

Review

# Glass Additive Manufacturing Technologies: Approaches, Applications, and Challenges

Edwin Francis Cárdenas Correa <sup>1,\*</sup> , Edgar Absalón Torres Barahona <sup>1</sup>  and Alison Dayana García Rodríguez <sup>2</sup>

<sup>1</sup> Department of Electromechanical Engineering, Universidad Pedagógica y Tecnológica de Colombia, Tunja 150003, Colombia; edgar.torres@uptc.edu.co

<sup>2</sup> Department of Mechanical Engineering, Universidad de Guanajuato, Guanajuato 36000, Mexico; ad.garcia.rodriguez@ugto.mx

\* Correspondence: edwin.cardenas01@uptc.edu.co

## Abstract

Glass additive manufacturing (AM) is a developing technology, particularly in comparison to metals and polymers, both of which have had their processes and applications extensively studied. Its potential lies in fabricating complex, even micrometric, geometries that are difficult or impossible to achieve via traditional molding, as well as in producing components with unique optical properties. The diversity of AM techniques, alongside the challenges associated with the high melting point, rheological control, and fragility of glass, necessitates a comprehensive analysis of current developments. Accordingly, this review presents a systematic review, conducted in accordance with the PRISMA protocol, of recent literature regarding AM technologies that fabricate glass via particle fusion to form solid components. This review explicitly excludes techniques utilizing glass fibers as reinforcement, as that constitutes a separate field of inquiry. The results demonstrate sustained growth within the field, with a predominance of technologies based on photopolymerization and ink extrusion, both of which offer high resolution and microstructural control. Ultimately, this review establishes the current state of the art, identifying critical challenges and emerging lines of research to guide future development. It is intended to serve as a foundational reference for researchers and professionals seeking to initiate or expand their work in glass AM.

**Keywords:** additive manufacturing; materials; glass; 3D printing technologies

## 1. Introduction

Additive manufacturing (AM), historically and popularly referred to as 3D printing, has emerged as a novel industrial method for producing components with complex, customized geometries while simultaneously minimizing material waste [1,2]. For the purposes of this review, the standard international term ‘additive manufacturing (AM)’ will be preferentially used to encompass all layer-by-layer fabrication techniques. Although AM development has predominantly focused on polymeric and metallic materials, glass AM has emerged as a viable alternative due to the material’s unique refractory, optical, and thermal properties [3,4]. Furthermore, the capacity of AM to fabricate sophisticated glass structures enables the development of high-performance components that are difficult or impossible to produce via conventional molding techniques.

Utilizing glass in these technologies presents unique challenges related to its melting temperature, rheological behavior, and intrinsic fragility [5–7]. These specific characteristics



Academic Editor: Jing Shi

Received: 24 June 2026

Revised: 5 August 2026

Accepted: 6 August 2026

Published: 7 August 2026

**Copyright:** © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

drive the development of various AM techniques, which are broadly classified into direct and indirect methods. Direct methods involve the localized fusion of the material, whereas indirect methods require a subsequent post-printing processing stage, such as furnace sintering, to achieve the final component properties. In glass AM, printability can be defined as the ability of a given glass feedstock, ink, melt, filament, or photosensitive precursor to be processed reproducibly into a three-dimensional architecture with sufficient dimensional fidelity, shape retention, and interlayer cohesion throughout deposition, consolidation, and immediate post-processing [8].

During the early 2010s, foundational glass AM research primarily focused on biological applications, demonstrating that Direct Ink Writing and Selective Laser Sintering could produce bioactive glass scaffolds with controlled interconnected porosity and tailored mechanical strength after sintering [9,10]. By 2013–2014, the field advanced through more systematic control of feedstock formulation and processing, including the use of single organic additives such as carboxymethyl cellulose [11,12]. In parallel, stereolithographic ceramic manufacturing demonstrated the feasibility of producing glass–ceramic components with homogeneous microstructures and high density [13]. This advancement mapped out the diverse multi-technology landscape that preceded the rapid expansion of glass AM after 2015.

The integration of glass fibers into composite materials to enhance mechanical properties, such as elastic modulus and impact resistance, constitutes a distinct research domain [14,15]. Conversely, the fabrication of monolithic parts via glass AM, without reinforcing fibers, opens various application fields, including advanced optics [16], nanostructures and microfluidics [17], photonic devices, and microtoroidal resonators [18]. In this context, it is necessary to distinguish the capabilities and characteristics of monolithic glass AM from those of glass-reinforced composite AM. This review focuses on AM processes that involve the fusion of vitreous material particles, examining the underlying technological principles, processing strategies, and relationships between printing parameters. This scope eliminates the influence of reinforcing elements, enabling a focused analysis of the intrinsic phenomena governing glass AM, such as viscosity and the structural quality of the printed components.

The article is structured as follows: Section 2 outlines the methodology employed, including the use of the PRISMA protocol for systematic reviews. Section 3 presents a descriptive literature analysis, detailing publication trends and thematic maps of recent research derived from bibliometric data. Subsequently, Section 4 provides a thematic analysis of glass AM, examining the materials and printing technologies utilized, as well as the processing parameters required to produce printed components. Finally, Section 5 discusses the primary challenges, opportunities, and future directions for research.

## 2. Materials and Methods

The focus of this review is to analyze additive manufacturing technologies applied to the fabrication of glass components—excluding fiber reinforcement approaches—to establish their level of technological development, the involved processing parameters, and their implications for final performance and sustainability. In this context, the following research questions were posed:

- Which additive manufacturing technologies exhibit the highest potential for the advancement of glass AM?
- What are the novel applications currently being investigated in the domain of glass AM?
- What are the critical factors and challenges associated with the implementation of AM using recycled glass?

- In what ways does glass AM facilitate sustainable development?

To address these questions, this review is structured according to the PRISMA methodology, utilizing a specific checklist designed for systematic analysis to ensure clear, transparent, and reproducible results. Texts were classified using explicit inclusion and exclusion criteria to rigorously and precisely prioritize the studies. Additionally, a flow diagram is provided to clarify the article selection and exclusion process. The implemented steps are detailed below.

Following the formulation of the research questions, a bibliographic search of the Scopus database was conducted in July 2025. Regarding the choice of a single repository, Scopus was chosen because it offers an extensively broad and practical coverage for engineering and materials science disciplines. Utilizing this single robust database ensures a highly consistent metadata structure, which minimizes raw data compatibility errors during the bibliometric compilation while capturing the core scientific production of the field.

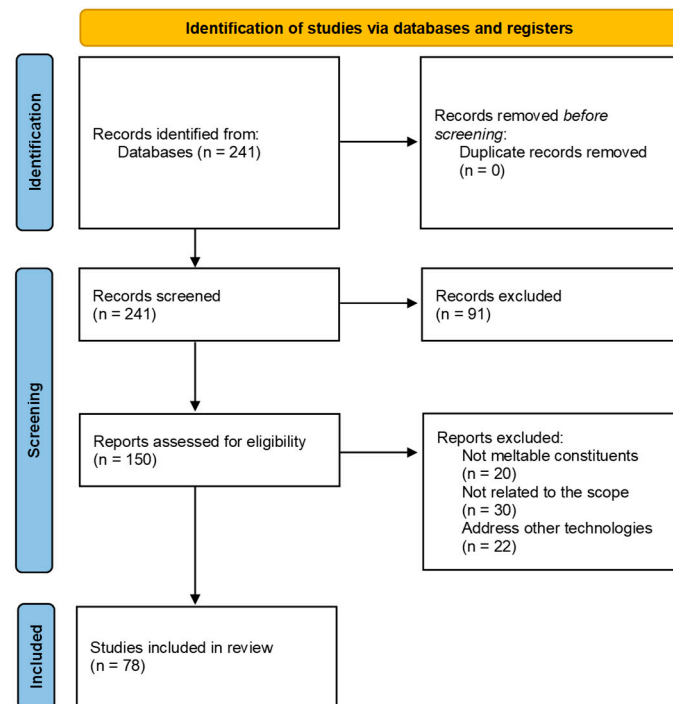
Strategic search terms were selected to compile the pertinent literature, ensuring a broad and inclusive search to identify relevant studies. The search strategy utilized the query ("Glass print\*" OR "Print\* glass" OR "Additive manufactur\* of glass" OR "Glass 3D print\*" OR "Glass-based additive manufacturing" OR "Glass prototyping"). Terms such as "recycling," "sustainability," and their variants were deliberately omitted to facilitate a broad search and allow for a comprehensive literature analysis. Exploratory searches showed that adding these restrictive terms directly to the Boolean equation produced very few records. To mitigate omission bias, they were systematically extracted and assessed from the final records obtained using the PRISMA methodology. This process identified 241 records published between 2015 and 2025; extending the search prior to 2015 yielded no additional records.

Figure 1 presents the PRISMA flow diagram illustrating the process stages. Initially, 241 documents were identified via the search query. Subsequently, inclusion criteria were applied—limiting the selection to English-language texts, journal articles, and review articles—to prioritize studies with significant results and robust methodologies. To assess the potential selection bias introduced by the inclusion criteria that restricted the final selection to English publications, a language distribution analysis was conducted. From the initial set of 241 records, 229 (95.02%) were published in English. Contributions in other languages accounted for only 4.98% of the total, consisting of texts in Chinese (9 articles), German (1), Korean (1), and Turkish (1). Consequently, limiting the review to English-language documents maintains peer-review consistency while preserving the thematic, bibliometric, and technological insights of the glass additive manufacturing landscape.

