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A comprehensive review of ceramic additive manufacturing: Advancements in Direct Ink Writing (DIW) and tribological properties of 3D-printed ceramics

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ABSTRACT

This paper provides an overview of the latest trends in 3D printing of ceramics, with a specific focus on the Direct Ink Writing (DIW) method and tribological considerations. DIW is a flexible and accurate method for depositing ceramic materials, allowing for detailed designs and geometric versatility. It has shown promise in a range of applications, from personalized medical implants to intricate architectural structures. To date, there is a notable absence of comprehensive surveys encompassing the tribological aspects of 3D-printed ceramics within academic discourse. A review paper addressing this gap would significantly contribute to the understanding of the tribological behaviour of 3D printed ceramics and provide valuable insights for further research in this domain. By reviewing recent literature and experimental results, this review intends to offer valuable insights into the latest advancements in ceramic 3D printing using the DIW method.

1. Introduction

Ceramic materials are highly suitable for tribological applications and have been extensively employed in various engineering fields as triboelements because of their exceptional hardness, excellent wear resistance, strong chemical resistance, and stability under high temperatures. Their properties make ceramic pairs ideal for use in demanding environmental conditions, including those with high loads, rapid speeds, elevated temperatures, and corrosive environments [1,2]. However, conventional ceramic processing is costly, involves many steps, and takes a long time. It also struggles with creating complex structures due to ceramic hardness and brittleness. These issues can be largely addressed by using Additive Manufacturing (AM) technology [3].

3D printing, also known as additive manufacturing, encompasses various methods of creating parts by layering materials incrementally, which is essentially distinct from conventional subtractive manufacturing approaches [4–6]. AM enables numerous new applications and permits processing of a diverse array of materials [7]. This technology provides benefits such as speed, flexibility, sustainability, risk reduction, and accessibility [8]. The application of this technology to ceramic materials has become increasingly notable in recent years [6].

3D printing technology, when paired with ceramic materials, not only accelerates the production of ceramic components but also enables the creation of intricate and highly customisable ceramic objects. This capability finds application across various industrial and commercial sectors [9]. Unlike traditional ceramic moulding methods, 3D printing enables the rapid prototyping of complex structures [10]. The development of new ceramic processing techniques for creating 3D ceramic structures will offer significant opportunities in structural, energy, environmental, and biological applications [11].

In the past, additive manufacturing was primarily used for producing expensive, customised components and prototypes, but there is now a growing emphasis on near-net-shape mass production and the creation of spare parts [12,13]. Consequently, AM has diversified into many

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areas. It now plays a crucial role in healthcare by producing custom prosthetics, implants, and bioprinted tissues. The aerospace industry benefits from its ability to create lightweight, intricate parts, while in construction, AM has enabled innovations such as 3D-printed buildings. As the technology continues to advance, it is introducing new applications and improving manufacturing processes across various sectors [14]. This shift highlights an increasing significance placed on the surface properties and tribological performance of the produced parts [12].

Moreover, AM of ceramics allows for the production of precise and intricate structures at various scales. This feature allows for the incorporation of ceramic materials and lubrication structures, offering a promising approach for the production of ceramic-based lubrication materials [15]. Therefore, studying the tribological behaviour of 3D-printed ceramics is crucial.

3D printing methods can be divided into categories depending on whether the raw material is in a liquid, powder, or solid form [16]. They can also be grouped based on the deposition technique and the method used for material fusing or solidification [17]. These methods can create high-quality and complex products. However, no single processing technology is flawless, as each one has its unique strengths and weaknesses [3].

Out of all the additive manufacturing techniques available, the most versatile 3D printing method, suitable for a wide variety of materials, is DIW [15]. DIW is an additive manufacturing technique which is classified as a material extrusion technology and is known with other names such as robocasting technique or Robot-Assisted Shape Deposition [18–20]. DIW offers precision and the ability to create complex geometries, meeting the needs of high-value applications such as medical micro-scale bio-printing. It can fabricate intricate internal porous structures that conventional methods cannot, allowing for better manipulation of physical or chemical properties in 3D parts [21]. This method is a straightforward, flexible, and cost-effective approach suitable for a diverse range of materials [15]. DIW enables the quick creation of intricate shapes using ceramic materials at reduced cost, making it a prominent method in additive manufacturing for producing ceramic structures. Furthermore, to maintain structural integrity, the DIW of ceramics usually avoids the need for heating or photopolymerization processes. This is due to the shear-thinning properties, which enable the material to self-support during the printing process [22].

This technique enables the design of three-dimensional shapes with creative freedom, detailed patterns, and specific material characteristics [23]. One notable advantage of this method is that, unlike other techniques such as vat polymerization, it can theoretically be applied to any ceramic material [15,24]. Another benefit is that DIW can achieve high densities and mechanical properties similar to those produced by traditional manufacturing methods. In contrast, other additive manufacturing techniques, such as selective laser sintering, frequently face challenges with density and defects that can affect mechanical properties. Finally, DIW offers several unique capabilities. One example is its ability to create parts with graded compositions by mixing two different ceramic suspensions during the process [25]. Another distinct advantage is DIW's capability to align high aspect ratio particles through the shear forces exerted in the nozzle [26,27]. These advantages highlight the significance of further studying this method for ceramic 3D printing.

This paper reviews recent advancements in ceramic 3D printing, emphasising the DIW method. It explores the ceramic materials and processing parameters used in DIW and other AM techniques. The study also examines the tribological properties of 3D-printed ceramics compared to traditional methods. Applications in various industries are discussed, along with the challenges and future research directions to enhance the capabilities and applications of 3D-printed ceramics.

2. Direct Ink Writing method for ceramic additive manufacturing

According to the International Standard ISO/ASTM 52900:2015, AM technologies are classified based on deposition technique, feedstock type, and material fusion or solidification. The main categories include material extrusion, binder jetting, vat photopolymerization, powder bed fusion, material jetting, direct energy deposition, and sheet lamination [28]. Material extrusion utilises a paste or slurry composed of ceramic materials [29]. The process involves creating a 3D structure by depositing layers of material onto a build platform. This is achieved by extruding a ceramic-loaded filament, ceramic-loaded paste, or pre-ceramic polymer filament via an orifice, adding each layer sequentially. Ensuring successful material extrusion requires careful regulation of the paste or filament's rheological properties and the incorporation of a high concentration of ceramic particles [30].

DIW, which is also referred to as Robot-Assisted Shape Deposition, Direct Write Fabrication, or Robocasting, is a technique that falls under the category of material extrusion methods [17]. DIW, introduced by Cesarani and his team at Sandia National Laboratories, was developed in 1997 to fabricate concentrated materials like ceramic pastes combined with an organic binder [31]. Following that period, researchers from various fields beyond structural ceramics have increasingly adopted this technique worldwide. Since 2006, there has been an exponential growth in the published literature on DIW, with significant contributions from various engineering and scientific disciplines [15].

In DIW technique for ceramics, the feedstock typically involves a liquid known as 'ink,' which is a suspension containing ceramic particles. This ink is a viscous, non-Newtonian slurry with distinct rheological properties, available in polymer-based or aqueous forms, where the configuration of phases of liquid and solid serves as the printing material at ambient temperature [11,18]. Fig. 1 presents a schematic of the DIW process, depicting its main components and the processing sequence.

2.1. DIW operational mechanism

The DIW additive manufacturing technique can be classified into two major processes (Fig. 2):

Discontinuous droplet-based method (also referred to as drop-on-demand inkjet printing): This method involves printing heads ejecting discontinuous droplets onto the substrate to create images through heat-induced ink bubble explosions (e.g., in bubble jet and thermal inkjet printers) (Fig. 2a) [32].

Continuous paste-based/filamentary ink approaches: In this approach, pressurised ink is expelled through a nozzle and divides into consistent droplet due to surface tension (Fig. 2b). Drop-on-demand inkjet printing offers several advantages: economical ink delivery and high printing

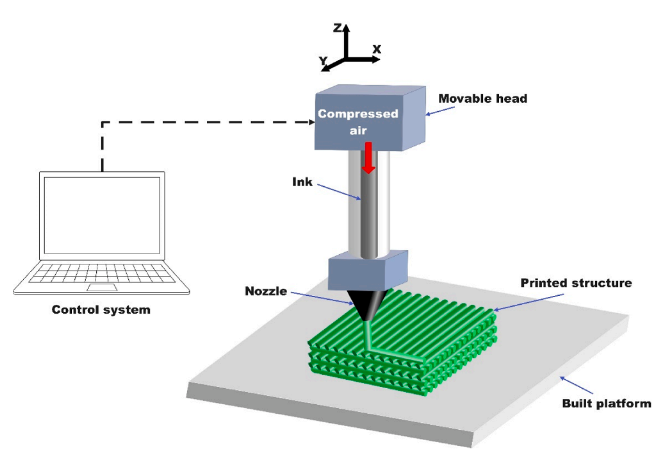

Fig. 1. A schematic of DIW process.

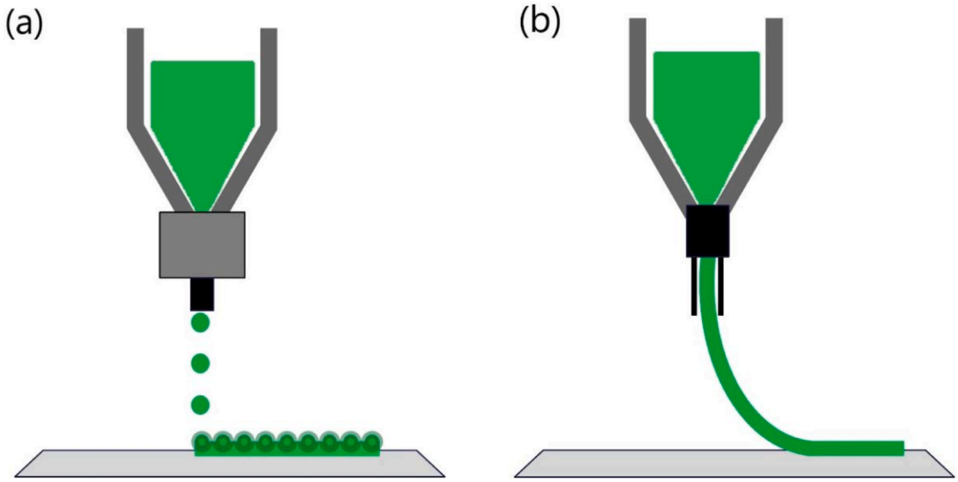

Fig. 2. A schematic representation of DIW methods: a) droplet deposition and b) continuous filament extrusion.

resolution due to the use of dilute suspensions. However, it is limited to printing in only two dimensions. On the other hand, extrusion printing is advantageous because it is highly versatile, allowing for deposition of a wide range of materials and achieving higher material density, capable of forming 3D structures. Its drawbacks include a complex post-printing process (such as removal of surfactant and heat treatment processes) and lower feature resolution [33].

In general, the process of DIW deposition involves three main stages: firstly, the ink flows through the syringe barrel and printing nozzle; secondly, it is ejected from the nozzle; and thirdly, it is deposited onto the underlying printed layers. In each of these crucial steps, a critical aspect is the ability to customize ink at meso- and microscales to ensure it is suitable for printing [34,35].

DIW employs three distinct extrusion methods for constructing 3D structures via continuous filament writing with either thick paste or liquid droplets (as depicted in Fig. 3):

Electric piston: In this method, the speed of the piston is managed through a computer-generated printing program to extrude the monolith during the process.

Pneumatic: For pneumatic extrusion, ink paste is pushed out by air pressure from a system linked to the computer and printer during printing.

Screw injection: This method involves a screw extruder layer within the extrusion syringe, controlled by a computerised printing program using a three-axis motion robot or a commercial 3D printer.

