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Role of Surface-Chemistry in Colloidal Processing of Ceramics: A Review

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Abstract Colloidal processing of ceramics has gained significant attention in recent years owing to its widespread application in biomedical and various industrial sectors. Polymer-assisted colloidal synthesis offers additional advantages and possibilities for development of advanced ceramic materials. This review enumerates the ancient techniques for ceramic production, the factors influencing the surface chemistry in colloidal processing of ceramics, together with the description of the interparticle forces, such as electrostatic and van der Waals interaction, steric and depletion, that contribute majorly to surface chemistry involved in colloidal processing of ceramics. The literature pertaining to the surface chemical interactions of various ceramic materials with polymeric additives are surveyed. Finally, the developments underlying major advancements in colloidal processing of ceramic materials are highlighted.

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1 Introduction

The archaeological pottery portrays ceramic components as one of the oldest manufactured materials [1]. Pottery artefacts were discovered at various archaeological sites worldwide, providing insights into the early stages of ceramic production. Over the centuries, ceramic technology has advanced with improvements in kiln design, glazing techniques, and the discovery of new clay types. Ceramic production expanded beyond pottery to include the manufacturing of tiles, bricks, figurines, sculptures, and other functional and artistic objects [2]. Hitherto, the typical system used to create ceramic materials was dry grinding of compacts [3]. Due to dry pressing, inhomogeneous densification could be observed that resulted in decreasing the strength and stability of the material [4]. For the manufacture of low-tech parts, dry pressing promised to be a novel approach, however, for applications that required high consistent quality ceramics, this approach proved to be disadvantageous. This is because of major reasons including: (1) de-agglomeration of dry powder or removal of defects present in the powder at the time of manufacturing was difficult, and (2) to achieve prior manufactured products, shape restrictions and disproportionate machining hindered the processing and also made it uneconomical for production of complex ceramic structures. Subsequently, dry pressing paved the way for colloidal synthesis techniques to create more meaningful shapes for widespread applications and extending their scope for both thick and penetrable ceramic creation [5]. The term "colloid" refers to the particles possessing one-dimensional size ranging from 10^{-3} to 1 μm. All colloidal systems have a distinctive property showing large contact area between dispersion medium and the particles [6]. Colloidal synthesis enables the integration of different components or dopants into the ceramic matrix, leading to

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the development of composite or multifunctional materials. These systems combine the properties of different materials to achieve enhanced performance or new functionalities through regulation of basic suspension "structure" and its progression during formation [7–12].

The major strength and reliability of ceramic materials is attained by inter-particle forces that control isolation and elimination of agglomerates and defects during colloidal processing [13]. Polymer-assisted colloidal synthesis offers advantages such as the ability to control the morphology, porosity, and structure of the final ceramic material. It allows for the fabrication of complex and tailored ceramic structures. The use of polymers as templates or precursors also enables the synthesis of ceramic composites and hierarchical structures [14, 15]. The advancements in the field of ceramic material production have expanded their application in contemporary life including their usage in electronic components, aerospace, automobile, medical equipment, industrial applications and chemical processing [16].

The main focus of this paper is to review the surface chemistry involved in the colloidal processing of ceramics. The review is divided into various sections beginning with a brief history of ancient techniques adopted for the manufacture of ceramics. This is followed by a description of the factors influencing surface chemistry of ceramic materials with polymeric additives. Additionally, various inter-particle forces, such as van der Waals, electrostatic, and steric controls governing colloidal processing in the presence of polymers and electrolytes, are discussed. The surface-chemical interactions of ceramic materials with polymeric additives and surfactants are enumerated. Finally, developments and applications underlying the importance of surface-chemistry in colloidal synthesis for production of bio-ceramics, adoption of additive manufacturing techniques and molecular modelling tools as sustainable strategies for ceramic production are highlighted.

2 Historical Perspective

The origins of ceramic processing using colloidal science can be traced to the ancient manufacturing of earthenware products exploiting the plasticity of clays. The clay particles dispersed in water were the first colloidal dispersion employed by humans, but without a clear comprehension of the process. [17]. Intercalation of water between clay particles allowed formation of a double-layer-like force that helped to maintain plasticity and also permitted it to deform on application of shear stress. Since centuries, this mixing of ceramics with water did not only serve as paste for pottery formation, but was also used for formation of slips for processes like slip casting. At the end of the eighteenth century,

