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REVIEW ARTICLE

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Sustainable ceramics derived from solid wastes: a review

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ABSTRACT

Wastes from different manufacturing processes and energy generation units are attributed to the ecological and health issues. Instead of land-filling, the waste can be recycled or reused to convert marketable value-added products with high ecologic and economic interest. Ceramics are attracting particularly in waste recycling perceptions. From this eco-friendly propensity, in the last two decades, an increasing number of studies have demonstrated the possibility to use alternative ingredients in the place of conventional raw materials (e.g., most common ternary clay-quartz-feldspar system) for the fabrication of ceramics. Researchers are trying to incorporate the wastes and industrial by-products like fly ash (FA), rice husk ash (RHA), blast furnace slag (BFS), sludge, glass waste, polished tile waste, eggshell and others for making different ceramics. The present review is aimed to provide an up-to-date overview of the recent waste-derived ceramics including refractories, glasses, whitewares, oxide and non-oxide ceramics with the correlation of waste incorporation limits, manufacturing routes, and properties of the ceramics. The investigation reveals that ceramic industries have huge potential to utilize the wastes as substitution of the natural raw materials. The waste to value-added ceramics conversion not only solves the disposal problems but also conserves the natural resources.

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Waste; refractory; tile; fly ash; mullite

1. Introduction

“Ceramic” is a Greek word, earlier it was expressed as clay-based wares, i.e., “pottery”. Nowadays, ceramic has the more roomy meaning as inorganic, nonmetallic or metalloid solid compounds that are predominantly bonded with a mixed type of bonding (both ionic and covalent bonds), and now pottery is just a part of the ceramic world. Richerson (2000) [1] has explained the term ceramic as “most solid materials that aren’t metal, plastic, or derived from plants or animals.” Ceramics have some unique characteristics, which are not offered by the metals or other solids, including a high melting point, good chemical inertness, brittleness, high-temperature stability, heat and electrical insulation ability [2]. Therefore, ceramics have a huge range of applications in modern society and expect the demand for ceramics will be more strongly increased in the near future. In a very broad term, ceramics are used in modern day-to-day life as bricks, glass, tiles, tablewares, sanitarywares, space, cars, abrasives, biomedical (artificial bones and teeth), and electrical or electronic devices applications [3]. In all these ceramic products are mostly manufactured by the consuming of the massive amount of raw materials from nature. The oldest and most used raw material of ceramic is natural clay. Generally, the pottery is made by the conjunction of raw materials like clay, silica, and a certain amount of alkali-bearing materials (feldspar) as fluxes. The refractory industries are used the source of alumina, magnesite, chrome, dolomite, zircon,

quartz, and little or no clay as raw materials according to the specialized refractory. Recently, a wide variety of ceramic materials have been developed for different advanced fields like electrical or electronics, nuclear power, and structural engineering. For example various nitrides or carbides for heating elements; abrasives and engineering construction materials; zirconia, beryllia, and thoria for advanced refractory; rutile for ferroelectric materials and uranium oxide as a nuclear fuel element application [4,5]. The huge intakes of natural ingredients by the ceramic industries created a shortage of these natural resources and affected the ecosystem. Therefore, researchers are trying to find a substitute for natural ingredients for ceramics.

On the other hand, the growing population of the whole world is demanding an expansion of industrial production to fulfill the requirements of a populace. It is creating two kinds of the problem on the ecosystem, i.e., generating pollution or excessive wastes and disappearance of the natural resources. From the standpoints of the economies, one way to minimize these problems is to recycle these industrial by-products or wastes as main streams of industrial production. In agree with this realization, each manufacturing sector is looking to increase the profit by reducing the extraction of virgin resources and utilizing the wastes into the products [6]. In this aspect, the ceramic industries also have good environments for the utilization of by-products or wastes in their productions. Therefore, many researchers have been performed in the last



two decades to accomplish this objective in the ceramic industries. Thus, some wastes, e.g., rice husk ash (RHA) [7–9], fly ash (FA) [10–12], blast furnace slag (BFS) [13], waste marble powder [14], oil production waste [15], paper-processing residues [16], polished tile waste [17], bottom ash [18], water treatment sludge [19], petroleum waste [20], and glass waste [21] have been recognized as potential materials to reuse in the making of different ceramics. Subsequently, some studies have also been found to analysis the benefit of wastes for the formulation of different ceramics.

Andreola *et al.* (2016) [22] have briefly discussed about the utilization of fluxing, plastifying, and fuel wastes for the production of ceramics mainly tiles and bricks. The role of glass wastes in the tiles and bricks manufacturing and the addition level of this waste is also discussed. Silva *et al.* (2017) [23] have extensively discussed about the glass waste collection and processing. It is used as a secondary raw material for the preparation of ceramic-based products such as tiles, glass-ceramics, bricks, foams, porcelain, and glazing. Vieira and Monteiro (2009) [24] have categorized the wastes into three groups: (1) fuel wastes – it can influence the sintering process of ceramic; (2) fluxing wastes – it contents of alkaline and alkaline earth compounds, which affect the sintering temperatures by forming liquid phases; (3) property-affecting wastes – it is modified the behavior of ceramics. The effect of both economic and technological advantages in the incorporation of these wastes into red ceramics is deeply addressed. However, other sector of ceramics is not covered in this review. Rawlings *et al.* (2006) [25] have briefly discussed about the different synthesis routes of glass-ceramic using several silicates based wastes like slag, filter dust, FA, coal combustion ash, mud, sludge, and glass cullet. According to our investigation of the literatures, no such review articles are found that is covered the entire field of ceramics for a discussion on “wastes as a replacement for natural ingredients in different sustainable ceramics.” This study depicts a complete summary of current progress about the utilization of the wastes as a substitute for virgin raw materials in the fabrication of different ceramics, including both traditional and advanced fields.

2. Chemical composition of wastes

Some wastes like FA, RHA, blast furnace slag (BFS), water treatment sludge, polished tile waste, sludge, and red mud have been identified as replacement of natural ingredients for different ceramics fabrication. The chemical compositions of these wastes are tabulated in Table 1. However, the characteristics and chemical composition of the wastes are very much influenced by environmental circumstances of the parent materials origin along with the acquired process parameters during the making of the ceramics.

Table 1. Chemical composition of wastes.

Waste	SiO ₂ (wt.%)	Al ₂ O ₃ (wt.%)	CaO (wt.%)	MgO (wt.%)	Na ₂ O (wt.%)	K ₂ O (wt.%)	Fe ₂ O ₃ (wt.%)	TiO ₂ (wt.%)	Other (wt.%)	LOI
Coal fly ash [10]	55.57	21.47	5.12	2.97	3.42	1.22	6.80	-	0.60	2.83
Blast furnace slag [13]	41.30	14.30	32.70	7.30	-	0.9	0.8	1.10	1.60	-
Porcelain tiles [17]	68.96	19.79	0.41	1.13	2.62	2.73	0.98	0.23	-	3.15
Rice husk ash [38]	91.48	-	0.36	0.32	0.04	1.40	0.05	0.01	5.24	3.50
Petroleum sludge [40]	28.62	0.20	2.70	0.50	-	-	0.08	1.10	39.08 (BaO)+12.81	14.91
Iron ore tailings [52]	84.21	0.58	0.50	1.26	-	-	11.42	-	2.03	-
Serpentine [53]	39.09	0.64	0.40	34.73	0.01	0.01	9.21	-	1.14	14.77
High alumina fly ash [58]	41.97	39.90	6.41	0.60	0.19	0.50	1.96	-	4.83	3.64
Water treatment sludge [70]	53.70	15.80	14.40	3.60	0.40	3.20	5.00	0.7	3.20	-
Red mud [81]	33.57	27.66	15.26	-	3.54	1.76	7.56	3.36	-	7.29
Fish bones (calcined at 700°C) [188]	0.07	0.35	55.80	2.13	5.65	0.18	0.08	-	35.60 (P ₂ O ₅) ₊ 0.14	-

3. Utilization of wastes

Recently, the utilization of wastes in several productive sectors has acquired more attention from many researchers. The present study has attempted a review of their works with reference to ceramics, including refractory, whiteware, glass, oxide, and non-oxide ceramics.

3.1. Refractory

3.1.1. Porous insulation refractory

Generally, refractories are used for two purpose, i.e., (1) as a protective barrier of vessels from the corrosion and erosion by the hot flue gases, molten salts, liquid metals and slags; and (2) to maintain the inside required temperature of vessel by preventing the flow of heat (insulate). For the first one, high refractoriness and dense refractories are basically used, because it is directly contacted with the furnace or kiln environments. Low thermal conductivity (σ), moderate refractoriness, porous and lightweight refractories are generally used for the insulation of furnaces. Researchers are mostly trying to incorporate the wastes in the insulation refractories.

In recent years, few works have been found to introduce the wastes in the composition of insulation refractories. A comprehensive study for the wastes containing insulation refractories with various parameters is listed in [Table 2](#). It has been observed that the addition of wastes in the insulation refractory compositions can improve their insulation behavior, porosity, and strength up to a limit. Ramezani *et al.* (2018) [26] have studied the effect of waste serpentine (mining waste) on the insulating behavior of basic insulation refractories. The refractories are synthesized using the waste serpentine (after calcined at 1550°C) along with dead-burned magnesia, expanded perlite, and calcined alumina as starting raw materials and fired at 1250, 1350 and 1450°C. The calcined serpentine incorporation is improved the thermo-mechanical properties of the refractories. 43 wt.% dead-burned magnesia, 20 wt.% calcined alumina, 17 wt.% expanded perlite and 20 wt.% calcined waste serpentine containing specimen shows the lowest σ due to high insulating forsterite phase in the system. Hassan *et al.* (2019) [27] have studied the pore formation ability of waste bagasse (residue from sugar cane

processing) in the fireclay insulating bricks. Bricks are prepared by the addition of bagasse (0 to 5 wt.%), polystyrene (1 to 2 wt.%), kaolin and fired at 1250°C. The bagasse is found a good replacement of conventionally expensive petrochemical additives (polypropylene, polyethylene, and polystyrene), which are generally used as a pore creator in the insulation bricks. Sutcu *et al.* (2012) [28] have fabricated anorthite ($\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot2\text{SiO}_2$) based insulating refractories using waste paper-processing sludge (30 wt.%) as a calcium oxide source and sawdust (0 to 30 wt.%) as a pore former. The samples are prepared through the slurry casting route and fired at 1200 and 1300°C. The porous and lightweight anorthite is formed at 1200°C by the reaction of calcium oxide (from sludge) and aluminum silicate (from clays). Sawdust incorporation into the composition has hugely influenced the porosity and pore size in the anorthite matrix, as displayed in [Figure 1](#). The size of the pores is significantly increased with the addition of sawdust from 0 to 30 wt.% through the burning of organic matters. The porosity is increased from 57 to 74%, and σ is decreased from 0.25 to 0.13 (W/m·K) at room temperature. Mandal *et al.* (2017) [29] have synthesized insulation bricks by utilizing the aluminum plant wastes (FA and red mud) along with sawdust. FA (0 to 100 wt.%), red mud (100 to 0 wt.%) and sawdust (0 to 10 wt.%) are mixed with an adequate amount of water and pressed with a uniaxial pressure of 15 MPa. The bricks are fired at 1000, 1100 and 1200°C. 60:40 weight ratios of FA and red mud along with 7.5 wt% sawdust containing fired bricks (1100°C) meets the required properties as per standard IS: 2042 for Type-A insulation bricks.