Electric piston and pneumatic techniques are similar in that the

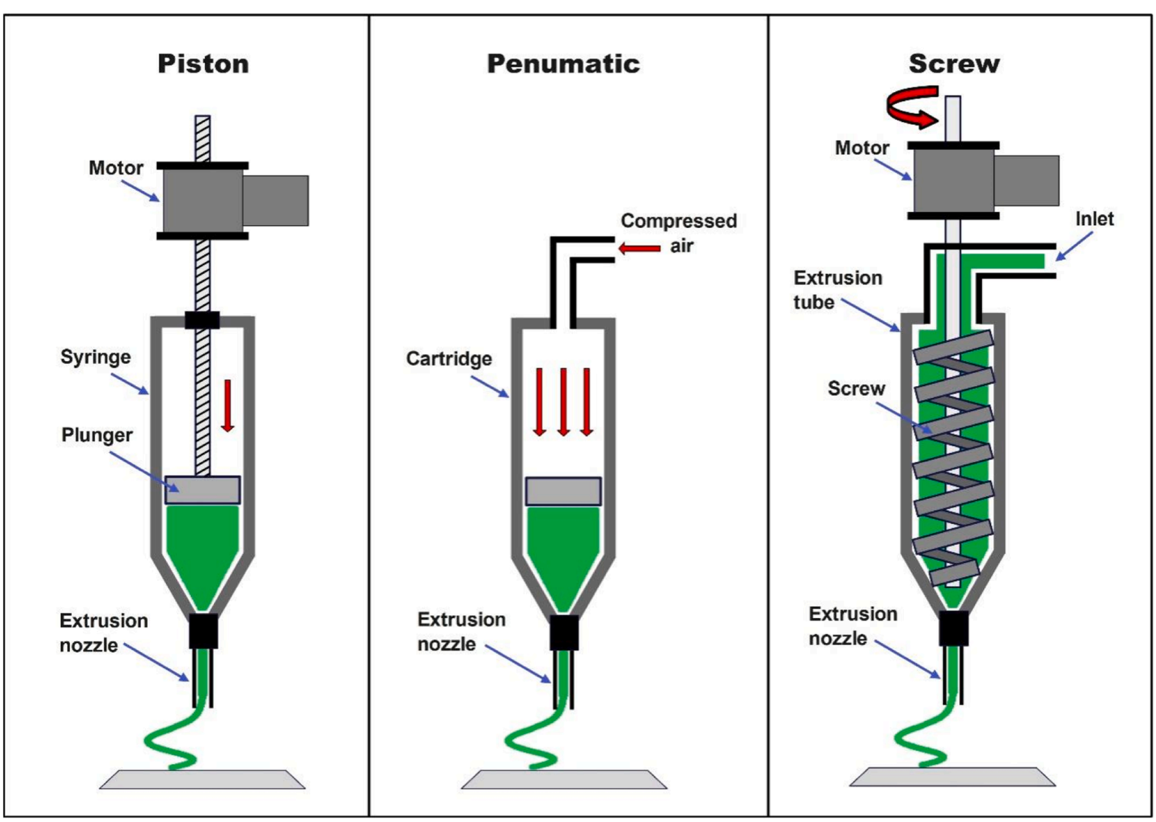

Fig. 3. Illustration showing the functional principles of the extrusion-based 3D printing technique.

primary source of the continuous filament is the gel paste ink, and also they employ air pressure or mechanical pressing for extrusion. However, in the screw injection method, the continuous filament ink source is powder slurry, which is achieved through direct mixing. In addition, before extrusion through the nozzle, the screw injection method forms the filament by blending colloidal slurry from a separate inlet within the screw extruder layer [35,36].

The DIW head is fitted with a dispenser that ends in a nozzle. To produce 3D parts, the computer-aided design (CAD) model is print layer by layer with precise control from the robotic arm. The pseudo-plastic feedstock is extruded through a moving nozzle, which is precisely controlled to form the desired two-dimensional pattern [28,37]. Robocasting typically involves higher ceramic solid loading than Ink-Jet Printing, necessitating larger nozzle sizes (typically 100–1000 μm). However, to prevent clogging, the optimal nozzle diameter generally ranges from 400 to 800 μm [17]. Once a layer has been printed, the supporting structure is repositioned downward by the thickness of the layer just added. Following this adjustment, an additional layer is applied on top of the previous one, gradually building the part through a layer-by-layer procedure. Following the printing phase, the process advances to de-binding and sintering to remove the binder and ensure maximum densification [37].

Machine parameters, such as nozzle size and printing speed, impact the resolution of the printing. Typically, XY layer resolution ranges from 100 to 1200 μm, while z resolution ranges from 100 to 400 μm. The minimum feature size is around 500 μm. Opting for nozzles with a smaller diameter generally results in improved printing resolution, though it necessitates higher extrusion pressures and extended build times to avoid clogging. Likewise, decreasing the printing speed often enhances shape accuracy and detail, though it leads to longer overall printing durations [15].

2.2. Ink preparation

In the DIW technique, the properties of the ink, slurry or feedstock are essential. This feedstock is produced by combining fine ceramic powder with binder materials, appropriate additives, and deionised water. Powders are typically blended and mixed in tumbler mixers [38,39].

In order to achieve ceramic parts with superior mechanical properties after high-temperature sintering, using pastes with high solid content and viscosity is preferred, as it allows for the extrusion of 3D components with significant density through narrow nozzles [40]. Formulating inks with viscoelastic properties and high solid content ensures that extruded filaments retain their shape. This facilitates the construction of suspended structures that are self-supporting, with line spacing that can be varied. Such precision and flexibility are not possible with other AM methods like powder bed printing [41,42].

The ink should also have adequate yield strength and stiffness to support itself after printing, which reflects a substantial elastic component in its viscoelastic behaviour. The ceramic content in the binder/additive and ceramic powder paste should be over 50 % for optimal densification and to minimise dimensional inaccuracies. Shear-thinning behaviour is preferred, as it facilitates extrusion through smaller nozzles at reduced pressure. That is, slurry must maintain shape integrity post-printing and exhibit high shear thinning for smooth extrusion through fine nozzles [17,43].

In preparing the slurry, ensuring the uniform dispersion of micro/nanoparticles is critical for achieving high-quality and accurate printed parts. Key factors for successful DIW include the slurry's pseudoplastic behaviour upon dispensing and the even distribution of particles. Typical ceramic slurries contain particles ranging from 1 to 100 μm in size, distributed homogeneously to produce fine-detail microscale prints, the slurry's particle sizes must be much smaller than the final part's resolution, often achieved by using a vibratory sieve to eliminate large agglomerates [44].

To summarise, Inks must possess several key characteristics: homogeneity, freedom from air bubbles, a high ceramic powder volume fraction, and appropriate flow properties for extrusion. Water-based inks are preferred for their ease of use, cost-effectiveness, reduced toxicity, and extended drying time. Lowering the organic content helps achieve quick burnout and ensures high-density final products. To meet these requirements, several methods have been investigated, including high solids loading pastes that dry as they are printed, polymer-solvent inks that depend on solvent evaporation, and colloidal ceramic suspensions where particle interactions are controlled by van der Waals forces, leading to a less stable network [45].

The behaviour of starting suspensions in terms of rheology is mainly affected by several factors, including solid loading, additive type and concentration, particle size distribution and density, and a preparation method that guarantees uniform solid/liquid interactions. Additionally, the effective breakdown of hard agglomerates is vital, as it greatly influences the suspension's flowability, homogeneity, and sintering performance. For achieving full densification of green bodies at lower sintering temperatures and maintaining a consistent build pattern, it is essential to ensure a uniform texture devoid of air bubbles [46]. When in contact with the substrate, the material must dry rapidly to maintain its shape and establish the layer. One of the main challenges in DIW is producing high-density components while avoiding nozzle blockages, which relies on achieving even particle distribution in the slurry [44].

In order to prepare ink for DIW process, understanding how additives interact with ceramic powders is crucial for modifying the rheological properties of ceramic suspensions and for optimising the structural characteristics after post-treatment [47]. The distribution of particle sizes in ceramic powder significantly affects the rheological properties of the paste and the density of the finished components. Differences in particle size, ranging from 0.2 to 200 μm, can significantly affect viscosity and yield stress. Finer powders are favoured in ink formulation because they disperse more effectively and sinter more readily. In contrast, larger particles offer better flowability but tend to settle more easily. Maintaining a narrow particle size distribution at a consistent particle volume fraction increases the overall surface area of the suspended particles by decreasing the distance between them, which improves particle-to-particle interactions [48]. Impact of powder physical characteristics on ink rheology and post-treatment process is listed in Table 1.

Therefore, optimising the slurry's rheology, particle size

Table 1
Influence of powder physical features on paste rheology and post-treatment process [46].

Shape & Size		Characteristics and Effects
Mixed Size Distribution		- Better packing and higher sintered densities as small particles fill voids between larger ones. - Simplified de-binding process.
Platelet-like Shape	Low Filling Fraction (up to 20 μm)	- Improved particle dispersion and sinterability. - High yield stress and storage modulus. - Higher total solid loading suitable for robocasting. - Easier extrusion due to particle alignment under shearing. - Suitable for extrusion at small tip diameters.
	High Filling Fraction (∼ 40 μm)	- Lower total solid loading suitable for robocasting - Lower yield stress and storage modulus. - Instability and high viscosity, leading to paste sedimentation. - Inhibits extrusion at low tip diameters (0.5 mm).
Spheric-like Shape		- Higher paste flowability due to lower interparticle interaction. - Reduced packing density.

Table 2
Summary of recent advancements in DIW ceramic additive manufacturing.

Research	Focus	Materials & Parameters	Innovation/Contribution	Results
Haize Jin et al. (2019) [49]	Highly porous ceramic parts with DIW	Si_2N_2O ceramics tetraethylene glycol dimethylether, 1-hexanol	introduced a versatile method combining colloidal gel ink and DIW enabling in-situ synthesis of high-performance ceramics	Si_2N_2O parts with frame density 1.07–1.14 g/cm^3 , apparent porosity 53.13 ± 1.29 %, dielectric constant 4.24, and dielectric loss 0.0049
Guiyan Yang et al. (2022) [50]	DIW using supramolecular micelles gel	Alumina, Supramolecular micelles gel, adjustable pore sizes at multiple scales	Introduced a gel with excellent printability using DIW for precise control over pore structures	Reduced heat-exposed chip temperature to 34.2 °C from 54.8 °C without the cap.
Haichao Xu et al. (2021) [51]	Fabrication of high-performance SiC ceramics	GO-CNT ratio of 1:2, flexural strength, fracture toughness	Development of Toughened SiC Composites	Flexural strength of 337.4 MPa, fracture toughness of 4.58 MPa·m1/2
Tianyu Yu et al. (2020) [52]	Customized slurries for dental components	YSZ, 60 vol% solid loading	Custom Slurry Formulation for Dental Applications	Sintered components with 98 % density, superior mechanical properties
Raymond et al. (2021) [53]	Customized nozzles for DIW	α-tricalcium phosphate (α-TCP) poloxamer-based hydrogel	Nozzle Design Innovation	2.5 times greater surface-area-to-volume ratio, improved biological efficacy
Yang et al. (2023) [54]	Large-sized Si_3N_4 ceramics	CMC hydrogels, varying solid content	Large-Scale Ceramic Fabrication	Dense, homogeneous structures without defects
Zhang et al. (2020) [55]	YAG transparent ceramics	Al_2O_3 Y_2O_3 MgO Glycerol ISOBAM 104	Transparent Ceramic Fabrication	Relative density 99.7 %, 70 % in-line transmittance
Ji et al. (2021) [56]	Enhanced optical properties of YAG ceramics	YAG ceramic slurry Cellulose content	Enhancing Optical Properties of YAG Ceramics	High optical quality, 81.5 % in-line transmittance at 1064 nm
Hossain et al. . (2023) [57]	High-density PZT ceramics	50–52.5 vol% lead zirconate titanate (PZT) ceramic, Glycerol, polyvinyl alcohol, dispersant (DISPERBYK−180)	High-Density Piezoelectric Ceramics	Relative density > 97 %, comparable to die-pressed samples
Hall et al. (2021) [58]	DIW of PZT ceramics	Paste compositions with 11–14 wt % water content	Stable Paste Formulation for DIW	Densities up to 95 % of theoretical value
Kumar Parupelli et al. (2023) [59]	Calcium magnesium phosphate ceramics	PCL addition for scaffold roughness	Bone Implant Materials Development	Enhanced cell attachment and growth
Zhao et al. (2023) [60]	Ti/β-TCP composite scaffolds	Composite porous scaffold	Biocompatible Scaffold Fabrication	Compressive strength 45 MPa, elastic modulus 1 GPa
Yongqin Zhao et al. (2023) [61]	DIW with up-conversion particles	Al_2O_3 powder UCPs ($NaYF_4$:Yb, Tm) BYK−111 as dispersants Phenylbis (2,4,6-trimethyl benzoyl) phosphine oxide (BAPO)	Unsupported Ceramic Fabrication	Complex structures without support, diameters 410 μm to 3.50 mm
Aleksei Dolganov et al. (2021) [62]	Rheological study and printability of titania inks	Titania inks, weight ratio of 1:0.8:0.1 TiO_2:H_2O	Improved Near-net-shape Electrochemical Metallisation (NEM) Process, introduced removable support structure for printing	Enhanced production quality and stability of green bodies, reduced residues for biomedical applications
Yarahmadi et. al (2025) [63]	Rheological properties	TZ−3YSB, Zpex, Zpex−4, Zpex-smile; 73 wt% TZ−3YSB, 71 wt% Zpex variants; Y_2O_3 content	Optimisation of extrusion process, thermosensitive rheological behaviour, correlation with pluronic gelation, hardness, and toughness comparison	Shear-thinning behaviour, viscosity reduction with shear rate; better recovery and hardness for Zpex variants; optimal extrusion at 71–73 wt%.
Bhandari et al. (2025) [64]	Rapid debinding and sintering of alumina ceramics fabricated by DIW	Alumina inks; nozzle sizes 0.41 mm and 0.84 mm; UHS, PSPS, and FF sintering.	Single-step debinding and sintering; optimised rheology for DIW; rapid densification with refined microstructure.	Nearly fully dense alumina via UHS and PSPS; FF caused cracks; smaller nozzle and higher ceramic loading improved density.

distribution, morphology, and wetting properties is crucial for achieving desired print results. The ball milling process, whether dry or wet, is effective in achieving a well-dispersed and uniform slurry. Precise adjustment of organic binders, additives, and dispersants is essential for achieving optimal performance [47].