slip casting was used for manufacturing a large number of clay products [18]. One of the notable milestones in the development of colloidal processing was the work of the Scottish scientist, Thomas Graham, referred to as the "father of colloid chemistry." In the mid-1800s, Graham conducted extensive studies on the diffusion of substances in solution and recognized the presence of particles dispersed in liquids, now known as colloids. His work laid the foundation for understanding colloidal phenomena and their significance in various applications since 1845 [19]. Following this, in 1909, Ashley applied the knowledge of colloid theory to describe the properties of clay [20]. Later during 1950s, suspension-based processes for manufacturing metal-ceramics (or cermets) were developed, though the real application only started after three decades. Ceramic materials gained popularity in the industrial sector in 1980s and 90 s after development of pure materials for production of advanced ceramics having high density. In a seminal paper, it was demonstrated for the first time that by adopting colloidal processing route, high-strength sintered alumina with 1.04 GPa bend strength could be obtained [21]. Eventually, colloidal processing played a crucial role in the manufacturing of advanced ceramics with a high degree of dependability [22].

3 Factors Influencing the Surface Chemistry of Ceramic Materials with Polymeric Additives

The surface chemistry of ceramic materials can be influenced by several factors when polymeric additives are introduced. The surface qualities of any polymer inevitably affect the properties of ceramics including wetting, bonding, contact, and biocompatibility. Some of the key factors that can impact the surface chemistry of ceramic materials with polymeric additives are highlighted below:

(a) *Polymer composition* The composition of the polymer additive can significantly affect the surface chemistry of ceramic materials [23]. Different polymers possess unique chemical properties, such as functional groups and molecular weight, which can interact differently with the ceramic surface [24]. The presence of specific functional groups can facilitate chemical bonding or interactions between the polymer and the ceramic material.

(b) *Polymer concentration* The concentration of the polymer additive plays a crucial role in surface chemistry. Higher concentrations of polymers can lead to increased polymer-ceramic interactions, resulting in modified surface properties [25]. Additionally, the concentration can influence the phase separation behaviour

of the polymer within the ceramic matrix, affecting the distribution of the polymer at the surface.

(c) *Polymer molecular weight* The molecular weight of the polymer additive can influence the surface chemistry of ceramics. Higher molecular weight polymers tend to exhibit stronger interactions with the ceramic surface due to increased chain entanglements and extended conformations. This can lead to enhanced adhesion and surface modification effects (Fig. 1) [26].

(d) *Polymer compatibility* The compatibility between the polymer and ceramic material is essential for achieving desired surface chemistry [27]. Compatibility ensures good wetting and spreading of the polymer on the ceramic surface, leading to improved adhesion and surface modification [28]. Incompatibility can result in phase separation or poor interactions, limiting the effectiveness of the polymer additive.

(e) *Processing conditions* The processing conditions during the incorporation of the polymer additive can affect the surface chemistry of ceramics [29]. Parameters such as temperature, pressure, and duration of processing can influence the degree of polymer-ceramic interaction and the formation of interfacial bonds [30]. Proper processing conditions are crucial to achieving desirable surface modifications.

(f) *Surface preparation* The surface preparation of the ceramic material before incorporating the polymer additive is critical. Cleaning, roughening, or function-alizing the surface can enhance the interaction between the polymer and ceramic surface, leading to improved adhesion and surface modification [31]. The surface roughness and chemistry play a role in determining the strength and stability of the polymer-ceramic interface.

(g) *Environmental factors* Environmental conditions, such as humidity, temperature, and exposure to chemicals, can affect the surface chemistry of ceramic materials with polymeric additives [32]. These factors can influence the stability, degradation, or reactivity of the polymer on the ceramic surface, potentially altering the surface properties over time.

It is important to note that the specific combination of ceramic material and polymeric additive, as well as the intended application, dictate the extent and nature of the surface chemistry modifications. Different ceramic systems and polymers exhibit unique interactions and behaviour, making it essential to consider these factors when designing and engineering ceramic materials with polymeric additives.

4 Forces Governing the Surface Chemistry in Colloidal Processing of Ceramics

Various surface chemical forces are involved in the colloidal processing of ceramics in the presence of polymeric additives. For efficient processing of these ceramic and polymeric additives, control of inter-particle attraction or repulsion, governed by Derjaguin–Landau–Verwey–Overbeek (DLVO) forces, is mostly studied [33] (Fig. 2).

