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A REVIEW OF THE DEVELOPMENT OF THE GEL CASTING METHOD FOR POROUS CERAMIC FABRICATION

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ABSTRACT

The objective of this paper is to present an overview of the development of gel casting methods on synthesis techniques and the characteristics of gel casting porous ceramics and its applications. The gel casting method is a colloidal ceramic synthesis method that requires a short period for the ceramic body to develop. This review provides the latest developments in the gel casting process of synthesizing porous ceramics. At the beginning of the gel casting method development, the acrylamide (AM) system was the most commonly utilized system. Over time, the use of the AM system began to be minimized because of its toxicity. Researchers began to develop natural polymers as pore templates and natural minerals as raw materials in the gel casting method. In addition to polymers and raw materials, the gel casting process also requires additives such as gelling agents and dispersants. At the end of this review, a mapping of how to select the additives in the gel casting process, for AM systems and non-AM systems for the fabrication of porous ceramics is presented. The characteristic of porous ceramics produced by AM and non-AM systems are almost similar. Porous ceramic applications have been used as bone tissue supports, energy storage, filters, and catalyst support. This review will be a reference for future research related to the process of fabrication of advanced porous ceramics using the environmentally friendly gel casting method.

Keywords: Low Toxic, Non-Toxic, Porous Ceramic, Non-Acrylamide System.

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INTRODUCTION

The synthesis of advanced materials in the form of porous ceramics is currently experiencing very rapid development. Material processing procedures can increase the reliability of ceramic materials, one of which is the colloidal method. Several colloidal synthesis methods are being developed tape casting[1-4], sol-gel[5-8], dip coating[9,10], slip casting[11,12], injection moulding[13-15], extrusion[16-18], and gel casting.[19-23] The process of colloidal synthesis has numerous advantages and disadvantages. However, gel casting is one of the colloidal methods with several advantages, such as complex ceramic bodies can be formed if the procedure of shaping and removing the ceramic body is performed correctly.[24] The creation of a ceramic green body does not necessitate using a porous mold.[25,26] Besides versatility, the gel casting technology was initially created to produce dense ceramic bodies, but it was later expanded to generate porous ceramics.[27] The ceramic green body developed has high strength, reaching more than 3 MPa.[28] It is easy to release the organic compound during combustion, devoid of a particular burnout step, and material qualities are extremely homogenous.[27] During the 1990s, the US Oak Ridge National Laboratory's Metals and Ceramics Division-Ceramic Processing Group pioneered the gel casting method.[25,29] It has been the subject of research in the field of ceramic reliability until today. The gel casting method is based on in situ

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polymerization, which involves dispersing the polymer into ceramic raw material such as alumina powder[30-32], alumina silica[33], silicon carbide[21,33-35], silicon nitride[36], and zirconium.[37] At the beginning of gel casting method development, the polymer that is generally used as polyacrylamide, by dispersing AM monomer with methylene bis-acrylamide (MBAM), crosslinked into a ceramic raw material using ammonium persulphate (APS) initiator, and tetramethyl ethylenediamine (TEMED) catalyst.[25,35] This method requires a high cost in the synthesis process, and the materials used are toxic. In the 2000s, a low-gel casting ceramic synthesis method began to be developed, including using natural material binders with pure chemical compounds as the raw material.[38-40] From 2010 to 2015, the researchers started to study the synthesis of low-toxicity gel casting ceramics.[41-44] However, the raw materials used were still chemical compounds. Thus, from 2016 to 2019 researchers initiated using natural minerals as raw material for porous ceramics fabrication. Natural minerals have been successfully used as raw material for porous ceramics, including kaolin,[45-47] fly ash,[47,48] zeolite, and clay.[49-51] In addition to using raw materials from natural minerals, binders with low toxicity have also been developed recently.[33,49,50] Entering the 21st century, gel casting ceramic synthesis methods are increasingly being developed by producing transparent ceramic membranes,[22] ceramic membranes with high thermal expansion and permeability properties.[52,54] The raw materials and binders come from natural materials, hence environmentally friendly at a low cost. In addition, a copolymer binder consisting of isobutylene and maleic anhydride, known as ISOBAM is recently being developed.[21,56] The formation of pores in a ceramic body determines the characteristics of ceramic.[50] Porous ceramic characteristics produced by the gel casting method resulted in strong green ceramic bodies,[35,56] muscular sintered ceramic bodies,[31-33,36,57] high porosity of sintered ceramic bodies,[57,58] an excellent flexural strength of ceramic bodies,[33,55] and high water permeability.[56] Based on these characteristics, gel-casting porous ceramics are applied as thermal insulators, drug delivery, catalyst support, and microfiltration agents. In this review, the development of gel casting methods in the fabrication of porous ceramics, the mapping of selection of the additives for AM and non-AM systems, the characteristics, and the utilization of porous ceramics are presented.

Gel Casting Method for Porous Ceramic Fabrication

Gel casting was created to solve some of the constraints on more complicated ceramic shaping techniques, as discussed in the introduction section. The gel casting techniques can be summarized by several main stages, which are slurry preparation, gelling addition, degassing, casting, unmolding, drying under controlled conditions, and rebinding,[27] as illustrated in Fig.-1.