2.3. Ink rheology

Needless to say, an ink is typically considered printable if it can be extruded as a continuous filament through a designated nozzle and can be employed to produce structures that accurately replicate the computer-generated design. To achieve printing of devices with a small footprint, the physical characteristics of the inks need meticulous customisation. Inks intended for larger-scale systems may not be suitable for microfabrication due to potential clogging at the initial stages of printing. Specifically, the ink must flow smoothly without forming large, hard agglomerates that could block the deposition nozzle [65].

The rheology of the inks is a critical factor in the DIW process and is essential for creating geometries that can maintain their shape. The material must support its own weight with minimal deformation after printing [66]. The ink's printability and shape retention directly contribute to DIW's essential capability to form self-supporting extruded layers [15]. In other words, achieving high-precision DIW monolith printing without base layer deflection necessitates the ink possessing the correct physical properties [35]. Therefore, a major challenge in DIW is creating a suspension that exhibits suitable rheological behaviour.

This process imposes strict requirements on the rheological behaviour of the inks: they must flow smoothly through a narrow opening while resisting deformation immediately after printing. To achieve these rheological characteristics, two main strategies are employed. One approach involves formulating a low-viscosity ink that undergoes gelation after printing, rapidly acquiring a high yield strength to prevent deformation post-printing. The second strategy focuses on engineering inks with meticulously controlled rheological properties. These suspensions must exhibit viscoelastic behaviour with sufficient yield stress to support the layer-by-layer deposition process. Shear-thinning is essential in rheology for ensuring continuous flow without interruption or particle blockage, describing how fluids decrease viscosity as shear rates rise due to their non-Newtonian nature. This property facilitates smooth ink flow through nozzles, even under lower extrusion pressures, ensuring effective extrusion processes [34,67].

The Herschel-Bulkley model can predict the flow characteristics of the slurry. According to this model, ideal non-Newtonian fluids remain static below a specific yield stress. When the applied stress exceeds this threshold, the fluids display shear-thinning behaviour, causing their viscosity to drop markedly as the shear rate increases. This phenomenon is mathematically described by the Herschel-Bulkley equation as below:

$$\tau = \tau y \quad + k\dot{\gamma}^{n} \tag{1}$$

Where τ represents the applied shear stress, τy denotes the yield stress, $\dot{\gamma}$ indicates the shear rate, n stands for the shear-thinning exponent, and K is the viscosity parameter.

The literature indicates that in DIW, it is advantageous to have a low value for the shear-thinning exponent (n) to maintain a low extrusion pressure and enhance mixing. Similarly, a low viscosity parameter (K) is important for the same reasons. Conversely, a high yield stress (τ) is necessary to ensure the integrity of the final part post-printing, preventing any failures. It is noteworthy that these parameters influence each other. Additionally, they depend on other factors such as the nozzle characteristics, the size of the printed object, and the density of the ink. Therefore, determining the optimal values for these parameters is challenging [68,69].

After the ink is expelled from the printing head, it needs to swiftly turn into solid-like substance from a shear-thinning fluid one to accurately attain the shape. Inside the nozzle, the shear stress surpasses the yield stress, causing the material to flow. Upon leaving the nozzle, the stress is released, and the material becomes a viscoelastic solid. It is essential for the printed structure to hold its shape until it fully solidifies after the deposition process. Post-printing, the ink's rheology must be meticulously controlled to avoid sagging of stacked filaments under their own weight and to minimise bending in overhanging sections [70].

Due to the challenges of relying on mathematically derived models, the rheological properties of ink are commonly evaluated through experimental methods using a rotational rheometer. To assess shear-thinning properties in inks, flow ramp tests are utilised, while oscillatory tests provide information on their viscoelastic behaviour. Furthermore, extensional rheology and three-interval thixotropy tests are performed to determine the inks' printability [71].

2.4. Ink design

In 3D printing, the inks consist of various functional components, and precise control of their interactions is essential. During the formulation process, two main goals are targeted. First, the ink needs to satisfy specific rheological properties to ensure it is printable. Second, once the solvent is removed and post-processing is complete, the device should possess particular functional attributes, including mechanical integrity and high density. The functional properties must be balanced simultaneously in ink design. To improve printability, it is common to add inactive and non-conductive agents such as stabilisers, surfactants, and viscosifiers to the active components. Unfortunately, these additives can impair the electrochemical performance of the final product. Removing them involves high-temperature post-processing, which complicates and raises the cost of manufacturing. This process can also negatively affect the properties of the electroactive material, leading to possible decomposition or unwanted phase transitions. Nevertheless, recent innovations have resulted in the creation of electroactive materials that also serve as rheology modifiers, successfully overcoming these issues [34].

DIW inks are composed of binders, additives, functional fillers, and solvents, each playing a specific role in the printing process [72,73]. Functional fillers determine the final device's properties, with nanomaterials often used because they are small enough to prevent nozzle clogging and promote ink stability by reducing sedimentation [34].

Binders, typically polymers, help particles adhere to each other and to the substrate. They also stabilise the ink and prevent particle sedimentation. However, using minimal binders is crucial to avoid ink inhomogeneities, which can affect the printed structure's performance [74,75]. Solvents are essential for providing the necessary fluidity for extrusion and deposition. While organic solvents can be problematic due to flammability, toxicity, or residue, aqueous solvents are preferred for their cost-effectiveness and sustainability [34]. Choosing solvents with a regulated evaporation rate, enabling the creation of inks from both aqueous and non-aqueous mixed systems, is one of the primary difficulties associated with the DIW technique. Making a careful choice is crucial to ensure the ink flows and extrudes continuously through small nozzles, preventing nozzle clogs while printing and minimising defects in the finished parts [46]. Additives are included to fine-tune particular properties including rheological behaviour, drying rate, and particle dispersion, ensuring the ink behaves as needed during the printing process [34].

2.5. Printability of the ink

For an ink to be deemed printable, it must be capable of being extruded through a chosen nozzle as a continuous filament that can construct structures closely matching the digital model. Additionally, the printed structure's shape must be maintained throughout deposition, drying, and post-processing stages [43].

Typically, a high molecular weight polymer blend is used as the binder system to improve flowability, raise viscosity, and function as a bonding agent that keeps particles together until the final de-binding process. Selecting and optimising the additive system is critical to ensure additives burn out efficiently during multi-step heat treatments. This also prevents the formation of internal flows and cracks in the final product's microstructure [46]. Coagulants function as specialised polymers that act like adhesives, providing resistance to external forces and augmenting the viscoelastic behaviour [72].

2.6. Types of DIW inks

Ceramic inks for DIW can be classified into colloidal, polymeric, emulsion or foam, and organogel inks. These classifications are based on their various formulations [76].

Colloidal inks are created by adjusting interparticle interactions in an aqueous suspension, facilitating a transition from fluid to gel. A colloidal ink is formulated by dispersing ceramic particles in water with the aid of a dispersant to create a suspension that is both highly loaded and low in viscosity. The negative charge introduced by the dispersant, which binds quickly to the ceramic particle surfaces, leads to electrostatic repulsion and ensures that the suspension remains well-dispersed [47,77].

Gelation occurs by carefully managing the system's environment to induce flocculation, which adjusts the interplay among van der Waals, electrostatic, and steric forces [78]. Various methods can be employed to achieve gelation in colloidal inks, including adjusting the pH, where lowering the pH towards the isoelectric point (IEP) enhances attractive interactions between particles, promoting gelation. As an alternative, printable gels can be developed by incorporating salt species into the system. These salts work by neutralising the charges present between ceramic particles and within the polymer layers established during the dispersion process [79]. Another common technique to induce gelation involves the addition of polyelectrolytes, as they can serve as bridging flocculants [76].

While colloidal inks rely on the inter-particle network to achieve desired viscoelastic properties, polymeric inks primarily derive these properties from a polymeric matrix [76]. Even though polymeric inks are water-based, their strength comes from a three-dimensional network that includes a polymer gel, ceramic particles, and water. Consequently, the rheological behaviour of polymeric inks is primarily influenced by the polymer matrix itself, rather than the interactions occurring directly between the particles [76]. A significant type of polymeric ink utilises hydrogels. Hydrogels are composed of a network of polymers with a porous structure that holds water. Water absorption in hydrogels is facilitated by the hydrophilic groups present on the polymer chains. Meanwhile, their durability against dissolution is maintained through cross-linking between these chains [80]. A hydrogel-based ink gaining popularity in DIW of ceramics employs Pluronic hydrogels. These inks do not require complex manipulation of interparticle forces, as the hydrogel serves as a carrier for ceramic powders [45]. The strength needed for the ink is provided by the gel matrix, enabling it to print a wide range of materials with different compositions, size of the particles, and shapes [81].

An emulsion consists of two or more liquids that do not mix. In emulsion inks, the interfaces are between oil and water, while foam inks involve interfaces between liquid and gas. Both emulsion and foam inks can be utilized to create ceramics with high porosity. Originally, emulsion and foam gels were developed for gel-casting ceramic materials. Nevertheless, to be suitable for DIW, emulsion inks must possess the necessary rheological properties. Thus, they need to be stabilised using surfactants [82]. The tendency of emulsion inks to thin under shear stress is caused by the limited attraction between the oil droplets that have ceramic particles on their surfaces. When shear force is applied, this network of attractive forces is broken, causing the droplets to deform. At higher shear rates, the network struggles to re-establish, resulting in the ink displaying shear thinning properties [83].

Organogels are formed by dissolving polymers in organic solvents, with their transition from liquid to solid typically occurring through solvent evaporation immediately after filament deposition. Since the behaviour of gel-embedded suspensions does not depend on the surface chemistry of the particles, this method has the advantage of being potentially compatible with various ceramic powders [84]. Fig. 4 compares organogel inks with colloidal suspensions and hydrogel-based inks in ceramics.

2.7. Post-processing

In general, final density, microstructure, and surface quality significantly influence the overall performance, especially the mechanical properties of ceramic components. Therefore, improving these properties is the main purpose of post-processing [85].