i. Electrostatic forces:
   Colloidal particles often carry an electrical charge on their surface, which leads to electrostatic interactions between them. These forces arise due to the presence of ions in the solution or dissociation of functional groups on the particle surface. The magnitude of the electrostatic force decreases with increasing distance between the particles. A medium with high dielectric constant, like water, enables the substance to acquire a surface electric charge [34]. Stern or Helmholtz layer contains some of the immobile counter-ions rigidly bound to its surface [35]. A high electric field at the surface causes dissociated ions to induce repulsive interaction, whereas a stronger coulombic attraction is generated towards the surface [36]. As a result, dissociated ions and charged surface of particle form an electrical double layer [37]. On close proximity of two similar charged particles, an electrostatic repulsion occurs between two surfaces as the double layers overlap [38]. Thus, electrostatic stabilization prevents particles from agglomerating together [39]. The most
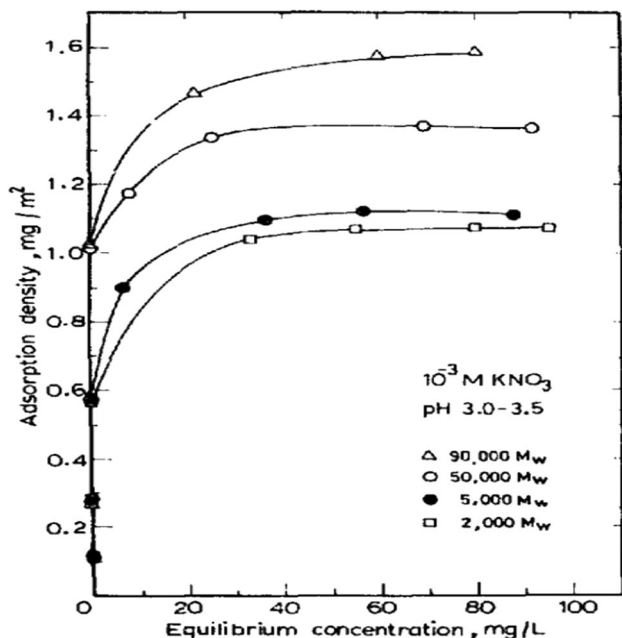

Fig. 1 Adsorption isotherms of polyacrylic acid of different molecular weights on alumina (Adapted from Santhiya et al., 1998 with permission)
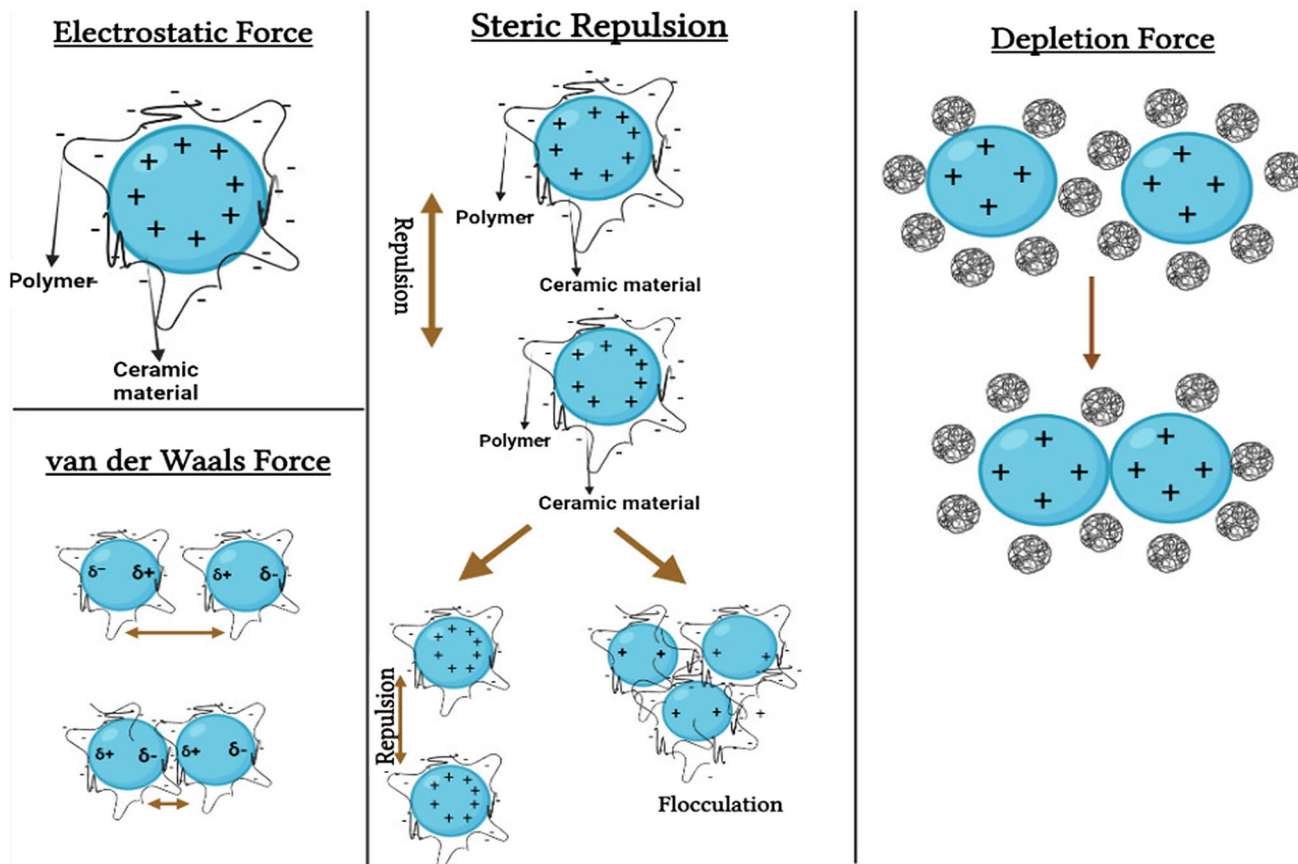
Fig. 2 Forces governing the surface-chemistry involved in colloidal processing of ceramics