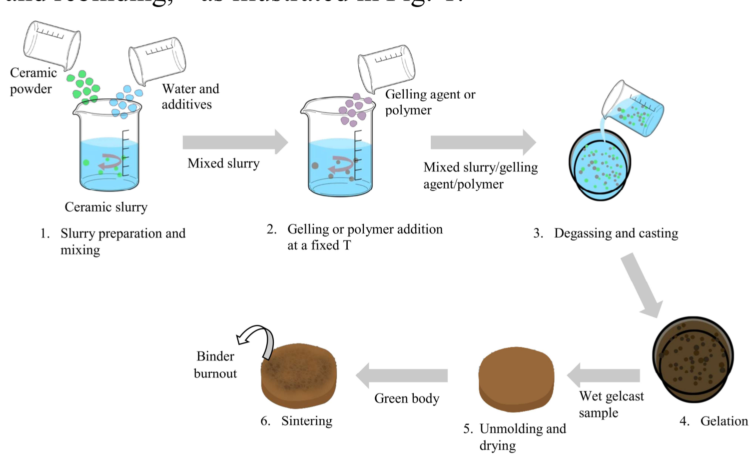

Fig.-1: Illustration of Gel casting Method for Porous Ceramics Fabrication

All manufacturing processes (e.g., powder suspension, shaping procedure, pore formation, and sintering process), notably certain important parameters, must be carefully regulated to create porous ceramic objects that are highly dense and defect-free ceramic pieces. The crucial steps in gel casting are the development of an adequate powder suspension in terms of rheological properties, solid loading, uniformity, and stability. It is highly correlated with the physical and mechanical properties of the resulting green body ceramic.[61] In addition, it is also related to the particle rearrangement process, which leads to the non-uniform density of the ceramic green body, and the separation of the constituents due to differences in density and particle size.[62] For example, the rheological properties of 50% by weight SiC slurries with varying starch content were described, with shear thinning behaviors for slurry structure breakdown under shear stress. The organic additives in the slurry bind to the particle surface, causing micellar bridging and the formation of an association network. The viscosity rises fast as the starch content rises.[33] Generally, the higher gelling agent content, the higher the slurry viscosity. As reported before, which used ISOBAM as a gelling agent, microgel formation started shortly after mixing the gelling agent into the slurry.[62] Additionally, ISOBAM also acts as a dispersant and affects the viscosity. However, pH adjustment or dispersants may not work with increasing solid loading. Gelation time is also an important factor in the colloidal suspension technique, which will affect the characteristics of the green body ceramic. If the gelation level is high, it will experience difficulties in the casting process. Still, if the gelation level is too low, it will affect the sedimentation of ceramic powder in the slurry.[33] In conclusion, green body ceramic should be considered one factor that influences a good gel casting process. To achieve this, the casting process must be considered, which depends on the viscosity of the suspension, and is directly proportional to the amount of gelling agent and solid loading. Besides that, pore formation and pore arrangement features are also important properties of porous ceramics fabrication.[66] Pore formation in ceramics can be accomplished in several ways. The first one is to add a sufficient amount of polymer to the slurry to produce high porosity, which can then be targeted following dispersion in water. Starch is one of the polymers utilized as a pore template; during the sintering process, this polymer will be removed, leaving pores with a similar shape as starch in situ. The results obtained indicate that the gel casting method can be used to produce homogeneous pores; with increasing starch content, the number of pores on the ceramic surface increases.[33,70] The mechanism of pore formation in gel casting ceramic bodies is different from traditional pore formation. In the gel casting method, there is a weak interconnection of grains, and the degree of incorporation of grains is low. The gap generated in the gel casting green body is bigger than those formed in the traditional synthesis, suppressing raw material grains interconnection with increasing sintering temperature. The grains are then getting closer to each other. They will form grain groups while also forming a pore template, an increase in sintering temperature, and complete grain group fusion to generate massive raw materials grains. However, due to the enormous distance, the big grains created cannot combine with one another. This suggests that translucent pore development in gel cast ceramics differs from traditional ones.[69] The pore formation is largely determined by the sintering process. At this stage, the polymer manufacturing process occurs in the ceramic body. Thus, it greatly determines the performance of the porous ceramic body. The sintering temperature has an impact on the ceramic body's crystal nucleation, and the holding duration has an impact on the crystal growth.[70] The crystallinity of the ceramic base material increases as the sintering temperature rises, the porosity reduces, and the compressive strength increases.[45]

Natural gels or binders used in the manufacturing of gels are also thermos-reversible gravimeters (TRG). In gel casting systems, polysaccharides and other natural binders, gums, and other ingredients are commonly employed. Starch, ovalbumin, chitosan, alginates, gelatin, carrageenan gum, and other materials can be used in a natural gel casting procedure. These solutions do not pose the same environmental problems as alcohol solvents because they are water-soluble.[70] When hydrated polysaccharides are chilled, they form ordered double helices, which are later reheated to create irregular circular chains. Monosaccharides are combined to make polysaccharides, which are complex carbohydrates. Between the gel temperature and the melting temperature of polysaccharides, there is a significant hysteresis. The melting temperature of carrageenan gel, for example, is 20-25ºC greater than the gelation temperature.[72] In addition to the polymer chain in the ceramic body releasing, in the sintering process, the ceramic powder oxidation process also occurs.[34] Researchers use SiC as the basic material for making ceramics. During the sintering process treatment, the exterior of the SiC porous ceramic is exposed to the air and then oxidized, with the reaction on Eq. (1).

$$
\begin{aligned}
&SiC_{(s)} + \tfrac{3}{2}O_{2\,(g)} \rightarrow SiO_{2\,(s)} + CO_{(g)} \\
&SiC_{(s)} + 2O_{2\,(g)} \rightarrow SiO_{2\,(s)} + CO_{2\,(g)} \qquad (1)
\end{aligned}
$$

The resulting SiO_2 layer is denser than the SiC matrix, according to SEM micrographs. The oxidation process is carried out by the following processes: (1) oxygen migrates into the sample, (2) oxidation process at the SiC/SiO_2 interface, and (3) gas product diffused away from the sample.

Development of Low Toxic Gel Casting Method

Generally, forming porous ceramics by the gel casting method applies an AM system as a polymer or pore template. In addition to polymers, as previously described, dispersants or gelling agents are also used. However, currently, a new method has been developed using only deionized water as a hydrating agent and gelling agent, then mechanical and ultrasonic stirring, followed by a degassing process.[31] The raw materials used are the Al_2O_3 amorphous phase and the MgO Pericles phase. The gel is formed after the addition of deionized water, and the composition and phase of the green body ceramic changes. That is, the hydration reaction has occurred in the gel casting process. The reactions that occur are shown in Eq. 2.

$$\rho\text{-}Al_2O_3 + 2H_2O \rightarrow Al\,O(OH) + Al\,(OH)_3$$
$$Mg\,O + H_2O \rightarrow Mg\,(OH)_2 \quad (2)$$

The synthesis of submicron porous ceramics using a “water-based” gel casting method, illustrated in Fig.-2.[62] The first step is raw materials’ suspension is inserted into a metal mold, and a cross-linked network is created by polymerizing the monomer, then wetted. Green bodies are dried at a temperature of 70-110 ºC, and pores have begun to form. The polymer in dried green bodies burns out at 600 ºC for 2 hours, and this process is called degreasing. The samples are then sintered at temperatures of 1300 ºC, 1350 ºC, and 1400 ºC for 2 hours to produce porous ceramics.