Standard post-printing procedures involve additional curing, taking away support structures, applying protective or functional surface coatings, smoothing the surface through polishing, and making adjustments to the physical and mechanical properties. These processes are crucial for achieving the final desired characteristics of the printed

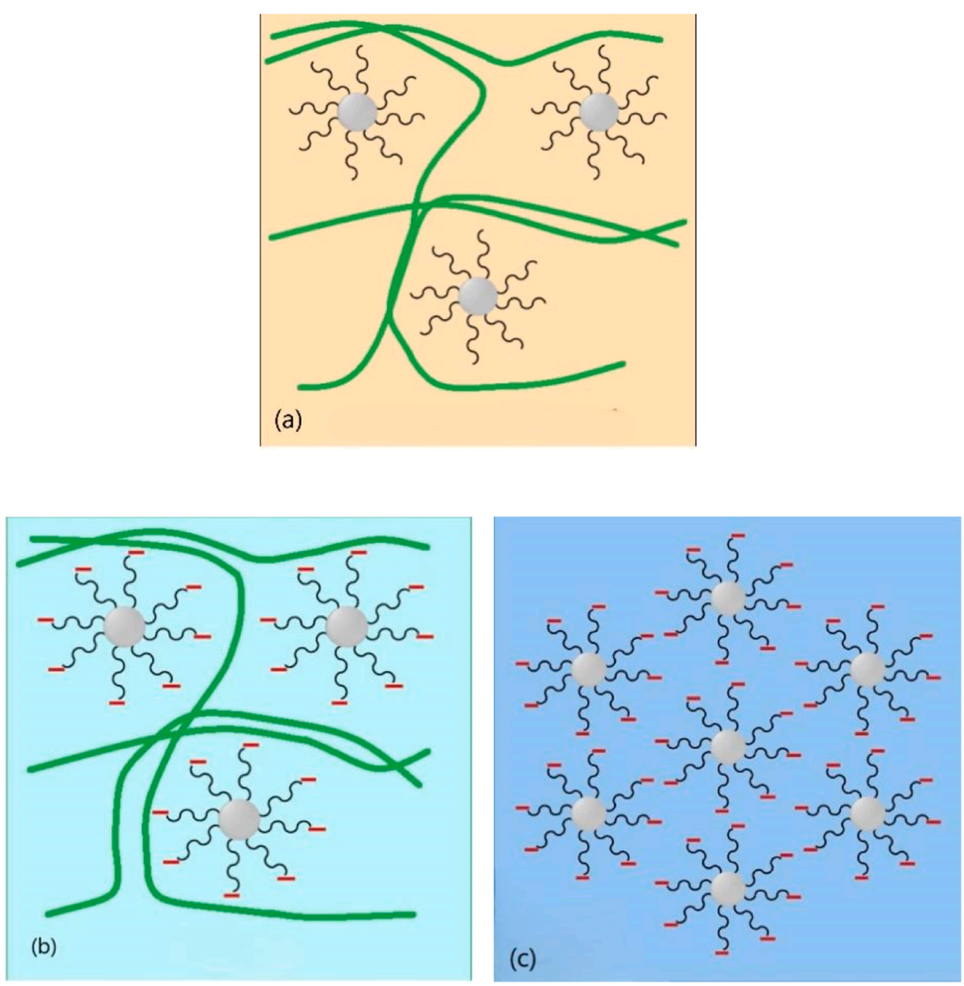

Fig. 4. A schematic diagram illustrating the interparticle interactions in the three different ceramic inks for DIW: a) organogel-based inks, b) hydrogel-based inks, and c) colloidal suspensions. Steric stabilization is depicted with black lines, while red negative charges represent electrostatic interactions, forming polyelectrolyte complexes in colloidal inks. Green lines symbolize polymer chains in gel-embedded inks [84].

components [86].

The DIW technique generally reduces the need for extensive post-processing, making it a cost-effective and environmentally friendly additive manufacturing approach. Processes such as drying, binder removal, and sintering after deposition are essential to achieve the desired physical and mechanical properties of the printed part. Additionally, post-processing procedures such as infiltration can enhance final mechanical properties. However, achieving a high level of finish in DIW ceramics often requires the use of smaller nozzles, additional machining after printing, or a combination of additive and subtractive manufacturing techniques [46].

Heat treatments applied after printing are crucial for drying and eliminating organic materials, as well as for solidifying the components. It is vital that these treatments are suited to all materials involved to accurately manage dimensional variations and ensure the creation of stable interfaces [87].

Removing liquid through drying is critical to avoid defects like warping or cracking [18]. High particle loading suspensions help maximise green body density and reduce drying shrinkage, minimising these issues. Once dried, maintaining complex shapes restricts densification options [18,88].

Techniques such as hot pressing are unsuitable for complex shapes, and hot isostatic pressing, though effective, is costly and time-consuming [85]. Pressure-less sintering is a less resource-intensive alternative, but achieving high density can be difficult without sintering aids, which may alter material properties [89]. The sintering method, whether pressure-less or pressure-assisted, greatly impacts the microstructure and density of ceramics, along with the chosen temperature schedule and atmosphere. The quality of the surface finish relies heavily on the dimensions of the extrusion nozzle and the thickness of each layer deposited. By refining the ink composition and employing smaller nozzles, it might be possible to diminish the surface roughness of ceramic structures, thus potentially lowering expenses associated with grinding and polishing [16]. It is vital to select the right post-processing methods and to precisely manage the temperature and timing for both sintering and degreasing procedures. Optimising the post-processing sequence and incorporating segmented steps can lead to substantial improvements [90].

2.8. Application of DIW

In the field of ceramic science, DIW methods have primarily been used to produce ceramics like Al_2O_3, MOx materials such as titania (TiO_2) and ZnO, as well as bioceramic structures from oxide mixtures [91–93]. Among these products, only a few examples, such as T-LGO monolith and $ZnV_2O_6@Co_3C_2O_8$/GO, involve a single-step process that does not require a binder. Other DIW processes require binders, including cross-linking agents, to guarantee that the ink has the required rheological characteristics for printing. The primary uses of these products have been in the areas of biomedical applications, environmental pollution mitigation, and energy applications [35].

2.8.1. Biomedical applications

Biomaterials fabricated using DIW are known for their capability to achieve high-resolution production of complex geometric shapes while minimising waste of active ingredients [91]. Additionally, DIW allows precise control over the size, shape, and structure of these biomaterials, ensuring they possess desired physical, mechanical, and biological properties, including osteoconductivity [94].

These capabilities make DIW highly attractive for biomedical uses including organ fabrication and tissue regeneration. Biocompatible 3D biological scaffolds have become indispensable in fields like tissue engineering, regenerative medicine, and bone cell repair. Artificial organs derived from these scaffolds must closely interact with cells such as stem and osteoblast-like cells and to facilitate the development of bone-forming characteristics. Over the past decade, 3D printing, especially DIW, has revolutionised organ and tissue engineering. DIW's ability to handle multiple materials for complex, layered assembly and its rapid solidification of gel inks, aided by sophisticated design software, have been pivotal. Merging the advantages of DIW with the mechanical robustness and biological compatibility of 3D-printed nanomaterials has positioned DIW scaffolds as leading materials for medical applications in artificial organs and surgical tissues [35]. For instance, studies on TiO_2 by various groups have highlighted its excellent biocompatibility. Research by Wang and Elsayed focused on DIW-produced TiO_2 and Sr/Mg-doped hardystonite ceramics, showing that MC3T3-E1 cells adhered to the surface of 3D-printed TiO_2 bioceramic scaffolds after a five-day period of in vivo cell culture, despite being washed on days one and three for population analysis [94].

2.8.2. Environmental pollution mitigation

Environmental research places a strong emphasis on removing air pollutants such as volatile organic compounds (VOCs) and nitric oxide (NOx) [95]. Addressing these issues involves utilising suitable catalysts or absorbents, with highly porous honeycomb structures being preferred for their large surface area, strength, and ability to withstand high temperatures [96]. The traditional method of synthesising honeycomb structures is known for its complexity and high cost. In contrast, DIW offers a faster and more efficient approach to creating intricate structures, including honeycombs [96]. Hence, the use of the DIW method to produce high-porosity honeycomb ceramic scaffolds has gained popularity for creating effective air filters or adsorbents for removing pollutants [96,97].

DIW-printed monoliths made from TiO_2 have shown significant potential in removing gaseous environmental pollutants through different technologies. In 2012, de Hazan et al. [98] demonstrated that 3D-printed Al_2O_3 functionalised with TiO_2 had strong photocatalytic activity in decomposing formaldehyde, comparable to traditional TiO_2 powder.

2.8.3. Energy applications

DIW, originally designed for ceramic manufacturing, is now gaining attention for its applications in the energy sector, expanding the range of printable materials. The primary challenges in materials formulation involve developing printable inks from energy materials that meet stringent rheological requirements for constructing intricate structures and eliminating the need for thermal post-processing [34]. DIW is poised to transform technology across the field of electronics [99,100]. This technique is recognized as a highly promising technique for manufacturing advanced batteries with intricate microstructures and superior performance [101]. As an example, Cheng et al. [101] demonstrated an innovation by adapting a robotic deposition system into a high-temperature DIW 3D printer and creating a solid-state electrolyte ink, which made it possible to 3D print hybrid solid-state electrolyte batteries. They utilised an elevated-temperature DIW method to apply a polymeric electrolyte onto MnO_2 cathodes. The electrolyte formulation included poly (vinylidene fluoride-co-hexafluoropropylene) (PVDF-co-HFP) dissolved in NMP, with TiO_2 added to enhance ink printability and wettability. Interestingly, higher TiO_2 concentrations unexpectedly reduced viscosity by decreasing the entanglement density of polymeric chains following their adsorption onto ceramic particles.

3. Recent advancement

In recent years, remarkable improvements in material properties, fabrication methods, and application have been reported in DIW of ceramics [17,34,84]. In the following, major developments in this field will be reviewed, which highlights the innovative techniques and research findings that are shaping the future of ceramic additive manufacturing.

3.1. Application-based advances

Application-driven advancements focus on creating materials with distinct properties, developing innovative processes, and designing functional solutions tailored to industry needs. Recent progress in key application areas highlights how researchers are refining DIW technology to tackle challenges and deliver cutting-edge solutions across various sectors.

3.1.1. Biomedical and bio-compatible applications

Ceramic biomaterials are increasingly favoured in biomedical applications due to their biocompatibility, mechanical strength, and biological functionality. Additive manufacturing, including DIW, supports these properties by enabling customisation. In addition, it can integrate with digital imaging, and requires minimal setup [102].

Recent advancements in DIW have drawn attention for producing ceramic-based biomaterials, particularly for bone regeneration. This technique achieves mechanical properties comparable to cortical bone, as seen in dense components with high relative densities [103]. For instance, researchers fabricated intricate zirconia structures, such as molar tooth prototypes, without requiring organic binders. Using an 88 wt% zirconia slurry with Dolapix CE64 dispersant, sintered parts reached 97 % theoretical density, yielding impressive mechanical properties (1485 HV Vickers hardness, 4.11 MPa·m$^{1}/^{2}$ fracture toughness), comparable to traditional slip-casting methods. The printed tooth is shown in Fig. 5 compared to human molar. Moreover, in Fig. 6 the correlation between solids loading and density is demonstrated for both robocasting and slip casting [104].

In bone tissue engineering, DIW has demonstrated potential for creating scaffolds with superior mechanical and biological properties [103]. Kumar Parupelli et al. [59] developed calcium magnesium phosphate (CMP) ceramics with precise resolution and uniform pore structures. The incorporation of Poly(ε-caprolactone) enhanced ion release, cell attachment, and surface roughness, addressing the slow degradation rates of calcium phosphate ceramics. Similarly, a Ti/β-TCP composite porous scaffold achieved mechanical properties comparable to cancellous bone, with a compressive strength of 45 MPa and an elastic modulus of 1 GPa. The scaffold's layered pore structure further promoted biological compatibility, making it suitable for bone regeneration. Fig. 7 compares the mechanical properties of DIW 3D printed ceramic composites for different compositions [60].

Additionally, DIW has gained popularity in dentistry by overcoming limitations of traditional methods, such as material inefficiency and design constraints. The technology allows the controlled extrusion of high-viscosity, highly filled materials to create robust dental restorations while reducing resin exposure and environmental impact [105]. Overall, these advancements highlight the versatility and potential of DIW in biomedical applications, particularly for addressing limitations of traditional ceramic processing techniques.

3.1.2. Energy, sensing, and optical applications

DIW has gained significant attention in energy applications, particularly for components like electrodes, electrolytes, and separators in batteries and supercapacitors. The challenge lies in meeting stringent rheological requirements for these inks, but recent advancements are addressing these issues, enabling the creation of 3D structures with strong mechanical integrity [34].

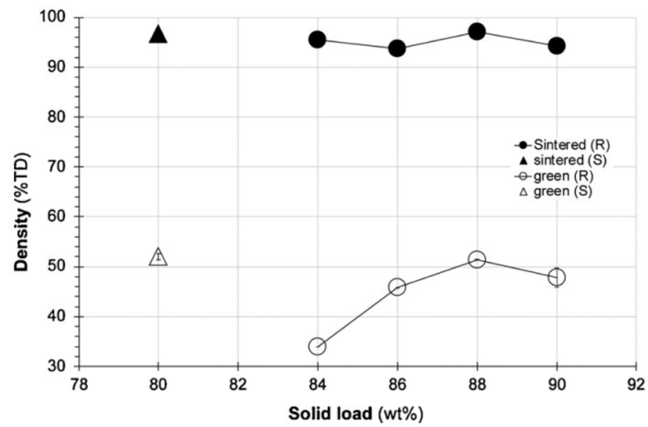

Fig. 6. The relationship between solids loading and the density of parts is illustrated for both robocasting and slip casting, with hollow symbols representing green parts and solid symbols representing sintered parts [104].