Conference proceedings and editorial letters were excluded from the analysis. While conference papers frequently present valuable early-stage insights in rapidly advancing technological fields, full-length articles published in indexed journals were prioritized to ensure the standard of double-blind peer-review rigor, methodological completeness, and fully validated experimental data. This screening step resulted in the reduction of the dataset from the initial 241 records to 91. Although this approach may introduce potential selection bias, it was deemed appropriate in order to exclude studies that did not meet predefined standards of methodological rigor.

The final selected publications, designated as "included studies," were exported and processed using the Bibliometrix 5.0 package (implemented in the R environment) for data cleaning, author normalization, scientific performance analysis, and the construction of bibliometric indicators. Keyword co-occurrence and co-citation networks were analyzed and visualized using VOSviewer V.1.6.20 to facilitate the identification of thematic clusters.

These procedures constitute the descriptive analysis, which defines the research patterns and emerging areas within the studied domain.



**Figure 1.** PRISMA Flow Diagram of Study.

Following the descriptive analysis, a thematic analysis was conducted to systematically examine the materials used, compare the different technologies, assess their inherent limitations, and identify future research opportunities in glass AM.

### 3. Descriptive Analysis

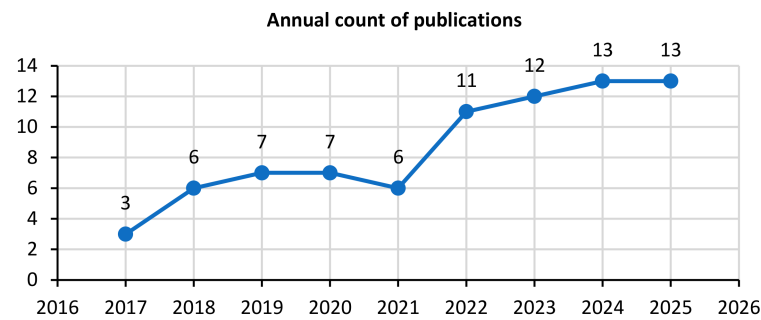
This section provides a descriptive analysis of recent advances in additive manufacturing technologies applied to the fabrication of glass components. VOSviewer was used to categorize the primary themes of the publications, while Bibliometrix was utilized to conduct a comprehensive metadata analysis of the included records.

#### 3.1. Primary Information Analysis

Figure 2 illustrates the temporal distribution of the analyzed articles. The trend, exhibiting an annual growth rate of 20.12%, highlights a rapidly expanding research field and indicates increasing interest among new researchers. The prevalence of 73 research articles, compared to five review articles, suggests that this field is in an active production phase. Notably, the number of publications continues to increase; records spanning up to mid-July 2025 had already reached the total productivity of the preceding year.

Source analysis reveals that 25% of the publications involve international collaboration. This cooperative network is vital for knowledge exchange and the global dissemination of research findings.

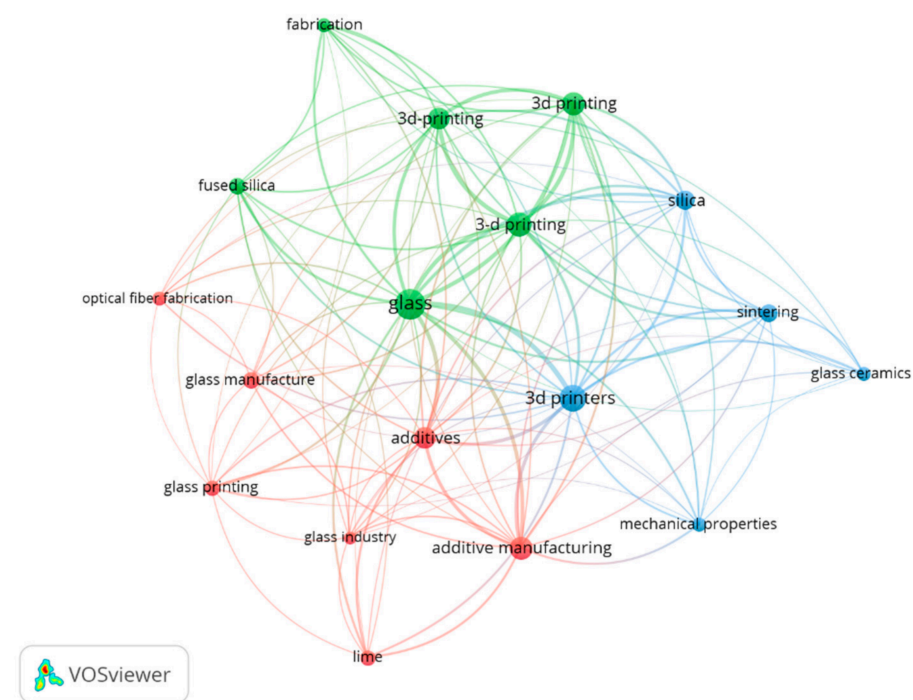
The search strategy was specifically tailored to isolate studies on glass additive manufacturing via particle fusion or sintering. Although these criteria defined a primary dataset of 78 core publications, additional reference studies were qualitatively incorporated and discussed within the Section 4 to complement the quantitative synthesis and mitigate potential thematic omissions.



**Figure 2.** Distribution of the 78 Publications Related to Glass Additive Manufacturing.

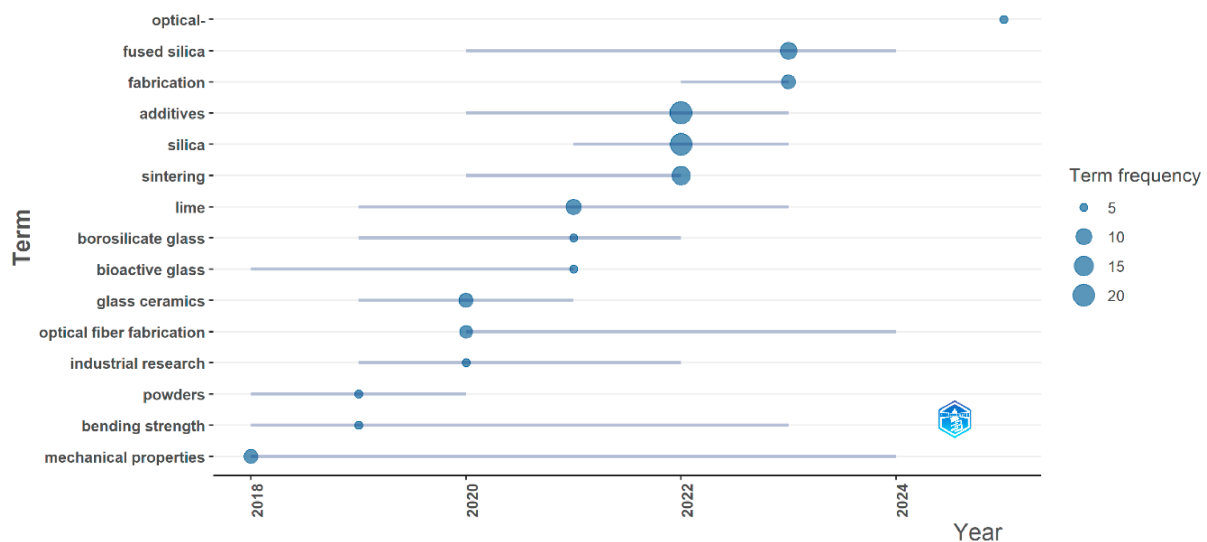
### 3.2. Co-Occurrence and Trends

The co-occurrence map (Figure 3) demonstrates that the central term is “glass,” which exhibits a high correlation with “3D printing.” Three clearly differentiated subthematic clusters are identified. The first cluster (green) forms the core of research activity surrounding the term “glass” and demonstrates that glass additive manufacturing is directly associated with silica fusion. The second cluster (red) focuses on the analysis of additives and specific applications. The third cluster (blue) emphasizes the component sintering process and resulting mechanical properties. Collectively, these findings indicate that research recurrently addresses process development, material studies, and the properties achieved via glass AM.



**Figure 3.** Co-Occurrence of All Keywords Related to glass AM Literature.

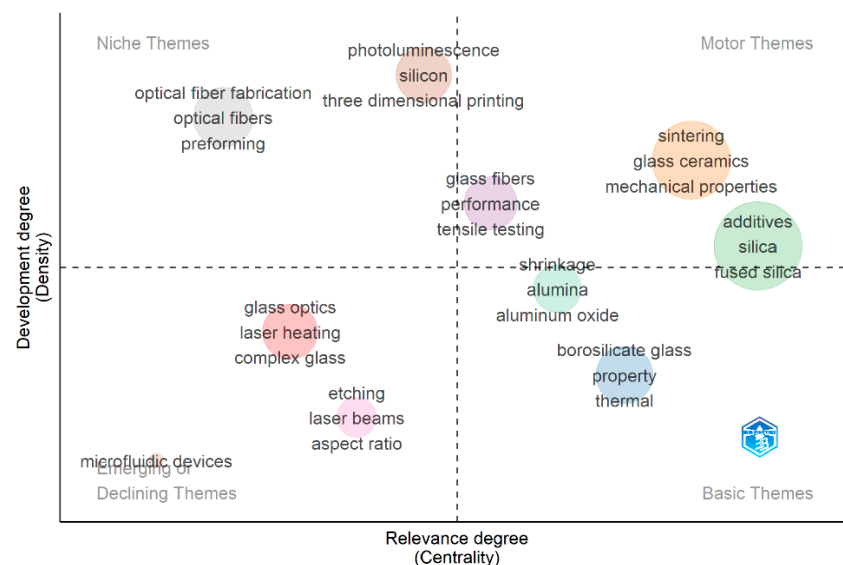
The exclusion of redundant or equivalent keywords, such as “3d printing” and “3-d printing,” reveals the general trends shown in Figure 4. These trends suggest a transition from basic characteristics toward the investigation of specific aspects, such as manufacturing processes and the role of additives, and, more recently, the analysis of the thermal and optical properties of the printed parts.