FA is a fine solid waste produced during ignition of coal and it contains mostly silicoaluminium mineral with minor other constituents like CaO , MgO , and Fe_2O_3 [30]. Thus, it has a great potential to use as a ceramic raw material. Sukkae *et al.* (2018) [31] and Otero *et al.* (2004) [32] have prepared the insulation refractory bricks by utilizing the FA and local clay. The lower σ , linear shrinkage, and bulk density are obtained with the incorporation of FA in the composition. Bragança *et al.* (2008) [33] have synthesized the insulation bricks using coal combustion ashes. During the coal combustion, two types of ashes are generated, i.e., FA (fine particle size) and bottom ash (coarser particle size). FA is used in place of kaolin clay up to

Table 2. Name of wastes used in the insulation refractories compositions along with some important properties.

Wastes						
Name	Amount (wt.%)	Firing temperature (°C)	Thermal conductivity (W/m·K)	Porosity (%)	CCS (MPa)	References
Sludge, RHA	90, 10	1200	-	40	10	[25]
Serpentine	20	1450	0.49 at 1000°C	67.80	2.74	[26]
Bagasse	3	1250	0.37 at 800°C	58	4.08	[27]
Paper processing waste, sawdust	30, 30	1300	0.13 at 30°C	74.10	0.61	[28]
Aluminum plant's waste, sawdust	92.5, 7.5	1100	0.55 at 600°C	62	7.5	[29]
Fly ash	75	1000	0.163 at 600°C	71.16	5.05	[32]
Fly ash	10	1350	4 at 800°C (W/m·°C)	-	0.92	[33]

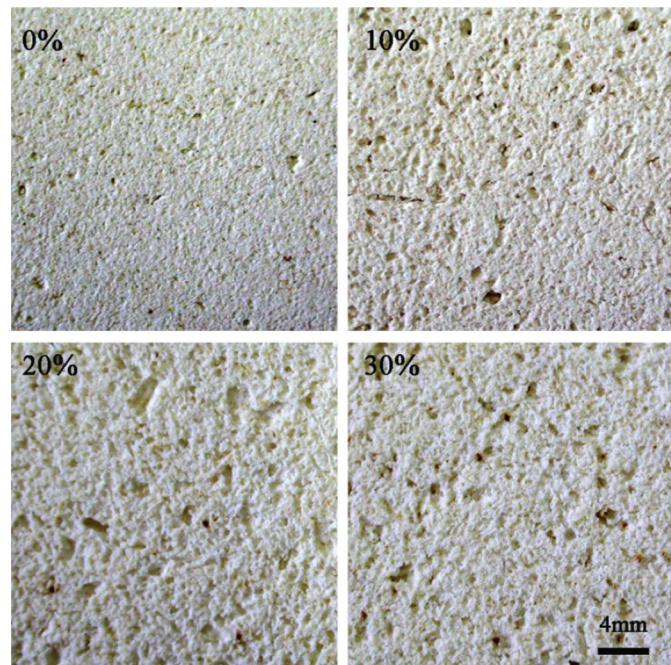


Figure 1. Illustration of the variation of pore size of anorthite according to the percentage of sawdust addition. Copyright with the permission from Ref [29].

10 wt.% for the insulation refractory bricks fabrication and bottom ash (10 wt.%) is used as a replacement of chamote in the composition of commercial bricks. The presence of ashes in the compositions (10 wt.%) decreases the density and σ of the bricks. Conversely, it is slightly diluted the mechanical strength of the bricks compared with the commercially available insulation bricks.

Low σ value (0.140 W/m·K) and amorphous silica containing RHA make useful as an ingredient for the fabrication of insulation refractory [34]. The RHA containing insulation bricks are prepared by the mixing of binder (fluxing materials), plasticizers (no plasticity of RHA) and pore former with RHA [35–37]. RHA is also used in steel industries for the insulation of ladles, tundishes, and trough [35,38]. The insulation of RHA increases the thermal shock resistance of the refractories. The low σ of RHA leads to a slow reduction of molten iron temperature during casting and helps to maintain uniform solidification. Ewais *et al.* (2017) [39] have prepared the insulation refractory bricks using water treatment sludge with various amount of RHA (0–10 wt.%) and fired at 800–1200°C. Filter press and casting technique are used with the sludge, and sludge-RHA mixtures specimens, respectively. Specimen, containing 90 wt.% sludge and 10% RHA and fired at 1200°C, shows a good physico-mechanical properties regarding insulation bricks.

3.1.2. Dense working refractory

Moreover, some researchers are also attempted to introduce the waste ingredients for the fabrication of high-temperature applicable dense working

refractories. Khalil *et al.* (2018) [40] have synthesized the high-temperature refractory using the petroleum waste sludge (0 to 100 wt.%) with natural raw bauxite (100 to 0 wt.%) and fired at different temperatures up to 1600°C. The petroleum sludge (oil processing waste) contains barium oxide (39.08 wt.%), silicon oxide (28.02 wt.%) and sulfur trioxide (21.9 wt.%) as main components. 40 wt.% of the sludge and 60 wt.% of bauxite containing refractory is considered as optimum composition according to the evaluated physico-mechanical properties, which are fulfilled the international standards of refractories. Stonys *et al.* (2016) [41] have studied the effect of mineral wool produced dust waste as a replacement of commercial micro-fine silica for the preparation of refractory concrete. Slight improvement in physico-mechanical properties is observed with the waste incorporation up to 2 wt.%.

Al metal extraction through plasma processing has produced a waste on the surface of molten Al, i.e., aluminum dross. It is composed mostly of ceramic phases like $MgAl_2O_4$ (~48 wt.%), AlN (~28 wt.%) and $\alpha-Al_2O_3$ (~7 wt.%). Yoshimura *et al.* (2008) [42] have used this waste directly (without any purification or calcination) as a replacement of calcined alumina in the refractory castables. According to the investigated physical properties, Al dross waste can be used up to 5 wt.% without compromising the properties of the refractory castables. They have also studied the anti-oxidant characteristics of Al dross waste in a resin-bonded refractory. However, the oxidation test indicates that the waste is unable to protect the carbonaceous (resin bonded) matrix against oxidation. Ribeiro *et al.* (2005) [43] have been used Al-rich sludge, which

is resulting from wastewater treatment of surface coating or aluminum anodizing industries, and other low-cost ingredients (kaolin, ball clay, and diatomite) for making mullite-based refractories. Oliveira *et al.* (2008) [44] have also made mullite refractory by utilizing slate sludges. It is generated during the cutting and polishing processes of slate with alumina and finished of Al-made architectural profiles.

Magnesium aluminate (MgAl_2O_4) spinel is a superb refractory material due to some unique, desirable properties like high melting point ($\sim 2135^\circ\text{C}$), high chemical inertness and strength at elevated temperature, high thermal shock resistance, low thermal expansion, and good corrosion resistance. These characteristics are made it an excellent candidate for the lining of rotary cement kilns, glass tank furnaces, steel ladles, and other refractory applications [45,46]. Some studies have been found to investigate the synthesis of MgAl_2O_4 materials with good performance from the wastes or industrial by-products. Meng *et al.* (2017) [47] have developed MgAl_2O_4 spinel refractory raw material by an electric-melting method using waste chromium slag as a replacement of conventional alumina sources and achieved superior thermal shock resistance and slag resistance material. Arianpour and Turan (2017) [48] have used waste filter powders from aluminum production industries as an alumina source to produce dense MgAl_2O_4 . 30 wt.% sintered magnesia ($\text{MgO} \sim 95.66$ wt.%) and 70 wt.% filtered powder ($\text{Al}_2\text{O}_3 \sim 92.92$ wt.%) containing sample shows maximum density value after calcination and sintering at 1300 and 1700°C , respectively. Zhang *et al.* (2019) [49] have studied the feasibility of MgAl_2O_4 spinel synthesized from aluminum dross. 87.34 wt.% of alkali-treated dried dross and 12.66 wt. % of MgO containing sample, sintered at 1400°C , is retained greater than 70% of MgAl_2O_4 phase with the compressive strength of 69 MPa. Ewais *et al.* (2015) [50] have synthesized nano MgAl_2O_4 through the co-precipitation method using waste aluminum and magnesium scrap.

Magnesium silicate (Mg_2SiO_4), known as forsterite, is another refractory mineral used in rotary cement kiln, glassmaking furnace, non-ferrous metal smelting, and steel-making as ladles, torpedo's, continuous casting tundish, drainage, and other casting accessories [51]. Jing *et al.* (2009) [52] have fabricated Mg_2SiO_4 using waste iron ore tailings and active magnesia through the solid-state reaction method at 1450°C . Abi *et al.* (2015) [53] have developed 99.24% forsterite phase at 1300°C from waste serpentine and magnesium chloride hexahydrate through sintering reaction technique. Ferronickel slag is a waste produced during nickel-metal processing. It is retained around 30 wt.% of MgO . Gu *et al.* (2018) [54] have utilized this waste for fabricating of forsterite as major phase containing refractory. Ferro-nickel slag is mixed with 15 wt.% of sintered magnesia and sintered at 1200 to 1500°C .

Above 1400°C of sintering temperature, refractory retains only forsterite phase with compressive strength ~ 106.9 MPa, apparent porosity $\sim 5.8\%$, and bulk density ~ 2.88 g/cm 3 .

3.2. *Whitewares*

3.2.1. *Tiles*

Tiles, the most popular and rapidly growing ceramics, are used in the construction and building activities. Rapid urbanization, modernization, and renovation of older buildings, rise in population and government policies on infrastructure development are primarily responsible for the growth of the global tiles market. The global tiles market worth was projected at US\$ 70.9 billion in 2018, and an estimated compound annual growth rate (CAGR) during 2011–2018 was $\sim 9.1\%$. The projected market revenue will be reaching above US\$ 107.2 billion by 2024 and expected CAGR during 2019–2024 forecast periods will be $\sim 7.2\%$ [55]. Different types of clay, silica, feldspar, zircon sand, alumina, and other natural resources are the key ingredients for the manufacturing of nearly all kinds of ceramic tiles. The huge consumption of naturally occurring minerals is affecting several environmental issues. Therefore, the environment-friendly substitution of natural ingredients is essential in the forthcoming years. Some wastes and industrial by-products have been found as sustainable replacement of virgin raw materials in tiles, as illustrated in Table 3. Certain key components like the amount of wastes, replacement of minerals (like clay, feldspar, and quartz), firing temperature, and categories (like porcelain, floor, wall, and glazed tiles) of waste-containing tiles are pointed in Table 3.