Recent developments in DIW techniques have enabled the fabrication of high-density 3D-printed PZT ceramics for sensing and energy harvesting applications. Hossain et al. [57] demonstrated that optimised aqueous-based ink formulations, combined with precise printing parameters, allowed the production of dense piezoelectric ceramics while maintaining their functional properties. This demonstrates DIW's potential in manufacturing components for energy applications. Fig. 8 illustrates the static rheological behaviour of PZT inks with different solid loadings and dispersant ratios in their study. Similarly, Hall's team [58] confirmed DIW's effectiveness in producing PZT ceramics with dielectric and piezoelectric properties comparable to traditional methods. Their study highlighted the importance of solids loading in paste formulations, noting that reducing water content by 3 wt% significantly increased viscosity, improved extrusion flow, and enhanced shape retention. Sintered samples achieved up to 95 % of theoretical density, with no phase decomposition, showcasing the robustness of this approach. Figs. 9 and 10 present comparisons between 3D printed and commercial PZT ceramics in terms of their density and piezoelectric charge coefficient, respectively.

Transparent ceramics, although promising for 3D printing, face challenges in composition diversity and transparency levels [106]. Despite these challenges, DIW has made notable progress in the fabrication of high-quality glass ceramics, as demonstrated by Yang et al. [107], who produced $CaMgSi_2O_6$ glass ceramics using DIW. Their use of high-temperature sintering improved material density and crystallinity, which shows DIW's ability to fabricate complex structures for use in electronic packaging and optical devices. In another study, Zhang et al. [55] employed DIW with an aqueous slurry enhanced by the water-soluble polymer Isobutylene-Maleic Anhydride Copolymer (ISOBAM) to fabricate transparent YAG ceramics. The 3D-printed samples achieved 99.7 % relative density and 70 % visible-spectrum in-line transmittance, nearly matching the 99.8 % density obtained via cold isostatic pressing, as demonstrated in Fig. 11. This study highlights

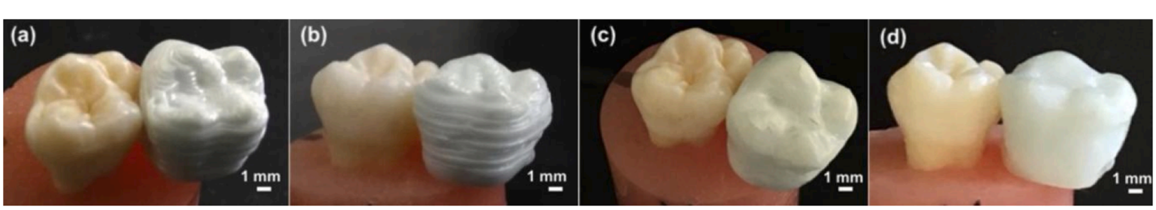

Fig. 5. A molar tooth prototype, fabricated with optimised paste, is shown on the right of each image, alongside a human molar for comparison. Views include the as-printed sintered model (a, b) and the sintered model after brushing the green body (c, d) [104].

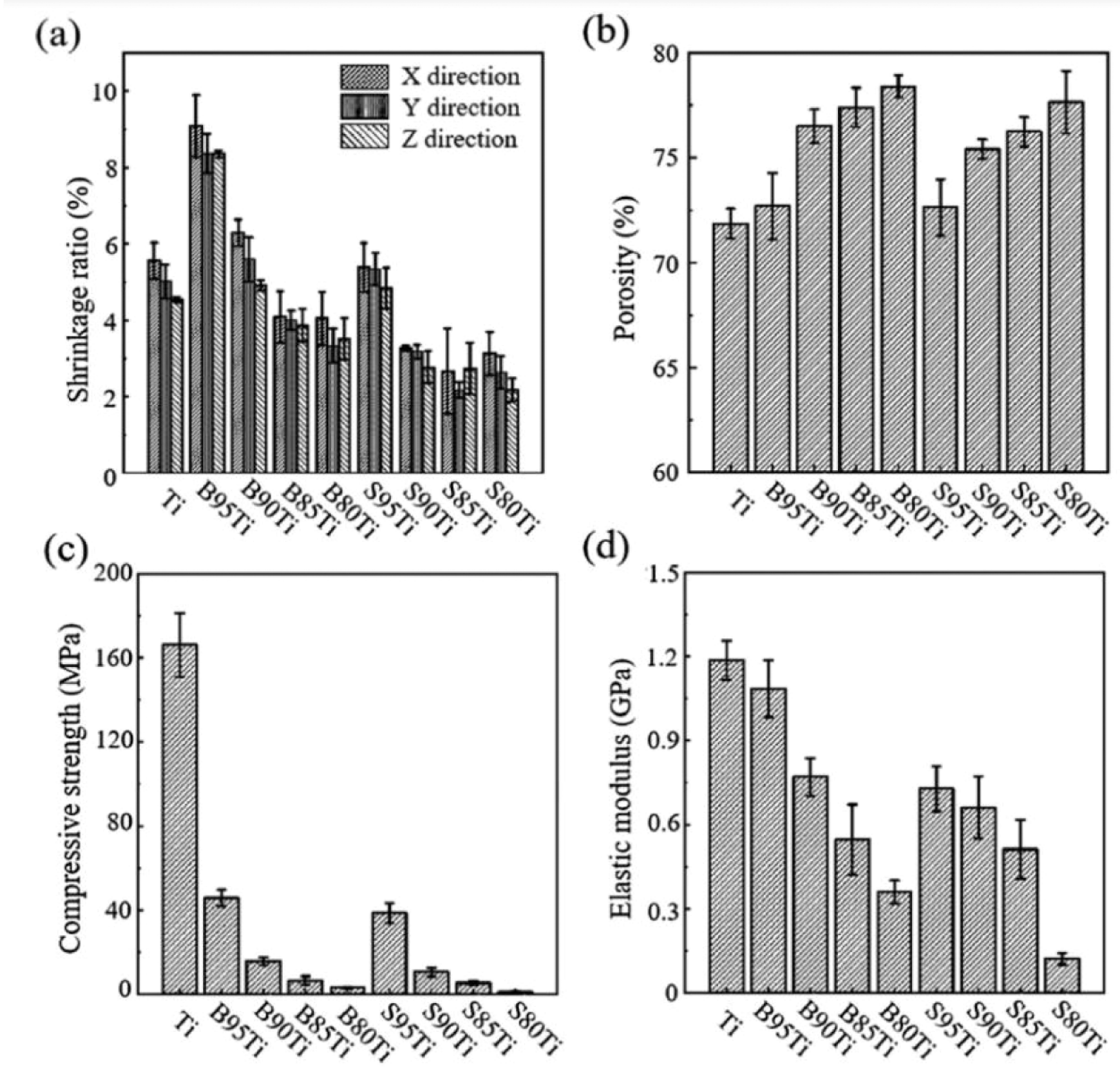

Fig. 7. The mechanical properties of sintered Ti scaffolds and Ti/β-TCP scaffolds, including (a) shrinkage, (b) porosity, (c) compressive strength, and (d) elastic modulus, are shown as a function of different Ti/β-TCP powder ratios (5/95, 10/90, 15/85, and 20/80 vol%) and particle sizes (S and B) [60].

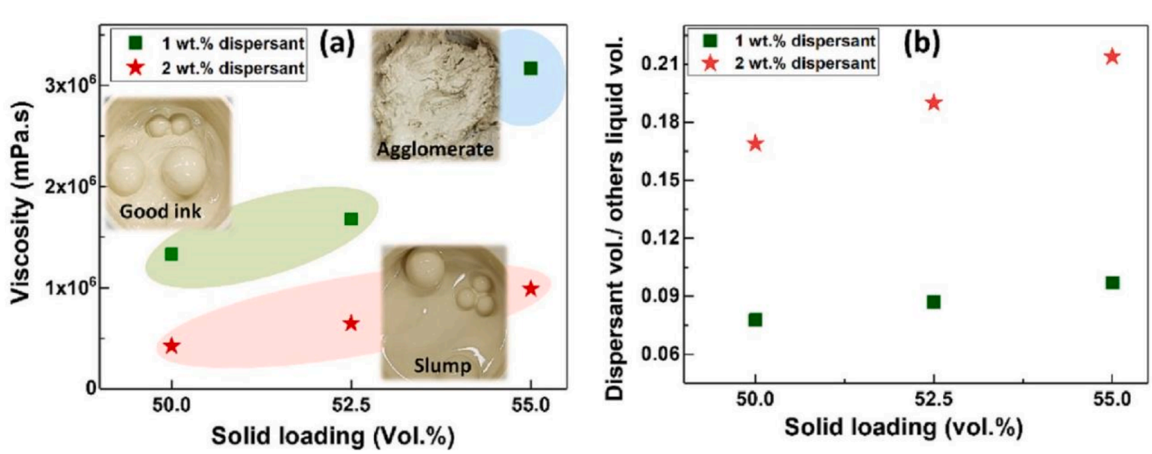

Fig. 8. Rheological behaviour of PZT inks under static conditions with different solid loadings and dispersant amounts: (a) viscosity as a function of solid loading; (b) relationship between the ratio of dispersant volume to other liquid volume and solid loading [57].

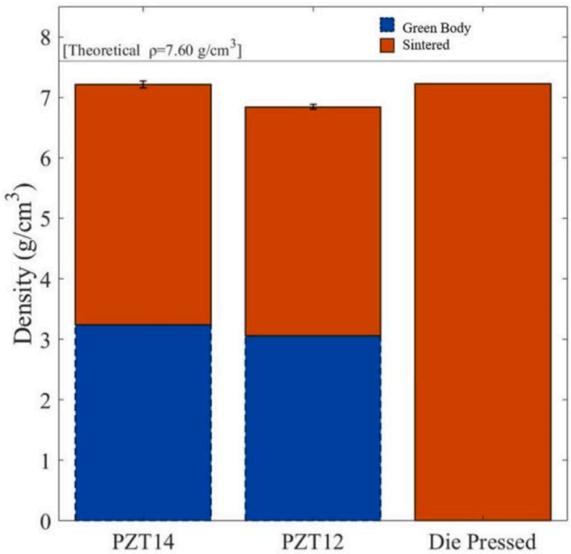

Fig. 9. Comparison of the density achieved by PZT 3D printed ceramics before and after sintering with that of sintered Die Pressed PZT [58].

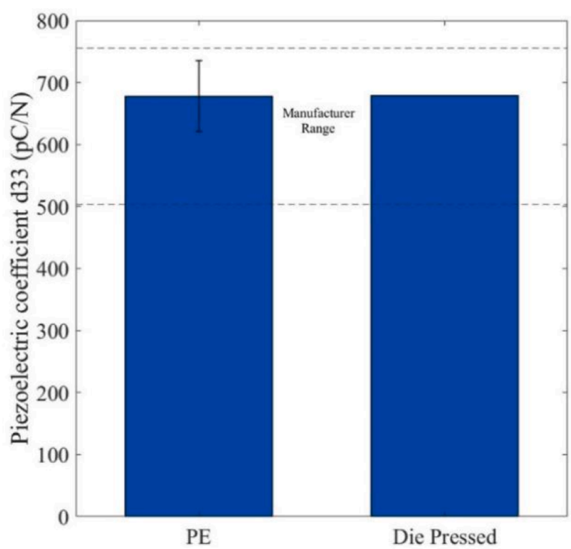

Fig. 10. Comparison of the piezoelectric charge coefficient (d33) of 3D printed ceramic (PE) with commercial PZT ceramic [58].

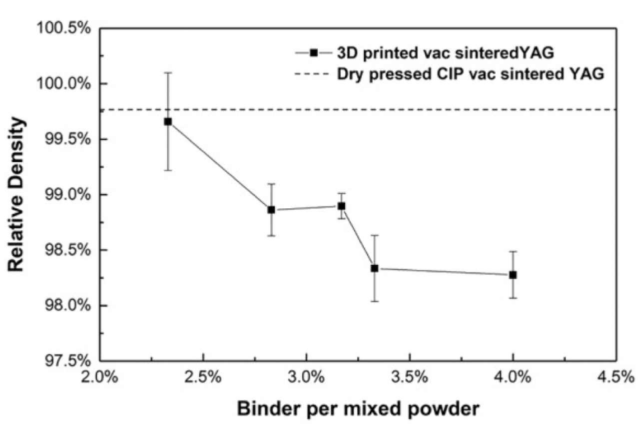

Fig. 11. Variation in relative density with different binder concentrations in the mixed powder [55].

DIW's potential to manufacture high-performance transparent ceramics with properties suitable for advanced optical technologies. However, the ceramics produced in the study were limited to simple shapes.

Seeley et al. [108] also explored DIW for producing fully dense transparent YAG/Nd:YAG ceramic rods, though they observed significant deformation in the green body. Achieving high-aspect-ratio cylindrical structures remains a challenge, requiring more than just optimisation of the slurry's rheological properties.

