to the formation of specific crystalline phases or promoting pore formation, respectively. Knowing the chemical composition of wastes is essential for planning formulations and, consequently, for obtaining desirable characteristics in the final product [62]. Organic waste has different constituents such as cellulose, hemicellulose, and lignin, which open up many opportunities to add value and can be a low-cost alternative for use as porogenic agents in the manufacture of porous ceramics [13]. According to Laksaci et al. [63], the pyrolysis of lignocellulosic materials results in the formation of three phases: coal, oils (tar), and gases. A rudimentary porosity is obtained from the carbon fraction as a consequence of the release of elements such as hydrogen, oxygen, and nitrogen in the form of gases and tar, leaving a rigid carbon skeleton formed by aromatic structures [16, 63]. The chemical compositions of some organic wastes from the agroindustry used as porogenic agents in the production of porous ceramics are listed in Table I.

Rice husks, an important by-product of the rice milling process, are an organic waste consisting of approximately 40 wt% of cellulose, 30 wt% of lignin, and 20 wt% of silica [64]. Furthermore, this waste is formed by the combination of volatile material (60-65%), fixed carbon (10-15%), and ash (17-23%) [65, 66], and can absorb water in the range of 5-16% [67]. These properties provide important benefits in the production of porous ceramic materials, as they reduce the unit weight and improve the thermal properties of the pieces. The use of rice husks in the production of clay bricks makes an economic contribution and also serves as an energy-efficient material for construction [12]. In tropical regions, significant amounts of organic waste come from banana cultivation, such as banana leaves and pseudostem [68]. Banana is one of the most consumed fruits in the world and is commercially cultivated in about 120 countries [13]. For each ton of banana produced by the agroindustry, approximately 3000 kg of pseudostem, 160 kg of stem, 480 kg of leaves, and 440 kg of peel are generated [69]. Studies carried out by Arcaro et al. [13] pointed to a moisture content of approximately 7.81 wt% in banana leaves. According to the researchers, biomass moisture is an important factor, as it directly interferes with other parameters, such as the heating value, which decreases with increasing moisture content and thermal conductivity [13, 68, 70]. They also verified the contents of volatile solids, fixed carbon, and ash corresponding to 78.16, 15.59, and 6.20 wt%, respectively. The volatile solids content indicates the presence of organic matter, represents the lignocellulosic and carbon fractions present in the samples and expresses the amount by weight of the biomass components that are first burned [13, 70, 71].

Mathematical models to predict the thermal conductivity and mechanical strength of clay ceramics containing organic additives were developed by Nigay et al. [14]. Ceramic properties were predicted from parameters such as true density, degree of swelling, particle size distribution, and particle form factor of the organic additives. According to the authors, the extent of the increase in the porosity of the bodies during the sintering process depends on the density of the added organic additives, so that the low-density ones occupy a larger volume than the high-density ones, resulting in greater porosity. They demonstrated that the addition of 8 wt% of olive stone flour promoted an increase of 12% in porosity of the ceramics, while the addition of 8 wt% of wheat straw (less dense) resulted in an increase of 20%. Nigay et al. [14] also demonstrated that organic additives that have a relatively high particle form factor, such as olive stone flour, result in the formation of round pores. Consequently, the thermal conductivity of the material is decreased due to the low thermal conductivity of the air in these pores. On the other hand, organic additives with low particle form factors, such as wheat straw, result in the formation of oriented pores. This means that heat diffusion

| Organic waste          | C   | H   | N   | O   | S   | LoI | Ref. |
|------------------------|-----|-----|-----|-----|-----|-----|------|
| Rice husk              | 44.60 | 5.60 | -   | 49.30 | -   | -   | [12] |
| Banana leaf            | 43.28 | 6.23 | 0.98 | -   | 0.49 | -   | [13] |
| Olive stone flour      | 49.80 | 6.00 | 0.40 | 42.00 | -   | -   | [14] |
| Wheat straw            | 43.10 | 5.50 | 0.70 | 28.50 | -   | -   | [14] |
| Active yeast           | 64.12 | -   | -   | 28.12 | 0.75 | -   | [15] |
| Coffee waste           | 58.48 | 7.31 | 1.05 | -   | -   | -   | [16] |
| Sawdust                | 44.21 | 6.02 | 5.06 | -   | -   | 99.67 | [17] |
| Grape seed             | 50.16 | 6.62 | 2.17 | -   | -   | 97.03 | [17] |
| Cherrie seed           | 50.42 | 6.19 | 1.96 | -   | -   | 99.66 | [17] |

LoI: loss on ignition.
is highly limited through stacking clay sheets and porosity. Table II summarizes the properties of some porous ceramic materials that were obtained from the use of organic waste as porogenic agents. The data reveal that ceramic bodies with a high level of porosity, low thermal conductivity, and satisfactory mechanical strength can be obtained from waste such as rice husks [12], banana leaves [13], olive stones [14], wheat straw [14], yeast [15] and coffee waste [16, 72]. Additionally, it is observed that the most porous ceramic materials produced using organic waste in their composition are applied in the civil construction industry, such as porous clay bricks and foams for thermal and/or acoustic insulation. The increase in the number and size of pores after the incorporation of agricultural waste in burnt clay bricks can be attributed to the combustion of organic matter and the reduction in the amount of fluxing oxides [73] so that bodies produced with higher contents of organics have higher apparent porosity values.

**Biomass ash:** biomass, considered one of the most promising sources of renewable energy [74], has great potential to provide energy for heating, electricity, and transport, being increasingly used on a world scale. The agroindustry produces huge amounts of waste around the world, most of which is composed of biomass that can be used as fuel to obtain electrical and thermal energy. However, the combustion process of this material generates a large amount of ash, and its disposal has become an environmental and economic issue [25]. Biomass ash is commonly disposed of in landfills close to power plants, but this alternative is the least attractive in environmental management [27]. The accumulation of ash can damage the soil and surroundings, contributing to air and water pollution. In addition, space limitations can make landfill disposal problematic [25, 75, 76]. There are two main types of ash: bottom ash, which corresponds to the portion of non-combustible residue found in the furnace or incinerator, and fly ash, which escapes through the chimney and must be retained to prevent its release into the atmosphere [77]. The quality and quantity of ash generated in a plant are greatly influenced by the characteristics of the biomass and the combustion technology used [78]. The potential for reused ash is determined by its chemical and physical