**Figure 4.** Trend Analysis of Consolidated Keywords and Research Themes by Year.

### 3.3. Interrelation of Themes and Global Overview

An analysis of keywords within the conceptual structure of glass AM research is presented in Figure 5. “Motor themes” are characterized by a high degree of development (Density) and high relevance to other themes (Centrality). The map reveals that research on mechanical properties and additive analysis drive these investigative lines. “Basic themes” exhibit a transversal character that articulates with numerous developments. These themes primarily relate to specific component materials, such as alumina and borosilicate glass.

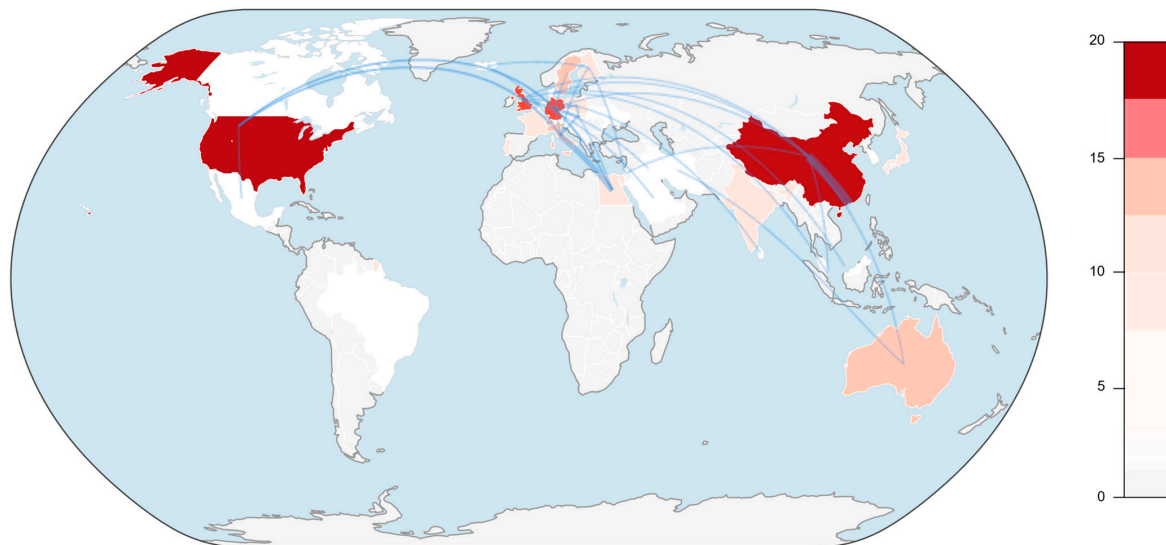


**Figure 5.** Thematic Map of Glass Additive Manufacturing Literature.

“Niche themes,” including photoluminescence and the development of optical fiber-based technologies, constitute highly specialized areas of active research. Finally, themes with a lower degree of development may be interpreted either as losing relevance (e.g., traditional laser printing techniques) or as opportunities for future research, notably including microfabrication and addressing the intrinsic problems of printed parts.

Regarding author collaboration, the international cooperation diagram (Figure 6) demonstrates that the United States and China are the primary hubs of scientific research production. Western Europe (specifically the United Kingdom, Germany, and France) serves as another significant nucleus for knowledge generation and research. Furthermore,

broad international cooperation is observed, which drives and provides opportunities for nations with limited research productivity, such as countries in Latin America and Africa.



**Figure 6.** Country Collaboration Map in Glass Additive Manufacturing Research. The Color Scale Indicates the Number of Publications per Country, Highlighting the United States, China, and Germany as the Prominent Nodes. The Connecting Blue Arcs Represent Active International Co-Authorship Pathways, Illustrating the Collaborative Links Between Principal Research Clusters.

The macro-level bibliometric and conceptual mapping presented in this section provides a structured foundation that directly dictates the trajectory of the subsequent thematic analysis. This global and collective framework of scientific production highlights the accelerated growth of publications and the consolidation of global co-authorship networks. Consequently, it establishes the structural baseline required to explore the technical fundamentals behind these research trends. Consequently, to understand the research themes identified within the field's conceptual structure, it is necessary to move beyond general metric descriptions toward a detailed qualitative evaluation of materials and fabrication systems. To this end, the subsequent section develops a thematic analysis focused on the physical properties of the diverse glass families utilized while classifying additive manufacturing technologies alongside the processing parameters and intrinsic defects that govern the ultimate quality of monolithic glass components.

## 4. Thematic Analysis

### 4.1. Glass in Additive Manufacturing: Properties and Applications

Glass is an inorganic material characterized by its hardness, transparency, chemical stability, durability, versatility, and recyclability [19]. Its applications range from optical components and microstructures for photonics to microfluidic devices and biomedical tools, where its dimensional accuracy and intrinsic properties offer notable advantages over conventional materials [20]. However, incorporating glass directly into additive manufacturing processes presents challenges related to its fragility, elevated melting temperature, and viscous behavior during printing. Research in this area therefore focuses on establishing printability and post-processing conditions that best preserve the material's intrinsic properties.

#### 4.1.1. Types of Glass in AM

The scientific literature primarily classifies glasses by their chemical composition. The most common are silicate glasses, based on silicon dioxide ( $\text{SiO}_2$ ), which account for the

vast majority of applications. Specialized variants include chalcogenide and phosphate glasses. The selection of glass type and printing technique depends on the required dosage form, processing temperature, intended application of the printed components, and desired resolution, among other characteristics [21]. The primary types of glass used in additive manufacturing can be differentiated as follows:

**Silica Glass:** These glasses are characterized by a high silicon dioxide ( $\text{SiO}_2$ ), content, typically exceeding 90%, which provides a highly stable amorphous structure and outstanding optical properties. They exhibit high transparency across a wide spectral range, high chemical resistance to most corrosive agents, and notable thermal stability. Additionally, their low thermal conductivity and reduced thermal expansion coefficient (approximately  $0.5 \times 10^{-6} \text{ K}^{-1}$  for fused silica) confer excellent resistance to thermal shock [22–25]. Nevertheless, their optical and mechanical properties can be significantly compromised by impurities (e.g.,  $\text{OH}^-$  groups or metallic contaminants) and the specific processing conditions used during fabrication [23,24].

Within this family, fused silica (or quartz glass) represents the highest-purity form ( $\text{SiO}_2 > 99\%$ ) and offers the best functional performance. This material is further distinguished by excellent structural homogeneity and high optical transmission ranging from the ultraviolet to the near-infrared spectra [22,26]. These characteristics make it particularly suitable for advanced applications, including micro-optics, optical fibers, microfluidic devices, and high-precision systems.

In the context of additive manufacturing, fused silica is rarely processed directly because its elevated softening point (exceeding 1500–1700 °C) limits its compatibility with conventional glass AM technologies. Instead, it is processed via Stereolithography (SLA), Digital Light Processing (DLP), or Direct Ink Writing (DIW) technologies using indirect approaches, such as colloidal suspensions, photopolymerizable resins loaded with silica nanoparticles, or sol–gel routes [20,26]. These methods require subsequent debinding and sintering stages to achieve adequate densification and optical transparency.

Despite its advantages, the additive manufacturing of silica presents significant challenges. Notable issues include volumetric shrinkage during sintering, residual porosity generation, and a tendency toward opacity in processes such as Selective Laser Sintering (SLS) or Selective Laser Melting (SLM) when advanced post-processing strategies are omitted [20,27–29]. Furthermore, the elevated cost of high-purity raw materials and the complexity of microstructural control pose additional barriers to its large-scale adoption.

**Soda-Lime Glass:** With a typical composition of  $\text{SiO}_2\text{-Na}_2\text{O-CaO}$ , soda-lime glass is the most common commercial variant, typically sourced from bottles, windows, or recycled cullet. Processed as a filament, powder, or granules [20,30], it is low-cost, widely available, and includes sustainable recycling. It features the lowest processing temperatures ( $\sim 1000\text{--}1200$  °C) and lower viscosity compared to other silicates [31]. It exhibits favorable fusion properties and versatility across techniques such as Fused Deposition Modeling (FDM), Directed Energy Deposition (DED), DIW, and SLA, while also enabling the fabrication of large-scale, complex structures in varied colors [21]. Its primary drawbacks include a higher thermal expansion coefficient, the potential for devitrification (crystallization) during heating, limited optical clarity and surface finish without post-processing, and lower thermal and chemical resistance compared to borosilicate or pure silica.

**Borosilicate Glass:** This material is structurally network-modified by alkaline oxides within a  $\text{SiO}_2$  and  $\text{B}_2\text{O}_3$  matrix and exhibits good chemical stability, high thermal shock resistance, and a low coefficient of thermal expansion ( $\sim 3\text{--}6 \times 10^{-6} \text{ K}^{-1}$ ) [32]. These intrinsic physicochemical attributes render it highly advantageous for advanced additive manufacturing processing, utilizing either powder or filament feedstocks in laser-directed energy deposition or glass-loaded photopolymer resins in stereolithography [20,33,34]. While its

intermediate melt viscosity enables precise kinetic flow control and geometric accuracy during layer deposition [33,34], the thermal gradients and localized reboil phenomena characteristic of unconditioned environments induce critical constraints, including residual stress accumulation, microcracking, and gas bubble entrapment; consequently, large-scale or high-rate direct printing remains unfeasible without stringent closed-loop thermal regulation [20,33]. Nevertheless, recent breakthroughs in tailor-made borate-enriched compositions have successfully bypassed these thermo-mechanical limitations, expanding the application paradigm of additively manufactured borosilicate architectures into advanced biomimetic fibrous matrices tailored for localized ion release and tissue engineering [35].