In another attempt to tackle the challenge of producing transparent glass ceramic using DIW, Ji and co-workers [56] achieved transparent YAG ceramics by optimising slurry plasticity with cellulose and adjusting solids loading. The green bodies exhibited structural stability with a relative density of 57.5 %, while vacuum sintering at 1700 ℃ yielded high-quality transparent ceramics. After polishing, a 1.2 mm thick sample achieved 81.5 % in-line transmittance at 1064 nm, demonstrating excellent optical properties.

A more recent study introduced a UV-curable ceramic slurry for creating thin-walled, high-aspect-ratio YAG ceramic tubes via UV-assisted DIW. The rapid UV curing enhanced shape stability, while optimised debinding and sintering processes resulted in transparent ceramics with superior optical quality. This method holds promise for future fabrication of complex, multi-component transparent ceramics. Fig. 12 shows the impact of UV curing, composition, and sintering on the resulting ceramics [109].

3.1.3. *Environmental pollution mitigation*

As previously stated, highly porous structures are favoured in environmental pollution mitigation due to their extensive surface area, strength, and resistance to high temperatures [96]. Porous ceramics are extensively researched for their unique properties, such as low thermal conductivity, reduced density, a low dielectric constant, and inherent chemical stability [110]. Traditional methods for shaping ceramics such as slip casting and gel-casting, are costly and slow due to the expenses associated with moulds [49]. To overcome these challenges, Haize Jin et al. [49] developed a DIW-based approach using strong colloidal gel inks formulated with high boiling point organic solvents. These inks demonstrated exceptional stability and elastic recovery, enabling the fabrication of single-wall Si_2N_2O ceramic parts free from residual carbon. The resulting ceramics demonstrated an optimised microstructure, superior mechanical strength, and improved dielectric properties, highlighting the effectiveness of this approach for high-performance porous ceramics. Similarly, Guiyan Yang et al. [50] developed supramolecular micelle-based gels for fabricating hierarchically porous alumina ceramics with tunable pore sizes across millimetre, micrometre, and nanometre scales. These materials exhibited superior thermal insulation and precise pore control, reducing heat-exposed chip temperatures significantly. This method addresses the limitations of traditional manufacturing, advancing applications in portable devices and electronics.

3.2. *Innovative methods and techniques*

To address the growing demands of advanced ceramic applications, researchers have explored innovative methods and techniques in DIW. These approaches aim to overcome longstanding challenges in DIW of ceramics. By integrating novel material systems, customizing DIW components, and optimising ink formulations, these advancements enhances performance of 3D-printed ceramics [17].

Hybrid composites incorporating graphene and carbon nanotubes hold immense promise for addressing the brittleness of silicon carbide ceramics, a major challenge in advanced applications like aerospace and thermal systems [51]. Haichao Xu et al. [51] utilised DIW combined with liquid silicon infiltration to fabricate SiC ceramics reinforced by a 3D graphene oxide (GO) and carbon nanotube (CNT) hybrid. The optimal GO-CNT ratio of 1:2 enhanced toughness, achieving uniform dispersion within the matrix and superior mechanical properties.

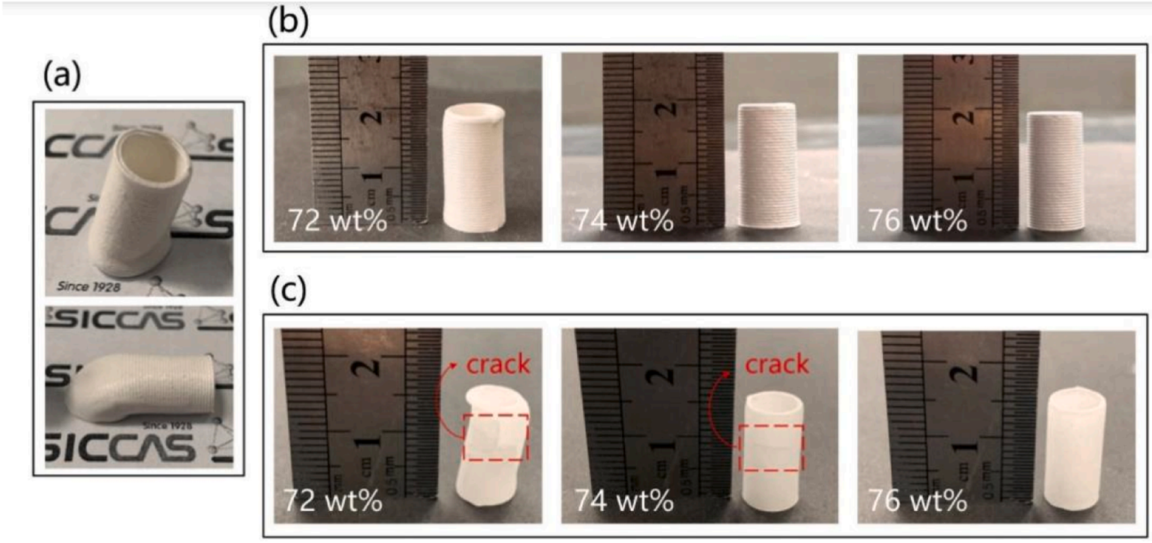

Fig. 12. (a) Samples without UV curing, (b) debinded ceramic green bodies prepared from slurries with varying solids loadings, and (c) the resulting ceramic forms [109].

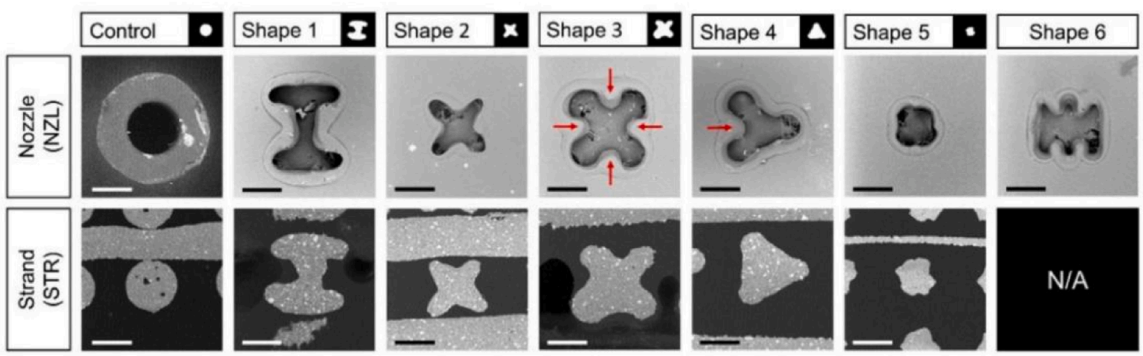

Fig. 13. A comparison between the nozzle orifice (NZL) and the cross-section of the 3D-printed strands (STR) for various tested geometries. Sharp curvature regions of the nozzles, where shape preservation was compromised, are indicated by red arrows [53].

In addition to material innovations, the customization of nozzles in the DIW process has contributed to advances in the field. In a novel approach, Raymond et al. [53] modified the DIW technique by replacing the standard circular nozzle with a bespoke modular non-circular design (Fig. 13). Using specially developed inks, they were able to print structures with complex filament cross-sections. This modification led to a significant increase in the surface-area-to-volume ratio of the printed elements, more than 2.5 times greater than those made with traditional cylindrical nozzles.

Further progress has been made in the additive manufacturing of large-sized Si_3N_4 ceramics. Yang et al. [54] employed DIW with stable, hydrogel-based suspensions to fabricate large Si_3N_4 ceramics. By adjusting rheology with CMC hydrogels and varying solid content, they optimised ink printability and stability for large-scale manufacturing.

Yongqin Zhao et al. [61] developed a novel approach to ceramic 3D printing by combining DIW with up-conversion particles (UCPs)-assisted photopolymerization (UCAP). This method integrates DIW with near-infrared induced UCP-assisted photopolymerization, allowing the printing of unsupported multi-scale and large-span ceramics. This method facilitates on-site filament curing with diameters between 410 μm and 3.50 mm. By applying this technique, they were able to build complex ceramic structures such as torsion springs, three-dimensional bends, and cantilever beams without the need for support. This innovative approach is expected to advance the unsupported 3D manufacturing of intricate ceramic shapes.

A very recent study by Bhandari et al. [64] further contributes to this field by investigating the rapid debinding and sintering of alumina ceramics fabricated through DIW. They prepared inks with two different ceramic loadings and printed log-pile structures using two different nozzle diameters. The samples were then subjected to various rapid sintering methods, including ultra-fast high-temperature sintering (UHS), pressureless spark plasma sintering (PSPS), and fast-firing (FF). The results showed that UHS and PSPS successfully densified the samples, while FF in air caused cracks. Notably, the study highlighted that both debinding and sintering could be achieved in a single step, and the ceramic loading and nozzle size significantly affected the densification process, with larger binder content and nozzle size leading to lower densities.

These advancements in material formulations, nozzle design, and sintering methods exemplify the potential of DIW technology to meet the demands of advanced ceramics, opening the door to more complex and high-performance 3D-printed ceramic components for diverse industrial applications.

3.3. Material properties and densification

Recent advancements in DIW 3D printing have significantly improved densification of resulting ceramics [104,58,107]. One notable development involves highly pure alumina and yttria powders mixed with 0.2 wt% MgO in aqueous media, with additives such as carboxymethyl cellulose and polyethyleneimine. These ceramics exhibited an average Vickers hardness of approximately 14.5 GPa and a relative density above 95 % after sintered at temperatures of 1600 and 1650°C. It is reported that attained structures were comparable with results of traditional techniques for the same materials [111]. This indicates the potential for high-performance ceramic components in various applications. The outstanding densification and mechanical performance are attributed to several key factors, including the particle size distribution of the Al_2O_3–Y_2O_3 system, the development of a well-dispersed and extrudable ceramic ink with optimal rheological properties, and the implementation of an optimised sintering cycle. SEM micrographs of the composites sintered for 2 hours at 1600°C and 1650°C are presented in Fig. 14. The uniform distribution of phases confirms effective material mixing and reactive sintering, yielding a refined microstructure.

Another notable advancement is the development of yttria-partially-stabilized zirconia ceramics using a high-solid loading slurry (60 vol%) for DIW. This extrusion-based AM technique, developed by Tianyu Yu et al. [52], achieved 98 % density and outperformed binder jetting and selective laser sintering in terms of fracture toughness, flexural strength, and compressive strength.

Incorporating nanoparticles has also been a key area of improvement for densification. A recent study explored the impact of nano-silica on the densification and rheological properties of DIW inks. By incorporating varying amounts of nano-silica (0–10 wt%) from waste rice husk ash into aqueous alumina-silica inks, the researchers found that higher nano-silica content reduced the solid-to-liquid ratio, improving packing efficiency and reducing porosity. The inclusion of nano-silica also enhanced the inks' rheological behaviour by increasing particle collisions and aggregation, which affected printability [112].

3.4. Rheology and process optimisation

The rheological properties of ceramic inks play a critical role in determining both the extrusion process and the filament's performance [63]. However, controlling the rheological properties of ceramic slurry is a complex challenge to meet the demands of 3D printing [113]. To address this, Aleksei Dolganov and his team [62] optimised titania inks for DIW to improve the Near-net-shape Electrochemical Metallisation (NEM) Process. They evaluated the rheological properties and extrudability of various ink formulations, finding that a TiO_2: H_2O: PEG (1:0.8:0.1) formulation was most effective. Viscosity issues at high shear rates were mitigated by adding 0.1 wt% oleic acid, enhancing product quality. The team also introduced a new printing method using removable support structures, improving stability during drying and reducing warping. Organic additives were selected for compatibility with biomedical applications. Similarly, Yarahmadi et al. [63] investigated zirconia-based ceramic inks, highlighting shear-thinning behaviour for efficient extrusion and identifying optimal loadings of 73 wt% for TZ-3YSB and 71 wt% for Zpex variants. Zpex-4 and Zpex-smile exhibited superior hardness, while TZ-3YSB and Zpex showed greater fracture toughness, offering insights for dental applications.