| Composition                  | Final product           | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m⁻¹.K⁻¹) | Compressive strength (MPa) | Ref.   |
|------------------------------|-------------------------|----------------------|-----------------------|----------------------------------|---------------------------|--------|
| Coarse rice husk (5-15 vol%) + brick raw material | Porous clay brick       | 700 ºC/1 h           | ~34-46                | ~0.30-0.20                       | ~4-1                      | [12]   |
|                              |                         | 800 ºC/1 h           | ~37.5-49              | ~0.28-0.16                       | ~8-2                      |        |
|                              |                         | 900 ºC/1 h           | ~37.48                | ~0.34-0.17                       | ~10-2                     |        |
|                              |                         | 1000 ºC/1 h          | ~37-48                | ~0.40-0.18                       | ~11-2                     |        |
| Ground rice husk (5-15 vol%) + brick raw material | Porous clay brick       | 700 ºC/1 h           | ~36-41                | ~0.40-0.27                       | ~4-2                      |        |
|                              |                         | 800 ºC/1 h           | ~39-44.5              | ~0.34-0.24                       | ~9-5                      |        |
|                              |                         | 900 ºC/1 h           | ~38-44                | ~0.39-0.25                       | ~9.25-5.75                |        |
|                              |                         | 1000 ºC/1 h          | ~37-43.5              | ~0.45-0.29                       | ~9-6                      |        |
| Banana leaf (30-50 wt%) + crushed glass bottle | Thermal insulating glass foam | 700 ºC/30 min       | ~75-85                | ~0.15-0.06                       | ~3.50-2.25                | [13]   |
| Olive stone flour (4-8 wt%) + clay | Porous clay brick       | 950 ºC               | ~36-42                | ~0.70-0.60                       | -                         | [14]   |
| Wheat straw (4-8 wt%) + clay  |                         | 900 ºC               | ~40-50                | ~0.60-0.45                       | -                         |        |
| Active yeast (10-50 wt%) + alumina powder | Porous alumina ceramic | 1600 ºC/2 h          | 30.2-63.8             | -                                | 19.5-1.8                  | [15]   |
| Coffee waste (10-30 wt%) + red clay | Porous red ceramic       | 1150 ºC              | ~30-42.81             | ~0.53-0.37; ~0.56-0.39; ~0.60-0.45 | -                         | [16]   |
| Spent coffee ground (15 wt%) + red clay | Porous clay ceramic      | 1000 ºC/1 h (MM)     | 55.51 (TP)            | -                                | -                         | [72]   |

*MM: manual pelletization; PP: powder pressing; TP: total porosity; °: 10 ºC; °: 25 ºC; °: 40 ºC.*
Table III - Chemical compositions (%) of ashes from different types of biomass.

| Biomass ash                        | SiO$_2$ | Al$_2$O$_3$ | K$_2$O | Na$_2$O | CaO   | MgO   | Fe$_2$O$_3$ | TiO$_2$ | Others | LoI | Ref.  |
|-----------------------------------|---------|-------------|--------|---------|-------|-------|-------------|---------|--------|-----|-------|
| Rice husk ash                     | 75.42   | 6.81        | 2.17   | 1.29   | 3.54  | 1.54  | 3.98        | -       | -      | 4.05| [20]  |
| Sugarcane bagasse ash             | 77.21   | 6.87        | 2.59   | 1.24   | 3.65  | 1.45  | 4.69        | -0.37   | 4.71   | [19]|
| Ash from sludge from olive oil    | 85.41   | 1.98        | 0.31   | 0.25   | 2.61  | 0.73  | 2.58        | -       | -      | 9.21| [20]  |
| Corn cob ash                      | 87.97   | 1.84        | 0.32   | 0.28   | 2.65  | 0.72  | 2.65        | -0.15   | 10.45  |     | [19]  |
| Corn cob ash                      | 8.60    | 56.95       | 0.47   | 2.09   | 0.84  | 0.27  | 1.92        | 0.08    | 25.73  |     | [21]  |
| Untreated coffee husk ash         | 18.35   | 59.16       | -      | -      | -     | 0.73  | 1.21        | 0.05    | 20.47  |     | [22]  |
| Brazil nut shell ash              | 1.24    | 0.58        | 46.46  | 0.14   | 17.70 | 4.51  | 0.56        | 0.08    | 7.66   |     | [23]  |
| Wood ash                          | 6.38    | 1.94        | 32.86  | 0.82   | 10.84 | 5.36  | 0.67        | 0.93    | 12.44  | 27.50| [24]  |
| Ash from pomace from olive oil    | 48.60   | 5.94        | 1.85   | 0.92   | 18.10 | 3.20  | 3.26        | 1.39    | 1.10   | 15.62| [25]  |
| Extraction industry               | 35.77   | 11.32       | 2.99   | 3.08   | 20.94 | 3.93  | 8.71        | 0.49    | 11.73  |     | [21]  |
| Olive pomace ash                  | 16.44   | 7.03        | 19.69  | -      | 35.43 | 6.83  | 2.16        | 0.20    | 6.05   | 5.60 | [26]  |
| Ash from sugarcane bagasse ash    | 10.88   | 1.68        | 38.01  | 0.13   | 13.07 | 1.92  | 1.38        | 0.13    | 7.24   | 25.53| [27]  |

LoI: loss on ignition.

Properties. Ashes are composed of minerals absorbed by the biomass itself or incorporated into it during harvesting, and by unburned organic material [79]. Components of interest such as silica, potassium, chlorine, sodium, phosphorus, sulfur, iron, magnesium, calcium, and titanium can be found in biomass ash even after thermal processing [22, 80-82], as shown in Table III. Table III shows a wide variation in the chemical composition of the ashes, which is linked to the different types of biomass from which they originate. Rice husk and sugarcane bagasse ashes are mainly composed of SiO$_2$ [19, 20], which can be used as alternative sources of silica in the production of ceramic materials. On the other hand, corn cobs [22], coffee husks [23], and Brazil nut shells [24] ashes have K$_2$O as the main oxide in their chemical compositions, allowing their use as sources of fluxing oxides in ceramic masses. Although wood ash and olive oil extraction process bagasse ash are mainly composed of SiO$_2$, they also have high CaO contents [21, 25], being considered good sources of auxiliary fluxing oxides.

Kazmi et al. [18] demonstrated, in their studies, that rice husk ash (5 wt%) can be satisfactorily incorporated into ceramic masses in order to obtain lightweight bricks for the construction industry. The reduction in the weight of the bricks, due to the greater porosity (39.71%), can result in a reduction in structural loads and, consequently, in savings. Kazmi et al. [19] also produced lightweight bricks using rice husk ash (5-15 wt%). With satisfactory values of porosity (~37.5-40%) and mechanical strength (~6.5-5 MPa), bricks showed potential to be used in building insulation, in moderate climate environments, and in the presence of sulfates. The incorporation of rice husk ash also contributed to a significant improvement in efflorescence resistance.