common additives imparting electrostatic stabilization to colloidal suspensions are polyelectrolytes. Polyelectrolytes contain an ionizable group like sulfonic or carboxylic group, that blocks copolymers containing ionizable segments [40]. Investigations on alumina and zirconia suspensions as a function of pH showed that electrical double layer forces acted as regulators in determining the behaviour of suspensions. There was a significant difference in single and mixed suspensions with respect to pH. The DLVO theory was used to study the effect of electric double layer force on yield stress [41, 42].

ii. Van der Waals forces

Van der Waals forces are a type of intermolecular force that arise due to fluctuations in electron distributions. These forces include London dispersion forces, which arise from temporary fluctuations in electron density, and Keesom forces and Debye forces, which arise due to the orientation and induced polarization of dipoles [43]. Van der Waals forces are generally attractive and act over short distances. They become significant when particles are in close proximity to each other, even in the absence of an electrical charge. All

the ceramic materials are subjected to van der Waals attractive forces. The value of the Hamaker constant is an assessment of the magnitude of interaction between ceramic materials and polymeric additives [44]. A higher Hamaker constant indicates stronger van der Waals forces, suggesting a stronger interaction between the ceramic material and the polymeric additive. Conversely, a lower Hamaker constant suggests weaker interaction. By knowing the Hamaker constant of the ceramic material and the polymeric additive, researchers and engineers can assess the potential for adhesion, compatibility, or dispersion between these materials. This information can be crucial in various applications, such as composite materials, coatings, or adhesives, where the interaction between ceramics and polymers is of interest [45].

iii. Steric forces

Steric or entropic forces arise from the repulsion between particles due to the overlap of their surface layers [46]. These forces are influenced by the size, shape, and surface chemistry of the particles, as well as the presence of polymer chains or other molecules attached to the particle surface. Steric forces can pre-

vent particles from coming too close to each other and thus stabilize colloidal dispersions [47]. Therefore, short-range structure of densely packed colloidal particles can be determined by steric force [48]. The presence of steric forces has important implications for the short-range structure of densely packed colloidal particles. Due to the repulsive nature of steric forces, they can prevent or inhibit the formation of close-packed arrangements or aggregation of particles. Instead, the particles tend to arrange themselves in a more dispersed or loosely packed manner, forming structures, such as random close-packed or disordered arrangements [49]. Electrolyte concentration does not affect steric interactions between particles and is stable at low and high concentration of particles [50]. Longer and more densely packed polymer chains tend to provide stronger steric repulsion, effectively increasing the distance at which particles can approach each other before experiencing significant repulsion [34].

iv.   Depletion forces

The interaction between large colloidal particles suspended in continuous phase consisting of polymers, non-ionic surfactants, polyelectrolytes and small particles is termed as depletion interaction [51]. These forces arise from the entropic effects caused by the presence of non-adsorbing polymer molecules or large particles in the colloidal system. When non-adsorbing polymer molecules or large particles are added to a colloidal suspension, they can create an excluded volume effect. This effect leads to a decrease in the available volume for colloidal particles to move freely [52]. As a result, colloidal particles tend to aggregate or cluster together to minimize the entropic penalty associated with their restricted movement [53]. On increasing the free polymer concentration, the thickness of depletion layer decreases [54]. The depletion attraction occurs when the non-adsorbing polymers or particles create a region of lower particle density between them. This leads to an effective attraction between colloidal particles, causing them to come closer together. On the other hand, the depletion repulsion occurs when the non-adsorbing components create a region of higher particle density, resulting in an effective repulsion between colloidal particles [55]. On increasing the depletant concentration, non-adsorbing molecules induce depletion stabilization [56]. Electrostatically stabilized colloidal particle exhibits similar interaction as non-adsorbing polymer at large separation [57]. Demixing polymer segments from solvent results in repulsive interaction and inhibits particle aggregation thereby inducing depletion stabilization [58]. The flocculation of colloidal suspensions using population bal-

ance model has also been demonstrated for polymer bridging on ceramic suspensions [59].