The distinction between soda-lime and borosilicate glasses is indeed critical for additive manufacturing processability. In glass additive manufacturing, borosilicate glass generally shows better thermal processability than soda-lime glass, especially in laser-based and filament-fed routes, because its lower coefficient of thermal expansion is associated with higher thermal-shock resistance and a lower tendency toward fracture during deposition [36–38]. By contrast, soda-lime glass is more mature as a proof-of-feasibility feedstock in laser powder bed fusion, but it still commonly exhibits porosity, opacity, and sensitivity to processing conditions such as laser energy density, scan speed, and substrate preheating [39,40]. Nevertheless, Laser Powder Bed Fusion (LPBF) of soda-lime glass has already enabled the fabrication of complex three-dimensional and multilayer geometries, including parts with potential use in chemically inert, low-pressure functional applications such as flow reactors and structured catalysts [40,41]. In filament-fed glass AM, borosilicate has also been positioned as a stronger candidate for transparent and optical parts, provided that thermal-shock-induced fracture, bubble entrapment, and residual stress are controlled through temperature management and post-deposition annealing [36,42]. From a commercial perspective, this distinction matters because borosilicate aligns more naturally with higher-value applications in optics, technical glassware, and thermally demanding components, whereas soda-lime remains more relevant for scale-up, architecture, and chemically resistant functional parts due to its widespread industrial use, low cost, and compatibility with high-volume glass markets [37,41,43–45].

#### 4.1.2. Other Less Common Types of Glass

**Phosphate Glasses:** Characterized by phosphorus pentoxide ( $P_2O_5$ ) as the primary network former, phosphate glasses constitute a class of vitreous materials with a low glass transition temperature ( $T_g$ ) and adjustable chemical stability, thermal expansion, and optical clarity. These characteristics, alongside their compositional versatility, make them particularly attractive for advanced AM applications. Compared to silica-based glasses, phosphate glasses exhibit lower viscosity and greater ease of processing. This facilitates their implementation in techniques such as FDM, DIW, DLP, SLA, and Binder Jetting (BJT), enabling the production of dense, high-resolution structures with controlled functional properties.

In particular, these materials have demonstrated high potential in photonic and biomedical applications. Their capacity for rare-earth doping allows for the fabrication of functional optical devices—such as waveguides, sensors, and laser systems—while conserving luminescent properties post-printing [46]. Furthermore, the ability to adjust their refractive index and thermal stability by incorporating modifier oxides or fluorinated species expands their applicability in advanced photonics and luminescent thermometry [47]. Their chemical stability also makes them viable candidates for lab-on-a-chip microfluidic devices.

**Germanate and Germania–Silicate Glasses:** These glasses have emerged as complementary matrices for the additive manufacturing of optical components due to their

elevated transparency and properties comparable to those achieved via conventional methods. Techniques such as DIW have enabled the production of defect-free structures with high optical quality [48,49]. Nevertheless, both phosphate and germanate glasses face persistent challenges associated with fragility and the generation of thermal stresses during sintering, which can adversely affect their final properties. Furthermore, the limited availability of compositions optimized for glass AM restricts their industrial scalability. Despite these limitations, current evidence positions these glass families as advanced functional materials with significant potential in biomedical applications.

**Aluminosilicate Glasses:** This family of vitreous materials is based on  $\text{SiO}_2\text{--Al}_2\text{O}_3\text{--}(\text{Na}_2\text{O}, \text{K}_2\text{O}, \text{CaO})$  systems. Here, aluminum oxide acts as a network former that increases structural connectivity through Si–O–Al bonds, substantially improving the material's mechanical and chemical properties [30,50]. They exhibit a higher elastic modulus, hardness, and fracture resistance compared to conventional glasses such as soda-lime. These characteristics make them appropriate for applications with high mechanical demands. Additionally, they exhibit high chemical resistance and processing temperatures that can exceed 1400–1600 °C [50]. While these elevated temperatures provide excellent thermal stability, they represent a significant limitation for glass AM; the resulting high melt viscosity and elevated thermal requirements hinder processing via direct techniques. Consequently, their fabrication typically requires indirect methods and the use of high-power lasers [30].

**Chalcogenide Glasses.** This family of non-oxide glasses is based on chalcogens (S, Se, Te) combined with elements such as Ge, Sb, Ga, or As. They are widely studied as optical materials in the infrared (IR) range due to their low glass transition temperature. This characteristic allows for processing at moderate temperatures, typically below 400 °C for sulfide and selenide systems [51–53]. They combine three key features advantageous for additive manufacturing: transparency in the mid-to-far-infrared spectrum, a low softening temperature, and high viscoplastic fluidity. These properties permit extrusion or infiltration below 400–450 °C, far lower than the temperatures required for conventional oxide glasses [54–56]. However, many historical compositions incorporate arsenic, which introduces toxicological concerns. Furthermore, limitations such as sensitivity to crystallization in certain compositions, as well as lower hardness and mechanical resistance compared to crystalline materials, restrict their widespread integration into demanding environments [55,57,58].

**Bioactive Glasses:** Bioactive glasses (BGs) and mesoporous bioactive glasses (MBGs) have evolved into multicomponent systems doped with metallic oxides ( $\text{TiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CeO}_2$ ,  $\text{ZnO}$ ,  $\text{Ga}_2\text{O}_3$ ) to integrate advanced functionalities into scaffolds produced via additive manufacturing. These dopants enable the combination of properties such as bioactivity, controlled drug release, antibacterial activity, angiogenesis, and magnetic or photocatalytic responses within the same material, all while maintaining the characteristic hydroxyapatite formation capacity of these systems [59–62]. In this context, glass AM has become a key tool for fabricating highly porous structures with controlled geometries, facilitating critical processes such as cellular migration, vascularization, and bone regeneration [63,64].

The primary application of these materials is in bone tissue engineering, where scaffolds printed using techniques such as DIW or DLP exhibit elevated osteoconductivity, cytocompatibility, and the capacity to induce cellular differentiation [65,66]. Additionally, the development of polymer-bioactive glass composites has improved processability and mechanical properties, mitigating the intrinsic fragility of the glasses and expanding their clinical applicability [67].

Nevertheless, precise optimization of the composition, particle size, binder systems, and printing parameters is required to ensure extrusion stability, geometric fidelity, and ade-

quate mechanical–biological performance [59,62,67,68]. Furthermore, challenges associated with shrinkage control during sintering and process scalability persist [63].

**Metallic Glasses:** Metallic glasses, or bulk metallic glasses (BMGs), are characterized by a unique disordered, non-crystalline atomic structure lacking long-range translational symmetry [69]. Due to this amorphous arrangement, which inherently eliminates traditional dislocation-mediated crystalline slip mechanisms, BMGs possess good mechanical properties—such as ultra-high yield strength, superior hardness, and excellent wear resistance—compared to conventional crystalline alloys [69,70]. However, their widespread structural applicability remains critically constrained by localized shear banding under mechanical loading, which triggers macroscopic catastrophic failure and severely limits tensile ductility at room temperature [70,71].

**Precursors and Inks:** Indirect additive manufacturing of high-purity silica glass components has undergone major advances driven by the development of highly specialized nanocomposites and organosilicon-derived precursors. On the one hand, nanocomposites—typically photocurable resins loaded with SiO<sub>2</sub> nanoparticles, such as the commercial Glassomer formulation—enable high-resolution geometric structuring through Vat Photopolymerization techniques, including SLA and DLP, followed by thermal debinding and sintering steps to consolidate fully dense and transparent glass bodies [20,27,72–74]. On the other hand, the use of molecular and polymeric precursors—such as polyhedral oligomeric silsesquioxanes (POSS), hydrogen silsesquioxanes (HSQ), methylsilsesquioxanes (PSQ), liquid silicone rubbers (LSR), and silicon alkoxides such as tetramethoxysilane (TMOS) and tetraethoxysilane (TEOS)—provides an alternative chemical route based on direct polymer-to-glass conversion under controlled thermal conditions [18,20,75–80]. This molecular approach enables submicrometer resolution, reduces isotropic volumetric shrinkage, and supports the fabrication of miniaturized diffractive optical elements, complex microfluidic networks, and high-precision integrated photonic devices [18,75,80]. Simultaneously, the development of functional inks and high-viscosity pastes optimized for DIW has substantially expanded the processability of silica-based, aluminosilicate, and bioactive glass compositions [19,21,81–84].

A comparison of these materials and their applications is presented in Table 1.