Results obtained by Eliche-Quesada et al. [25] indicate that it is possible to obtain ceramic bricks with up to 10 wt% of rice husk ash that meet technological standards. And, when sintered at 1000 °C, they deliver the mechanical performance required by standards for clay masonry materials, while reducing thermal conductivity by more than 30%. The incorporation of rice husk ash promotes the formation of high porosity, mainly closed porosity. According to Eliche-Quesada et al. [25], the addition of this type of ash in the clay matrix can result in the formation of a liquid phase with sufficient viscosity to avoid the release of gases from the decomposition of organic matter and CaCO$_3$ present in the matrix, that would cause open porosity. This behavior is desirable, as high-porosity bricks are preferred in terms of weight and thermal performance [20, 25]. Andreola et al. [83] also observed an increase in the closed porosity as a function of rice husk ash content.

Sugarcane bagasse ash has also been extensively studied for the manufacture of lightweight bricks [84]. In the sugar-alcohol industry, the sugarcane stalk is crushed to extract the juice and the remaining fibrous waste is called bagasse [28], which composition is approximately 26.6-54.3 wt% of cellulose, 22.3-29.7 wt% of hemicellulose and 14.3-24.5 wt% of lignin [85, 86]. Currently, sugarcane bagasse is burned in boilers to produce steam, which can be used in manufacturing processes and also to drive turbines for the production of electricity [86]. As a result of this burning process, large quantities of solid waste known as sugarcane bagasse ash are generated around the world. It is estimated that each ton of bagasse produces about 25 kg of ash [86]. Kazmi et al. [19, 20] and Maza-Ignacio et al. [84] demonstrated that the partial replacement of clay with
sugarcane bagasse ash results in lighter bricks compared to conventional ones. According to the researchers, this behavior may be related to the lower content of fluxing oxides and higher content of organics present in these ashes in comparison to clay, and also to the presence of calcite, which undergoes thermal decomposition during the sintering process, generating gases that contribute to increased porosity. Ashes from the combustion of rice husks [15, 18-20, 25] and sugarcane bagasse [18-20, 84, 87] have shown great potential to be used as alternative raw materials in the production of porous ceramic materials, in particular, lightweight bricks for applications in the construction industry, as shown in Table IV.

In general, ash that has significant levels of fluxing oxides (K₂O, Na₂O) and auxiliary fluxing oxides (CaO, MgO) in its composition tends to reduce the sintering temperature because the melting capacity of the waste lowers the melting point of the clay matrix. In this sense, the greater amount of alkaline oxides-rich ash incorporated in the clay matrix contributes to the formation of a liquid phase at lower temperatures and, consequently, adequate viscosity is reached more quickly, avoiding the release of gases resulting from the thermal decomposition of organic material and other compounds of carbon, causing open porosity. According to Eliche-Quesada and Leite-Costa [27], high amounts of ash (>20 wt%) can lead to the formation of too much open porosity, as well as larger macropores and small particles that become isolated and nearly spherical, characteristics of the viscous flow sintering mechanism. The joining of the pores and the increase in their size indicate the beginning of a coalescence process. Table V presents works that were carried out aiming at the use of ash rich in fluxing and auxiliary fluxing oxides together with clay mixtures to obtain porous ceramics.

Corn cob ash with good properties is generally derived from natural green corn cob through a controlled combustion process [22, 80, 82]. This is a material with a large amount of potassium compounds (KCl, K₂SO₄, and KHCO₃) that help to reduce the sintering temperature of a ceramic body [82], making it suitable as a fluxing additive in ceramics technology. Furthermore, the ability of potassium compounds to diffuse easily into water [89] or any other solvent [90, 91] made it a potential material for use in membrane applications [22]. Kamarudin et al. [22] used corn cob ash as a porogenic agent and sintering additive, together with metakaolin, in order to obtain hollow fiber ceramic membranes to be applied in water filtration and oil-water separation processes. The authors found that, compared to standard hollow fiber membranes made entirely from metakaolin, those made from ash had significant

Table IV - Properties of porous ceramic materials obtained from the use of rice husk and sugarcane bagasse ashes.

| Composition                                      | Final product            | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m⁻¹.K⁻¹) | Compressive strength (MPa) | Ref.  |
|--------------------------------------------------|--------------------------|----------------------|-----------------------|----------------------------------|---------------------------|------|
| Rice husk ash (5%) + sugarcane bagasse ash (5%) + clay | Porous clay brick        | Fired in coal kiln/45 days | 39.71                 | -                                | 5.10                      | [18] |
| Rice husk ash (5-15%) + clay                     | Porous clay brick        | 800 ºC/36 h          | ~37.5-40              | -                                | ~6.50-5                   | [19] |
| Rice husk ash (10-50%) + alumina powder          | Porous alumina ceramic   | 1600 ºC/2 h          | 42.9-49               | -                                | ~69.7-53.9                | [15] |
| Rice husk ash (10-30%) + clay                    | Porous clay brick        | 900 ºC/4 h           | ~37.5-46              | -                                | ~30-13.5                  | [25] |
| Rice husk ash (5-15%) + clay                     | Porous clay brick        | 1000 ºC/4 h          | ~37-45                | 0.7-0.68                         | ~35.9-17.5                |      |
| Carbonized rice husk (5-30%) + tabular alumina + α-Al₂O₃ powder | Highly porous alumina ceramic | 1600 ºC/2 h | 26.8-82.4              | 0.82-0.19 (200 ºC)                   | 32-45                     | [88] |
| Sugarcane bagasse ash (5-15%) + clay             | Porous clay brick        | 800 ºC/36 h          | ~42-44                | -                                | ~7-4                      | [19] |
| Sugarcane bagasse ash (5-15%) + clay             | Porous clay brick        | 800 ºC/36 h          | ~35-40                | ~0.45-0.35                       | 7.2-5                     | [20] |
| Sugarcane bagasse ash (30%) + kaolinite clay     | Ceramic membrane         | 900 ºC/2 h           | 37.4                  | -                                | -                         | [87] |
| Sugarcane bagasse ash (40%) + clay               | Resistant lightweight fired brick | 1000 ºC/6 h | ~50                    | -                                | ~7.5                      | [84] |
|                                                   |                          | 900 ºC/6 h           | ~49                   | -                                | ~8                        |      |
advantages over the porous membrane configuration. The dissolution behavior of corn cob ash during the preparation of the ceramic suspension was favorable to increasing the viscosity, inducing the formation of sponge-like structures with high performance for filtration applications. The studies demonstrated the feasibility of producing highly porous (62.03%) hollow fiber ceramic membranes, with good flexural strength (41.61 MPa) and permeability (1359.93 L.m⁻².h⁻¹), and efficient oil/water removal (74.73%) at a relatively low sintering temperature (1200 °C).