The use of FA is rapidly extended for the preparing of ceramic tiles. For example, Chandra *et al.* (2008) [56] have prepared low-temperature firing wall tiles by addition of low alkali pyrophyllite and sodium hexameta phosphate (SHMP) with FA and fired in the temperature range 950 to 1050°C . Olgun *et al.* (2005) [57] have developed wall tiles by replacement of K-feldspar with FA and tincal waste (boron process waste) in the range of 2 to 10 wt.%. Ji *et al.* (2016) [58] and Wang *et al.* (2017) [59] have fabricated tiles using high alumina containing FA as main raw material, and they have introduced 60 wt.% and 70 wt. % of FA in the composition, respectively. While Luo *et al.* (2018) [11] have fabricating fully FA-based mullite containing ceramic tiles, these works are significant to verify the possibility of using FA as a substitution of traditional natural materials for ceramic tile fabrication. Additionally, the consumption of FA is also favorable to enable the improvement of ceramic properties. In particular, Wang *et al.* (2018a) [60] have made dense/foam bi-layered thermally insulation ceramic tiles

Table 3. Name of wastes used in the compositions of tiles.

Name	Wastes	Amount (wt.%)	Replacement of minerals	Firing temperature (°C)	Type of tiles	References
Polished tile waste		50	Proportionally replaced all the basic raw materials	1120	Porcelain tiles	[17]
Fly ash		~50	-	950	Wall tiles	[56]
Fly ash, tinical waste		10, 5	Feldspar	1020	Wall tiles	[57]
High-alumina fly ash		60	Feldspar and quartz	1200	-	[58]
High-alumina fly ash		70	-	1300	-	[59]
Fly ash	Cyclone dust, filter dust (separately added)	100	Clay, feldspar and quartz	1300	Floor tiles	[11]
Sanitaryware waste		7.5	-	1190	Porcelain tiles	[61]
Kaolin		15	Pegmatite	1210	Wall tiles	[62]
Ceramic sludge		15	Kaolin	1145	Floor tiles	[63]
Ceramic sludge		10	Proportionally replaced all the basic raw materials	1160	Wall tiles	[64]
Sewage sludge		20	Proportionally replaced all the basic raw materials	1180	Floor tiles	[64]
Sewage sludge		60	Proportionally replaced all the basic raw materials	1210	Split tiles	[69]
Sewage sludge		70	-	980	Glaze tiles	[70]
Sewage sludge		7	Proportionally replaced all the basic raw materials	1150	Floor tiles	[71]
EAF slag		40	-	1150	Floor tiles	[73]
Blast furnace slag		33	Kaolin, Limestone	1136	Wall tiles	[74]
Basalt waste		5	Feldspar	1150	Porcelain tiles	[75]
Hard rock dust		40	Feldspar	900	Roof tiles	[77]
Red mud		65.8	-	1180	Floor tiles	[81]
Glass waste		41	Proportionally replaced all the basic raw materials	1080	Stoneware tiles	[86]
Iron ore tailings		65	Feldspar	1200	Porcelain tiles	[89]
Coffee husk ash		10	Feldspar	1180	Floor tiles	[91]
Fish bone ash		10	Feldspar	1175	Stoneware tiles	[92]
Rice husk ash		10	Clay	850	Roof tiles	[93]

using high-alumina FA and waste glass by a single pressing and a single-firing process.

Ceramic industries also have generated solid wastes during their different processing stages like the grinding of raw material, polishing of fired products, and shorting (quality check) of final products. Recycling these wastes as raw materials for the same industry is more favorable waste management method. For this trend, El-Fadaly *et al.* (2010) [61] have added the ceramic industries wastes (cyclone and filter dust) in the base composition of floor tiles. Ke *et al.* (2016) [17] have reused the polished tile waste (0 to 70 wt.%) as a raw material in the porcelain tiles. 50 wt.% waste containing sample sintered at 1120°C, meets the required properties as per standard ISO:13,006 for porcelain tiles. Tarhan *et al.* (2017) [62] have developed porcelain tiles using sanitaryware waste by replacing of pegmatite (5 to 15 wt.%) or Na-feldspar (5 to 15 wt.%). Sanitaryware waste in place of Na-feldspar has diluted the properties, whereas using sanitaryware waste in place of the pegmatite is attributed to an improvement of thermo-mechanical properties of tiles. Tarhan *et al.* (2016) [63] have also recycled the sanitaryware waste in place of kaolin (max. 15 wt.%) for the preparation of wall tiles. Wastewater treatment unit of tile plants is also produced a new waste, namely ceramic sludge. Amin *et al.* (2019) [64] have examined to recycle this waste for preparing of floor and wall tiles. The dried sludge powder is mixed (0 to 50 wt.%) with the basic composition for the preparation of wall and floor tiles. The pressed green wall and floor tiles are fired at 1160°C and 1180°C, respectively. According to internationally harmonized Egyptian standards requirements, 10 wt.% sludge for wall tiles and 20 wt.% sludge for floor tiles can be used as a replacement.

Water treatment plants are discharged a waste that is called sewage sludge (SS), which is commonly used for landfills. It contains some amount of pollutants, like pathogenic microorganisms, heavy metals, organic contaminants, and so on. They are easily ascribed to secondary environmental pollutions [65,66]. Therefore, social and environmental pressure is growing worldwide for controlling this pollution by developing the recycling technologies of SS [67]. Several studies have been performed to utilize the SS in the productive sector. Some works on the preparing of ceramic tiles from SS have been carried out. Li *et al.* (2007) [68] have added dried SS in the composition of tiles and observed that the compressive strength of the tiles decreases gradually and the bending strength is slightly improved with the incorporation of sludge. Zhou *et al.* (2013) [69] have developed split tiles by using SS from wastewater treatment plant without any pretreatments. The composition with 60 wt.% crude SS, 20.6 wt.% feldspar, 15.2 wt.% quartz, and 14.2 wt.% kaolin shows the optimal formulation and meets the required properties of fine-grade split tiles according

to the ISO: 13,006:1998. Cremades *et al.* (2018) [70] have proposed the utilization of SS up to 70 wt.% for the preparation of glazed tiles. Amin *et al.* (2018) [71] have prepared the floor tiles by the mixing of dry SS (0 to 30 wt.%) powder with the stander composition of floor tiles. According to the ISO standards for floor tiles, the maximum permitting limit of SS addition is 7 wt.% for 1150°C fired sample.

Steel plants generate solid waste, i.e., slag, which may be a good choice as alternative raw materials for ceramic tile due to its chemical composition. It consists of various chemical compounds like SiO_2 , Al_2O_3 , CaO , MgO , along with some minor compounds such as FeO , MnO_2 , and TiO_2 [72]. Sarkar *et al.* (2010) [73] have studied the feasibility of developing vitreous tiles using steel melting electric arc furnace (EAF) slag. They have found that the amount of slag can be used up to 30 to 40 wt.% with other basic raw materials in the sintering temperature range between 1100°C and 1150°C. Teo *et al.* (2014) [74] have also prepared ceramic floor tiles using 40 wt.% of EAF slag with 20 wt.% silica, 10 wt.% feldspar, and 30 wt.% ball clay, and sintered at 1150°C. Ozturk and Gultekin (2015) [13] have applied BFS for preparing the wall tiles and concluded that the incorporation up to 33 wt.% of BFS in the wall tile composition results in an improvement of strength about ~ 25%.

Granite dust waste is produced in the rock mining during blasting and crushing of rocks. It is retained a high amount of SiO_2 and Al_2O_3 with some amount of fluxes (Na_2O & K_2O) and coloring compound (Fe_2O_3) [75]. So far, this waste can also be considered as alternatives for the conventional raw materials of ceramics. For instance, granite waste is found suitable as a sand replacement due to low plasticity and reduces the possibility of dimensional defects. It is an alternate of feldspathic ingredients that make glassy phases at lower temperatures for the fabrication of floor tiles [76]. Pazniak *et al.* (2018) [75] have studied the effect of granitic rock and basalt waste incorporation into the porcelain tiles. The addition of granitic and basalt rock wastes in place of feldspar exhibits the possibility of their limit in tiles industry as fluxes. Sample with 5 wt.% of basalt and sintered at 1150°C, show the same properties like the industrial porcelain tiles. Sultana *et al.* (2015) [77] have developed roof tiles using hard rock dust (10 to 50 wt.%) with clay. Hojamberdiev *et al.* (2011) [78] have investigated the effect of granite waste addition in the composition of floor tiles as an alternate of quartz. They have observed that 30 wt.% granite waste containing specimens shows good physico-mechanical behavior and fulfill the state standard (no. 6787–2001) for floor tiles.

Alumina extraction through the Bayer process has produced waste, i.e., red mud (RM). An enormous amount of RM is generated worldwide every year and disposed of as landfills. RM is a residue of aluminum



hydroxides, silica, calcium carbonate, titanium, and other metallic oxides. Ceramic industries can consume this waste because its chemical composition is very similar to primary ceramic raw materials. Xu *et al.* (2019) [79] have introduced up to 40 wt. % of different type of RM for the preparation of ceramic tiles. Yang *et al.* (2009) [80] have prepared two layers of floor tile bodies with bending strength about 80 MPa using RM and bauxite tailings as the main ingredients. Wang *et al.* (2018) [81] have fabricated mullite-based high-strength floor tiles using RM with kaolin and ammonium molybdate (catalyst). 65.8 wt.% RM, 28.2 wt.% kaolin and 6 wt.% ammonium molybdate containing 1180°C sintered samples show a flexural strength about 185.6 MPa.

Recently, boron mining wastes have also been used in the composition of tiles to reduce the sintering temperature. Boron waste contains 10 to 30 wt.% of boron oxide (B_2O_3), which aids to vitrify through the formation of the glassy network. Mostly, it helps to minimize the energy consumption for tiles production. 5 to 6 wt.% boron mining wastes containing samples are able to reduce the sintering temperature around ~60 to 70°C [82,83].

Nowadays, the waste glass powder is another material used to replace the conventional fluxing materials in tiles manufacturing for decreasing the sintering temperature [84,85]. Gualtieri *et al.* (2018) [86] have developed low-temperature stoneware tiles by the incorporation of waste glass in the base triaxial composition and promoted a modification on the sintering temperature. A tile composition containing 41 wt.% of glass waste (34 wt.% borosilicate and 7 wt.% soda-lime-silica glass) and 59 wt.% of traditional raw materials (i.e. 16 wt.% quartz, 28 wt.% clay, 15 wt.% feldspars) is reduced the sintering temperature around ~135°C (1080°C instead of 1215°C). Revelo *et al.* (2018) [87] have made a transparent glaze for tiles using 20 wt.% of waste cathode ray tubes glass with conventional frit.