**Table 1.** Classification and Properties of Glasses Used in Additive Manufacturing.

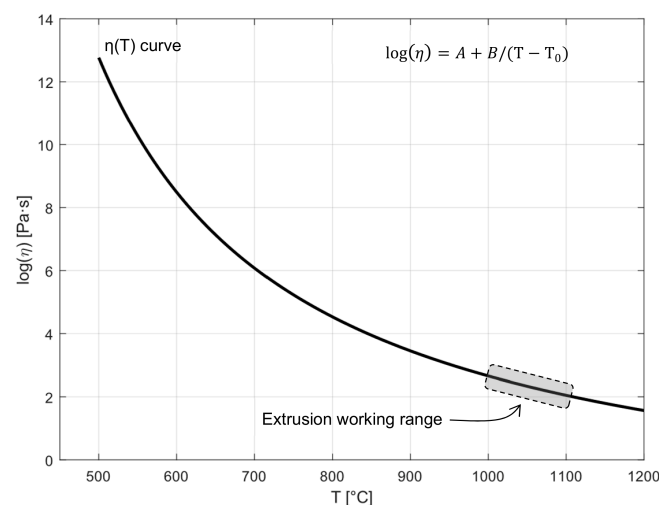
| General Class | Subclass         | Reported Material/System                                                             | Description/Key Properties                                                                                                | Applications                                           | References                     |
|---------------|------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|--------------------------------|
| Oxide glasses | Fused silica     | Quartz glass, fused silica, Corning 7980, Heraeus F300                               | High purity (>99% SiO <sub>2</sub> ), high UV-IR transparency, low thermal expansion, high thermal and chemical stability | Micro-optics, optical fibers, microfluidics, photonics | [20,22,26,29,72,85–91]         |
|               | Soda-lime        | Soda-lime glass, recycled cullet, recycled powder, microspheres                      | Low cost, high availability, recyclable, low viscosity, moderate processing temperature                                   | Construction, packaging, large-scale structures        | [7,20,21,31,37,40,41,81,92–95] |
|               | Borosilicate     | Borosilicate glass, B-SiO <sub>2</sub> 7070                                          | Low thermal expansion, good chemical and thermal resistance                                                               | Chemical and thermal devices                           | [20,21,32,34,44,96]            |
|               | Aluminosilicates | SiO <sub>2</sub> –Al <sub>2</sub> O <sub>3</sub> –Na <sub>2</sub> O–K <sub>2</sub> O | High mechanical strength and chemical resistance, high processing temperature                                             | Electronics, sensors, advanced structures              | [30,50,97]                     |
|               | Glass–ceramics   | Lithium disilicate, wollastonite, AP40                                               | High mechanical strength, microstructural control                                                                         | —                                                      | [62,98–101]                    |

Table 1. Cont.

| General Class      | Subclass              | Reported Material/System                                                                             | Description/Key Properties                                                        | Applications                                                       | References               |
|--------------------|-----------------------|------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------|--------------------------|
| Non-oxide glasses  | Chalcogenides         | As <sub>40</sub> S <sub>60</sub> , Te-As-Se, TAS                                                     | IR transparency, low T <sub>g</sub> , high fluidity                               | Infrared optics, sensors                                           | [19,21,51,52,55,102,103] |
|                    | Fluorides             | ZBLAN                                                                                                | Low melting temperature, IR optical applications                                  | —                                                                  | [104,105]                |
| Functional glasses | Phosphates            | CaO–P <sub>2</sub> O <sub>5</sub> –TiO <sub>2</sub>                                                  | Low T <sub>g</sub> , high bioactivity, easy processability, adjustable properties | Microfluidics, biomaterials, photonics                             | [21,46,106–108]          |
|                    | Bioactive             | ICIE16, BP1                                                                                          | Bioactivity, bone regeneration, drug delivery                                     | Tissue engineering, bone regeneration, drug delivery, angiogenesis | [59,60,63,100,109–111]   |
|                    | Germanates            | GeO <sub>2</sub> –SiO <sub>2</sub>                                                                   | High optical transparency, photonic applications                                  | Waveguides, optical devices                                        | [48,49,112]              |
|                    | Doped                 | SiO <sub>2</sub> + rare earths, SiO <sub>2</sub> –TiO <sub>2</sub>                                   | Advanced optical properties, luminescence                                         | —                                                                  | [47,113,114]             |
| Composites         | Polymer-glass         | PLA + glass fiber, epoxy + glass                                                                     | Mechanical improvement, fragility reduction                                       | —                                                                  | [8,20,107,115–117]       |
| Metallic glasses   | Bulk Metallic Glasses | Co <sub>47.6</sub> B <sub>21.9</sub> Fe <sub>20.4</sub> Si <sub>5.1</sub> Nb <sub>5</sub> , FeCrMoBC | High strength, high hardness, amorphous structure                                 | Advanced structural components                                     | [21,118,119]             |

#### 4.1.3. Effects of Glass Viscosity

Glass rheology, particularly the viscosity–temperature relationship ( $\eta(T)$ ), is a parameter that enables the glass AM of both molten glass and components intended for sintering. Glass viscosity varies across multiple orders of magnitude with temperature. Mathematical models describe this behavior, allowing for the definition of narrow processing windows where glass flows without losing its structural integrity [120–123]. Figure 7 illustrates the temperature-dependent dynamic viscosity of soda-lime glass based on the Vogel–Fulcher–Tammann (VFT) equation. The results demonstrate that the VFT equation can predict glass viscosity at specific temperatures, allowing for flow estimation and process adaptation. In molten glass extrusion printing, the simultaneous control of temperature, flow rate, and advance speed relies on this  $\eta(T)$  curve. Operating within a viscosity range of approximately  $10^2$ – $10^3$  Pa·s yields a continuous, stable filament with robust interlayer adhesion—a prerequisite for developing optically transparent glass printers [6].



**Figure 7.** Dynamic Viscosity of Soda-Lime Glass as a Function of Temperature, Evaluated Using the VFT Equation, where  $A = -2.47$ ,  $B = 3964.8$ ,  $T_0 = 241.5$  are data obtained in [6] from Commercial Soda-Lime Glass Nuggets.

However, this trend cannot be directly extrapolated to other glass families; in borosilicates, aluminosilicates, and chalcogenides, the thermo-viscoelastic response was also validated over wide temperature intervals but remained constrained within associated limits [124]. Furthermore, in glass AM, not all processing routes operate within a continuous melt regime. For instance, chalcogenide glasses integrated into inkjet printing are processed as nanoparticle inks with tailored viscosities—representing a rheological regime entirely distinct from that of direct molten glass extrusion, yet similarly governed by the strategic selection of glass composition and organic vehicle [56]. On the other end of the spectrum, low-temperature phosphate glasses for extrusion-based multi-material printing emerge as highly attractive candidates due to their  $T_g$ , which is significantly lower than that of conventional silicates, thereby facilitating seamless co-printing with metals, polymers, and sacrificial materials [108]. This limitation aligns with established glass-science principles, which demonstrate that VFT parameters exhibit a strong dependency on the specific temperature interval selected for fitting near the  $T_g$ . Consequently, both the derived kinetic fragility index and the specified working range should not be regarded as strictly invariant material constants; instead, they must be interpreted as phenomenological parameters that are sensitive to the prior thermal history and to the particular fitting constraints imposed during data analysis [125].

In techniques such as DLP, the rheology of slurries and inks dictates printability. Viscosity and its dependence on shear stress must facilitate smooth nozzle flow, homogeneous layer deposition, and rapid stiffness recovery to maintain part geometry [90,126,127]. Silica suspensions with ~60 wt% solids exhibit viscosities on the order of  $10^3$ – $10^4$  mPa·s at low shear gradients. Optimizing this mixture reduces viscosity and enhances densification, yielding sintered glasses with >99% density and high transmittance [90]. Analogous to hydrogels and aerogels, researchers seek strong shear-thinning behavior and viscoelastic properties that balance extrudability with structural stability [126,127]. Ultimately, the ability to predict and adjust glass viscosity as a function of temperature, composition, and strain rate links rheological design to the optical, dimensional, and mechanical quality of components fabricated via glass AM.

## 4.2. Additive Manufacturing Technologies Applied to Glass

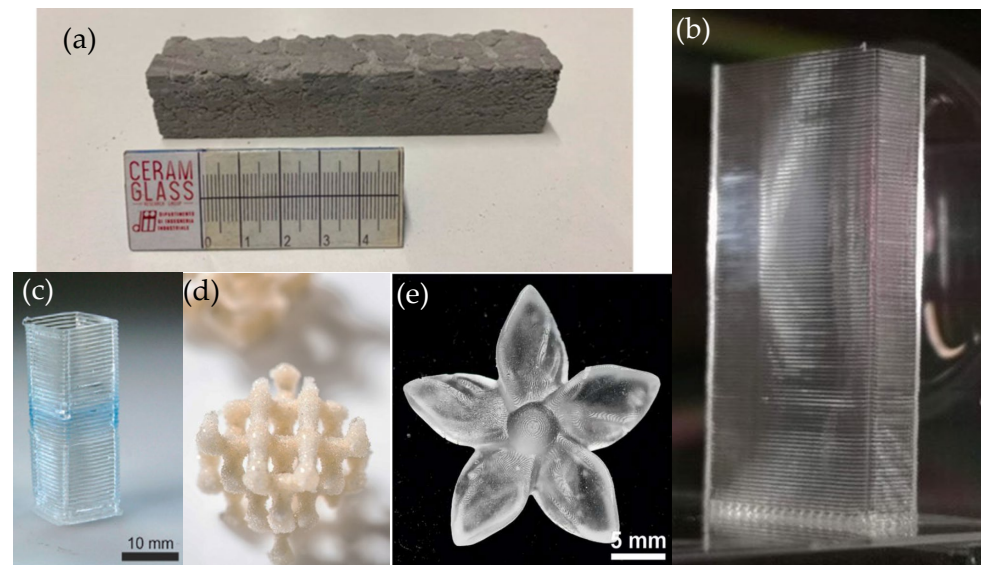
### 4.2.1. Description and Classification

Direct methods produce the final part in a single stage, whereas indirect methods require post-processing—such as washing, machining, sintering, or curing—to achieve the desired geometry and properties. The ISO/ASTM 52900 standard classifies additive manufacturing processes into seven broad categories, five of which are commonly applied to glass AM [128]. Figure 8 displays representative glass components produced via several of these additive manufacturing technologies.