Brazil nut shell ash is a waste resulting from the direct combustion of the nut’s shell. This ash, rich in alkaline elements such as potassium and calcium, has the potential to lower melting points during sintering and therefore can be an inexpensive and attractive waste material to replace traditional flux materials used in ceramic production, namely feldspars. The Brazil nut-based industry is an important emerging local business in the Amazon region, Brazil. In this region, large amounts of nutshell waste are produced, which are often used as biofuel for heating and electricity generation, resulting in the production of 80 to 150 ton of ash over a period of approximately six months [24]. Escalera et al. [24] demonstrated that it is possible to obtain highly porous ceramic bricks (up to 60% porosity) at relatively low sintering temperatures (750-950 °C) by using Brazil nut shell ash. Olive pomace comes from the oil production process and consists of components present in the fruit, with the exception of oil, such as crushed stone pieces (15 wt%), pulp with residual oil (20 wt%), and water (65 wt%) [92]. The residual oil is normally recovered by solvent extraction after drying the bagasse, and this process generates another waste called dry olive cake or ‘orujilo’ [26]. Both bagasse and dry olive cake are rich in organic material and potassium [93], and both can be used as fuel for the generation of thermal and electrical energy in industries, producing a large amount of ash (4-8% of waste burned) [26].

Table V - Properties of porous ceramic materials obtained from the use of ash rich in fluxing and auxiliary fluxing oxides from biomass burning.

| Composition (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m⁻¹.K⁻¹) | Compressive strength (MPa) | Ref. |
|------------------|---------------|----------------------|-----------------------|----------------------------------|---------------------------|------|
| Corn cob ash (0-50%) + kaolin powder | Ceramic hollow fiber membrane | 1200 °C/3 h | ~19.4-62 | - | - | [22] |
| Brazil nut shell ash (0-30%) + diatomaceous earth | Porous brick material | 750 °C/1 h | ~25-60 | - | ~2-5.9 | [24] |
| | | 850 °C/1 h | ~7.5-52 | ~0.23-0.76 | ~7.5-19 | |
| | | 900 °C/1 h | ~5-42.5 | - | ~9-17 | |
| Pomace ash from olive oil extraction industry (0-30%) + clay | Lightweight clay brick | 950 °C/4 h | ~28-35 | ~1-0.90 | ~47.5-22.5 | [21] |
| Milled washed olive pomace ash (5-10%) + clay | Lightweight clay brick | 1025 °C | - | ~0.68 (10%) | - | [26] |
| Micronized washed olive pomace ash (5-10%) + clay | | | - | ~0.71 (5%) | - | |
| Olive pomace bottom ash (10-50%) + clay | Porous clay brick | 950 °C/4 h | 28.3-39 | 0.99-0.82 (20%) | 47.96-10.2 | [27] |
| Wood ash (10-30%) + clay | Porous clay brick | 900 °C/4 h | ~33-37 | - | ~53-34.3 | [25] |
| | | 1000 °C/4 h | ~32-34 | 1-0.75 | ~55-40 | |

Table VI - Chemical compositions (%) of eggshell and mollusk shell wastes.

| Waste | SiO₂ | Al₂O₃ | K₂O | Na₂O | CaO | MgO | Fe₂O₃ | Others | LoI | Ref. |
|-------|------|-------|-----|------|-----|-----|-------|--------|-----|------|
| Avian eggshell waste | - | - | 0.80 | 0.20 | 52.40 | 0.60 | - | 0.30 | 46.50 | [28] |
| | 0.09 | 0.03 | - | 0.19 | 50.70 | 0.01 | - | 1.02 | 47.80 | [94] |
| Oyster shell waste | 0.60 | <0.10 | <0.10 | - | 53.70 | 0.90 | <0.10 | - | 44.50 | [30] |
| | 0.69 | 0.42 | - | 0.98 | 52.57 | 0.65 | - | 0.20 | 44.49 | [31] |
| Mollusk shell powder | 0.40 | 0.16 | - | - | 53.80 | - | - | 1.34 | 44.30 | [32] |

LoI: loss on ignition.
Table VII - Properties of porous ceramic materials obtained from the use of eggshell and mollusk shell wastes.

| Composition (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m\(^{-1}.K^{-1}\)) | Compressive strength (MPa) | Ref. |
|------------------|---------------|----------------------|-----------------------|-------------------------------------------|---------------------------|-----|
| Avian eggshell waste (1-30%) + crushed glass bottle | Glass foam | 900 °C/30 min | 60-95 | 0.18-0.06 | 1.50-0.15 | [28] |
| Avian eggshell waste (1-5%) + crushed cathode ray tube glass (PG, FG) | Glass foam | 600-800 °C/15 min | - | - | 0.76-5.88 (97% FG); 1.26-14.82 (97% PG) | [95] |
| Raw avian eggshell waste + chamotte | Thermal insulation construction material | 1100 °C/24 h | - | 0.25 | 0.45 | [29] |
| Calcined avian eggshell waste + chamotte | Wall tile material | 1150 °C/1 h | 37.53 | - | 0.35 | [94] |
| Avian eggshell waste (15%) + red clay + quartz | Vitro-crystalline foam | 800-900 °C/30-120 min | 81-91 (9% waste) | 0.08-0.06 (9% waste) | 2.3-0.7 (9% waste) | [30] |
| Oyster shell waste (1-15%) + crushed glass bottle | Porous ceramic | 700 °C/3.5 h | ~52-49 | - | ~0-5 | [31] |
| Oyster shell waste (0-40%) + low-grade diatomite | Porous ceramic | 900 °C/3.5 h | ~45.8-45 | - | ~0-25 | |

PG: panel glass; FG: funnel glass; "+" 3% waste.

27]. De La Casa and Castro [26], Eliche-Quesada et al. [21], and Eliche-Quesada and Leite-Costa [27] demonstrated the feasibility of using olive pomace ash in the production of lightweight masonry bricks. For this, they replaced the clay (10%, 30%, and 50%), usually used in the manufacture of bricks, with ash. The systematic analysis of the results in the aforementioned works shows that there was a reduction in the bulk density of the pieces and, consequently, in the thermal conductivity in relation to bricks produced entirely with clay.

**Egg and mollusk shells waste:** Table VI presents the chemical compositions of wastes from egg and mollusk shells. All of them are mainly composed of CaO (>50%) and have a high loss on ignition (>40%), which means a high content of organic material. The eggshell corresponds to approximately 10 wt% of the egg and contains about 94 wt% of carbonate calcium (CaCO\(_3\)) in its composition [28], while the shell of an oyster corresponds to more than 70 wt% of this mollusk and is composed of approximately 96 wt% CaCO\(_3\) [30]. Although both are not considered hazardous wastes, their inadequate disposal can result in considerable environmental disturbances due to the large volume that is produced [28, 30]. Considering that the thermal decomposition of calcium carbonate generates CO\(_2\), the possibilities for reusing this waste include its use as a porogenic agent in the production of low-density ceramic materials [17], as shown in Table VII. According to Teixeira et al. [30], oyster shell waste was shown to be a strong candidate as an alternative porogenic agent to replace mineral calcium carbonate (commercial), since the release of CO\(_2\) by it corresponds to a sufficient amount to produce the expansion of a soda-lime glass at its softening temperature for the production of vitreous foams.