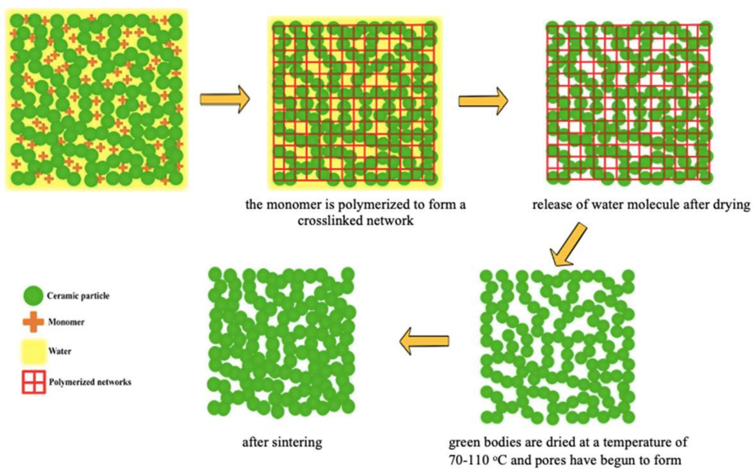

Fig.-2: Illustration of the Formation of Porous Ceramics by “Water Based” Gel casting Method

They developed a low-toxic gel casting system of comparable or better quality to the previously used AM system. Yüzbasi and Graule suggested that in the 2010s, a methyl acrylamide-N,N′-methylene acrylamide (MAM-MBAM) monomer system was developed, which was acceptable for aqueous gel casting and had lower toxicity than the original AM system. The results obtained also produce a strong and complex ceramic body.[71] The MAM-MBAM system has been applied to create alumina porous ceramics, using a polystyrene sphere (PS) as a sacrificial template. The ceramic character obtained is in the form of macro pores with high strength.[72] In addition, N-N-dimethyl acrylamide (DMAA) has also been used as a pore-forming agent with low toxicity in the gel casting synthesis process. Both Al_2O_3 and Y_2O_3 were used as raw materials, while as pore-forming agents, DMMA and PS were employed.[30] The findings revealed that PS size and content notably affect the microstructure and characteristics of slurry, green, and sintered materials. The addition of fine PS led to a higher porosity in the green body than the course one, producing a remarkable decrease in flexural strength, ranging from 28.50 MPa to 11.50 MPa; however, overall, it exhibited a fairly high strength for mechanical processing. DMMA was also investigated as a polymer in the creation of Si_3N_4 porous ceramics by aqueous gelling.[73] The increases in calcination temperature enhanced the growth of the $\alpha \rightarrow \beta$–Si_3N_4 and β–Si_3N_4 transformation phases in Si_3N_4 ceramics with varying solid loadings. Nonetheless, increases in solid loading have an inhibitory effect, because mass movement in the gas phase is inhibited due to pore connectivity disruption. The findings suggested that the DMAA system could be useful in developing high-performance porous Si_3N_4 ceramics using gel casting processes.

Development of Nontoxic Gel casting Method

Numerous nontoxic gel casting systems have been established. There are two categories of solidification methods in a gel casting system: chemical dispersed medium effect mechanism and physical dispersed medium effect mechanism. Polymer crosslinking with 2-hydroxyethyl methacrylate (HEMA),[80,81] metal ion complexation, temperature-activated crosslinking of polymers (gelatin and carrageenan), gelation of reversible biopolymers, and freeze casting are examples of these systems. In addition, several types of polymers and gelling agents that have been used in the gel casting method with nontoxic properties are corn starch,[42] glycols,[53] agar,[70] gelatin,[82,83] and citric acid.[78] Moreover, besides the use of natural polymers, the application of natural minerals as raw material for gel casting porous ceramics has also been developed. The synthesis of porous ceramics based on kaolin, fly ash, and a mixture of kaolin and fly ash, then studied the formation of it's pores using dolomite.[47] Compare to fly ash membranes, kaolin ceramic membranes feature smaller pore diameters, stronger mechanical strength, and better chemical stability. Kaolin and fly ash are combined with increasing porosity, strength, and stability while reducing pore size and permeability. Dolomite has better permeation qualities (increased porosity and smaller pore size) than calcium and sodium carbonate when used as a pore-former. Porosity reduces as the sintering temperature increases, and elevates as the kaolin content rises. However, as the sintering temperature escalated, the mean pore diameter and permeability increased, while the kaolin content was reduced. Increased sintering temperature and kaolin content improve strength and stability. Not only using natural materials, but the utilization of waste containing silicon has also been used as the base material for gel casting porous ceramics. For example, the use of silicon kerf waste as a raw material, along with SiC and corundum powder, and the AM system as a polymer. The gel casting method was used to create porous silica/porous mullite ceramics. At 1350°C, SiC and C in silicon kerf waste can be oxidized during the sintering process. Mullite porous ceramics were manufactured entirely from silicon kerf waste.[79] A novelty of the gel casting method was also developed using an aqueous gel casting process in the fabrication of $MgAl_2O_4$ porous ceramics, using Al_2O_3 and MgO powder as raw material, and deionized water as hydration agent.[31] The influence of deionized water on the materials' hydration characteristics, actual porosity, bulk density, microstructure, pore size distribution, and compressive strength were evaluated. The amount of deionized water injected, controlled the porosity, and microstructure of the porous $MgAl_2O_4$ ceramic, according to the findings. The release of absorbed water and the disintegration of hydration products such as boehmite, brucite, and bayerite generate the porous structure. The produced porous $MgAl_2O_4$ ceramic has an elevated apparent porosity (52.5–65.8%), a tiny average pore size structure (approximately 1-3 μm), and a comparatively good compressive strength (12-28 MPa) after determining the amount of deionized water applied. The novel aqueous gel casting technology, which is simple to use, is considered to be a potential contender for producing Al_2O_3 porous ceramics. In addition to using low-toxic or non-toxic materials, another development on gel casting methods is that they can be used in the synthesis of fine-pored ceramics.[80] Gel casting is a reasonably straight forward approach for producing porous materials with high specific surface area and exposed porosity researchers. The powder is disseminated in a silica sol, with NH_4Cl serving as the gelling initiator. Experimental design theory is also shown to be effective in the production of excellent porous materials with high porosity and specific surface area. Recently, a patented air-soluble alternating copolymer comprising ISOBAM has received attention. In fact, it can produce solid green bodies. The microstructure of solid load (up to vol 80%) and low organic content (<1wt%), indicates no cracking.[57] It has been proved that transparent ceramics can be effectively produced using gel casting with ISOBAM.[22,51,66] SiC porous ceramics were also successfully synthesized using ISOBAM as a gelling agent.[21] To overcome the problem of ISOBAM being difficult to crosslinked and gel with non-oxide ceramics, a novel method of changing the surface of forming SiC was implemented. SiC powder was first pre-oxidized, then the surface was modified with a silane coupling agent for the $-NH_2$ functional group, allowing it to cross-link with ISOBAM to produce a green body with a consistent structure. Because there was a small amount of organic content in the mix, no additional rebinding was necessary before sintering. The shadow corresponds to the oxide thickness, which has a linear connection with the SiC particle size. In addition, the slurry's solid content was regulated between 40-52%, and the porosity of the finished product fluctuated between 50-60% after sintering. Some examples of porous ceramics produced by the gel casting method using a low toxicity and nontoxic system with their characteristics, for the last 5 years are shown in Table-1.