During the processing of iron ore, a huge volume of ore is rejected (ore tailings) as mud for damping. This waste is also considered as a raw material for the production of tiles by several researchers. Fontes *et al.* (2019) [88] and Chen *et al.* (2013) [89] have developed brown or red porcelain tiles using iron ore tailings with kaolin, sand, and fired at 1200°C.

Coffee husk ashes (CHA) are contained mostly alkaline-earth and alkaline metals [90]. It has huge potential as an advanced fluxing material to substitute the traditional feldspars for clay-based ceramic formulations. Acchar *et al.* (2013) [91] have studied the fluxing characteristics of CHA compare to feldspar in the floor tiles body. They have concluded that 10 wt.% CHA in place of feldspar shows the sintering temperature nearly 1180°C and the flexural strength, water absorption, linear shrinkage values have met the specification with the floor tile standards (ISO:13,006, NBR:13,817,

and EN:176). Naga *et al.* (2014) [92] have fabricated stoneware tiles by partially replacing the K-feldspar through fishbone ash. More than 10 wt.% of fishbone ash addition dilute the physico-mechanical properties of tiles. Thus, a partial replacement of K-feldspar by fishbone ash is feasible for the composition of stoneware tiles. Silva and Surangi (2017) [93] have investigated the effect of RHA addition in the composition of roof tiles. 10 wt.% replacement of clay by RHA shows around ~45.97% enhancement in the breaking strength, reducing the density and improvement in the thermal behaviors of tiles.

3.2.2. Sanitaryware

Ceramic sanitaryware encompasses those components and fixtures that are related to sanitation purpose, including a number of products such as water closets, washbasins, faucets, bathtubs, and others. The projected global sanitaryware CAGR is 5.0 % from 2018 to 2025 [94]. Therefore, a huge amount of natural ingredients like quartz, feldspar, kaolin, and different type of clays are required, and their demand could be increased in the forthcoming year. Regarding environmental legislation, industries are adopting wastes or by-products for sustainable productions. However, limited research articles are found related to the utilization of the waste for sanitaryware products. Tarhan (2019) [95] has investigated the effect of wall tile wastes incorporation (1 to 10 wt.%) into the fireclay sanitaryware composition. He has concluded that the addition of wall tile waste up to 10 wt.% reduces the thermal expansion coefficient, water absorption, high-temperature deformation, and improves the strength of the fireclay products. Kim *et al.* (2015) [96] and Marinoni *et al.* (2013) [97] have developed porcelain sanitaryware by substituting of feldspar through the glass wastes. Gungor *et al.* (2019) [98] have studied the effect of galvanized waste (~65% ZnO) addition into sanitaryware composition in place of kaolin and albite. Sample with 10 wt.% ZnO containing waste reduces the firing temperature of sanitaryware bodies from 1250°C to 1200°C. It is attributed around ~4.75% of energy saving. Moreover, galvanized waste addition is ascribed to a lower firing temperature, greater whiteness, decreased water absorption, and faster densification.

3.3. Glass and glass-ceramics

3.3.1. Glass

Glass is a nonmetallic, non-crystalline or amorphous inorganic solid that has unlimited applications in our modern life as numerous products or components like window panels, bottles, optoelectronics, transports, fiber optic cables, tablewares, and so on. Glasses are generally made with a combination of oxygen-based compounds or various oxides. The main sources of

these oxides are sand (for SiO_2), feldspar (for SiO_2 , Al_2O_3 , Na_2O or K_2O), soda ash (for Na_2O), limestone (for CaO) and cullet (recycled glass). The goal of the glass industries is to use the economical and locally available high-quality ingredients. Nowadays, most of the raw materials (without cullet) for glass manufacturing are collected from nature. Presently, deep attention is required to find out the alternate of natural resources for making the glasses. However, very limited studies have been conducted in this direction. Kaewkhai and Limsuwan (2012) [99] have prepared color glasses by using RHA as a silica source. Erol *et al.* (2007) [100] have developed glasses by melting of three different types of FA at 1500°C and annealed at 600°C. Sheng *et al.* (2003) [101] have also made glass using FA with 10 wt.% of Na_2O . Melting and annealing are done at 1200°C and 520°C, respectively. Park and Park (2017) [102] have synthesized glass balls through the melting of mixtures of red mud, gold tailing, and waste limestone at 1500°C, followed by granulation process. Kashif and Ratep (2018) [103] have used heat-treated sugar cane bagasse as a replacement of silica for making glasses. Xu *et al.* (2014) [104] have produced $\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ system glass using blast furnace slag. 67.37 wt.% slag containing glass shows better performance than the ordinary glass, according to alkali/acid resistance and bending strength.

Additionally, some researchers have also been found to prepare foam glass by utilizing wastes. Foam glass is majorly used as thermal insulation material due to their low σ and densities [105]. Moreover, it has excellent sound absorption and flameproof capability compared with the organic substances [106]. Fang *et al.* (2017) [107], Souza *et al.* (2017) [108] and Ji *et al.* (2019) [109] have synthesized foam glass by recycling the waste glasses with foaming agents such as wool waste, eggshell wastes, and Li_2CO_3 , respectively. Chen *et al.* (2012) [110] have studied the foam glass-forming ability of FA with sodium borate ($\text{Na}_2\text{B}_4\text{O}_7$) and calcium carbonate (CaCO_3) as a flux agent and foaming agent, respectively. 70 wt.% FA containing

and 800°C fired samples exhibit excellent comprehensive properties like porosity (52%), bulk density (0.876 gm/cc), and compressive strength (2.09 MPa). Bai *et al.* (2014) [111] have developed foam glass at 950°C with ~81% porosity using waste glass, FA and SiC as pore-forming agents.

3.3.2. Glass-ceramic

Glass-ceramics (GC), refers to a composite material, constitute with fine polycrystalline grains, which are embedded in its amorphous (glass) matrix. The crystallinity is developed through the controlled heat-treatment at particular temperatures with certain periods for nucleation and growth process of suitable composition. GC is expressed as distinct characteristics than glassy or crystalline states of respective composition [112].

Vitrification of wastes to develop GC or glassy silicate products have been known for the last four decades. Some silica-containing solid wastes, such as FA, slag from the steel plant, filter dust, different types of sludge, mud from metal processing industries, glass cullet are found to have excellent potential for fabricating of GC [25]. Rawlings *et al.* (2006) [25] have comprehensively discussed about the GC from silicate wastes by different processing routes in their review article. They have described four methods, i.e., (i) conventional method (two-stage), (ii) Modified conventional method (singlestage), (iii) petrurgic method, and (iv) powder method. These methods are generally used for manufacturing GC from wastes. Blast-furnace slag (BFS) and FA are found more promising wastes for preparation of GC.

GC made from BFS and FA is very much used as building materials for architectural and construction components. Wang *et al.* (2014) [113] have presented an overview of the fabrication of GC using coal FA as an ingredient. Detail description about the acquired methodologies for the preparation of GC from FA along with the major crystal phases, corresponding properties, and probable application of those materials

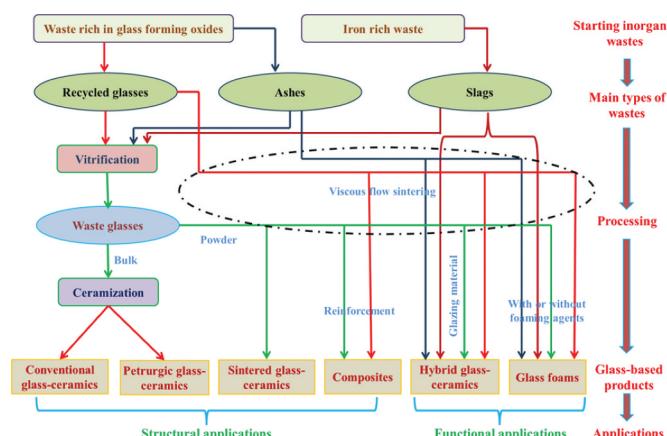


Figure 2. A scheme methodology used for glass-ceramics formulation from wastes [115].



are described. Class C type FA ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \geq 70$ wt%) is much more appropriate for making $\text{CaO}\text{-}\text{Al}_2\text{O}_3\text{-}\text{SiO}_2$ system GC. This system is retained usually anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$), wollastonite (CaSiO_3) and diopside ($\text{CaMgSi}_2\text{O}_6$) as main phases and it has a huge application on constriction as decoration or insulation material. Generally, class F type FA ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \sim 50\text{-}70$ wt%) can be used to prepare $\text{MgO}\text{-}\text{Al}_2\text{O}_3\text{-}\text{SiO}_2$ system-based GC. It retains phases like mullite ($2\text{Al}_2\text{O}_3\text{-}\text{SiO}_2$) and cordierite ($2\text{MgO}\cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$) mainly. The GC derived from F class FA is being suitable as a wide range of infrared drying and heating material. Chinnam *et al.* (2013) [114] have reviewed on iron-containing silicate-based wastes and demonstrated the potential for GC products. Blast furnace flue dust, jarosite, copper flotation waste, lead foundry slag, nickel leaching residues, and goethite are the examples of iron-containing wastes for the fabrication of GC.

The proper selections of iron-containing wastes, processing parameters for dense and porous GC along with proper catalytic activity, optical, magnetic and electrical properties are discussed. Rincón *et al.* (2016) [115] have provided a current status of solid waste-derived glass-based materials, mainly GC, and correlated between manufacturing or formulations technologies with properties. They have covered all the possible glass-forming oxides containing wastes with effective formulation routes in their discussion, as represented in Figure 2. The effective transformation depends on both the starting materials and the adopting manufacturing methods. The silica-rich wastes are favorable to obtain the glass or GC, and iron-rich wastes influence the functionalities inducing the porosity in glass-based materials along with magnetic, catalytic, electrical and optical properties. Direct sintering of solid wastes combined with glass cullet has been a low-cost alternative route for glass-ceramics manufacturing with limited hazardousness.

3.4. Oxide ceramics

3.4.1. Mullite

Mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) is an important oxide ceramics having a nominal chemical composition of ~28 wt% SiO_2 and 72 wt% Al_2O_3 [116,117]. This material exhibits some excellent properties like high refractoriness ($>1700^\circ\text{C}$), low density (~3.17 g/cm³), high creep and oxidant resistance, thermal stability, high modulus of rupture (HMOR), low dielectric constant, good corrosion resistance and low coefficient of thermal expansion ($\sim 4.5 \times 10^{-6} \text{ K}^{-1}$) [116–120]. These properties of mullite are enabled to use in a wide range of high-temperature structural applications, along with chemical, electrical, electronic, and optical applications [121]. Mullite mineral can be found mainly at the Mull Island, Scotland, and the name (mullite) comes from its origin

Table 4. Waste containing mullite along with formation temperature and properties.