**INORGANIC WASTE**

Table VIII lists the chemical compositions of various inorganic industrial wastes used as alternative raw materials in the production of porous ceramics. Among them, those from the brewing [33, 34], ornamental rocks [35-37], ceramic [35, 38-42], metallurgical [43, 44] and mining [45-49] industries, thermal power plants [96-98] and others [13, 50, 51, 99] stand out. It is observed that the vast majority of these wastes are mainly composed of SiO\(_2\), that is, they can be used satisfactorily as sources of silica in ceramic technology. Exceptions are some mineral tailings, which have high CaO and MgO contents [46-49].

**Diatomaceous earth waste from the brewing industry:** Diatomites are single-celled organisms, abundant in fresh and salt water, that produce complex-shaped cytoskeletons made of silica. When diatoms die, their silica shells accumulate on the sea floor and thick layers of these shells are fossilized into diatomaceous earth or diatomite [101, 104-106]. Diatomaceous earth, a fine-grained material with a porous structure, is rich in hydrated amorphous silica and has low thermal conductivity, high melting point, high surface area, and low density, in addition to being essentially inert to most chemical liquids and gases [33, 106]. Diatomaceous earth is commonly used by the brewing industries during the beer filtration and clarification steps. When applied in this way, it has a very short shelf life, as it becomes saturated with organic material, derived from the beer fermentation.
| Industry             | Inorganic waste                        | SiO₂ | Al₂O₃ | K₂O   | Na₂O  | CaO   | MgO   | Fe₂O₃ | TiO₂ | Others | LoI  | Ref. |
|----------------------|----------------------------------------|------|-------|-------|-------|-------|-------|-------|------|--------|------|------|
| Brewing industry     | Diatomaceous earth waste               | 91.02| 1.23  | 0.59  | -     | 1.99  | -     | 4.40  | -    | 0.73   | -    | [33] |
|                      |                                        | 74.61| 5.48  | 1.45  | 1.32  | 0.48  | 0.12  | 0.73  | 0.30 | 0.54   | 13.40| [34] |
| Ornamental rock       | Granite scrap                          | 66.13| 15.15 | 1.32  | 1.83  | 3.75  | 3.05  | 3.04  | -    | -      | 7.58 | [35] |
| industry             | Quartzite waste                        | 73.77| 13.37 | 3.92  | 3.52  | 1.38  | 0.23  | 2.57  | -    | 0.14   | 0.64 | [36] |
|                      |                                        | 79.62| 12.43 | 4.44  | -     | 0.63  | 0.95  | 1.11  | 0.13 | 0.69   | -    | [37] |
| Ceramic industry      | Ceramic tile polishing waste           | 68.77| 21.74 | 2.39  | 2.64  | 1.32  | 1.02  | 0.79  | 0.49 | 0.12   | 0.95 | [38] |
|                      | Porcelain polishing waste             | 64.30| 17.70 | 1.25  | 3.51  | 1.55  | 2.14  | 0.65  | 0.34 | -      | 0.80 | [39] |
|                      | Porcelain tile polishing residue      | 67.10| 20.50 | 2.40  | 3.00  | 1.80  | 1.40  | 1.70  | 0.70 | 0.70   | 0.50 | [100]|
|                      | Stoneware polishing residue           | 64.10| 16.50 | 2.10  | 4.40  | 1.40  | 4.60  | 0.50  | 0.50 | 1.90   | 4.00 | [40] |
|                      | Ceramic waste                         | 78.62| 10.56 | 1.48  | 3.37  | 0.99  | 0.97  | 1.00  | -    | -      | 2.36 | [41] |
|                      | Fired clayey material residue         | 47.14| 28.22 | 0.91  | 4.59  | 1.37  | 1.98  | 11.44 | -    | -      | 3.47 | [35] |
|                      | Ceramic sludge                        | 56.45| 15.68 | 2.82  | 1.37  | 7.79  | 2.24  | 0.52  | 0.12 | 9.79   | 3.20 | [101]|
|                      | Porcelain sludge                      | 66.83| 16.84 | 1.52  | 0.55  | 2.08  | 1.83  | 1.06  | -    | 0.08   | 9.20 | [42] |
| Metallurgical industry| Chromium slag                         | 33.78| 26.33 | 0.22  | 0.18  | 4.99  | 21.67 | 3.75  | -    | 7.95   | 0.17 | [43] |
|                      | Nickel smelting slag                  | 50.97| 5.02  | 0.18  | 2.59  | 1.36  | 29.97 | 7.76  | -    | -      | 0.95 | [44] |
| Mining industry       | Germanium tailing                     | 66.68| 10.82 | 2.56  | 4.69  | 6.55  | 3.66  | 3.54  | 0.92 | 0.58   | -    | [45] |
|                      | Lead-zinc mine tailing                | 14.30| 4.52  | -     | -     | 28.0  | 1.72  | 25.09 | -    | 23.67  | 2.61 | [46] |
|                      | Extracted titanium tailing            | 21.30| 8.90  | -     | 0.50  | 35.2  | 9.50  | 2.50  | 11.00| 11.10  | -    | [47] |
|                      | Asbestos tailing                      | 36.05| 0.71  | 0.11  | -     | 6.03  | 44.64 | 11.28 | -    | 1.18   | -    | [48] |
|                      | Vitrified asbestos-containing waste   | 35.70| 7.40  | 0.10  | <0.05 | 35.1  | 12.60 | 7.00  | 1.50 | 0.60   | -    | [40] |
|                      | Iron tailing                          | 60.11| 6.79  | 1.56  | 0.32  | 6.60  | 8.66  | 14.73 | 0.58 | 0.63   | -    | [102]|
| Power plant           | Coal fly ash                          | 52.30| 28.60 | 0.06  | 0.40  | 5.80  | 1.60  | 4.10  | -    | 2.40   | 4.60 | [96] |
|                      | High alumina fly ash                 | 48.49| 41.20 | -     | -     | 3.31  | 0.20  | 3.37  | 1.30 | -      | 2.13 | [97] |
|                      |                                          | 55.05| 31.97 | -     | -     | 1.58  | -     | -     | 1.68 | -      | [98] |
|                      |                                          | 42.59| 48.27 | 0.56  | -     | 2.14  | 0.41  | 2.36  | 2.41 | 1.26   | -    | [103]|
| Others               | Investment casting* waste            | 36.20| 53.30 | 0.90  | 0.40  | -     | 1.70  | 1.40  | 6.10 | -      | [50] |
|                      | Cathode ray tube glass               | 58.72| 3.72  | 5.56  | 7.01  | 4.03  | 3.32  | -     | -    | 17.95  | -    | [45] |
|                      | Glass waste                          | 70.95| 2.16  | 0.02  | 16.76 | 9.60  | -     | 0.10  | 0.05 | 0.03   | 0.33 | [13] |
|                      | Silicon kerf waste                   | 70.00| 0.90  | -     | 11.50 | 12.7  | 3.90  | 0.40  | -    | 0.60   | -    | [47] |
|                      | Coal gangue                          | 75.01| 0.09  | 0.02  | -     | 0.50  | -     | 5.27  | -    | 19.13  | -    | [51] |
|                      | Coal slime                           | 52.70| 18.10 | 2.51  | 2.00  | 1.57  | 1.50  | 4.77  | 0.75 | 0.76   | -    | [99] |
|                      |                                          | 58.29| 23.85 | 2.69  | 1.90  | 3.62  | 1.51  | 4.64  | 0.76 | 1.19   | [99] |