- **Binder Jetting (BJT):** This process involves the successive deposition of a binding agent onto a thin layer of powder material to form a three-dimensional “green” part. Since a subsequent sintering process is mandatory to burn off the binder and densify the glass particles, the processes developed under this category are established as indirect methods. In glass printing, BJT enables the creation of parts with controlled porosity and complex shapes featuring internal channels that are difficult to achieve via conventional methods [101,129]. Because printing occurs at room temperature, thermal stresses are avoided [130], thereby reducing the risk of cracking and microfissures.
- **Directed Energy Deposition (DED):** This technology continuously feeds powder or wire material toward a specific point, where a focused thermal energy source (e.g., a laser beam or plasma arc) melts and selectively deposits it onto a surface. Since the final shape and properties are achieved immediately during the fusion stage

without requiring subsequent thermal consolidation, the processes developed under this category are established as direct methods. For glass printing, DED achieves high density and transparency comparable to conventionally manufactured glass [21,42,86]. Final part quality depends on the interplay between laser power, deposition speed, and material feed rate [21,42].

- **Material Extrusion (MEX):** This category encompasses two prevalent glass printing technologies: FDM and DIW (also known as robocasting). FDM feeds solid material into a heating system where it melts and is selectively deposited through a moving nozzle. It enables the creation of complex glass structures with high transmittance and favorable optical properties [19], and it supports the use of composite materials. DIW operates similarly to FDM [20], though the process occurs at room temperature using a paste-like material. Proper paste formulation may affect both printing and post-processing. DIW yields micrometric parts with high transparency and low porosity [19]. While FDM typically functions as a direct process, in glass AM, diverse DIW approaches do not directly print molten glass, but rather a precursor ink loaded with particles that necessitates subsequent post-processing steps to achieve fully consolidated components [68,131].
- **Powder Bed Fusion (PBF):** In this category, a thin layer of powder is distributed over a platform, and a controlled thermal energy source selectively fuses particles according to a digital model. This process repeats cyclically until the three-dimensional part is complete. The unfused powder acts as a natural support, facilitating the fabrication of high-precision parts with fine features and complex geometries without requiring additional support structures [93,118]. PBF encompasses both direct and indirect processing routes depending on the consolidation mechanism. Technologies such as SLS, SLM, and LPBF fall within this category; SLS was historically the first PBF process and differs from SLM/LPBF in its degree of powder consolidation. Generally, SLS relies on partial melting or sintering, whereas SLM/LPBF achieves complete melting to yield fully dense parts, thereby functioning as a direct process [132]. Due to the low fluidity of glass powder, PBF is primarily utilized for applications where high transparency is not essential [20].
- **Vat Photopolymerization (VPP):** In this category, a light or laser source selectively polymerizes a resin to solidify areas corresponding to cross-sections of a 3D model. VPP is widely regarded as one of the most established and versatile additive manufacturing routes for producing glass-related components from resins loaded with glass particles or ceramic-derived precursors, particularly when high resolution, dimensional accuracy, surface quality, and geometric complexity are required [74,80,133–135]. Across glass-printing implementations, the main differences between VPP subcategories generally concern the light-delivery strategy, the achievable resolution, fabrication speed, and process scalability [136]. For glass fabrication via VPP, three broad technological groups can be distinguished. First, macroscale component production utilizes established technologies such as SLA, DLP, Masked Stereolithography (MSLA), and Liquid Crystal Display (LCD) printing to achieve a practical balance between resolution and productivity. Second, high-precision microfabrication—employing Optical Micro-Stereolithography (O $\mu$ SL), Projection Micro-Stereolithography (P $\mu$ SL), Direct Laser Writing (DLW), and especially Two-Photon Polymerization (TPP)—enables the fabrication of micro-optical elements, photonic crystals, and microfluidic devices with micrometric or sub-micrometric resolution.



**Figure 8.** (a) Binder Jetting-Printed Glass Component, Scale in cm (Adapted from [137], under CC BY 4.0 License); (b) 21 mm High Rectangular Structure via DED (Adapted from [138], under CC BY 4.0 License); (c) Multi-Material Printed Glass Structure with Distinct Colored Interfaces Fabricated via FDM (Adapted from [5], under CC BY 4.0 License); (d) 10 mm Structures with Potential Catalytic Applications via LPBF (Adapted from [37], under CC BY 4.0 License); and (e) Uncoated 15 mm Diameter Fused Silica Flower via LCD/VPP (Adapted from [74], under CC BY 4.0 License).

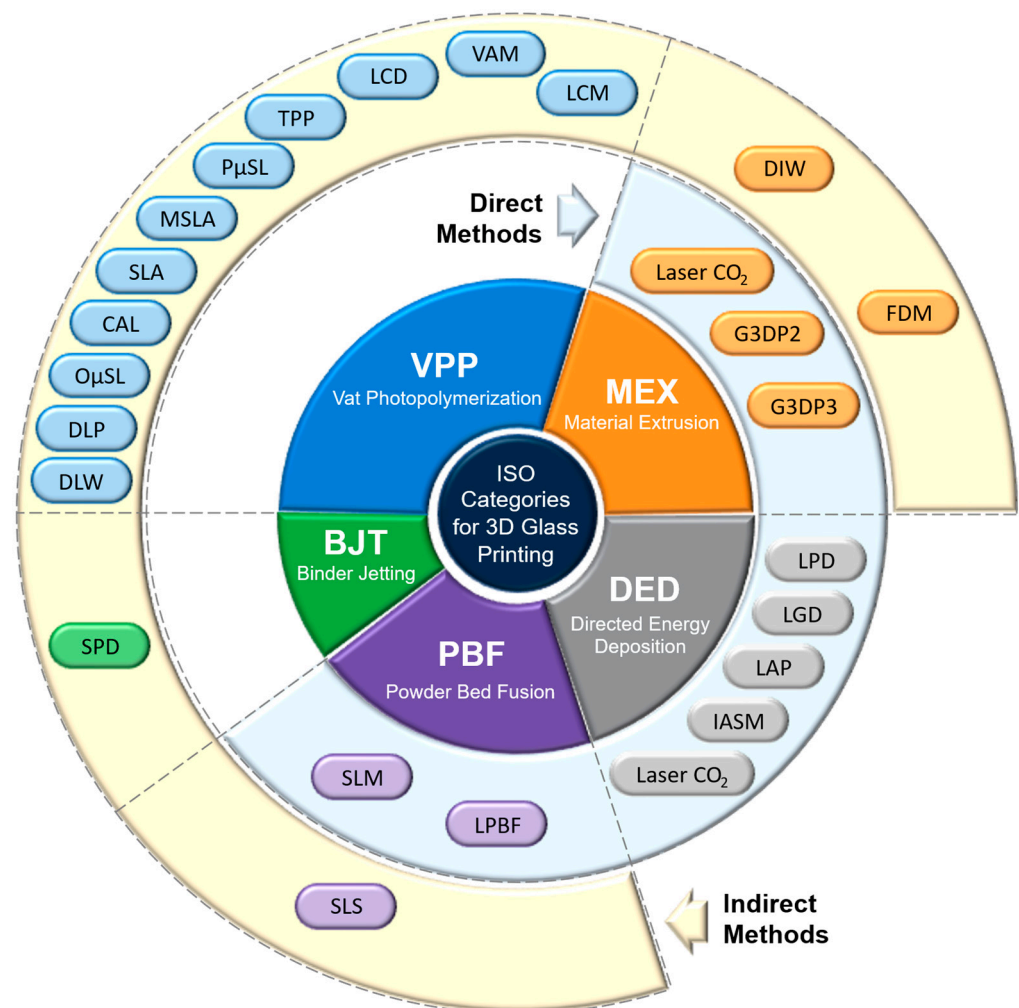
Finally, emerging approaches such as Lithography-based Ceramic Manufacturing (LCM), Computed Axial Lithography (CAL), and Volumetric Additive Manufacturing (VAM) are being explored to reduce layer-related defects and shorten manufacturing times. However, their potential to improve final densification after sintering remains dependent on the specific material system and processing conditions [136]. These processes are generally considered indirect methods, because the printed part is typically a photopolymerized green body that must then undergo pyrolysis, sintering, or related conversion steps to obtain the final glass component.

Figure 9 outlines five of the seven basic additive manufacturing categories alongside their respective technological variants for glass processing. This representation highlights the diversity of existing technologies, encompassing both direct and indirect processing methods. Based on the literature reviewed, indirect methods account for approximately 78% of the applicable technologies, primarily because they offer superior geometric control and mitigate the risk of defects during printing. Furthermore, specialized proprietary technologies have been developed specifically for fabricating vitreous components, including Glass 3D Printing Version 2 (G3DP2) [7,139,140] and various CO<sub>2</sub> laser implementations [42,49,83,89,138].

In glass additive manufacturing, hybrid approaches remain an emerging direction rather than a fully consolidated field, yet relevant demonstrations have already combined two printing or processing technologies within a single manufacturing route [16,20,141,142]. These strategies aim to merge the geometric freedom of extrusion-based deposition with the enhanced shape complexity, local densification, print speed, or functional control enabled by photopolymerization, volumetric printing, and laser-assisted processing [142–144].

- **Extrusion plus photopolymerization** has already been demonstrated for transparent silica, enabling more complex geometries, reduced rheological constraints, and fully dense glass after heat treatment; however, the evidence still centers on process demonstration rather than broad application validation [141].