Waste	Other ingredients	Mullitization temperature (°C)	Properties	Products	References
Fly ash	Bauxite	1450	Bulk density ~1.73 g/cc, Porosity~ 45%, flexural strength ~45 MPa	Membrane	[123]
Fly ash	Bauxite, V_2O_5 and AlF_3	1300	Open porosity ~50%, flexural strength ~69 MPa	Membrane	[124]
Fly ash	Al_2O_3 , starch and polyurethane sponge	1600	Porosity ~76%, Compressive strength 2.33 MPa	Porous mullite	[126]
Fly ash	Boehmite, Sodium hydroxide and hydrochloric acid	1200	Particle size <0.3 μm	Powders	[129]
High-alumina fly ash	Sodium hydroxide and hydrochloric acid	1600	Porosity~1.2%, Bulk density ~2.78 g/cc, Compressive strength ~169 MPa	Mullite body	[131]
Coal gangue	Bauxite and corn starch	1400	Porosity ~48%, flexural strength ~66 MPa	Membrane	[134]
Kaolin	Alumina waste	1500	Porosity ~34%, flexural strength ~56 MPa	Mullite block	[137]
Kaolin	Aluminum slag	1400	-	Mullite body	[138]
Kaolin	Kaolin clay	1350	Density ~3.17 g/cc, Porosity near zero, modulus of rupture ~67 MPa	Mullite body	[140]
Rice husk silica	Aluminum nitrate	-	-	Mullite precursor	[142]

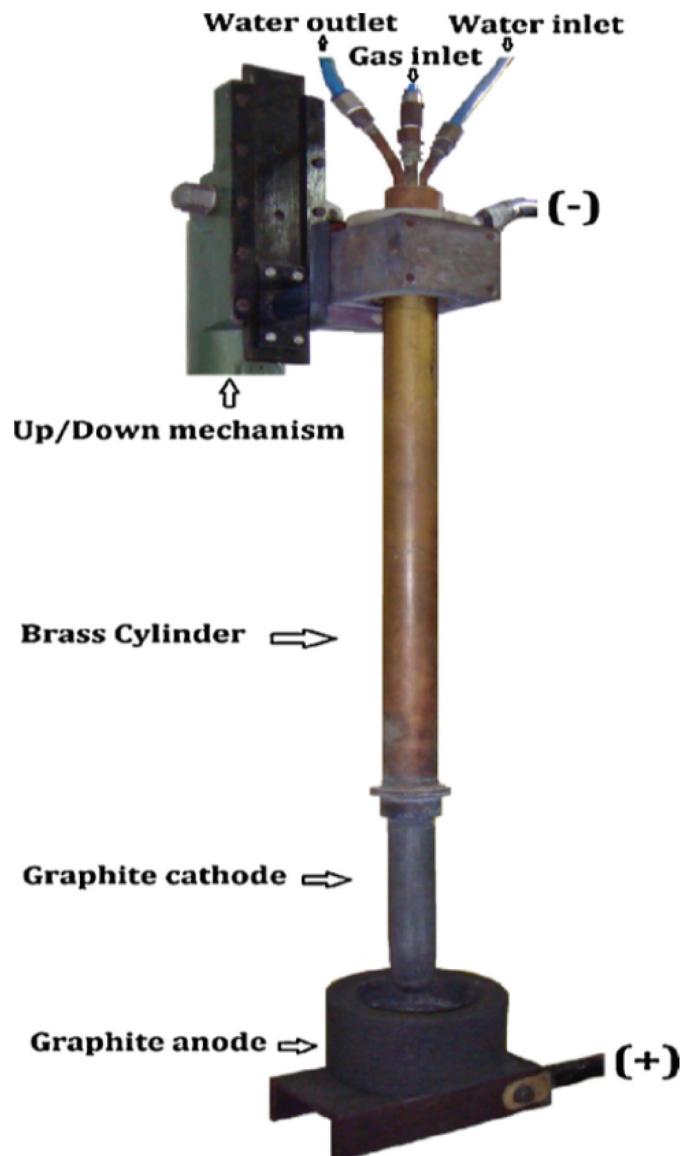


Figure 3. Schematic diagram of TAP torch. Copyright with the permission from Ref [135].

[116,121]. Generally, it can be synthesized through the thermal reaction (diffusion-reaction) of mixtures of natural or synthetic sources (clays, alumina, kaolinite, pyrophyllite, aluminum isopropoxide) of Al_2O_3 and SiO_2 at above 1300°C [116–118]. Recently, alumina and silicate-containing wastes or low-cost resources have been acquiring much attention to reduce the cost of mullitization. The name of the wastes with different parameters for mullitization is tabulated in Table 4.

In particular, coal FA has much potential as an ingredient for making the mullite due to its abundant availability and chemical composition. FA contains around ~54 wt.% and 35 wt.% of SiO_2 and Al_2O_3 , respectively. Therefore, bauxite [122–124], pure Al_2O_3 [125,126], $\text{Al}(\text{OH})_3$ [127], AlF_3 [124,128] and other sources of Al_2O_3 have been added into FA to maintain the stoichiometry weight ration of Al/Si (~2.55) for mullitization. Cao *et al.* (2014) [124] have developed low-cost mullite membrane using coal FA with natural bauxite (extra alumina source), V_2O_5 (sintering

additive) and AlF_3 (pore-forming agent and alumina source). They have concluded that 4 wt.% AlF_3 and 3 wt.% V_2O_5 containing specimens are completed secondary mullitization reaction at 1300°C with 86.75% mullite content. It shows the interlocking microstructure of anisotropically developed mullite whiskers with an open porosity ~50% and flexural strength ~69 MPa. Zhu and Yan (2017) [126] and Dong *et al.* (2009) [123] have also prepared porous mullite using FA and other alumina sources. Li *et al.* (2018) [129] have synthesized mullite powder from FA through mullitization and hydrothermal process. Boehmite sol is mixed with the pre-calcined FA powder and again calcined at 900–1300°C. Composition with 12 wt.% boehmite sol and calcination at 1200°C, shows 63.80 wt.% of mullite. The amount can be increased up to 96.4 wt.% through the proper alkali and acid treatment (hydrothermal process). Recently, high alumina containing FA is attained more interest for the formation of mullite because it contains more than > 45 wt.% of alumina.

Table 5. Name of the wastes and other ingredients used to derive synthetic wollastonite with formulation parameters.

Wastes & other ingredients	Process	Synthesis temperature (°C)	Application	References
Eggshells and commercial silica	Microwave heating	1100	-	[147]
Eggshells and rice husk ash	Sol-gel	850	Biomedical	[148]
Rice straw ash and calcium nitrate	Sol-gel	-	Biomedical	[149]
Silica sand and limestone	Solid-statereaction	1450	Biomedical	[150]
Stone processing wastes and silica fumes	Solid-statereaction	1100	-	[152]
Rice husk ash and cement kiln dust	Solid-statereaction	1100	Ceramic raw material	[153]
Zirconium oxychloride production slag and CaO	Sol-gel	1000	-	[154]

The combustion temperature of the coal-fired boiler is approximately 1300°C. It is nearest to the secondary mullite formation temperature. Thus, a large quantity of mullite is generated in the high-alumina FA through the reaction between FA containing alumina and silica. Zhang *et al.* (2018) [130] and Han *et al.* (2018) [12] have extracted mullite from the high-alumina FA through the alkali and acid treatment. Lin *et al.* (2015) [131] have synthesized mullite using only pretreated high-alumina FA. The alkali (20% NaOH solution) and acid (15% HCl solution) treatment of high-alumina FA can be increased the alumina content above 65 wt%. The pretreated high-alumina FA contents above 88 wt.% of mullite after sintering at 1600°C.

Coal gangue is a by-product during the mining of coal. It consists of 10–15 wt.% of raw coal along with quartz and feldspar as major mineralogical compounds [132,133]. Lü *et al.* (2014) [134] have fabricated porous mullite membrane from heat-treated coal gangue, bauxite, and corn starch. They have concluded that secondary mullitization reaction is started at around 1100°C and 84.7 wt.% of mullite phase is retained after 1400°C with 48% open porosity for 32 wt.% corn starch containing sample. Yugeswaran *et al.* (2011) [135] have made mullite ceramics using coal ash through the transferred arc plasma (TAP) process. The schematic representation of the TAP torch is shown in Figure 3. Bauxite is mixed with coal ash at 0 to 75 wt.% ratio and mixture masses are melted in the TAP torch through 10 kW input power for 3 min along with argon gas as a plasma former. The molten masses are cooled through a jet air on the melted samples. Samples with

50:50 wt.% of coal ash and bauxite yield mullite without free silica or silicate impurities.

Kaolin is the most studied low cost starting ingredient for the synthesis of mullite. Generally, it consists of kaolinite, mica, and quartz as well as other minor constituents. The phase transformations of kaolin containing kaolinite during heating are very important for the production of mullite. Kaolinite is transferred into meta-kaolinite through a dehydroxylation process in between 450°C and 600°C. Meta-kaolinite is promoted to the aluminum-silicon spinel and free amorphous silica above 900°C. The first mullite starts to nucleate above 1050°C, and amorphous silica crystallizes into cristobalite around 1200°C. Large amounts of crystalline mullite (secondary mullite) are developed by the mullitization reaction of silica with the addition of alumina sources at above 1250°C [136]. Hence, mullite-based ceramics have been intentionally produced using kaolin with other wastes or natural and synthetic raw materials such as kaolin–alumina waste [137], kaolin–aluminum slag [138], kaolin–alumina [139], Kaolin–mica rich kaolin waste [140] and kaolin clay–kaolin waste [141].

Sembiring *et al.* (2014) [142] have synthesized mullite using RHA derived silica and aluminum nitrate hydrate $[(\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O})]$. They have concluded that the mullite phase is started to form at around 1150°C. The mullite amount rapidly increases with increasing heat-treatment temperature from 1150 to 1350°C. Serra *et al.* (2016) [143] have also investigated the mullite formation ability of RHA as a conventional silica source. The stoichiometric $(3\text{Al}_2\text{O}_3:2\text{SiO}_2)$ amount of

Table 6. Waste derived cordierite with formulation temperature and type of forms.