*LoI: loss on ignition; *: lost-wax process.*
process, making its reuse as filtering material unfeasible. A large brewing company can generate approximately 30,000 kg/month of this waste [33, 107]. Diatomaceous earth waste, as well as other inorganic materials rich in amorphous silica, is convenient and promising for the production of porous ceramics due to its properties [108]. According to studies carried out in recent years (Table IX), highly porous ceramic materials can be obtained from the use of diatomaceous earth waste as porogenic agents. Using formulations containing ignimbrite, bentonite, and only 10 to 16 wt% of diatomaceous earth waste, Huanca and Nunes [33] produced highly porous ceramic supports (porosity of 79.76-81.62%) capable of reducing approximately 85% of the pollutants emitted by burning bricks and tiles from the red ceramic industry. Mateo et al. [34] produced ceramic bricks with high porosity (35.1-39.4%) using only 1 to 5 wt% of diatomaceous earth waste. The addition of the waste promoted an increase in open porosity and, consequently, a reduction in the bulk density of the bricks, contributing to their insulating characteristics. According to the researchers, the use of this waste as secondary raw material in the manufacture of ceramic bricks can present advantages from an economic and technological point of view.

**Waste from the ornamental rock industry:** the ornamental rock industry is of great importance to the world economy [109]. Its activities are mainly based on the extraction, cutting, and polishing of rocks such as granite, quartzite, marble, slate, and gneiss. The techniques used for this type of industry produce continuously high amounts of mineral waste, which are normally disposed of in landfills or directly into the environment, without any prior treatment [11, 110-112]. The inadequate disposal of mineral waste leads to the deterioration of flora and fauna and represents risks to human health since the fine mineral particles can be deposited in the lungs through breathing [11, 109, 112, 113]. In the granite processing industry, more specifically, it is estimated that 25% of the material is rejected during the sawing process, around 15% during the cutting and polishing steps, and 1% during the finishing process. The quartzite transformation industry, which involves fewer processing steps, produces approximately 1% of waste [109]. Granite and quartzite wastes are mainly composed of silicon oxide (SiO$_2$), but also contain aluminum (Al$_2$O$_3$), alkaline (K$_2$O and Na$_2$O), alkaline earth (CaO and MgO), and iron (Fe$_2$O$_3$) oxides in their chemical compositions [11, 35-37]. The silica present in these wastes largely comes from the quartz crystalline phase, while the alkaline and alkaline earth oxides are generally from impurities in the form of feldspar and micaeous mineral [11, 37]. The K$_2$O and Na$_2$O contents can act as fluxes, which, in reaction with silica and alumina, promote the formation of a liquid phase by eutectic reaction, which improves the sintering process [113].

Considering that some natural raw materials used in the manufacture of traditional ceramics derive from the decomposition of rocks, a similar mineralogical composition between them and the waste generated by the ornamental rock industry should be expected [11, 109, 114]. This means that waste from the extractive activity of ornamental rocks is a good substitute for raw materials with a high added value used in the production of ceramic materials, including porous ones. Table X presents works that were carried out aiming at the use of waste from the ornamental rock industry, together with clay mixtures, to obtain porous ceramics. Studies performed by Jiang et al. [35] demonstrated that it is possible to produce ceramic foams with a predominance of closed porosity using granite waste as the main raw material. With a ceramic mass consisting of 85 wt% of granite waste, the researchers obtained foams with suitable properties to be applied to the thermal insulation of buildings. According to Liu et al. [36], who also studied the use of granite waste (0-100 wt%) in the production of ceramic foams, the referred waste contributes to improving the uniformity of the pore size distribution. In a study carried out by Oliveira et al. [37], hollow fiber ceramic membranes were obtained from a mixture of 40 wt% of quartzite waste and 60 wt% of alumina. The results revealed that the quartzite waste, together with alumina, has chemical and mineralogical properties suitable for the formation of the mullite crystalline phase, which is desirable in porous ceramic materials as it contributes to the increase in mechanical strength.

**Waste from the ceramic industry:** the ceramic industry generates a considerable amount of wastewater in many steps of the manufacturing process, especially in the preparation of glazes and screen printing paints, slip preparation, and decoration. In an industrial plant that produces 300,000 m$^2$ of ceramic tiles per month, approximately 192 m$^2$ of wastewater is generated. After the filtering process, approximately 30 ton of solid waste (ceramic sludge) are left. Thus, it is estimated that approximately 10 ton of sludge per 100,000 m$^2$ of ceramic tile is produced [94]. Due to the continuous production of this sludge by the ceramic industry, its disposal has become a major problem from an environmental point of view [42]. It is reported that the annual production of ceramic sludge is around 86,660 ton in Brazil [94]. The polishing residue is another type of waste from the ceramic industry that deserves attention.

### Table IX - Properties of porous ceramic materials obtained from the use of diatomaceous earth waste from the brewing industry.

| Composition (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Compressive strength (MPa) | Ref. |
|------------------|---------------|----------------------|-----------------------|--------------------------|-----|
| Diatomaceous earth waste (10-16%) + ignimbrite + bentonite | Ceramic foam | 1100 ºC/1 h | 79.76-81.62 | 0.11-0.80 | [33] |
| Diatomaceous earth waste (1-5%) + clay | Porous clay brick | 950 ºC/6 h | ~35.1-39.4 | 18.2-22.4 | [34] |
It consists of fine powders from cutting and polishing or lapping processes [40]. It is usually reused as a by-product in the ceramic process for complete cycle industries, but in some cases, it is still discarded in landfills [40, 115, 116]. According to Zhu et al. [41] the contents of Al$_2$O$_3$ and SiO$_2$, together, are almost 90 wt% in this type of material.