5 Surface-Chemical Interactions of Ceramic Materials with Polymeric Additives

For providing excellent property to the formed ceramics, the combination of different constituents (microarchitectures) integrating ceramic and polymeric layers becomes essential [60]. Table 1 provides a brief overview of the most commonly used polymeric additives for ceramic materials. Different polyelectrolytes have been used with ceramic powders to study the electrokinetic and dispersion characteristics of ceramic suspensions [61]. Some examples of various ceramic systems are illustrated in this section.

5.1 Single Oxide Systems

Poly (acrylic acid) (PAA) and poly (vinyl alcohol) (PVA) were adsorbed onto alumina to study their surface-chemical interactions. On increasing the pH, the adsorption density of PAA decreased, while the opposite was observed for PVA (Fig. 3). High-affinity Langmuirian trend was observed for adsorption isotherm of PAA at acidic pH range, whereas it was low for PVA. After analysing the desorption studies, it was determined that around 80% PVA was desorbed in 3–9 pH range, whereas it was 70% for PAA in the pH range of 3–8. FTIR spectroscopic studies lent support for surface chemical interaction and hydrogen bonding mechanisms for PAA-alumina, compared to hydrogen bonding only for PVA-alumina system [63].

Spurred by the above study, Saravanan and Subramanian investigated the surface properties of zirconia suspension with widely used dispersants, ammonium poly(methacrylate) (APMA) and poly (ethylene glycol). In presence of APMA, adsorption density of PEG significantly reduced, however, the reverse was not true. Dispersion studies revealed that zirconia suspension was more stable in the presence of APMA, whereas no characteristic difference could be observed in the presence of PEG. Complexation of zirconium species with APMA was revealed by co-precipitation tests and FTIR spectral studies confirmed hydrogen bonding and complexation for APMA and hydrogen bonding alone for PEG, as the interaction mechanisms with zirconia [64].

Near-net shape alumina ceramics could be produced using the hydrolysis-induced hydrogel casting (GCHAS) technique [67]. Suspensions containing 50% solids yielded approximately 95% alumina forms of about 300 mm height and 130 mm diameter using GCHAS technique. Alumina was dispersed in an aqueous solution of methylene bisacrylamide and methacrylamide with polycarboxylic acid as a dispersing agent. The sintered (1600 °C, 2 h) mechanical

Table 1 Polymeric additives for ceramic materials

Name of polymer	Structure of polymer	References
Polyborosiloxanes		[62]
Polysiloxanes		[62]
Polyacrylic acid		[63]
Poly(methyl methacrylate)		[64]
Poly(Vinylidene fluoride) Hexafluoropropylene		[65]
Polycarbosilane		[62]
Polyethylene glycol		[64]
Polyvinyl alcohol		[66]

properties were essentially similar to those obtained by gel casting (GC), hydrolysis assisted (HAS) and normal dry pressing of lyophilized granules [67].

Slip casting was used to produce transparent alumina ceramics using three stabilization methods: (a) plasma treatment (b) electrostatic stabilization and (c) electrosteric stabilization [68]. Electrostatic stabilisation performed best in terms of all examined metrics (green body porosity and density, sintering temperatures, densities, and real in-line transmittance (RIT)). Plasma treatment produced similar outcomes, but exhibited low RIT, attributable to tiny cracks that reduced transparency. Despite having much bigger

pores, lower green density, and higher grain size, the standard electrosteric technique produced samples with higher transparency, compared to the plasma method [68].