Wastes	Other ingredients	Cordierite formation temperature (°C)	Type of material	References
Fly ash	Magnesium chloride and silica gel	1300	Dense	[158]
Fly ash	Magnesium carbonate	>1100	Membranes	[159]
Fly ash	Dolomite	1200	Membrane	[160]
Waste serpentine mine tailing and kaolin mine tailing	Alumina	1350	Dense	[162]
Sepiolite	Alumina	1300	Porous	[164]
Rice husk ash	Alumina, Magnesia	1350	Dense	[166]
Waste foundry sand	Magnesia, Fused silica	1250	Dense	[168]
Ferro-chromium slag	Alumina, silica	1350	Porous	[169]
Blast furnace slag	Aluminum sulfate, $[\text{Si(OEt)}_4]$	1300	Powder	[170]
Kaolin waste	Talc, Magnesia	1350	Dense	[171]

RHA (~94.74 wt.% SiO₂) and calcined alumina (Al₂O₃) containing dry pressed body is stared mullite formation at 1400°C and completed after at 1600°C.

3.4.2. Wollastonite

Wollastonite (CaSiO₃) is the most widely studied calcium silicate mineral. It has some widespread properties such as low thermal conductivity, low dielectric constant and loss, chemical inertness, corrosion resistance, low thermal expansion, fluxing properties, and whiteness [144]. These characteristics of CaSiO₃ are made them highly useful in ceramic industries, including metallurgical, paints, plastics, constructions, chemicals, and medicals [145,146]. The ceramic industries are consumed nearly 30–40% of wollastonite worldwide to advances the various performance parameters of ceramics. Therefore, the world demand for this mineral is steadily expanding. But, wollastonite is not available for so many countries, and large deposit mines have not been surveyed yet. Thus, many studies have been performed to synthesize synthetic wollastonite from low-cost waste ingredients through different synthesis techniques. The name of the wastes with process parameters to synthesis wollastonite is tabulated in Table 5.

Vichaphund *et al.* (2011) [147] have synthesized wollastonite powder through microwave heating and waste eggshells, commercial silica are used as CaO and SiO₂ sources, respectively. They have found that wollastonite formation is started at 800°C and single-phase wollastonite is developed at 1100°C. Palakurthy *et al.* (2019) [148] have developed cost-effective wollastonite ceramics for biomedical application from waste RHA and eggshells by the sol-gel method. Single-phase wollastonite has been achieved at only 850°C. They have studied the degradation and in vitro bioactivity behavior of waste-derived wollastonite and the test reveals that the material shows excellent bioactivity with lower degradation rates. Some investigations are also found to derive wollastonite bioceramics from rice straw ash [149], limestone-silica sand [150], and locally available CaO and SiO₂ sources [151]. Nour *et al.* (2008) [152] have prepared wollastonite at 1100°C through the solid-state reaction process using stone processing wastes and fumed silica as ingredients. Ewais *et al.* (2014) [153] have also followed the same route to synthesize the wollastonite with other ingredients, i.e., RHA and cement kiln dust. Wang *et al.* (2018) [154] have developed wollastonite using zirconium oxychloride production slag as a silica ingredient by a sol-gel route at 1000°C.

3.4.3. Cordierite

Cordierite (Mg₂Al₄Si₅O₁₈) is a famed oxide ceramics for its exciting properties such as very low thermal coefficient ((1–2)×10⁻⁶°C⁻¹ between 20°C and 800°C), elevated thermal stability, excellent insulator, low

Table 7. Waste derived hydroxyapatite with formulation parameters and properties.

Wastes	Method	Phosphate source	Formation temperature (°C)	Properties	Application	References
Oyster shell	Solid state	CaHPO ₄	1000	Ca/P ~ 1.54, Crystallite size ~40.8 nm, spherical shape	-	[178]
Oyster shell	Precipitation	(NH ₄) ₂ HPO ₄	900	Crystallite size ~89.5 nm	-	[179]
Mussel shells	Microwave	Na ₂ HPO ₄	1000	Rod like, Crystallite size ~30–70 nm,	Bone-tissues	[180]
Mussel shells	Microwave	Na ₂ HPO ₄	-	Ca/P ~ 1.67, flower like flakes, width ~100–200 nm & length ~2–5 μm	Orthopedic	[181]
Kina shells	Hydrothermal	(NH ₄) ₂ HPO ₄	-	Ca/P ~ 1.97, porous structure	Bone-tissues	[182]
Abalone shells	Hydrothermal	(NH ₄) ₂ HPO ₄	150	Nano rod	Bone-tissues	[183]
Fish scale	Co-precipitation	(NH ₄) ₂ HPO ₄	500	Ca/P ~ 1.65, flat-plate, crystallite size ~15–20 nm	Bone-tissues	[184]
Fish bones	Calcination	600	Ca/P ~ 1.42–1.53	Absorbent	[187]	
Fish bones	Calcination	700	Ca/P ~ 1.8, particle size ~ 55–70 nm	-	[188]	
Chicken bone	Calcination	-	Ca/P ~ 1.56	Bone regeneration	[189]	
Eggshells	Self-reaction	K ₂ HPO ₄	37	Ca/P ~ 1.67, Particle size ~ 41 nm	Orthopedic	[190]
Eggshells	Electrochemical	Synthetic urine	80	Ca/P ~ 1.67,	-	[191]
Eggshells	Co-precipitation	H ₃ PO ₄	120	Crystallite size ~45 nm	-	[192]
Phosphogypsum	Hydrothermal	KH ₂ PO ₄	200	Nano rod, diameter ~18 nm& length ~63 nm	-	[194]

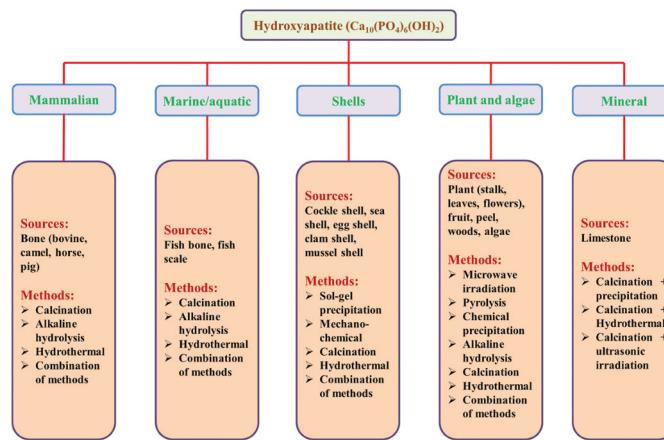


Figure 4. Summary of processes and sources for synthesis of HAp [195].

dielectric constant and good chemical durability. This makes it a promising candidate to fabricate components for the support of several applications like thermal insulators, furnace refractories, membranes, filters, integrated circuit boards, and catalysts [155–157]. The synthesis of pure cordierite by the advanced techniques is limited due to its expensive raw materials. Recently, researchers have focused their investigation on preparing low-cost cordierite using waste materials. Table 6 illustrates some examples of waste-derived cordierite with different parameters. Hajjou *et al.* (2017) [158] have developed cordierite ceramics using FA along with magnesium chloride and silica gel to maintain the stoichiometry of cordierite ($2\text{MgO}\cdot2\text{Al}_2\text{O}_3\cdot5\text{SiO}_2$). They have concluded that cordierite is started to form at 1200°C and the pure phase is obtained at 1300°C with a small amount of spinel. Dong *et al.* (2006) [159], Liu *et al.* (2015) [160] and Długosz *et al.* (2016) [161] have also used FA to fabricate the cordierite ceramics. Zhu *et al.* (2012) [162] have prepared cordierite by solid-state reactions with three different types of raw materials, i.e., waste kaolin mine tailing as the source of SiO_2 and Al_2O_3 , waste serpentine mine tailing as the source of SiO_2 and MgO , and alumina powder. Single-phase cordierite is achieved after sintering the pressed mixture mass at 1350°C for 3 h. Ramezani *et al.* (2017) [163] and Zhou *et al.* (2011) [164] have fabricated cordierite using waste serpentine and sepiolite (after heat treatment its transform into serpentine), respectively. Some studies also have found to investigate with RHA as an alternate of conventional silica sources for the preparation of cordierite [165–167]. Another author Xiang *et al.* (2016) [168] have used waste foundry sand (solid waste from metal casting industries) as a source of silica and alumina to prepared cordierite. Liu *et al.* (2016) [169] have prepared the porous cordierite ceramics using ferrochromium slag along with commercial silica and alumina powder without any pore-forming ingredients. They have found that 87 wt.% of the cordierite phase is developed in the system at 1350°C along with

open porosity around 32.8% and flexural strength about 47.26 MPa. Xingrong *et al.* (2013) [170] have utilized blast furnace slag for synthesizing cordierite powder. Cordierite phases are formed in the range of calcination temperature at 1200–1300°C. Almeida *et al.* (2018) [171] have investigated the cordierite synthesis from kaolin waste, magnesia, and talc powder. They have revealed that the beginning of the cordierite phase formation is at around 1250°C and more peaks are found at 1350°C.

3.4.4. Hydroxyapatite

Hydroxyapatite (HAp, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) is an extensively studied ceramic material due to some unique characteristics like superior biocompatibility, bioactivity, osteo-conductivity, thermodynamically stable in body fluid and chemical composition, which is very close to human bones and teeth [172,173]. HAp can take part in the bone augmentation and repairing bone defects without causing any inflammation and toxicity in the body [174]. Therefore, HAp has been employed for biomedical applications mostly in orthopedic, dental, odontology, drug delivery, and as a coating material for the non-bioactive implants [175]. Moreover, HAp has excellent ion exchange capability with low solubility in water, high stability under oxidizing, and reducing circumstances [176]. Thus, the attention has turned about the using of HAp in different fields, i.e., as an absorbent material in wastewater or soil treatment plant, adsorption of heavy metals [177]. Subsequently, several routes for the manufacturing of HAp with customizable physiognomies have been widely studied. Simpler approaches with employing inexpensive calcium sources and low energy consumption to synthesis HAp are offered a worthy research challenge. Recently, high calcium-containing some wastes, such as oyster shell [178,179], mussel shells [180,181], kina shells [182], abalone shells [183], fish scale [184–186], fish bone [187,188], chicken bone [189], eggshells [190–192] and phosphogypsum waste [193,194] have been effectively consumed as a calcium

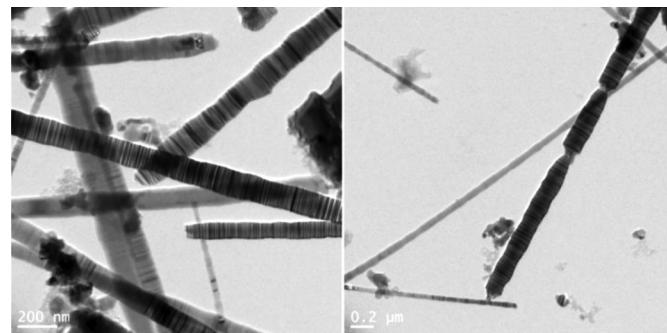


Figure 5. TEM images of e-waste derived SiC nanowires. Copyright with the permission from Ref [210].

source for the fabrication of HAp. **Table 7** illustrates a summary of the recent progress for the synthesis of HAp from wastes. Pu'ad *et al.* (2019) [195] have reviewed about the synthesis of HAp from different sources, mostly are wasted with acquired advanced fabrication techniques, as shown in **Figure 4**. They have deeply discussed about the effect of different advanced processes on the critical properties such as phase assemblage and crystallinity, Ca/P ratio, morphology, and particle sizes of waste-derived HAp. Holanda (2017) [196] has also reviewed on the recycling of calcium-rich wastes as alternative starting materials to produce nanostructured HAp for bio-ceramic applications. He has concluded that the calcium-rich waste materials are good candidates as renewable sources for nanostructural bio-ceramics production and eggshell is the most promising bio-waste for preparing of high purity HAp.