Due to the chemical and mineralogical compositions of the aforementioned residues, they have been identified as having great potential to be used as alternative sources of raw materials in the production of ceramic products, especially ceramic products with high porosity. Table XI shows some studies that demonstrate the feasibility of using waste from the ceramic industry in the production of porous ceramic materials. Monich et al. [40] produced high porous ceramics (74%) using only porcelain stoneware polishing residue as raw material. Zhu et al. [41] and Jiang et al. [35] produced ceramic foams with apparent porosity of up to 83% using ceramic wastes. De Silva and Hansamali [42] evaluated the progressive replacement of clay by porcelain ceramic sludge (20 to 60 wt%) in the production of porous bricks, obtaining promising results. According to the authors, the replacement of 40 wt% of clay with porcelain ceramic sludge resulted in a significant increase in the porosity of the bricks.

**Table X - Properties of porous ceramic materials obtained from the use of waste from the ornamental rock industry.**

| Composition (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m$^{-1}$.K$^{-1}$) | Compressive strength (MPa) | Ref. |
|------------------|---------------|----------------------|-----------------------|--------------------------------------------|---------------------------|------|
| Granite scraps (85%) + clay tailing | Closed-pore ceramic foam | 1250 °C/30 min | 83.31 | 0.05 | 0.85 | [35] |
| Granite scraps (10-100%) + turmeric residue | Ceramic foam | 1175 °C/1 h (50%) | ~0.100 | ~0.60 | [36] |
| Quartzite waste (40%) + alumina powder | Hollow fiber membrane | 1100 °C/1 h | ~27.5 | - | - | [37] |

**Table XI - Properties of porous ceramic materials obtained from the use of waste from the ceramic industry.**

| Composition (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m$^{-1}$.K$^{-1}$) | Compressive strength (MPa) | Ref. |
|------------------|---------------|----------------------|-----------------------|--------------------------------------------|---------------------------|------|
| Polishing stoneware residue (100%) | Highly porous glass-ceramic | 900 °C/1 h | 74.0 | - | 3.1 | [40] |
| Polishing stoneware residue (90%) + soda-lime glass | Ceramic foam | 1000 °C/3 h | ~40-83 | ~0.08-0.21$^a$ | ~0-9.3 | [41] |
| Ceramic waste (80%) + flux+cement+clay | Closed-pore ceramic foam | 1250 °C/30 min | 83.31 | 0.05 | 0.85 | [35] |
| Residue of fired clayey material from ceramic plant (14%) + granite scrap (85%) | Porous clay brick | 850 °C/1 week | - | - | ~2.2-2.9 | [42] |

$^a$: 10 wt% clay; $^b$: 10 wt% foam.
in a decrease of 6% in brick density, an increase of 32% in compressive strength, and an improvement in thermal performance compared to bricks produced entirely with clay. At 12:30 p.m., when a higher room temperature is expected, a temperature difference of 10°C was observed between the external and internal environments, isolated with bricks produced with 40 wt% of ceramic sludge, while a difference of only 4.20°C was observed for tests with conventional bricks.

Tailings from the mining industry: in general, tailings from the mining industry contain abundant compounds based on Si and Al, which are essential elements for ceramic materials [46], in addition to other compounds similar to those found in ceramic phases, such as CaO, MgO, Fe₂O₃, and TiO₂ [47]. The high contents of SiO₂ and CaO are similar to those found in glassy phases [117]. Thus, they are good alternative raw material options for the manufacture of glass-ceramic foams [47] and/or porous vitreous ceramics, as shown in Table XII. Liu et al. [46] used lead-zinc mine tailings (20 wt%) together with fly ash (48 wt%), red clay (12 wt%), and sodium borate (20 wt%) in order to produce glass ceramic foams. At 980°C, foams with a glassy phase belonging to the Ca-Al-Si-O system were obtained, a structure that allows the solidification of some heavy metals (Pb, Cr, etc.) present in the tailings, since stable chemical bonds can be formed between them [110]. Xi et al. [47] also produced glass-ceramic foams with satisfactory properties, but using tailings from the extraction of titanium in combination with glass waste, in a ratio of 2:8.

Asbestos tailings are considered hazardous solid waste due to their carcinogenicity [48], and their accumulation represents a serious threat to the health of the population and also to the environment [49]. Chemically, they are mainly composed of SiO₂, MgO, and Fe₂O₃, but also have small amounts of CaO and Al₂O₃ [118]. When subjected to a heating process, this waste undergoes a series of decomposition reactions that lead to the release of CO₂ [119]. This behavior can favor the formation of pores in low-density ceramic materials. As a result, porous glass-ceramics prepared with the addition of this type of waste present greater porosity and lower densification temperature [49, 120]. Zeng et al. [49] prepared porous vitreous ceramics using asbestos tailings together with coal fly ash, in proportions of 10:90, 20:80, and

| Composition | (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m⁻¹.K⁻¹) | Compressive strength (MPa) | Ref. |
|-------------|-------|---------------|---------------------|-----------------------|-----------------------------------|-----------------------------|------|
| Germanium tailing (40%) + cathode ray tube glass + SiC | Glass-ceramic foam | 880 °C/30 min | - | 0.68 | 3.32 | [45] |
| Lead-zinc mine tailing (20%) + fly ash + red mud + sodium borate | Glass-ceramic foam | 920 °C/1 h | 34.8 | - | 25.3 | [46] |
| Extracted titanium tailing + glass waste (2:8) | Glass-ceramic foam | 770 °C/30 min | 82.4 | 0.11 | 1.3 | [47] |
| Asbestos tailings (10-30%) + coal fly ash | Porous glass-ceramic | 1000-1220 °C/1 h | 41-51 | - | - | [49] |
| Vitrified asbestos-containing waste (70-90%) + soda-lime glass | Highly porous glass-ceramic | 900 °C/1 h | 80.9-87.3 | - | 0.20-2.4 | [40] |
| Iron tailing (45%) | Porous brick | 1100 °C/3 h | 85.5 | 0.38-7.58 | | [102] |

Table XII - Properties of porous ceramic materials obtained from the use of tailings from the mining industry.