5.2 Mixed Ceramic Oxide Systems

The surface chemical interactions using various polymeric additives was investigated in the presence of xanthan gum taking alumina and silica suspensions as ceramic materials [69]. In presence of xanthan gum, the adsorption maximum was observed at pH 2 for alumina, whereas no adsorption took place on silica. On increasing the xanthan gum
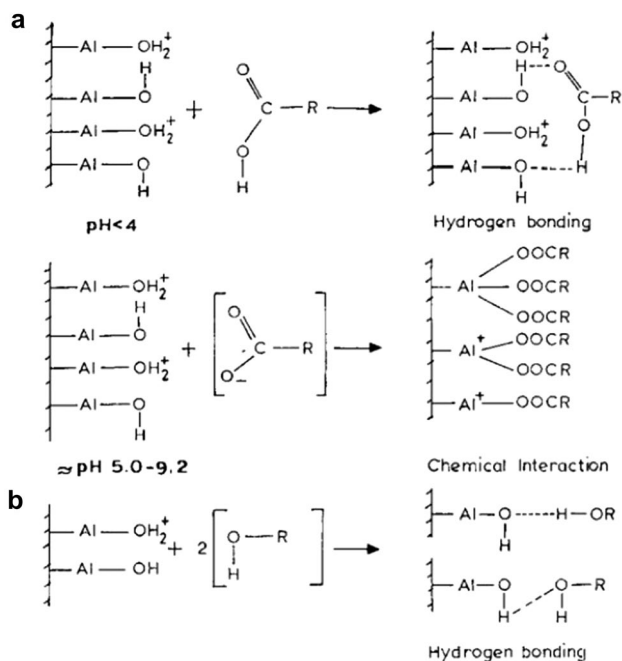
Fig. 3 Schematic representation of the interaction between **a** Alumina-PAA **b** Alumina-PVA (Adapted from Santhiya et al., 1999 with permission)

concentration, the isoelectric point of alumina shifted to the acidic pH range. Flocculation of alumina suspensions increased to approximately 92% on addition of xanthan gum beyond 50 ppm. However, silica suspension showed no observable effect on electrokinetic and flocculation property after xanthan gum addition [69].

Zirconia-alumina suspensions were used to study the effects of powder size, coverage, solid loading and dispersion during processing [70]. A tight packing size distribution alone was not enough for attaining high-density crude compacts and hence it was necessary to simultaneously control the suspension rheology while optimizing solid loading and dispersion dosage. Furthermore, it was emphasized that high green density did not guarantee the best sintering condition, especially if it was achieved by adding coarse powder [70]. A model to generate shear from a mixture of alumina–zirconia flocculated suspensions was developed, which could provide quantitative information on solids, composition, and particle size distribution for a better understanding of fine particles [71]. Clear macroporous ceramics composed of titania and zirconia were produced by two techniques, namely, by template-assisted colloid processing and the other by heterocoagulation. In both cases, consistent and uniform macropores were produced [72]. Yttria-stabilized tetragonal zirconia ceramic suspensions (Y-TZP) were investigated using colloid route to fabricate green bodies by slip casting [73]. The hardness (H) value of 17 and Young's modulus (E) of 250 GPa were obtained by nano-indentation. The samples were then subjected to low temperature degradation (LTD) treatment with conditions set at 130 °C, 240 h with 60-h increments. The Raman spectroscopy studies showed monoclinic phase in all samples with the Raman peaks centred at 180, 191, and 383 cm^{-1}, while nano-indentation after 240 h of LTD showed that H and E values were reduced to 10 and 175 GPa, respectively, indicating a significant reduction in mechanical properties [73]. Colloidal processing of tetragonal zirconia polycrystalline (Y-TZP) suspensions stabilized with yttria along with various dispersants resulted in highly transparent Y-TZP [74].

Zirconia-alumina composites ZTA-30 (70 Al_2O_3: 30 ZrO_2) and ZTA-60 (40 Al_2O_3: 60 ZrO_2) of utility in orthopaedic applications were prepared by colloidal processing and agglomerated by hydrolysis, slip and gel casting of ceramic mixtures containing 50% solids by volume [75]. For evaluation, the same ceramic composite was also stabilized with freeze-dried particle inlay (FG). Green (three-point bend) strengths (B 17 MPa) of ceramics consolidated using gel casting (GC) were higher than those cemented using other procedures. Additionally, after 1 h of sintering at 1600 °C, the GC ceramics demonstrated superior fracture toughness and flexural strength qualities, when compared to those cemented by other processes, including traditional die pressing (FG) [75].

5.3 Electroceramics

The tape casting of lead zirconate titanate (PZT) using dispersant D3021, poly(vinyl alcohol) binder, Surfynol SE-F wetting agent, and poly(propylene glycol) plasticizer [76] was carried out through the colloidal processing route. Measurements of pH, conductivity, and zeta potential were performed to assess the suspension stability in the presence of a dispersant. The isoelectric point of PZT was located approximately at pH 6.5. The results exhibited shear thinning rheological behaviour, corresponding to a weakly flocculated system with low time-dependent viscosity effects. Rheological and mechanical properties were further studied [76]. The thermal stability and degradation of Al_2O_3 and $(Ba,Sr)TiO_3$ (BST), and other organic additives for ceramic manufacturing were observed by mass spectrometry and thermal gravimetric analysis [77].