- **Paste printing combined with in situ laser melting** enabled the fabrication of fused silica without post-heat-treatment, including thin walls and embedded microfluidic channels; its main advantage is direct manufacturing without downstream sintering, although performance depends on careful optimization of both printing and laser parameters [16].
- **DIW combined with laser melting** also enabled in-process tuning of transparency and optical properties, including in situ nanoparticle synthesis and optical gradients; its main contribution is to couple the material versatility of DIW with the benefits of direct printing [144].
- **Embedded extrusion combined with volumetric additive manufacturing** enables multi-material architectures and microchannels below 120  $\mu\text{m}$ ; this is a recent platform technology and is not limited to dense monolithic glass alone [142].



**Figure 9.** Classification Scheme of Glass AM Technologies Categorized According to the ISO/ASTM 52900 Standard. The Inner Ring (Light Blue) Groups Direct Processing Routes, Whereas the Outer Ring (Yellow) Highlights Indirect Methods Relying on Polymer Binders and Post-Processing. Each Radial Sector Illustrates the Specific Techniques Associated with Its Parent ISO Category.

#### 4.2.2. Characteristics and Limitations

To move beyond isolated technical parameters, a cross-comparative assessment of glass AM processes is essential to evaluate their specific suitability for distinct applications. In practice, process selection entails balancing trade-offs among geometric complexity,

resolution, surface quality, transparency, thermal processing requirements, and volumetric throughput [18,80].

**Optics and Photonics:** For micro-optics, such as microlenses, endoscope objectives, and hyperspectral imaging devices, Vat Photopolymerization techniques—particularly TPP and DLP—offer distinct advantages over other processes. TPP achieves sub-micrometric resolutions [7,8,18,72–74,82,97,114]. It also yields high surface quality (roughness < 6 nm), which translates into reflectance and transmittance values exceeding 92–95% in pre-condensed liquid silica resins [18,145]. However, the critical drawback of TPP and DLP is their restricted build volume and isotropic linear shrinkage about 17% during post-printing sintering [80], which limits their scalability. Conversely, when larger optical components or multi-material chalcogenide glass fibers are required, Material Extrusion (MEX/FDM) yields significantly higher throughput [103]. However, this method sacrifices optical quality due to inherited inter-layer porosity, high roughness, and nozzle crystallization risks, requiring intensive post-processing to minimize scattering [46]. Layer-by-layer addition in glass AM techniques can induce a staircase effect, thereby increasing surface roughness and degrading overall optical quality. Recent research highlights that Mask Image Projection-based Vat Photopolymerization (MIP-VPP) offers a time-efficient and dimensionally accurate method for producing optical lenses by utilizing frustum layer stacking. This approach drastically mitigates the staircase effect, achieving an improved surface roughness of less than 10 nm with high resolution and without requiring post-curing [146,147].

**Biomedical Engineering:** In bone tissue engineering and dental restorations, the focus shifts from optical transparency to achieving controlled porosity and specific bioactivity. For these applications, BJT utilizing bioceramics exhibits merits compared to both VPP and PBF. BJT facilitates precise architectural porosity and mass transport channels by manipulating particle size gradations and binder saturation levels [101]. Nevertheless, its principal limitation pertains to the mechanical integrity in the green state and the dimensional shrinkage that occurs during subsequent post-processing. While DIW allows for complex bioactive glass scaffolds suitable for bone repair [68], it introduces risks of macro-cracking and clogging during high-viscosity ink extrusion, making BJT more reliable for high interconnected porous microstructures.

**Structural, Functional, and Microfluidic Components:** For macro-scale structural components and microfluidic chips, DED and Powder Bed Fusion PBF/SLM represent competing direct manufacturing pathways. DED techniques (e.g., LGD or CO<sub>2</sub> laser variants) enable the fabrication of high-density and transparent parts without lengthy thermal post-processing, making them attractive for aerospace and smart glass components [148]. However, DED is limited by residual thermal stresses and melt pool instability during multi-layer deposition, leading to cracking [149], and still demands careful optimization of processing parameters. On the other hand, SLM and LPBF can print functional components and micro-mechanics using borosilicate and soda-lime silica glass powders [37]; however, they inherently yield rough surfaces due to fast cooling rates and the balling effect [93]. For architectural and potentially structural applications at large scale, G3DP2 demonstrates that molten-glass additive manufacturing can achieve industrially relevant throughput, reliability, repeatability, and meter-scale fabrication while preserving geometric accuracy and optical transparency [7].

Table 2 summarizes the approximate resolutions, key characteristics, and limitations of each technology and its variants, facilitating a direct comparison of the different techniques.

**Table 2.** Comparison of Technologies Applied to Glass Printing.

| ISO Category | Technology                                           | Resolution                                                                                                         | Main Characteristics                                                                                                             | Limitations                                                                                                           | References      |
|--------------|------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-----------------|
| BJT          | Slurry Deposition Process (SDP)                      | >100 µm                                                                                                            | Low–medium transparency<br>Adjustable porosity                                                                                   | Shrinkage due to post-processing<br>Powder flowability                                                                | [101]           |
|              | Integrated Additive–Subtractive Manufacturing (IASM) | ~100 µm                                                                                                            | High dimensional accuracy<br>Low transparency<br>Adjustable porosity                                                             | Optical loss<br>Property changes in fused silica                                                                      | [84,88]         |
|              | Laser Automated Processing (LAP)                     | Deposit heights between 200–900 µm                                                                                 | Complex and semi-transparent parts                                                                                               | Proper adjustment of parameters such as laser velocity and power<br>Susceptibility to thermal shock.                  | [149]           |
| DED          | Laser Glass Deposition (LGD)                         | —                                                                                                                  | High transparency (>90%)<br>Surface roughness < 0.1 µm<br>Transmission of 75–89%                                                 | Anisotropic behavior<br>Residual stresses<br>Cracking<br>Melt pool instability                                        | [86]            |
|              | CO <sub>2</sub> Laser                                | <196 µm                                                                                                            | Avoids interaction between nozzle and molten glass<br>Surface roughness < 0.004 µm                                               | Complex multilayer structures<br>Microbubbles                                                                         | [49,138]        |
|              | Laser Powder Deposition (LPD)                        | Layer thickness between 600–1000 µm<br>Bead width between 520–2680 µm                                              | High-density parts similar to traditional glass<br>Process suitable for complex geometries                                       | Complex optimization of multiple parameters<br>Pore and bubble formation due to incomplete fusion                     | [150]           |
| MEX          | Direct Ink Writing (DIW)                             | ~100–500 µm                                                                                                        | Medium–low transparency<br>Allows modular materials and glass composition<br>Refractive index $1.461 \times 10^{-3}$ at 0.589 µm | Ink formulation<br>Post-processing can cause cracking and shrinkage                                                   | [8]             |
|              | Fused Deposition Modeling (FDM)                      | ~100–500 µm                                                                                                        | Low transparency<br>Inter-layer porosity<br>Rough surface                                                                        | Crystallization in nozzle<br>High shrinkage<br>Adhesion between layers                                                | [82,95,103,105] |
|              | Glass 3D Printing—Version 2 (G3DP2)                  | ~1000 µm                                                                                                           | High transparency<br>Industrial scale production                                                                                 | Shrinkage<br>Distortion                                                                                               | [7]             |
|              | Glass 3D Printing—Version 3 (G3DP3)                  | Bead width of 9000 to 16,000 µm<br>Layer height of 3000 to 6000 µm<br>Parts with height of $\sim 3 \times 10^5$ µm | Thick layers, allowing for unique optics and aesthetics                                                                          | Variability in dimensional accuracy<br>Surface quality<br>Thermal management and material behavior during fabrication | [140]           |
|              | CO <sub>2</sub> Laser                                | Lateral < 200 µm<br>Height > 500 µm                                                                                | Low roughness $\sim 0.12 \times 10^{-3}$ µm<br>Dense parts without voids between layers<br>Does not need thermal post-processing | Thermally induced stresses                                                                                            | [42]            |
|              | Laser Powder Bed Fusion (LPBF)                       | <200 µm                                                                                                            | Low transparency<br>High porosity<br>Does not induce crystallization                                                             | Heat distribution<br>Microcracks<br>Thermal stresses                                                                  | [37,40]         |
| PBF          | Selective Laser Melting (SLM)                        | >25 µm                                                                                                             | Low transparency<br>Rough surfaces<br>Fast cooling rates                                                                         | Balling effect<br>Stress concentrators<br>Splatter<br>Microbubbles                                                    | [21,93,118]     |
|              | Selective Laser Sintering (SLS)                      | Layer height ~150 µm                                                                                               | High dimensional accuracy<br>Dense parts                                                                                         | Control of thermal and energetic equilibrium<br>Porous and fused morphologies                                         | [33]            |

Table 2. Cont.