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Table XIII - Properties of porous ceramic materials obtained from the use of coal ash from thermal power plants.

| Composition (wt%) | Final product | Sintering conditions | Apparent porosity (%) | Thermal conductivity (W.m\(^{-1}\).K\(^{-1}\)) | Compressive strength (MPa) | Ref. |
|-------------------|---------------|----------------------|-----------------------|---------------------------------------------|---------------------------|-----|
| Coal ash + SiC powder (0.2:0.8 wt ratio) + pore former (PMMA, graphite) | Mullite bonded SiC ceramic membrane | 850 °C/2 h + 1000 °C/1 h | 36.36 (no pore former); 42.03 (graphite); 45.96 (PMMA) | - | - | [96] |
| Coal ash (40%) + bauxite (60%) + SiC (0-15%) + potassium feldspar (0-16%) | Porous mullite ceramic | 1450-1550 °C/2 h | 35.87-27.42\(^a\); 29.29-13.23\(^b\); 13.23-4.03\(^c\) | ~1.85-2\(^d\); ~1.90-3\(^e\); ~2.95-2.5\(^f\) | ~130-164\(^g\); ~150-260\(^h\) | [97] |
| Coal ash + Al(OH)\(_3\) (3:1 Al:Si ratio) + MoO\(_3\) (0-20%) | Highly porous mullite ceramic membrane | 1100-1500 °C/2 h | 41.65-29.75 (0%); 52.54-28.91 (5%); 55.71-29.58 (10%); 58.14-40.66 (20%) | - | - | [98] |
| Fly ash hollow sphere (30-60%) + aluminum silicate powder + egg white protein powder (12%) | Porous mullite ceramic | 1450 °C/4 h | 62.66-80.06 (TP); 27.84-54.87 (OP); 34.82-25.19 (CP) | 0.29-0.76 | - | [125] |

\(^a\): 0-15 wt% SiC; \(^b\): 1450-1550 °C; \(^c\): 0-16 wt% feldspar; \(^d\): wt% MoO\(_3\); TP: total porosity; OP: open porosity; CP: closed porosity.

30:70. The researchers demonstrated that after adding the tailings, the composition of the raw materials changed from the CaO-Al\(_2\)O\(_3\)-SiO\(_2\) system to the CaO-Al\(_2\)O\(_3\)-SiO\(_2\)-MgO system, which is beneficial for the formation of the indialite crystalline phase (2MgO\(\cdot\)2Al\(_2\)O\(_3\)\(\cdot\)5SiO\(_2\)). Furthermore, they observed that the produced glass-ceramics underwent a sudden self-expansion during the sintering process and that their porosity significantly increased with the incorporation of the waste, reaching values from 41% to 51%. Highly porous vitreous ceramics (apparent porosity of 80.9% to 87.3%) were also produced by Monich et al. [40], but in this case, the researchers used waste containing vitrified asbestos (70-90 wt%) together with soda-lime glass.

Coal ash from power plants: coal ash is generated in large quantities as a by-product of thermal power plants [96], and is considered to be highly hazardous to the environment due to its persistently toxic trace elements [98]. In this sense, environmentally friendly use of this type of waste is an important issue for the prevention of environmental pollution [96]. The main chemical components of coal fly ash (silica, alumina) are similar to those of clays and kaolin, which are used as starting materials to fabricate porous ceramics [98]. Thus, many works have been done over the last few years aiming at the production of porous ceramics using this type of waste [96-98, 121-124], as shown in Table XIII.

FINAL COMMENTS

The incorporation of industrial wastes in production processes to obtain porous ceramic materials is an alternative way to minimize their negative effects on the environment, contributing to the formulation of more sustainable development strategies and policies. In this sense, in recent years, increasingly higher levels of industrial waste in ceramic formulations have been studied, reaching up to 50 wt% for organics, mostly used as porogenic agents, and up to 100 wt% for inorganics, used as porogenic agents but also as silica and/or fluxing oxides providers. Thus, currently, highly porous ceramic materials can be entirely obtained using a single type of industrial waste or a mixture of two or more. In general, there is a tendency to use industrial waste for the production of lightweight ceramic bricks for structural applications, glass-ceramic foams for thermal and/or acoustic insulation in buildings, and membranes for filtration/separation processes.

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REFERENCES

[1] S.K. Hubadillah, M.H.D. Othman, T. Matsuura, A.F. Ismail, M.A. Rahman, Z. Harun, J. Jaafar, M. Nomura, Ceram. Int. 44 (2018) 4538.
[2] K. Stoeva, S. Alriksson, Waste Manage. 68 (2017) 732.
[3] A. Minelgaite, G. Liobikiene, Sci. Total Environ. 667 (2019) 86.
[4] S.Z. Salleh, A.A. Kechik, A.H. Yusoff, M.A.A. Taib, M.M. Nor, M. Mohamad, T.G. Tan, A. Ali, M.N. Masri, J.J. Mohamed, S.K. Zakaria, J.G. Boon, F. Budiman, P.T. Teo, J.
[113] L.F. Amaral, J.P.R.G. De Carvalho, B.M. Da Silva, G.C.G. Delaqua, S.N. Monteiro, C.M.F. Vieira, J. Mater. Res. Technol. 8, 1 (2019) 599.
[114] J.A. Junkes, P.B. Prates, D. Hotza, A.M. Segadães, Appl. Clay Sci. 69 (2012) 50.
[115] E. Rambaldi, L. Esposito, A. Tucci, G. Timellini, J. Eur. Ceram. Soc. 27, 12 (2007) 3509.
[116] F. Andreola, L. Barbieri, I. Lancellotti, C. Leonelli, T. Manfredini, Ceram. Int. 42, 12 (2016) 13333.
[117] H.T. Gao, X.H. Liu, J.Q. Chen, J.L. Qi, Y.B. Wang, Z.R. Ai, Ceram. Int. 44, 6 (2018) 6044.
[118] C. Leonelli, P. Veronesi, D.N. Boccaccini, M.R. Rivasi, L. Barbieri, F. Andreola, I. Lancellotti, D. Rabitti, G.C. Pellacani, J. Hazard. Mater. 135, 1-3 (2006) 149.
[119] A.F. Gualtieri, A. Tartaglia, J. Eur. Ceram. Soc. 20, 9 (2000) 1409.
[120] T. Liu, Y. Tang, L. Han, J. Song, Z. Luo, A. Lu, Ceram. Int. 43, 6 (2017) 4910.
[121] B. Ma, X. Ren, Y. Yin, L. Yuan, Z. Zhang, Z. Li, G. Li, Q. Zhu, J. Yu, Ceram. Int. 43, 15 (2017) 11830.
[122] L. Zhu, Y. Dong, L. Li, J. Liu, S.-J. You, RSC Adv. 5 (2015) 11163.
[123] L. Zhu, Y. Dong, S. Hampshire, S. Cerneaux, L. Winnubst, J. Eur. Ceram. Soc. 35, 2 (2015) 711.
[124] J. Cao, X. Dong, L. Li, Y. Dong, S. Hampshire, J. Eur. Ceram. Soc. 34, 13 (2014) 3181.
[125] Z. Yang, F. Yang, S. Zhao, K. Li, J. Chen, Z. Fei, G. Chen, J. Eur. Ceram. Soc. 41 (2021) 299.