Ammonium polymethacrylate surfactant was used to disperse lead lanthanum zirconate titanate (PLZT) particles at different pH levels. The adsorption density of the polymer and slurry rheology was studied as a function of pH, to explain the stabilization mechanism. At the optimum surfactant concentration and pH, loading of suspension up to 50% solids by volume, at a relatively low viscosity was achieved [78].

5.4 Ultra-high Temperature Ceramics

Colloidal processing of zirconium diboride (ZrB_2) ultrahigh temperature ceramics (UHTC) was investigated for formulating lattice forming systems. Colloidal route formed samples with higher density compared to samples produced by dry route with 99% density attained by hot pressing. It is envisaged that complex shaped ceramics can be formed from above-mentioned methods [79]. The suspension dispersion and colloidal processing of complex shaped ultra-high temperature ZrB_2 ceramics has been recently reviewed [80].

6 Developments and Applications Underlying Colloidal Synthesis for Ceramic Production

Colloidal processing for ceramic manufacturing imparts control over rheological properties, interparticle forces, structural evolution and drying behaviour thereby eliminating heterogeneities [81]. The major principle behind this methodology focuses on understanding interrelations between colloidal structure and its various properties [82]. Although the hypothetical comprehension of interparticle forces is fairly well established, the direct force estimations of ceramic materials having different colloidal chemistry, composition and crystallography are essential. The major consideration for processing ceramics requires stability of fabrication process to accommodate a wide range of properties.

6.1 Biopolymer Additives

Use of biopolymer additives for ceramic manufacturing offer great potential for colloidal processing [83]. Typical biopolymers used for ceramic applications are summarized in Table 2. For example, chitosan, a cationic bio-polymer, is considered to be biodegradable and non-toxic with a wide range of applications in pharmaceuticals, cosmetics, food processing and biomaterials [84]. Saravanan et al. (2006),

studied the surface chemical interactions of chitosan with silicon carbide (SiC) demonstrating maximum adsorption density at pH 7. On addition of chitosan to SiC suspension, zeta potential of SiC surface was + 30 mV at pH 2–5, whereas it increased to + 40 mV at pH 9–11. Based on these findings, it was found that chitosan served as an efficient biopolymer for SiC synthesis (Fig. 4) [85]. Saccharides (sucrose, galactose, lactobionic acid and L-ascorbic acid) are sustainable organic additives applied in colloidal synthesis [86]. They are commonly used as polymeric binders and dispersants owing to their non-toxic, and water-soluble properties [87]. Gel-casting of foams followed by use of surfactants and gelation of polysaccharides results in stable ceramic suspensions [88]. The sintering process generates a clean burnout on using saccharide-based derivatives compared to the conventionally used organic additives. Organic synthesis allows for modification of saccharides in different
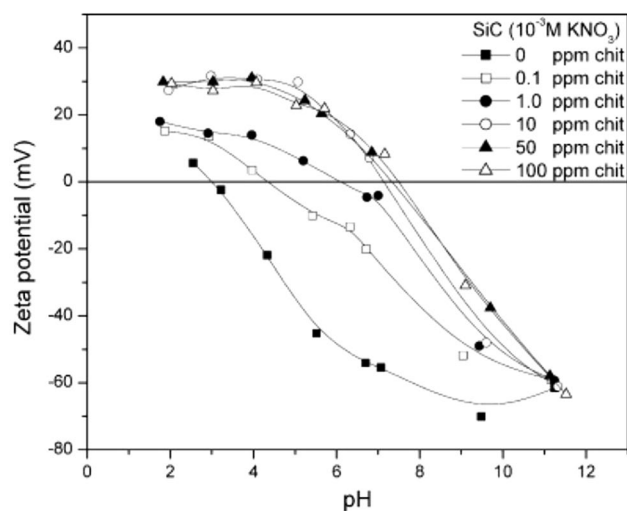
Fig. 4 Zeta potential values of SiC suspension as a function of pH, before and after interaction with chitosan (Adapted from Saravanan et al., 2006 with permission)