The reviewed studies indicate the remarkable adaptability and innovative potential of DIW in ceramic manufacturing, tackling key challenges across diverse applications. In biomedical applications, advancements in ink formulations, such as zirconia slurries with high solid content and calcium magnesium phosphate (CMP) scaffolds, demonstrate how DIW provides materials with controlled properties to achieve both biocompatibility and mechanical performance comparable to conventional methods. Similarly, in energy and sensing applications, progress in PZT and YAG ceramics indicates DIW's ability to produce dense, functional materials with performance comparable to traditional manufacturing techniques, while also enabling greater design complexity and customization. They also illustrate progress in addressing long-standing challenges in ceramic additive manufacturing, such as brittleness, densification, and scalability. For example, integrating graphene and carbon nanotubes into silicon carbide composites demonstrates the potential of hybrid methods to improve mechanical toughness. Additionally, developments in rheology and material stabilisation, such as the use of nano-silica and optimised high-solid-loading slurries, shows the efforts to enhance printability while maintaining the performance of the final product. Developing non-circular nozzles and

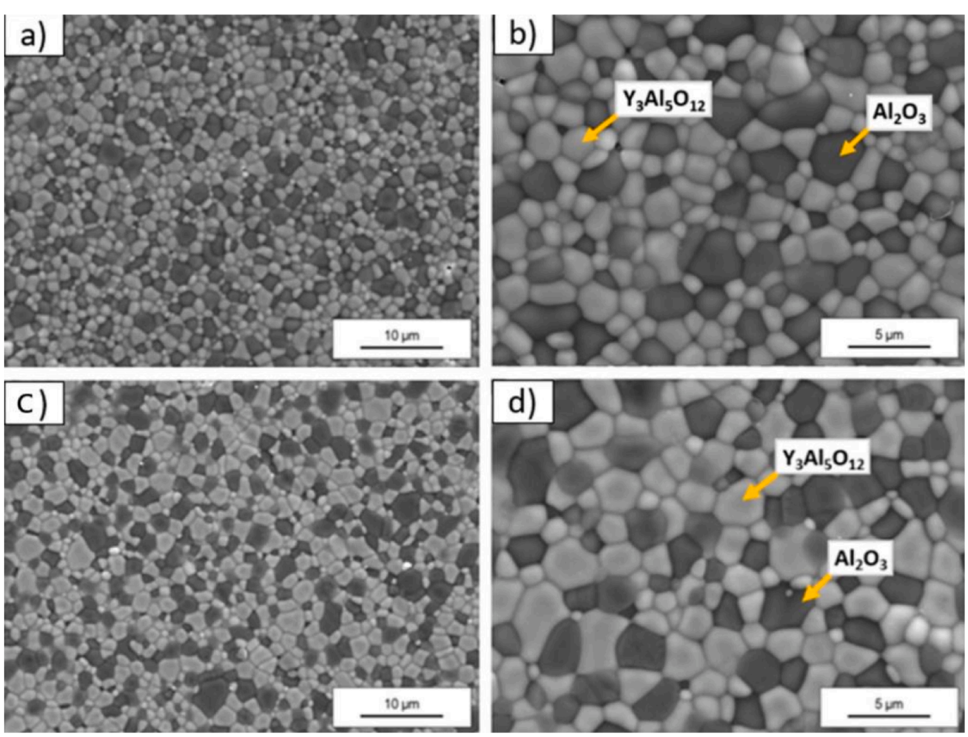

Fig. 14. SEM micrographs of Al_2O_3–YAG composites. Images (a) and (b) correspond to sintering at 1600°C for 2 hours, while images (c) and (d) pertain to sintering at 1650°C for 2 hours [111].

scaling up DIW processes shows how technical improvements can expand its applications while keeping it efficient.

These advancements show a clear move toward combining innovations from different fields to tackle current limitations, which enables DIW to meet the demands of high-performance applications in biomedical, environmental, and industrial fields. However, challenges like scaling up for mass production, ensuring material consistency, maintaining print quality, and managing costs still persist. This highlights the need for further research to optimise processes and establish standardized methods for assessing DIW-fabricated ceramics.

4. Tribological advancements in 3D-printed ceramics

Advancements in ceramic additive manufacturing have enabled the production of high-density ceramic components with improved mechanical characteristics and precise shape accuracy. Their particular functions for specific applications necessitate an assessment of the tribological performance of suitable materials [114]. Tribology, a field that gained formal recognition in 1966, explores the interactions of friction, wear, and lubrication between surfaces in relative motion within specific environments [115,116]. The tribological advancements in 3D-printed ceramics can be grouped into various areas, with each emphasising specific applications and optimisation approaches. The following sections review key studies in these areas, highlighting how tribological performance is being optimised for different industrial and biomedical applications.

4.1. Biomedical and bioceramics

Biomedical applications have a long-standing history with ceramics, attributed to their excellent biocompatibility and mechanical characteristics including tribological properties [114]. Most research on the tribological behaviour of 3D-printed ceramics has focused on biomedical applications.

In dental applications, efforts have been directed toward designing ceramic materials with improved wear resistance and fracture toughness to overcome challenges in dental restorations. Dental implants are gaining popularity due to their durability, versatility, enhanced functionality, and aesthetic appeal. At present, dental ceramics typically exhibit inadequate mechanical properties and lack sufficient fracture toughness. As 3D printing technology progresses, the application of this technology for crafting ceramic dental implants has emerged as a key focus in the realm of dental restoration [117,118]. That is, researchers are focusing on improving properties of these ceramic products by employing appropriate 3D printing techniques and refining the overall 3D printing process. For example, Branco et al. [119] optimised the amount of solid ZrO_2 for ink preparation of DIW 3D printing based on rheological behaviour of the paste and tribological and mechanical results. Focusing on wear, the study found that the composite with 25 % ZrO_2 showed the highest wear resistance and caused the least wear on opposing dental cusps (Fig. 15). The predominant wear mechanism was identified as two-body abrasion. Consequently, prosthetic components with 25 % ZrO_2 may serve as a viable alternative to conventional 3Y-TZP restorations with glaze, addressing problems such as abnormal wear on opposing teeth while preserving aesthetic qualities. In another study, Yang et al. [120] used stereolithography (SLA) to produce fluorapatite (FAp) ceramics for all-ceramic crowns and prosthetics. They investigated the impact of laser power and scanning speed on the mechanical and tribological properties of FAp glass-ceramics, comparing SLA samples with those made by traditional dry pressing. The study showed that optimisation of laser settings and a brief debinding process improves tribological and mechanical behaviour of these ceramics.

ZrO_2 ceramics are widely used in dental restoration because of their outstanding mechanical properties, biocompatibility, and aesthetic appeal [117]. Using vat photopolymerisation (VPP) 3D printing techniques, Zhang et al. [118] fabricated $ZrO_2(3Y)/Al_2O_3$ bioceramics designed for all-ceramic dental implants. Their study covered the optimisation process and wear performance of the bioceramic. Findings revealed that $ZrO_2(3Y)/Al_2O_3$ bioceramics produced by VPP hold great potential as a biomaterial for dental restoration applications. In the simulated oral environment wear test conducted in vitro, it was observed that artificial saliva imparted a lubricating effect. The wear mechanism changed from abrasive to adhesive wear with increasing load, highlighting the material's excellent wear resistance. In another study, Zhang et al. [121] efficiently utilised DLP technology to produce high-density ZrO_2 (3Y-TZP) ceramic dental crowns. The slurry used for printing had a solids content of 80 %. Following sintering at 1500 °C, the crowns displayed significantly improvement in mechanical properties and wear resistance. In addition, Branco et al. [122] investigated the tribological characteristics of human teeth in combination with zirconia created through robocasting, with a focus on understanding enamel wear patterns. They compared produced zirconia samples by unidirectional compression (UC) and robocasting (RC) in terms of their hardness, density, toughness, crystalline structure, and porosity. The study found that, despite the RC and UC samples having comparable properties, they differed in terms of surface roughness and porosity. Although the zirconia samples themselves did not show wear, the opposing cusps displayed similar wear patterns. The annual reduction in height and specific wear rate of dental cusps for RC and UC samples are depicted in Fig. 16. These results indicate that robocasting holds potential as an effective method for creating customized zirconia dental components, especially concerning their overall tribological performance.

In a recent study, Wei Shen et al. [123] studied the effect of Al_2O_3 whiskers on the properties of 3D-printed fluorapatite (FAp) glass-ceramics. They found that adding 15 % Al_2O_3 whiskers improved wear resistance by 85 %, reducing the wear rate to $2.4 \pm 0.2 \times 10^{-5}$

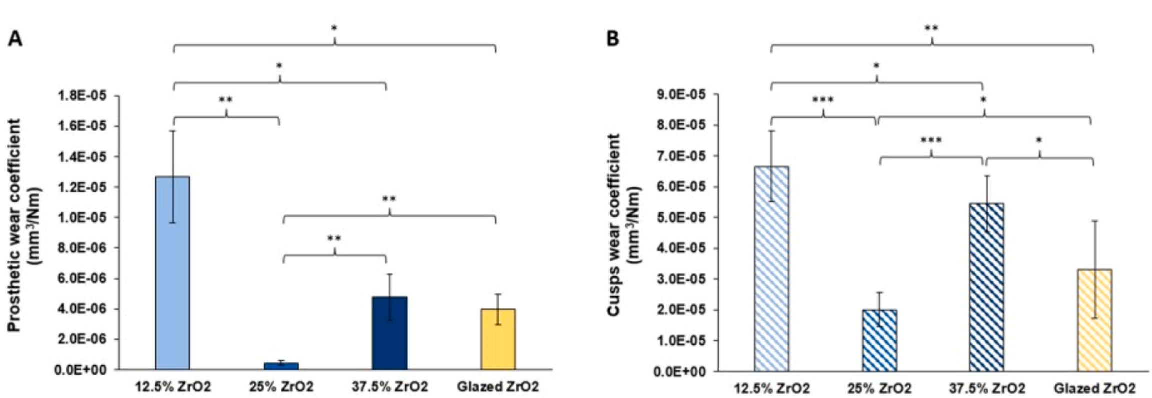

Fig. 15. (A) Wear on printed materials, (B) Wear on cusps. (A significance level of 0.05 was set, with asterisks indicating statistical differences between the data sets (* $p < 0.05$, ** $p < 0.005$, *** $p < 0.0005$) [119].

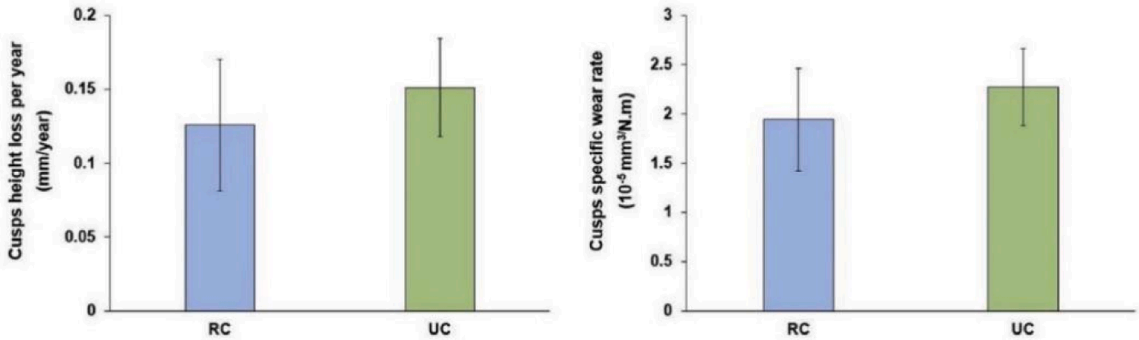

Fig. 16. Annual height reduction and specific wear rate of dental cusps tested with RC and UC samples [122].

mm^3 /N m. The whiskers enhanced mechanical properties and structural integrity, reducing microcracks and delamination. Wear mechanisms shifted from abrasive to primarily adhesive and fatigue wear with whisker inclusion.

The tribological properties of ceramics play a crucial role in bone applications, where minimising wear and mechanical failure is essential. The next study investigates the use of 3D-printed ceramics to create bone-like structures with improved tribological performance. For instance, in the study by Goyos-Ball et al. [124], porous structures were produced using robocasting with a composite of 10 mol% ceria-stabilised zirconia and alumina. The researchers discovered that round lattice structures exhibited compression strength comparable to cortical bone, were non-cytotoxic, and promoted osseous differentiation. Additionally, the printed parts demonstrated good aesthetics, chemical stability, and negligible corrosion and wear.

Orthopedic ceramic implants must exhibit high wear resistance and mechanical strength. Paterlini et al. [114] assessed DLP-printed alumina, yttria-stabilised zirconia (3YZ), and zirconia-toughened alumina (ZTA) with 10–20 wt% zirconia. ZTA demonstrated superior mechanical and surface properties, while alumina maintained consistent friction and wear. Zirconia showed higher wear rates, limiting its suitability. This research highlights DLP ceramics' potential for advanced orthopedic and industrial applications.