Table-1: The Examples of Porous Ceramics Produced by Gel casting Method, by Using a Low Toxic and Nontoxic System for the Last 5 Years

Raw material (solid loading, vol %)	Polymer	Gelling agent	Dispersant	Sintering temperature (°C)	Pore size (μm)	Porosity (%)	Mechanical strength (MPa)	Ref.
SiC (50%)	Starch as pore forming agent	ISOBAM	Tetra methyl ammonium hydroxide (TMAH) and polyvinyl alcohol (PVA)	1500	-	34.2-42.7	86.7-139.3	33
Clay	AM system	-	CMC	1100	0.05-0.106	-	104	19,20
Y_2O_3 (68%)		ISOBAM	ISOBAM and tetraethyl ortho silicate (TEOS) as sintered additives	1780 for 6 hours	10.0	-	-	64
Kaolin	AM system	-	CMC	1350 for 3 hours	>20	58.5	22.44-24.27	45
Al_2O_3 and Mg O	Deionized water as hydrating agent	-	-	1600 for 4 hour	1-3	52.5-65.8	12-28	31
Al N (55%)	ovalbumin	-	Tetra ethoxy silane	1600 for 6 hours	-	17-40	3 MPa	28
Si C (47.5-57.5%)	PVA		Ammonium PAA	1900 for 6 hours	-	59.6-97.6	45	34
SiC-Al_2O_3	AM system	-	PEG	1100 for 2 hours	0.0015-0.002	60.2-65.1	8.3-10.5	90
Al_2O_3 and Y_2O_3	DMAA as monomer and MBAM as cross linker	-	-	1780	-	36.34-52.91	258.42	60
Si_3N_4 (28–44%)	DMAA			1780	0.33-0.38	54.21-41.05	110.36–367.88	30
Si_3N_4 (36 or 38%)	triethanol amine lauryl sulfate	ISOBAM	CMC	1373K	-	68.9	20.8 ± 0.5	91
Al_2O_3 (30-50%)	PS as sacrificial template and AM system	-	Ethyl alcohol	1400-1650	20-796	60-70	3.7-24.4	72

β–Si3N4	DMAA	-	-	1300	0.43–1.04	41.77	378.5	73
Si3N4 (60%)	HEMA	PEG	PEI	1700	23.4	-	10.91-22.08	75
Al_2O_3 and SiO_2 (15%)	DMMA	-	Ammonium polyacrylate	1300	-	83.9-89.2	0.9-4.7	92
Silicon kerf waste (50-65%)	AM system	-	-	1350	-	25.4-84.1	3.6-20.54	79
$CaCO_3$-Al_2O_3	-	Pectin	-	1550 for 3 hours	-	66.4-75.1	0.71-2.06	93

Based on the result analysis of the research on porous ceramic fabrication using the gel casting method for the last 5 years, it can be concluded that gelling agents are not required in the AM system, as well as dispersants are only used if the raw material is in the form of natural minerals such as kaolin and clay. The selection of additives in the gel casting method for the fabrication of porous ceramics is made in a mapping shown in Fig.-3.

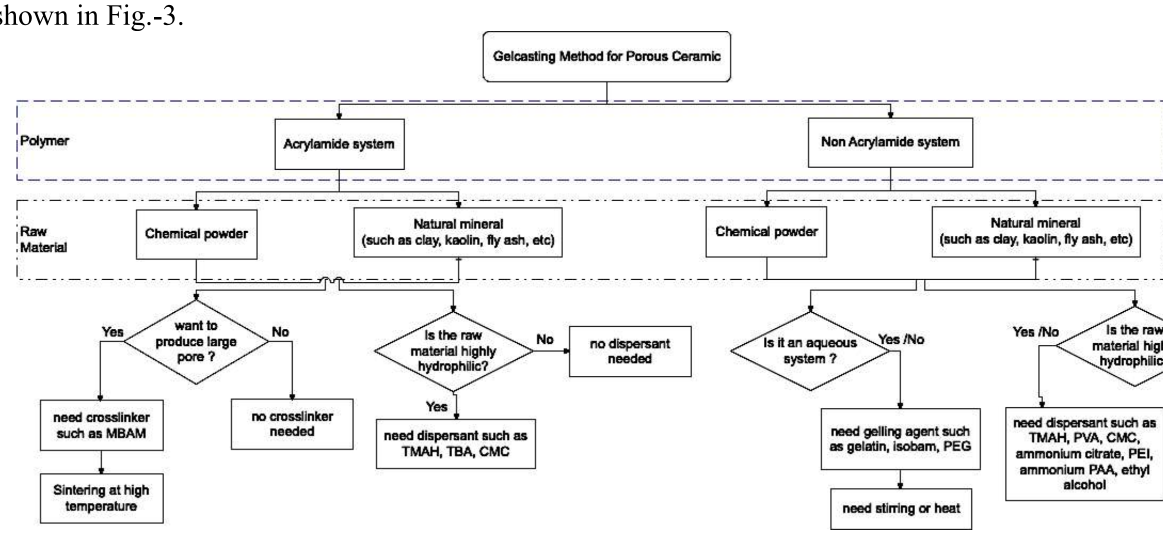

Fig.-3: Mapping of the Additive's Selection in the Gel casting Method for the Manufacture of Porous Ceramics

Application of Porous Ceramic

Porous ceramics are convenient filtration components in various applications. The porous ceramics are formulated to detach contaminants range from micrometer to nanometer on a wide variety of liquids.[92,93] Recently being developed porous ceramics are light but heavy in energy and environmental technology.[84] This method makes use of the intrinsic material's properties as well as the binder's porous configuration. It's important to note that there are four main fabrication methods for porous ceramic applications: partial sintering, template replication, sacrificial template, and direct foaming, as well as additive manufacturing techniques, which have emerged as a promising method for making porous ceramic components directly. Several methods have its own set of characteristics, such as porosity, pore size, pore connectivity, and pore dispersion. The results of research conducted before, exhibited the porosity ranged from 2.3% to 99%, and the pore size distribution within 3 nm until 3 mm showed large specific surface area, low density, strong thermal shock resistance, remarkable toughness, exceptional thermal insulation ability, excellent height, temperature stability, and low dielectric constant, which metals, polymers, and even their solid partners rarely offer.[84] Porous ceramics playing a part in the development of sustainable energy and future environmental applications due to its unique feature set. The most significant stages in successfully implementing this technology in this application are the selection of the proper type of ceramic, and the manufacturing of intricate structural features of the pores, both of them necessitate extensive research and understanding. The synthesis process is necessary for certain ceramics to acquire the correct pore structure and geometry, which determines the final product qualities, such as ordinary mechanical properties and additional advanced functionality. Ultra-high temperature ceramics are also important in the application of porous ceramics, these properties can already be produced by using the foam gel casting-freeze drying method.[85] Great potential of attractive porous ceramics for environmental and energy applications,[84] filter,[55] support catalyst,[85,86,87] energy conversion components,[88] harvesting devices for energy and insulators[89] are highlighted, related to the criteria and demand for manufacturing. Some applications of gel casting porous ceramics and other colloidal methods in the last 5 years are shown in Table-2.