Table 2 Biopolymers for ceramic applications

Sr. No	Biopolymer	Application	References
1.	Gelatin	Cosmetics, pharmaceutical industry, distillery, fingerprinting	[90]
2.	Cellulose	Biofuel, blending agent, drug delivery, coating	[91]
3.	Lignin	Photocatalyst, water treatment, immune booster, synthesizing polymers	[92]
4.	Starch	Agriculture, food industry, drug delivery	[93]
5.	Dextran	Anticoagulant, surgical treatment	[94]
6.	Curdlan	Food industry, immunomodulator, therapeutics	[95]
7.	Pullulan	Adhesives, binder, vegetables, paper industry, flocculant	[96]
8.	Gellan gum	Stabilizer in food, tissue regeneration and bone repair	[97]
9.	Agar	Electrophoresis, selection of antibiotic, chromatography, purification	[98]
10.	Scleroglucan	Construction, oil engineering, pharmaceutical industry, thickener	[99]

functional groups thereby opening a new range of applications in ceramic technology [89].

6.2 Additive Manufacturing

Additive manufacturing of three-dimensional (3D) structures commonly scaffolds, facilitates its use in tissue engineering applications [100]. Polycarbonate, polyamide and polyether ether ketone (PEEK) are widely used thermoplastic polymers for scaffold engineering using selective laser sintering technology [101]. Tribological testing and mechanical properties confirm new estimates on strength and rupture of 3D samples including a composition of PEEK + nano titanium oxide + or hydroxyapatite ceramics, thereby proving to be useful materials for biomedical applications [102]. Casting and machining are traditional fabrication methods for manufacturing of ceramics which are now being widely replaced by 3D printing that enables preparation of highly complex structures using computer-aided design (CAD) [103]. Ceramic 3D printing can be categorized on the basis of feedstock form as slurry-based, powder-based and bulk solid-based [104]. To further enhance the functional parts of ceramic structures, 3D printing process is integrated with feedstock preparation and post-treatments [105]. 3D printing also offers an advantage of forming porous ceramics [106]. In manufacturing of porous ceramics, three-dimensional lattice is separated into numerous small units, followed by spraying of binder on the ceramic surface bed, aided under computer control. Rheological properties and liquid content of binder are adjusted prior to extrusion of binder from print head [107]. Therefore, porous ceramics are formed by combination of hollow spheres on powder bed and binder. Hollow spheres allow to design the micropore size of porous ceramics thereby attaining porosity of 97% useful for application in industry and biomedical environment [107].

6.3 Bioactive Ceramics

Bioactive ceramics find their application for skeletal reconstruction as a result of diseases such as osteoporosis in aged or obesed, globally [108]. Areas of bone which are too large require healing by bioactive materials that replace damaged bone with glass ceramics. Bioactive glass–ceramics are polycrystalline in nature having very low contents of alkali oxides [109]. Apatite-wollastonite (A-W) is the most common glass–ceramic possessing high bending strength, fracture toughness and Young's modulus, compatible for orthopaedic applications [110]. This ceramic is majorly used for load-bearing areas of bone and is also used for vertical replacements, where high compressive strength is required [111].

6.4 Molecular Modelling

Molecular modeling techniques provide a powerful means to gain molecular-level insights into the interactions between ceramic powder surfaces and dispersants [112]. By understanding these interactions, researchers can develop strategies to enhance dispersion, improve the stability of ceramic suspensions, and optimize the formulation of dispersants for ceramic powder processing [113]. Molecular dynamics (MD) simulations can be used to study the behaviour of ceramic powder surfaces and dispersant molecules at the atomic level [114]. By simulating the motion and interactions of individual atoms over time, MD simulations can provide information on the structure, dynamics, and energetics of the system. The simulations can capture the adsorption and desorption of dispersant molecules onto the ceramic powder surface and explore the effects of different factors, such as pH, temperature, and concentration [115].

7 Summary

Colloidal processing of ceramics has been widely practised since ancient times. The traditional methodologies adopted for synthesis of ceramics like slip casting and drying processing time have limitations to form complex shapes. The surface-chemistry involved in the colloidal processing of ceramics using different organic additives strongly influences the behaviour and rheological characteristics of ceramic materials. The study of interparticle forces such as electrostatic, van der Waals, steric and depletion is important to better understand the surface chemical properties of ceramic suspensions. From a conventional perspective, ceramic applications had been limited to a narrow range. However, advancements in the field of colloidal processing using additive manufacturing (3D printing), synthesis of biopolymer composites, bioceramics, and porous ceramics along with shaping of complex ceramic structures, have paved the way for the utilization of ceramics in a wide range of applications such as tissue regeneration, bone formation, scaffold generation, injectable ceramics and also in coatings and inks. Thus, it is envisaged that the future advancements in colloidal processing of ceramics can significantly contribute in providing better opportunities for utilization of ceramic materials.

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