4.2. Industrial and engineering applications

The use of 3D-printed ceramics in industrial settings, especially for cutting tools and high-performance applications, requires materials with exceptional tribological properties. In this context, Wei Liu et al. [125] analysed how zirconia-toughened alumina (ZTA) ceramic cutting tools, created with vat photopolymerisation-based 3D printing, perform during cutting and how they wear over time. Their study examined how feed rate, cutting speed, and depth of cut influenced surface roughness and wear mechanisms. The tools demonstrated no microchipping during HT250 cutting, with adhesive and diffusive wear dominating at moderate speeds. At higher speeds and adjusted feed rates, abrasive wear became more significant. In addition, Wu et al. [126] studied the cutting efficiency and wear mechanisms of Al_2O_3 ceramic tools with chip-breaking grooves made via vat photopolymerization-based 3D printing. Their findings showed both abrasive and adhesive wear for alumina tools, while cemented carbide tools experienced adhesive wear and breakage. The tools had a relative density of 99.34 %, Vickers hardness of 18.3 GPa, bending strength of 513 MPa, and fracture toughness of 3.5 MPa·$m^{1/2}$. They also found that cutting speed, feed rate, and cutting depth affected flank wear and surface roughness, with cutting speed being the most influential factor.

Improving the tribological properties of 3D-printed ceramics is crucial for their performance in demanding applications. Researchers have been addressing this issue to enhance the durability and functionality of these materials. A. Amanov and R. Karimbaev [127] investigated the effects of ultrasonic nanocrystal surface modification (UNSM) on the mechanical and tribological properties of 3D-printed silicon carbide (SiC). They found that UNSM treatment reduced surface roughness, improved hardness, and decreased the coefficient of friction (COF) and specific wear rate. At room temperature, surface roughness decreased from 10.5 μm to 6.5 μm, and hardness increased from 2100 HV to 2500 HV. At high temperature, roughness and COF improved further, suggesting UNSM-treated SiC as a promising material for high-temperature applications like aerospace and optics.

Tables 3 and 4 summarise tribology advances in 3D printing of ceramics.

The table shows that notable advancements in material composition, 3D printing techniques, and post-processing methods have significantly enhanced the tribological performance of ceramics. In the biomedical field, advancements such as improved material formulations, modern 3D printing methods, and innovative surface treatments have enhanced wear resistance, fracture toughness, and biocompatibility, particularly in dental restorations and orthopedic implants. For industrial applications, tailored compositions and techniques like ultrasonic nanocrystal surface modification (UNSM) have improved performance under high mechanical loads, increasing cutting efficiency and reducing wear. Continued research in this area has the potential to further enhance material performance and expand its applicability across diverse sectors.

5. Challenges and future perspectives

DIW-printed items have shown remarkable performance and promise across various sectors, such as biomedical applications, energy storage and conversion technologies, and environmental pollution reduction. Despite its promise, Direct Ink Writing 3D printing faces several challenges in development. DIW-printed products often suffer from weak mechanical strength as a consequence of the layer-by-layer assembly process and physical crosslink interactions between gel precursors, which can hinder handling and prolonged use, especially in hybrid materials with gel ink printed constructs. The layer-by-layer deposition process in DIW faces a challenge when higher printing speeds compromise the integrity of the interface, whereas achieving a superior interfacial structure necessitates slower printing speeds [128]. Additionally, structural flaws including trapped gas, voids, or irregularities can affect the interface, resulting in insufficient bonding between layers. Several post-printing techniques, like hot or cold isostatic pressing and lamination, have been proposed to mitigate these issues [15].

To overcome these challenges, developing binder-free printable DIW hybrid nanomaterial gel inks, which could boost specific capacity and conductivity, is essential [35]. Current DIW inks often require additives that can be toxic and detrimental to performance. Investigating DIW inks made from pure nanomaterials without additives could improve print quality. Examining the rheological characteristics of binder-free hybrid inks is necessary to avoid structural defects. Optimising

Table 3
Summary of tribology studies of 3D-printed ceramics (2019–2024).

Materials	Findings	3D Printing Technique	Ref.
Investigated zirconia composites for dental applications	- Identified significant improvements in wear resistance for zirconia composites (25 % ZrO_2). - Porosity reduction led to better frictional performance	Robocasting	Branco et al. (2024) [119]
Explored 3D-printed fluorapatite (FAp) glass-ceramics for dental use	- Enhanced wear resistance with optimal SLA settings. - Achieved low friction coefficient through improved surface hardness.	Stereolithography (SLA)	Yang et al. (2021) [120]
Produced ZrO_2(3Y)/Al_2O_3 bioceramics for dental implants using VPP	- Demonstrated excellent wear resistance in simulated oral conditions. - Surface roughness optimized for reduced friction.	Vat Photopolymerization (VPP)	Zhang et al. (2022) [118]
Investigated DLP 3D printing for high-density ZrO_2 (3Y-TZP) crowns	- Achieved higher compressive strength and wear resistance compared to traditional crowns. - Reduced friction via improved microstructure.	Digital Light Processing (DLP)	Zhang et al. (2024) [121]
Studied tribological properties of ZrO_2 for dental applications	- Robocasting showed lower wear and better surface integrity compared to unidirectional compression. - Identified specific wear mechanisms on opposing cusps.	Robocasting	Branco et al. (2020) [122]
Examined porous ceramics made by robocasting with ceria-stabilized zirconia	- Porous zirconia composites showed similar mechanical properties to bone, reducing friction and wear. - Promoted osseous differentiation, supporting long-term performance in medical applications.	Robocasting	Goyos-Ball et al. (2017) [124]
Studied Al_2O_3 whiskers' effect on FAp glass-ceramics in SLA printing	- Al_2O_3 whiskers reduced wear by 85 %, enhancing tribological performance. - Reduced friction through structural reinforcement.	Stereolithography (SLA)	Wei Shen et al. (2024) [123]
Investigated DLP-printed ceramics for orthopedic applications	- ZTA composites exhibited superior wear and friction properties compared to alumina and zirconia. - Wear mechanisms revealed frictional stability over time.	Digital Light Processing (DLP)	Paterlini et al. (2021) [114]
Explored ultrasonic nanocrystal surface modification (UNSM) of SiC ceramics	- UNSM treatment significantly reduced surface roughness and friction.- Enhanced hardness and wear resistance, particularly at high temperatures.	Binder jetting	Amanov & Karimbaev (2021) [127]
Analyzed wear behavior of ZTA ceramic cutting tools using 3D printing	- Identified specific wear mechanisms under different cutting conditions. - Improved friction performance of ZTA cutting tools for industrial applications.	Vat Photopolymerization (VPP)	Wei Liu et al. (2023) [125]
Studied wear of Al_2O_3 ceramic tools with chip-breaking grooves via DLP 3D printing	- Al_2O_3 tools exhibited excellent wear resistance and low friction.- Improved surface properties reduced abrasive wear.	Digital Light Processing (DLP)	Wu et al. (2023) [126]

Table 4
Application-based classification for tribology studies of 3D-printed ceramics (2019–2024).

Study	3D-printing Techniques	Biomedical Applications	Industrial Applications	Porous Structures & Biocompatibility	Material Development & Tribological Improvement	Processing & Optimization
Branco et al. (Leucite-based composite pastes)	Robocasting	✓			✓	✓
Branco et al. (Tribological characteristics of human teeth with zirconia)		✓			✓	
Goyos-Ball et al. (Ceria-stabilized zirconia for bone restoration)		✓		✓	✓	
Wei Liu et al. (ZTA ceramic cutting tools)	Vat Photopolymerization (VPP)		✓		✓	
Wu et al. (High-performance Al_2O_3 cutting tools)			✓		✓	
Zhang et al. (ZrO_2/ Al_2O_3 bioceramics for dental)		✓			✓	✓
Yang et al. (Fluorapatite ceramics for dental)	Stereolithography (SLA)	✓			✓	
Wei Shen et al. (Al_2O_3 whiskers in FAp glass-ceramics)		✓			✓	
Zhang et al. (DLP for ZrO_2 (3Y-TZP) dental crowns)	Digital Light Processing (DLP)	✓			✓	
Paterlini et al. (DLP-printed ceramics)		✓			✓	✓
Amanov and Karimbaev (UNSM treatment for SiC)	Binder jetting		✓		✓	

electrical conductivity and mechanical strength in DIW products is crucial for applications such as energy storage devices. Advanced synthesis techniques and systematic studies are needed to effectively balance these properties [35].

The speed and printing resolution of DIW have not yet reached their ideal standards needed for widespread use and industrial application. As it stands, to create large-scale structures with complex designs and detailed architectural elements, it would be necessary to invest impractically long periods and substantial effort in ink formulation and parameter optimisation [87]. Additionally, many printed structures do not exhibit material properties that surpass those of cutting-edge 3D printed or conventionally produced counterparts [129]. For example, flexible piezoelectric nanogenerators produced through 3D printing generate less energy compared to their conventionally manufactured counterparts. Therefore, to serve as a replacement for current standard devices and structures, DIW must develop the ability for large-scale production along with improved efficiency [15].

DIW has lower energy demands compared to traditional manufacturing, but post-processing steps like drying or sintering can raise costs and time. To mitigate this, DIW practitioners seek to integrate shaping and consolidation in one operation or use more effective techniques for sintering, ensuring the process remains sustainable and cost-effective. However, reducing post-printing processes and optimising sintering techniques can present significant challenges [15]. DIW has a fixed cost per unit, making it cost-effective only for small production volumes due to its lower initial funding. Conversely, conventional manufacturing, despite higher primarily costs, becomes more economical with increased production volume [130]. However, DIW does not enjoy the advantages of economies of scale, unlike other additive manufacturing methods. Despite requiring the smallest initial investment, DIW cannot overcome this limitation. The difficulty in scaling up production is among the most important obstacles to DIW's widespread integration into mass production [15].

In fibre-reinforced composite manufacturing with DIW, nozzle clogging often occurs because the reinforcing fibres' length is roughly equivalent to the nozzle diameter. This means that even minor misalignments of fibres can block the nozzle. Thus, a major hurdle for DIW technology is minimising nozzle clogging through efficient pre-printing processing techniques [77].

Printing parameters like nozzle diameter and flow path constrain the resolution of printed fibres and patterns. DIW's ability to create detailed microscale architectures is well-established, but its application in nanoscale structures is underexplored, limiting its versatility. The technology lacks standardised guidelines for optimal printing conditions across different materials, hindering broader research and application development [15].

6. Conclusion

The review emphasises the expansive opportunities afforded by 3D printing and highlights crucial position of DIW in additive manufacturing. It covers advancements in material exploration and conducts an analysis of the tribological characteristics of 3D-printed ceramics compared to conventional techniques. Recent advancements in DIW of ceramics have revolutionised the field of additive manufacturing, which shows remarkable improvements in material properties, fabrication methods, and application potential. The innovative techniques and research findings reviewed highlight the dynamic progress in DIW, from optimizing printability and quality through rheological and finite element analyses to the development of high-performance ceramic composites. The incorporation of nanoparticles, as explored in recent research, has significantly impacted the densification and rheological properties of inks, further enhancing the printability and performance of DIW-fabricated ceramics. The customization of slurries for specific applications, such as dental components, and the development of modular nozzles have opened new avenues for creating intricate and high-performing ceramic structures. Moreover, DIW has proven instrumental in fabricating glass ceramics and transparent ceramics with impressive optical qualities, highlighting its potential in specialised fields like electronic packaging and optical devices. In the domain of tribological behaviour, DIW-fabricated ceramics have shown enhanced wear resistance and mechanical properties, making them suitable for biomedical applications, particularly in dental restoration. The ability to produce dense, high-performance ceramics with precise shape accuracy and favourable tribological properties underscores the transformative impact of DIW on ceramic additive manufacturing.

Advanced 3D printing techniques face a significant challenge with post-printing treatments due to their high energy demands, especially when manufacturers aim to eradicate structural defects within interlayer spaces. This challenge is particularly heightened in the pursuit of environmentally sustainable manufacturing, where the energy costs associated with consolidation processes like drying or sintering must be meticulously controlled. As a result, future research may prioritise strategies to simplify post-printing procedures, such as integrating consolidation and shaping into a unified step or adopting more efficient sintering technologies like cold or field-assisted methods. Furthermore, DIW technology encounters the ongoing issue of nozzle clogging, underscoring the critical research need for implementing effective pre-printing processing techniques. In general, directing efforts towards tackling the complexities related to ink rheology, structural integrity, and scalability in DIW 3D printing of ceramics represents a significant opportunity to advance the technology.

In conclusion, the continuous advancements in DIW technology are driving the evolution of ceramic manufacturing, offering unprecedented opportunities for creating high-quality, complex, and application-specific ceramic components.

Statement of originality

The authors declare that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere

CRediT authorship contribution statement

Otsuka Y.: Writing – review & editing, Validation, Methodology, Formal analysis. **Jamadon N.H.:** Writing – review & editing, Validation, Methodology. **Ghazali Mariyam Jameelah:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Alebrahim M.:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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