Table-2: The Application of Porous Ceramics

Major raw material(s)	Pore former	Sintering temperature (ºC)	Pore size (μm)	Porosity (%)	Mechanical strength (MPa)	Synthesis Method	Application	Reference
Hydroxyapatite	AM system	1200	15,43-34.76	58.48-82.63	-	Gel casting	Drug delivery	94
Diatomite minerals	triethanolamine lauryl sulphate	1100-1250	109-130.5	82.9-84.5	1.1 ± 0.07 MPa	Gel casting	thermal insulation materials	95
SiC	DMAA system	1750	-	1.25-21.85	115.66–220.50 MPa	Gel casting	EMW absorption	23
$Y_2Si_2O_7$	Ammonium citrat	1550	-	92.95	1.35	Gel casting	thermal insulation materials	89
Kaolin, fly ash, and dolomite	Natrium metasilicate	1000	0.62	46.3	49.4	Gel casting	Membrane for microfiltration	47
Al_2O_3	Sulphate salt	1600	65.80-368.38	87.65-95.71	62.4-384.31	Direct foaming	Bone scaffold	96
Al_2O_3	PVA	1200		28.96-35.34		Dip coating	Combustion analyzer	97
Al_2O_3 and natural diatomite	Methyl cellulose	1200	7.7	46	28	extrusion	membrane application, for instance, water filtration.	55
Quartz and calcite	$CaCO_3$	1375-1400	3-12	42-55	8-18	Extrusion	Membrane technology	58
SiC	PMMA	700	80	60	-	Dry pressing	Catalyst support on hydrogen production	98
Ni powder containing aluminum and cobalt oxide	-	800	1-3	40-60	15	Thermal explosion	Membrane catalytic converters	99
Natural zeolite and clay	Natural starch	900	-	31.09-53.29	-	Traditional method	Membrane for microfiltration	50
Al_2O_3	styrene	1300-1450	1-3	50	30-90	Traditional method	Ethylbenzene dehydrogenation catalytic converter	100

Natural clay	Cassava starch	1100	0.21-0.23	-	-	Gel casting	Catalyst support on phenol photodegradation	101

CONCLUSION

Based on the data obtained from reviewing several research in recent years, it is concluded that the gel casting method can be utilized for the synthesis of porous ceramics. At the beginning of the development gel casting method, the AM system was the common utilized system, however, over the time, the use of AM system began to be minimized because of its toxic nature. Researchers began to develop the use of natural polymers as pore templates in the gel casting method, and natural mineral as raw materials. There are several new gel casting methods, such as water-based gel casting without the use of additives and the use of deionized water as a gelling agent. The use of additives in the AM system and the non-AM system is different but produces almost the same characteristics. Porous ceramic applications have been used as bone tissue supports, energy storage, filters, and catalyst support.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest existed.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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REFERENCES

1. Q. Shang, Z. Wang, J. Li, G. Zhou, H. Zhang, and S. Wang, *Journal of Advanced Ceramics*, **6(1)**, 67(2017), https://doi.org/10.1007/s40145-016-0211-3
2. R. K. Nishihora, P. L. Rachadel, M. G. N. Quadri, and D. Hotza, *Journal of the Euopean Ceramic Society*, **38(4)**, 988(2018), https://doi.org/10.1016/j.jeurceramsoc.2017.11.047
3. H. De Teng, Q. Wei, Y. L. Wang, S. P. Cui, Q. Y. Li, and Z. R. Nie, *Ceramics International*, **46(15)**, 23677–23685(2020), https://doi.org/10.1016/j.ceramint.2020.06.141
4. D. Hotza, R. K. Nishihora, R. A. F. Machado, P. Geffroy, T. Chartier, and S. Bernard, *International Journal of Ceramic Engineering & Science*, **1(1)**, 21(2019), https://doi.org/10.1002/ces2.10009
5. Z. Pan, J. Guo, S. Li, X. Li, and H. Zhang, *Ceramics International*, **47(19)**, 27453(2021), https://doi.org/10.1016/j.ceramint.2021.06.168