3.5. Non-oxide ceramics

3.5.1. Silicon carbide

Silicon carbide (SiC) is an encouraging non-oxide ceramics due to its excellent characteristics such as

corrosion and wears resistance, good thermal stability, high mechanical strength and hardness, chemical inertness, wide band gap, and unique optical property. These unique properties are made them very useful in various engineering applications, including grinding media, heating elements, electronic devices, optic devices, catalyst support materials, reinforcement in ceramics, polymer and metal-matrix composites [197–199]. SiC powder is generally fabricated through the Acheson technique based on carbothermal reduction of a coal and quartz sand mixture at around ~2400°C [200]. There are some limitations like high reaction temperature and time, the presence of unreacted silica or carbon and large particle size of SiC with this carbothermal process. Bulky particles are decreased the sinterability characteristic of SiC and required further milling process. To eliminate of unreacted materials during synthesizing SiC through Acheson technique, extra acid treatments are required. Discovery a more efficient and economic synthesizing method is therefore a challenge for SiC.

During the last three decades; rice husk (RH) has acquired importance as a starting ingredient for the synthesis of SiC (particles and whiskers). Thus, Cutler

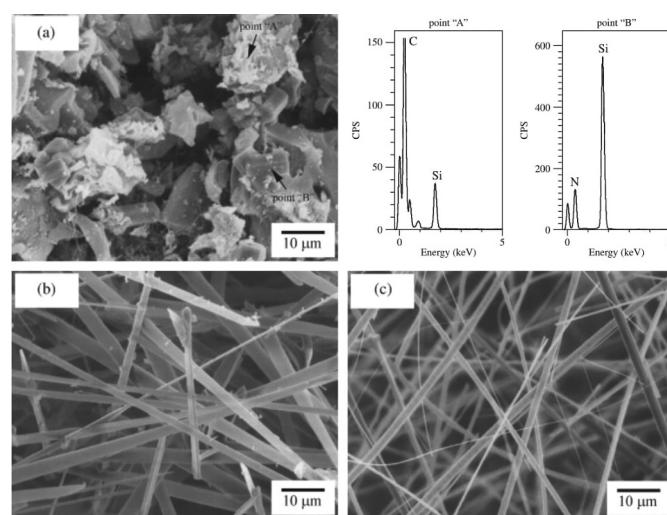
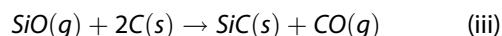
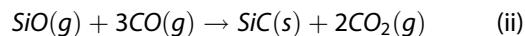
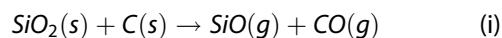


Figure 6. Scanning electron microscopic (SEM) images of (a) dark gray powder, (b) white whisker and (c) fibers synthesized by the carbothermal-nitridation of RH at 1450°C for 6 h. The graphs next to the SEM image of dark gray powder are electron-dispersive X-ray spectra measured at different locations in the gray powder sample. Copyright with the permission from Ref [229].

et al. (1974) [201] have first introduced RH for the fabrication of SiC. After that, many modifications have been made by several researchers for industrialization of this process. Recently, microwave heating and different catalyst activities have been investigated for the preparation of SiC from RH through different studies [202–205]. Certain metallic catalysts (Co, Fe, Pd, Ni, and Cr) are significantly enhanced the reaction kinetic between SiO₂ and C in the temperature at 1200–1600°C. These are ascribed to the desirable particle morphology with a high production rate. SiC from RH seems more promising due to low synthesis temperature and inexpensive ingredients. Commonly, all studies are followed two processing steps to utilize RH for preparing of SiC, i.e., firstly eliminating of volatile compounds (cooking) by control heating (400–800°C) in reducing atmosphere; and then heat-treated at high-temperature (>1300°C) for generating of SiC through the reaction between cooked RH containing SiO₂ and C [206]. The following common chemical reaction can be taken place during synthesizing of SiC from RH [200]:



Some other researchers are also found to fabricate SiC from different waste ingredients. Hossain *et al.* (2018) [207] have utilized the single-crystal silicon ingot cutting sludge for preparation of SiC. They have mixed this sludge with high purity C at different molar ratios and heat-treated at 1400–1600°C in Ar atmosphere. They have found that sludge to C mixture ratio at 1:1.4 and carbonization at 1550°C sample show optimum production efficiency of SiC. Kim *et al.* (2016) [208] and Li *et al.* (2014) [209] have also synthesized

SiC through carbonization route by utilizing waste silicon wafer and waste silica fume, respectively. Maroufi *et al.* (2017) [210] have approached a new process for the fabrication of SiC nanowires from e-wastes, i.e., obsolete computer monitor as a SiO₂ source and plastic shell as a source of C. First, obsolete computer monitor is crushed in to fine powder and plastic shell is also grounded after pyrolyzed at 1550°C. Both powders are mixed with a stoichiometric ratio of SiC and then pressed using a uniaxial hot-pressed at 180°C by applying 3 bar of pressure for 20 min. The pellets are heated at 1550°C in an Ar purge tubular furnace for 150 min. The fabricated SiC has appeared mostly of bamboo-like nanowires (length up to 10 μm and diameter ~ 30–200 nm), as displayed in TEM images Figure 5. Rajarao *et al.* (2014) [211] and Maroufi *et al.* (2017) [212] have also recycled electronic waste as a C source and e-waste glass source of SiO₂, respectively, for preparing SiC. Qadri *et al.* (2015) [213] have prepared SiC through the pyrolysis of the husks, stalks, leaves, and cob residues of corn plant above 1450°C in an inert atmosphere. Park *et al.* (2016) [214] have synthesized nano SiC (3–12 nm) via low-temperature pyrolysis (500°C) and magnesiothermic (650°C) of SiO₂/waste poly(vinyl butyral) mixtures in an Ar atmosphere. Gubernat *et al.* (2017) [215] and Polyakh *et al.* (2014) [216] have used shungite (amorphous coal) and steel plant wastes, respectively, to fabricate SiC. Additionally, some studies are found that the recovering of SiC from photovoltaic industry waste [217,218] and Si wafer cutting slurry [219–222] through different filtration processes like flotation, applied electrical field, hydrocyclone separation, and alkali-acid treatment.

3.5.2. Silicon nitride

Silicon nitride (Si₃N₄) is a high-temperature applicable non-oxide ceramic material. It retains some superb characteristics like low thermal expansion coefficient, higher thermal shock and creep resistance than other

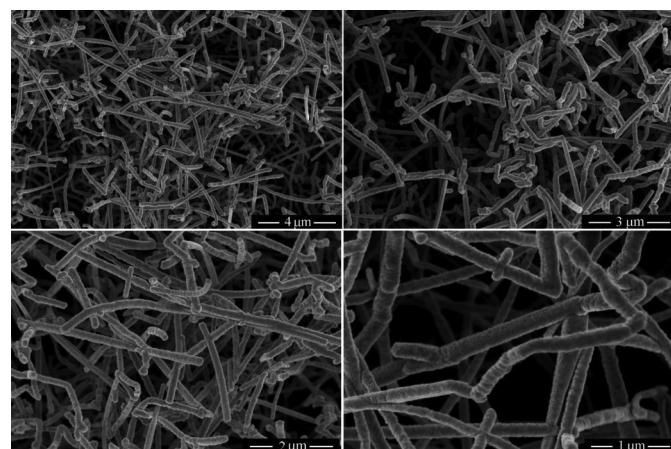


Figure 7. SEM images of e-waste derived Si₃N₄ nanowires with different magnification. Copyright with the permission from Ref [232].

ceramics, good corrosion resistance, and high-temperature strength. These features make it an utmost favorable candidate for high-temperature structural ceramics [223,224]. Thus, numerous processes have been developed to prepare Si_3N_4 powder. Most economical and famous route for the synthesis of Si_3N_4 powder is carbothermal-nitridation of silica [225]. Commercial available fine C and SiO_2 powder are generally used for this method. Highly reactive ingredients and their uniform distribution are enhancing the product yield from nitridation reaction. RH contains highly reactive C and SiO_2 with their homogeneous distribution. Hence, RH has huge potential as a starting ingredient for synthesizing Si_3N_4 . Some investigations have therefore been found Si_3N_4 fabrication through carbothermal-nitridation of RH [226–228]. Pavarajarn *et al.* (2010) [229] have deeply studied the mechanisms of Si_3N_4 whisker and fiber developed via carbothermal reduction-nitridation reaction of RH. First, clean RH (~83.52% organic materials) is pyrolyzed in a continuous Ar purge (36 L/h) tubular furnace at 600°C for 3 h to produce ash, which is contained around ~45.56% silica and 50.67% carbonaceous materials. 2 mm depth pyrolyzed ash is filled into alumina dish, and the carbothermal-nitridation reaction is accomplished in the tube furnace at 1400–1470°C for 3–10 h with a constant flow (50 L/h) of gas mixture (90% N_2 + 10% H_2). Whisker and fiber forms Si_3N_4 are developed through the vapor-solid mechanism, and they are formed in different locations on the dish. Cotton-like white fibers are found on the edges and outside the cavity of the dish, and white whiskers are found on top of the dark gray powder (a mixture of ash and Si_3N_4). Figure 6 shows SEM micrographs of formed three different powders. Gray powder is a mixture of rod-like grains (Si-rich, point "B" in Figure 6(a)) and irregular shape aggregates (C-rich, point "A" in Figure 6(a)). The length of the whisker is ~100 nm with a flat blade-like structure Figure 6(b), and fibers are smooth and round with a diameter of 200 nm–2 mm and length of several millimeters Figure 6(c). Fibers are mixture of α and β - Si_3N_4 , but whiskers are retained only a single crystalline form of α - Si_3N_4 .