6. S. Carstens, C. Splith, and D. Enke, *Scientific Reports*, **9(1)**, 1(2019), https://doi.org/10.1038/s41598-019-56294-1
7. E. K. Papynov, Shichalin, O. O., Mayorov, V. Yu, Modin, E. B., Portnyagin, A. S., Gridasova, E. A., Agafonova, I. G., Zakirova, A. E., Tananaev, I. G., Avramenko, V. A., *Ceramics International*, **43(11)**, 8509(2017), http://dx.doi.org/10.1016/j.ceramint.2017.03.207
8. A. Barmeh, M. R. Nilforoushan, and S. Otroj, *Journal of the Australian Ceramic Society*, **55(4)**, 1091(2019), https://doi.org/10.1007/s41779-019-00322-w
9. J. B. S. Hamm, A. Ambrosi, L. D. Pollo, N. R. Marcilio, and I. C. Tessaro, *Materials Chemistry and Physics*, **265**, 124511(2021), https://doi.org/10.1016/j.matchemphys.2021.124511
10. V. K. Rastogi, J. Bo, Sturzenegger, Philip N., Gonzenbach, Urs T. Vetterli, Marc Blugan, Gurdial Kuebler, Jakob, *Ceramics International*, **45(17)**, 21887(2019), https://doi.org/10.1016/j.ceramint.2019.07.199
11. H. Le Ferrand, *Journal of the European Ceramic Society*, **41(1)**, 24(2021), https://doi.org/10.1016/j.jeurceramsoc.2020.08.030
12. X. Li, Liu C., Sun B., Liu X., Zuo Z., Shu Y., Zeng X., Yi J., Chen H., Liu Y., He J., *Journal of the European Ceramic Society*, **41(6)**, 3501(2021), https://doi.org/10.1016/j.jeurceramsoc.2021.01.007
13. M. F. Bianchi, A. A. Gameros, D. A. Axinte, S. Lowth, A. M. Cendrowicz, and S. T. Welch, *Journal of Manufacturing Process*, **68**, 1767(2021), https://doi.org/10.1016/j.jmapro.2021.06.069
14. E. Tabares, S. C. Cifuentes, A. Jiménez-Morales, and S. A. Tsipas, *Powder Technology*, **380**, 96(2021), https://doi.org/10.1016/j.powtec.2020.11.022
15. R. Yavari and H. Khorsand, *Journal of European Ceramic Society*, **41(14)**, 6915(2021), https://doi.org/10.1016/j.jeurceramsoc.2021.07.050
16. T. An, K. T. Hwang, J. H. Kim, and J. Kim, *Ceramics International*, **46(5)**, 6469(2020), https://doi.org/10.1016/j.ceramint.2019.11.127
17. P. Fan, K. Zhen, Z. Zan, Z. Chao, Z. Jian, and J. Yun, *Chemical Engineering Transactions*, **55**, 77(2016), https://doi.org/10.3303/CET1655047
18. D. Liang, J. Huang, H. Zhang, H. Fu, Y. Zhang, and H. Chen, *Ceramics International*, **47(8)**, 10464(2021), https://doi.org/10.1016/j.ceramint.2020.12.235
19. S. E. Putri, D. E. Pratiwi, R. T. Tjahjanto, D. Mardiana, and Subaer, *Journal of Chemical Technology and Metallurgy*, **53(5)**, 841(2018)
20. S. E. Putri and D. E. Pratiwi, In Proceeding International Conference on Mathematic, Science, Technology, Education and their Applications, Makassar, Indonesia, pp. 412(2016).
21. C. Tian, X. Huang, W. Guo, P. Gao, and H. Xiao, *Ceramics International*, **46(10)**, 16047(2020), https://doi.org/10.1016/j.ceramint.2020.03.155
22. Q. Yao, Zhang L., Chen H., Gao P., Shao C., Xi X., Lin L., Li H., Chen Y., and Chen L., *Ceramics International*, **47(3)**, 4327(2021), https://doi.org/10.1016/j.ceramint.2020.09.266
23. S. Yin, L. Pan, X. Fang, Y. Wang, and J. Yang, *Journal of Alloys and Compound*, **889**, 161724(2022), https://doi.org/10.1016/j.jallcom.2021.161724
24. Z. Lu, K. Miao, W. Zhu, Y. Chen, Y. Xia, and D. Li, *Journal of the European Ceramic Society*, **38(2)**, 671(2018), https://doi.org/10.1016/j.jeurceramsoc.2017.08.002
25. O. O. Omatete, M. A. Janney, and S. D. Nunn, *Journal of the European Ceramic Society*, **17(2-3)**, 407(1997), https://doi.org/10.1016/S0955-2219(96)00147-1
26. M. A. Janney, O. O. Omatete, C. A. Walls, S. D. Nunn, R. J. Ogle, and G. Westmoreland, *Journal of the American Ceramic Society*, 81(3), 581(1998), https://doi.org/10.1111/j.1151-2916.1998.tb02377.x
27. L. Montanaro, B. Coppola, P. Palmero, and J. M. Tulliani, *Ceramics International*, **45(7)**, 9653(2019), https://doi.org/10.1016/j.ceramint.2018.12.079
28. W. H. Kok, W. K. C. Yung, and D. T. C. Ang, *Journal of the Australian Ceramic Society*, **55(1)**, 169(2019), https://doi.org/10.1007/s41779-018-0222-3
29. A. C. Young, O. O. Omatete, M. A. Janney, and P. A. Menchhofer, *Journal of the American Ceramic Society*, **74(3)**, 612(1991), https://doi.org/10.1111/j.1151-2916.1991.tb04068.x
30. S. Yin, L. Pan, K. Huang, T. Qiu, and J. Yang, *Journal of Alloys and Compounds*, **805**, 69(2019), https://doi.org/10.1016/j.jallcom.2019.07.018

31. L. Yuan, Z. Liu, X. He, B. Ma, Q. Zhu, and J. Yu, *Materials*, **10(12)**, 1(2017), https://doi.org/10.3390/ma10121376
32. S. Hooshmand, J. Nordin, and F. Akhtar, *International Journal of Ceramic Engineering & Science*, **1(2)**, 77(2019), https://doi.org/10.1002/ces2.10013
33. F. Wang, J. Yin, D. Yao, Y. Xia, K. Zuo, J. Xu, Y. Zeng, *Materials Science and Engineering: A*, **654**, 292(2016), https://doi.org/10.1016/j.msea.2015.12.061
34. T. Tu and G. Jiang, *Ceramics International*, **44(3)**, 3400(2018), https://doi.org/10.1016/j.ceramint.2017.11.133
35. D. C. Jana, G. Sundararajan, and K. Chattopadhyay, *Ceramics International*, **43(6)**, 4852(2017), https://doi.org/10.1016/j.ceramint.2016.12.117
36. A. Parsi, F. Golestani-Fard, and S. M. Mirkazemi, *Ceramics International*, **45(8)**, 9719(2019), https://doi.org/10.1016/j.ceramint.2019.01.222
37. K. Liu, C. Zhou, F. Chen, H. Sun, and K. Zhang, *Ceramics International*, **46(16)**, 25220(2020), https://doi.org/10.1016/j.ceramint.2020.06.313
38. Y. F. Liu, X. Q. Liu, H. Wei, and G. Y. Meng, *Ceramics International*, **27(1)**, 1(2001), https://doi.org/10.1016/S0272-8842(00)00034-1
39. S. Dhara, R. K. Kamboj, M. Pradhan, and P. Bhargava, *Bulletin of Materials Science*, **25(6)**, 565(2002), https://doi.org/10.1007/BF02710552
40. L. M. Rodríguez-Lorenzo and J. M. F. Ferreira, *Materials Research Bulletin*, **39(1)**, 83(2004), https://doi.org/10.1016/j.materresbull.2003.09.014
41. P. Bednarek and M. Szafran, *Journal of Thermal Analysis and Calorimetry*, **109(2)**, 773(2012), https://doi.org/10.1007/s10973-012-2411-6
42. Z. Nie and Y. Lin, *Ceramics Silikaty*, **50(4)**, 348(2015)
43. W. Wan, C. E. Huang, J. Yang, and T. Qiu, *International Journal of Applied Glass Science*, **5(4)**, 401(2014), https://doi.org/10.1111/ijag.12060
44. Y. Shao, F. Yang, Q. Qin, Y. Zhou, C. Chen, P. Liu, X. He, and Z. Guo, *Materials Today Communication*, **25(8)**, 101533(2020), https://doi.org/10.1016/j.mtcomm.2020.101533
45. Y. Sun, J. Zhang, S. Lu, and H. Liu, *Advances in Applied Ceramics*, **116(7)**, 362(2017) https://dx.doi.org/10.1080/17436753.2017.1329122
46. D. O. Obada, D. Dodoo-Arhin, M. Dauda, F. O. Anafi, A. S. Ahmed, and O. A. Ajayi, *Applied Clay Science*, **132–133**, 194(2016), http://dx.doi.org/10.1016/j.clay.2016.06.006 0169-1317
47. N. Malik, V. K. Bulasara, and S. Basu, *Ceramics International*, **46(5)**, 2020. https://doi.org/10.1016/j.ceramint.2019.11.184
48. S. Diana, R. Fauzan, N. Arahman, F. Razi, and M. R. Bilad, *Rasayan Journal of Chemistry*, **13(3)**, 1335(2020), https://doi.org/10.31788/RJC.2020.1335707
49. M. Messaoudi, N. Tijani, S. Baya, A. Lahnafi, H. Ouallal, H. Moussout, and L. Messaoudi, *South African Journal of Chemical Engineering*, **37(1)**, 1(2021), https://doi.org/10.1016/j.sajce.2021.03.004
50. A. Ma'Ruf and M. A. S. Al Fathoni, In Proceeding of International Conference on Engineering and Applied Technology, Mataram, Indonesia, **403(1)**, (2018), https://doi.org/10.1088/1757-899X/403/1/012006
51. Y. Rakhila, A. Mestari, S. Azmi, and A. Elmchaouri, *Rasayan Journal of Chemistry*, **11(4)**, 1552(2018), https://doi.org/10.31788/RJC.2018.1144025
52. K. M. Reddy and B. P. Saha, *Journal of Alloys and Compounds*, **779**, 590(2019), https://doi.org/10.1016/j.jallcom.2018.11.277
53. Y. Jin, Zhang B., Ye F., Zhang H., Zhong Z., Liu Q., Zhang Z., *Ceramics International*, **46(6)**, 7896(2020), https://doi.org/10.1016/j.ceramint.2019.12.009
54. P. Gao, Zhang L.,Yao Q., Shao C., Wei S., Zhou T., Chen H., Yang H., *Ceramics International,* **46(2)**, 2365(2020), https://doi.org/10.1016/j.ceramint.2019.09.227
55. F. Aouadja, F. Bouzerara, C. M. Guvenc, and M. M. Demir**,** *Boletín de la Sociedad Española de Cerámica y Vidrio*, (2020), 1(2021)**,** https://doi.org/10.1016/j.bsecv.2021.04.002
56. G. Ma, L. Xia, T. Zhang, B. Zhong, H. Yang, L. Xiong, L. Huang, X. Huang, and G. Wen, *Journal of the European Ceramic Society*, **40(9)**, 3462(2020), https://doi.org/10.1016/j.jeurceramsoc.2020.03.056

57. L. Lv, Y. Lu, X. Zhang, Y. Chen, W. Huo, W. Liu, and J. Yang, *Ceramics International*, **45(9)**, 11654(2019), https://doi.org/10.1016/j.ceramint.2019.03.039
58. N. Kouras, A. Harabi, F. Bouzerara, L. Foughali, A. Policicchio, S. Stelitano, F. Galiano, and A. Figoli, *Journal of the European Ceramic Society*, **37(9)**, 3159(2017), https://doi.org/10.1016/j.jeurceramsoc.2017.03.059
59. J. Seuba, S. Deville, C. Guizard, and A. J. Stevenson, *Scientific Reports*, **6(4)**, 1(2016), https://doi.org/10.1038/srep24326
60. S. Yin, L. Guo, L. Pan, S. Yan, H. Qiao, S. Zhang, J. Tang, H. Min, T. Qiu, W. Wan, and J. Yang, *Journal of Alloys and Compounds*, **819**, 152982(2020), https://doi.org/10.1016/j.jallcom.2019.152982
61. S. Yin, S. Jiang, L. Pan, L. Guo, Z. Zhang, J. Zhang, X. Li, T. Qiu, and J. Yang, *Ceramics International*, **45(16)**, 19925(2019), https://doi.org/10.1016/j.ceramint.2019.06.250
62. Z. Yang, N. Chen, and X. Qin, *Materials (Basel)*, **11(9)**, (2018), https://doi.org/10.3390/ma11091784
63. R. Yin *et al.*, *Journal of the European Ceramic Society*, **36(10)**, 2543(2016), https://doi.org/10.1016/j.jeurceramsoc.2016.03.013
64. Q. Yao, L. Zhang, Z. Jiang, G. Huang, T. Zhou, Y. Ben, S. Wei, R. Sun, H. Chen, and Y. Wang, *Ceramics International*, **44(2)**, 1699(2018), https://doi.org/10.1016/j.ceramint.2017.10.098
65. K. M. McDevitt, T. J. Thorson, E. L. Botvinick, D. R. Mumm, and A. Mohraz, *Materialia*, **7(5)**, 100393(2019), https://doi.org/10.1016/j.mtla.2019.100393
66. A. Chaubey, P. Konda Gokuldoss, Z. Wang, S. Scudino, N. Mukhopadhyay, and J. Eckert, *Technologies*, **4(4)**, 37(2016), https://doi.org/10.3390/technologies4040037
67. Z. Wu, Z. Zhou, and Y. Hong, *Journal of the European Ceramic Society*, **39(2-3)**, 547(2019), https://doi.org/10.1016/j.jeurceramsoc.2018.08.042
68. M. M. Hoog Antink, S. Beutel, K. Rezwan, and M. Maas, *Materialia*, **12**, 100735(2020), https://doi.org/10.1016/j.mtla.2020.100735
69. Z. Zhao, X. Li, X. Zeng, X. Zhang, and Q. Yan, *Journal of the European Ceramic Society*, **40(8)**, 2878, 2020, https://doi.org/10.1016/j.jeurceramsoc.2020.02.028
70. J. M. Wu, Y. X. Ma, Y. Chen, L. J. Cheng, A. N. Chen, R. Z. Liu, C. H. Li, Y. S. Shi, and J. P. Lin, *Ceramics International*, **45(16)**, 20961(2019), https://doi.org/10.1016/j.ceramint.2019.06.211
71. N. S. Yüzbasi and T. Graule, *Encyclopedia of Materials: Technical Ceramics and Glasses*, 146(2021), https://doi.org/10.1016/B978-0-12-803581-8.11767-9
72. M. Zhang, X. Li, Z. Xiu, J.G. Li, J. Li, M. Xie, and X. Sun, *Journal of Materials Science*, **54(14)**, 10119(2019), https://doi.org/10.1007/s10853-019-03576-8
73. S. Yin, L. Pan, Y. Liu, Y. Wang, T. Qiu, and J. Yang, *Ceramics International*, **46(4)**, 4924(2020), https://doi.org/10.1016/j.ceramint.2019.10.229
74. X. Feng, Wang, Y. Zhou Xie, C. Qun Peng, R. Chu Wang, D. Zhang, and Y. Feng, *Transactions of Nonferrous Metals Society of China*, **29(8)**, 1714(2019), https://doi.org/10.1016/S1003-6326(19)65078-8
75. Y. Wu, K. Xu, R. Yin, J. Li, and R. Xue, *Ceramics International*, **46(16)**, 25236(2020), https://doi.org/10.1016/j.ceramint.2020.06.315
76. Z. Wu, L. Sun, P. Wan, and J. Wang, *Ceramics International*, **41(10)**, 14230(2015), https://doi.org/10.1016/j.ceramint.2015.07.051
77. L. N. R. de M. Santos, J. de M. Cartaxo, J. R. S. Silva, A. M. Rodrigues, E. L. de A. Dantas, F. B. de Sousa, G. de A. Neves, and R. R. Menezes, *Journal of the European Ceramic Society*, **41(14)**, 7111(2021), https://doi.org/10.1016/j.jeurceramsoc.2021.07.060
78. Y. Lu, J. Liu, B. Ren, C. Wang, Y. Rong, K. Gan, J. Xu, and J. L. Yang, *Ceramics International*, **46(8)**, 11432(2020), https://doi.org/10.1016/j.ceramint.2020.01.119
79. Y. Han, L. Zhou, Y. Liang, Z. Li, and Y. Zhu, *Materials Chemistry and Physics*, **240(10)**, 122248(2020), https://doi.org/10.1016/j.matchemphys.2019.122248
80. B. Psiuk, A. Gerle, M. Osadnik, and A. Śliwa, *Advance in Materials Science and Engineering*, **20(17)**, (2017), https://doi.org/10.1155/2017/5923976