Moreover, Soltani *et al.* (2017) [230] have prepared Si_3N_4 coating using RHA derived silica via a chemical vapor deposition method. Abdulhameed *et al.* (2018) [231] have fabricated Si_3N_4 through hydrothermal reactions route at 100, 150, 200 and 300°C using RHA as source of SiO_2 , sugarcane bagasse as C source, NH_4OH , and HCl. The obtained powder at 100°C/24 h is contained ~92 wt.% Si_3N_4 , a mixture of α and β phases. Maroufi *et al.* (2018) [232] have recycled e-waste, i.e., obsolete computers for Si_3N_4 synthesis. Glasses and plastic shells are used as SiO_2 and C sources, respectively. These mixtures are heat-treated at 1550°C under atmospheric pressure N_2 purge furnace. The formed Si_3N_4 consists mostly of nanowire structure with

75 – 250 nm diameters and 2 μm lengths, as shown in Figure 7. Nanowires have appeared to Y-shaped and T-shaped morphologies in random direction with rough and twisted surface morphology. Other wastes like waste silica fume as a source of SiO_2 and waste carbon fiber reinforced polymer as a C source also used to fabricate Si_3N_4 by the other researchers [233,234].

Qadri *et al.* (2016) [235] have prepared Si_3N_4 and $\text{Si}_3\text{N}_4/\text{SiC}$ composite by thermal treatment of RH and wheat at and above 1300°C in different atmospheres. Different forms of Si_3N_4 are obtained by single-step heat-treatment at different temperatures in N_2 atmosphere, e.g., α - Si_3N_4 is formed at 1400°C and above that it retains the mixture of α and β - Si_3N_4 . The composite is synthesized via two steps, i.e., first SiC is formed by heat-treatment in Ar atmosphere, and then it is treated at 1450°C in a N_2 atmosphere. It is composed of α and β phase of Si_3N_4 and cubic phase of SiC. On the other hand, Zawrah *et al.* (2012) [206] have synthesized SiC and $\text{Si}_3\text{N}_4/\text{SiC}$ composite by pyrolysis of RH in Ar and N_2 atmosphere, respectively. Macadamia shell waste is also used as a source of C for the preparation of SiC and Si_3N_4 by Rajarao and Sahajwalla (2016) [236]. First char is prepared by the pyrolysis of shell waste at 800°C in an Ar atmosphere. SiC and Si_3N_4 are developed by the carbothermal (in Ar) and carbothermal-nitridation (in N_2) reaction, respectively, of SiO_2 -char mixture at 1550°C.

3.6. Ceramic membranes

Membrane technology is a promising candidate for the separation technology; it has wide range of industrial applications like drink water production, wastewater treatment, gas purification and alkaline or acidic media separation [237,238]. Recently, ceramic membranes have acquired more attention compared to other materials membrane due to good chemical resistance, thermo-mechanical stability, high separation efficiency, easy clean regeneration, anti-fouling performance and long lifetime [239,240]. However, the ceramic membranes are not much more commercially attractive than polymeric membranes due to its expensive cost. Thus, researchers are trying to develop low-cost ceramic membranes by utilizing wastes or low-cost ingredients.

Hubadillah *et al.* (2018) [241] have utilized RH extracted silica for the preparation of hollow ceramic membrane through the phase inversion-sintering technique. RH silica is mixed with polyethersulfone, N-methyl-2-pyroolidone and polyethyleneglycol 30-dipolyhydroxystearate in water and prepared a uniform dispersion through ball milling. The suspension is extruded by a spinneret (inner diameter ~1.2 mm and outer diameter ~2.8 mm) with a constant flow of 10 mL/min. After phase inversion in water of extruded mass is dried at room temperature

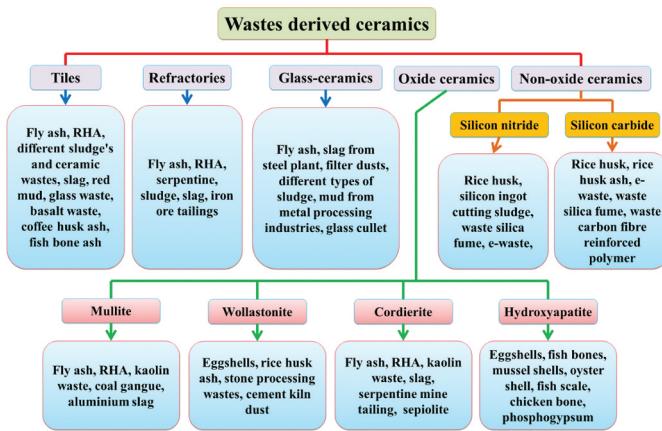


Figure 8. Different wastes used to derive ceramics.

and sintered at high temperature. 37.5 wt.% heat-treated RH content and 1200°C sintered specimen shows bending strength of ~71 MPa, open porosity of ~50% and permeate water flux of ~300 L/m².h. Tai *et al.* (2018) [242] have synthesized hollow fiber ceramic membrane for oily water separation using waste palm oil fuel ash (it is generated through the burning of palm kernel shells, empty fruit bunches and mesocarp fiber) through the combination of phase inversion and sintering method. 38 wt.% palm oil fuel ash containing 1050°C sintered membrane shows 96% oil rejection efficiency and 185.42 L/m².h permeate flux at 3 bar applied pressure. Tai *et al.* (2019) [243] have also utilized waste palm oil fuel ash for preparation of low-cost ceramic membrane. Jamalludin *et al.* (2018) [244] have synthesized ceramic membrane by utilized 60 wt% of sugarcane bagasse ash. 1000°C sintered hollow fiber membrane exhibits permeate water flux of ~466.2 L/m².h at the starting of the filtration process. FA is the another potential waste for fabrication of mullite-based low-cost membrane [123,124,134,159,160,245,246]. Fu *et al.*, (2019) [245] have prepared whisker-structured mullite membranes derived from FA and Al(OH)₃ as main ingredients with MoO₃ sintering additive. At 1300°C sintered and 20 wt. % MoO₃ containing membranes shows ~58% porosity and flexural strength of 35.9 MPa. Chen *et al.* (2016) [246] have fabricated mullite-based membranes for wastewater treatment using coal FA with bauxite and WO₃. 20 wt.% WO₃ and 1400°C sintered sample possesses flexural strength of ~68 MPa, open porosity ~51% and oil rejection ~ 99%. Cordierite containing membranes are derived by utilized organic wastes like sawdust, ion exchanger resin and starch up to 10 wt.% as pore former by Misrar *et al.* (2017) [247]. Hubadillah *et al.* (2020) [248] have synthesized HAp-based hollow membrane using waste cow bone for textile industry discharge wastewater treatment. At 800°C heat-treated bone powder is retained HAp as a major phase, which is used as a raw material for the preparation of membrane. 60wt.% HAp content and 1200°C

sintered sample demonstrates a good bending strength of ~202 MPa, average pore size of ~0.013 µm, porosity of ~35.4% and stable flux of 88.3 L/m².h. The membrane shows good removal performance (heavy metals (Fe, Zn, Cu, Cd and Cr) = 100%, color = 99.9%, turbidity = 99.4%, COD = 80.1%, and conductivity = 30.1%) from industrial textile wastewater.

4. Waste utilization and ceramic industries

In view of the environment, ecological and economic issues, science and technology developers are engaged to find the appropriate route of utilizing wastes for the production of value-added products. In these aspects, ceramic researchers are also investigated to recycle the industrial by-products or wastes to fabricate ceramics. Therefore, many research articles are published in recent years. But, industrially produced ceramics from waste ingredients are not yet widely matured. However, some tile industries are started to use wastes for the production of tiles [249,250]. But these numbers are very less because numerous conditioning features like the compatibility between natural raw materials and wastes, the characteristics of the final product, continues availability, transport costs, constant chemical compositions and the pre-treatments of wastes are limited the applications. Therefore, the more deep investigation is required in technological transfer from the academic to industry for commercialization the waste-derived ceramics. The technology transfer is becoming a confront from different perspectives, like ethics, knowledge, and risks of unsustainability. Therefore, more encouragement is required to industrial manufacture for recycling the wastes. The government may also lead to an increase the interest through making laws and policies. Sustainable production not only helps the ceramic industry but also saves the environment and society from pollution.

5. Conclusions

Today, the production of toxic and hazardous wastes from various sources are continuously increased, and at the same time, it is created difficulties in the form of dumping and pollution to the environment. The valorization of these wastes and up-grading as a substitute of primary natural resources can present numerous benefits, i.e., reduced the extraction volume of natural ingredients (resource conservation), less energy consumption throughout the subsequent processing (cost-effective), and lower pollutant releasing rates (improvement of society's health and safety). The recycling of the wastes for the production of ceramics is beneficial because it consumes a huge amount of natural raw materials. Even if, a small amount of waste incorporation is possible in the high production ceramics, it will effect into significant absorption of wastes. Numerous research studies are published in the last two decades regarding the waste utilization for the fabrication of ceramics, but technological transfer to commercial production is limited. However, some wastes are found huge potential to replace the convention natural resources for the manufacturing of ceramics, as concluded in Figure 8. Within this objective of the review, the following important facts can be drawn:

- FA can be found the most promising waste for development of the ceramics. It can be used to fabricate insulation refractories and ceramic tiles. High alumina containing FA is a good candidate to synthesis mullite ceramics through the incorporation of other Al_2O_3 sources by maintaining the stoichiometry weight ratio of Al/Si (~2.55).
- RHA can be used as a substitute for silica for making ceramics. Amorphous silica derived from RHA can be an interesting source to synthesis the advanced ceramic materials like mullite, wollastonite, cordierite, and others. RH is a good choice for carbothermal and carbothermal-nitridation reactions to form SiC and Si_3N_4 , respectively.
- Different type of sludge's (sewage and ceramic) and slag can also be used to manufacture the tiles.
- Silica-containing solid wastes like FA, slag from the steel plant, filter dust, sludge's, mud from metal processing industries, and glass cullet is found to have an excellent possibility to fabricate GC.
- Eggshell is the most promising bio-waste as a source of CaO for preparing of HAp. Other high CaO containing sources like oyster shell, mussel shells, fish scale, and fish bones also can be used to derive synthetic HAp.
- Tile and insulation refractory industries have

a massive potential to introduce waste ingredients more economically than other ceramic industries because of their range of properties.

The review should supply a comprehensive source of info to those involved in this area, both of academia and industry for finding new ways to recycling wastes in production of ceramics with viable and alternative technique. However, more investigation is required in regarding to sustainable development in ceramics with technology transfer from academic to industry.

Highlights

- It briefs an up-to-date overview on recent development in waste-derived ceramics.
- It covers traditional as well as advance ceramics fabricated from solid wastes.
- We study the feasibility of wastes as an alternative of the conventional resources.
- Fly ash and rice husk ash are found more suitable wastes for ceramic productions.
- It needs more investigations on technology transfer for commercialization.

Nomenclatures

FA:	Fly ash
RH:	Rice husk
RHA:	Rice husk ash
BFS:	Blast furnace slag
σ :	Thermal conductivity
CAGR:	Compound annual growth rate
SS:	Sewage sludge
EAF:	Electric arc furnace
RM:	Red mud
CHA:	Coffee husk ashes
GC:	Glass-ceramics
TAP:	Transferred arc plasma
HAp:	Hydroxyapatite

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Disclosure statement

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

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