81. L. Han, Y. Chen, H. Chang, F. Li, C. Liu, T. Shyng, Y. Zhu, G. Li, H. Zhang, Q. Jia, and S. Zhang, *Journal of the European Ceramic Society*, **41(12)**, 6070(2021), https://doi.org/10.1016/j.jeurceramsoc.2021.05.016
82. S. Gopi, A. Pius, and S. Thomas, *Ceramics Materials,* (2018), https://doi.org/10.5772/17111
83. K. K. Kandi, N. Thallapalli, M. S. Kumar, and C. S. P. Raod, *Materials Today Proceeding*, **18**, 2298(2019), https://doi.org/10.1016/j.matpr.2019.07.012
84. Y. Chen, N. Wang, O. Ola, Y. Xia, and Y. Zhu, *Materials Science and Engineering: R: Reports*, **143(8)**, 100589(2021), https://doi.org/10.1016/j.mser.2020.100589
85. Z. Wu, X. Liang, Z. Shao, H. Chen, J. Li, and J. Wang, *Materialia*, **18(7)**, 101158(2021), https://doi.org/10.1016/j.mtla.2021.101158
86. A. G. Dedov, Y. Z. Voloshin, A. S. Belov, A. S. Loktev, A. S. Bespalov, and V. M. Buznik, *Mendeleev Communications*, **29(6)**, 669(2019), https://doi.org/10.1016/j.mencom.2019.11.022
87. Morin, Jacson Victor, Endang Tri Wahyuni, Adhitasari Suratman, and Ahmad Ashari, *Rasayan Journal of Chemistry,* **13(2)**, 1225(2020), http://dx.doi.org/10.31788/RJC.2020.1325720
88. L. Miao X. Wu, Z. Ji, Z. Zhao, C. Chang, Z. Liu, and F. Chen, *Separation and Purification Technology*, **278(8)**, 119549(2022), https://doi.org/10.1016/j.seppur.2021.119549
89. Z. Wu, L. Sun, J. Pan, and J. Wang, *Scripta Materialia*, **146**, 331(2018), https://doi.org/10.1016/j.scriptamat.2017.12.017
90. L. Wan, Q. Tian, Y. Xiang, L. Chen, J. Song, X. Wang, and X. Guo, *Ceramics International*, **45(5)**, 5511(2019), https://doi.org/10.1016/j.ceramint.2018.12.008
91. L. Han, F. Li, L. Huang, H. Zhang, Y. Pei, L. Dong, J. Zhang, and S. Zha, *Ceramics International*, **44(15)**, 17675(2018), https://doi.org/10.1016/j.ceramint.2018.06.231
92. H. Li, C. Li, and L. Wu, *Journal of Alloys and Compounds*, **791**, 690(2019), https://doi.org/10.1016/j.jallcom.2019.03.225
93. L. Yuan, E. Jin, C. Li, Z. Liu, C. Tian, B. Ma, and J. Yu, *Ceramics International*, **47(7)**, 9017(2021), https://doi.org/10.1016/j.ceramint.2020.12.024
94. D. J. A. Netz, P. Sepulveda, V. C. Pandolfelli, A. C. C. Spadaro, J. B. Alencastre, M. V. L. B. Bentley, and Marchetti, *International Journal of Pharmaceutics*, **213(1–2)**, 117(2001), https://doi.org/10.1016/S0378-5173(00)00659-1
95. L. Han, F. Li, X. Deng, J. Wang, H. Zhang, and S. Zhang, *Journal of the European Ceramic Society*, **37(7)**, 2717(2017), https://doi.org/10.1016/j.jeurceramsoc.2017.02.032
96. E. Soh, E. Kolos, and A. J. Ruys, *Ceramics International*, **41(1)**, 1031(2015), https://doi.org/10.1016/j.ceramint.2014.09.026
97. A. K. Ismail, M. Z. Abdullah, M. Zubair, A. R. Jamaludin, and Z. A. Ahmad, *Journal of Energy Institute*, **89(1)**, 81(2016), https://doi.org/10.1016/j.joei.2015.01.008
98. M. Liao, C. Guo, W. Guo, T. Hu, H. Qin, P. Gao, and H. Xiao, *International Journal of Hydrogen Energy*, **45(41)**, 20922(2020), https://doi.org/10.1016/j.ijhydene.2020.05.244
99. M. V. Tsodikov, A. S. Fedotov, D. O. Antonov, V. I. Uvarov, V. Y. Bychkov, and F. C. Luck, *International Journal of Hydrogen Energy*, **41(4),** 2424(2016), https://doi.org/10.1016/j.ijhydene.2015.11.113
100. S. Fedotov, V. I. Uvarov, M. V. Tsodikov, S. Paul,P. Simon, M. Marinova, and F. Dumeignil, *Chemical Engineering and Processing - Process Intensification*, **160**, 108265(2021), https://doi.org/10.1016/j.cep.2020.108265
101. S.E. Putri, D.E. Pratiwi, R.T. Tjahjanto, Hasri, A. Irhamsyah, A. Rahman, A.I.W.S. Ramadani, A.N. Ramadhani, Subaer, A. Fudholi, *International Journal of Design & Nature and Ecodynamics*, **17**, 503(2022), https://doi.org/10.18280/ijdne.170403

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