| ISO Category | Technology                                      | Resolution                                                                                                                                           | Main Characteristics                                                                                                                                         | Limitations                                                                                                                              | References         |
|--------------|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| VPP          | Computed Axial Lithography (CAL)                | —                                                                                                                                                    | High resolution<br>Surface optical quality                                                                                                                   | Large-scale components                                                                                                                   | [74]               |
|              | Digital Light Processing (DLP)                  | ~50 $\mu\text{m}$                                                                                                                                    | Limited resolution<br>Low surface roughness<br>Optical transparency<br>High precision<br>Transparency ~90%<br>Minimal distortion<br>High transmittance > 95% | Cracking<br>Linear shrinkage ~30%<br>Air bubbles                                                                                         | [78,90,97,107,151] |
|              | Direct Laser Writing (DLW)                      | ~0.065 $\mu\text{m}$                                                                                                                                 | Linear shrinkage of ~6.1%<br>Transparent parts                                                                                                               | —                                                                                                                                        | [18]               |
|              | Liquid crystal display (LCD)                    | ~25–100 $\mu\text{m}$                                                                                                                                | —                                                                                                                                                            | Microstructures with high spatial resolution                                                                                             | [114]              |
|              | Lithography-based Ceramic Manufacturing (LCM)   | Layer height of 25 $\mu\text{m}$<br>Pixel size $25 \times 25 \mu\text{m}^2$<br>Dimensional precision with maximum deviations of $\pm 80 \mu\text{m}$ | High densification (>99%) after sintering<br>Excellent geometric precision and surface quality                                                               | Light scattering within the ceramic suspension reduces resolution<br>Shrinkage and warping during sintering                              | [99]               |
|              | Optical Micro-Stereolithography (O $\mu$ SL)    | ~0.8 $\mu\text{m}$                                                                                                                                   | Complex structures                                                                                                                                           | —                                                                                                                                        | [72]               |
|              | Projection Micro-Stereolithography (P $\mu$ SL) | Layer height of ~1–5 $\mu\text{m}$<br>Lateral of 1–10 $\mu\text{m}$                                                                                  | Microscale parts with size below 50 $\mu\text{m}$<br>Complex structures                                                                                      | Adequate design and fabrication of the slurry, with adequate rheological properties                                                      | [19]               |
|              | Stereolithography (SLA)                         | ~25–100 $\mu\text{m}$                                                                                                                                | Good surface quality<br>High transparency > 90%                                                                                                              | Resin formulation<br>Sintering shrinkage<br>Void formation                                                                               | [82]               |
|              | Two-Photon Polymerization (TPP)                 | <10 $\mu\text{m}$                                                                                                                                    | Transmittance >92%<br>Customized optical transparency<br>Reflectance ~100%<br>Surface roughness < $6 \times 10^{-3} \mu\text{m}$                             | Reduced volumes<br>Shrinkage ~20–30%<br>Large structures<br>Cracks                                                                       | [73,75,80,82,145]  |
|              | Volumetric Additive Manufacturing (VAM)         | —                                                                                                                                                    | Two-color irradiation<br>Localized control over the thickness of the polymerized region                                                                      | Increasing the thickness of the print volume<br>Lower polymerization rates due to wavelength intensity attenuation within the resin bath | [152]              |

#### 4.3. Characterization of Printed Parts

Characterization facilitates the evaluation of the structural integrity, functional performance, and optical quality of glass components obtained via AM. It also allows for the validation of process viability and correlates printing parameters with final properties. Literature analysis indicates that the final quality of printed parts depends on the interaction between process parameters, material consolidation mechanisms, and the defects inherent to specific technologies and materials.

##### 4.3.1. Printing Parameters

Precise control of printing parameters is indispensable for obtaining glass parts with the desired geometry, minimal defects, and functional properties. The most common parameters identified in glass AM technologies are detailed below:

- **Temperature:** In extrusion processes such as FDM and DIW, the nozzle, chamber, and print bed temperatures directly affect the viscosity of the glass or ink and the adhesion between layers [8,21]. The temperature must typically be maintained above the glass transition temperature ( $T_g$ ) but below the crystallization temperature ( $T_x$ ) [49,105]. For powder bed and DED technologies, preheating the substrate significantly reduces thermal gradients and prevents cracking due to residual stresses [40,49]. In indirect technologies, post-processing temperatures influence the removal of organic binders,

part shrinkage (typically 17% to 30% linear shrinkage), and the occurrence of unwanted crystallization [76,79,145].

- **Intensity and power:** The energy control of laser and UV light is critical; in photopolymerization technologies, these parameters dictate curing depth, polymerization speed, and spatial resolution. For example, in TPP, laser powers between 10 and 15 mW enable submicrometric resolutions, whereas excessive power generates methanol and water bubbles [75,145]. In LPBF, laser power determines glass densification: insufficient values (below 55 W) produce incomplete fusion and porosity, whereas powers exceeding 250 W induce evaporation, balling, and thermal cracking [37,93]. In hybrid technologies such as CO<sub>2</sub> laser-assisted FDM, the laser trajectory (spiral or zigzag) affects thermal uniformity and interlayer bonding quality [87].
- **Speed:** Printing speed and filament feed rate in FDM and DED determine the amount of material deposited per unit time and the bead morphology. The relationship between feed and scanning speeds is fundamental for controlling bead width, layer height, and interfacial fusion [86,138]. In SLA and SLM, laser scanning speed influences resolution and curing time; high speeds reduce energy density and increase porosity, whereas low speeds improve consolidation but extend printing time [20]. In TPP, slow laser scanning speeds increase crosslinking density and mechanical strength; however, oxygen permeation occurs during pyrolysis, which impedes the complete removal of organic matter and degrades final transparency [76].
- **Layer thickness:** This parameter affects vertical resolution, manufacturing time, and surface roughness. Generally, reduced layer thicknesses ( $\leq 50 \mu\text{m}$ ) improve dimensional accuracy and mitigate the “staircase effect,” but they increase printing time [97,98]. In powder bed technologies such as LPBF and BJT, the layer thickness must be adapted to the maximum particle size (typically 50–100  $\mu\text{m}$ ) to ensure adequate densification [37,130].

Regarding material composition and formulation, ink rheology and composition in DIW determine extrudability, shape retention, and subsequent shrinkage [8]. In BJT and PBF, the morphology of the glass powder (whether spherical or irregular) and its particle size distribution affect fluidity, packing density, anisotropic shrinkage, and final mechanical strength. Spherical particles offer superior flow and packing, whereas irregular particles can yield higher green densities but exhibit lower fluidity [93,130]. In PBF, optimizing the Particle Size Distribution (PSD) is necessary to balance powder flow and bed density. While very fine particles (less than 15 microns) improve sintering kinetics, they suffer from strong cohesive forces that impair flowability, leading to uneven powder layers. Conversely, larger particles (greater than 45 microns) flow well but reduce the packing density and laser energy absorption of the bed. Therefore, optimizing PBF processes requires a moderately wide, tailored PSD that allows smaller particles to fill the spaces between larger ones, maximizing bed density and preventing defects like porosity and balling [37,153]. In BJT, PSD optimization directly controls binder capillary action and post-print sintering shrinkage. A bimodal PSD—combining coarser glass particles with a smaller fraction of fine particles—maximizes the initial powder packing density. This limits excessive capillary migration of the liquid binder, which significantly enhances printing accuracy. Furthermore, the fine particle fraction increases the driving force during the subsequent thermal sintering step, allowing for high densification without sacrificing the dimensional stability of the printed part [154,155].

An emerging frontier in the field is Multi-Material Glass Additive Manufacturing (MMGAM), which is categorized into glass–glass systems featuring compositional gradients and hybrid systems combining glass with polymers, metals, or ceramics. The primary technical challenge in these architectures lies in interfacial compatibility, where

discrepancies in the coefficient of thermal expansion, viscosity, and sintering kinetics can induce delamination or critical residual stresses [156]. Nevertheless, spatially resolved doping and multicomponent glass networks enable the fabrication of multicolor luminescent elements and graded-index optics within a common silica backbone, positioning VPP as the most mature platform for fine-scale compositional tuning in multi-material glass processing [143,157].

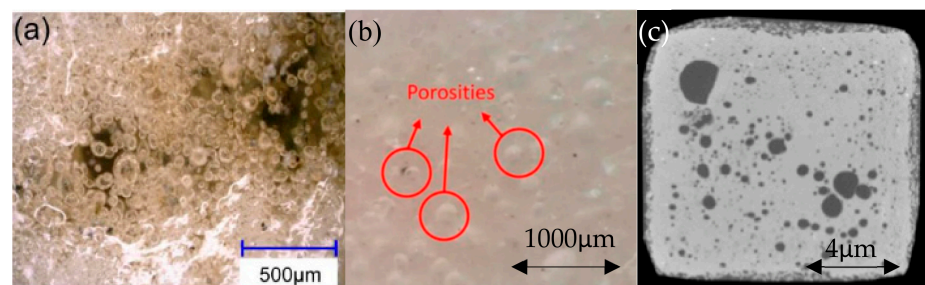
In addition to these parameters, certain technologies rely on specific variables, such as:

- **Pulse energy:** This is a critical parameter in the TPP process that determines the morphology of the writing voxel and the axial resolution of the fabricated parts. Pulse energies of 14–18 nJ achieve spot diameters of ~65 nm, whereas higher energies induce unwanted bubble formation [18,145].
- **Grayscale:** DLP projectors and devices can represent different levels of brightness between black and white for each pixel. In DLP technology, this capability allows for localized adjustments to pore size and crosslinking density within different regions of the same part [78,107], facilitating the creation of complex shapes with enhanced precision and surface finishes.
- **Binder saturation:** This influences the initial green strength and dimensional precision of parts produced via BJT. Optimal saturation levels (120–140%) minimize deformation and uncontrolled binder penetration [129,130].
- **Nozzle diameter:** In MEX technologies, this defines filament width, horizontal resolution, and extrusion pressure. Fine nozzles ( $\leq 400 \mu\text{m}$ ) capture finer details but increase the risk of obstruction and require higher extrusion pressures [8,158].

#### 4.3.2. Printing Defects

The most commonly reported defects include unwanted porosity, internal bubbles, cracking, excessive surface roughness, and geometric distortion. To a lesser extent, defects such as fractures, delamination, and deficient interlayer adhesion also occur.

Porosity and internal bubbles are observed in ~44% of the surveyed studies. These defects are generated by the incomplete fusion of the material (powder or filament) [93,118], gas entrapment during processing, boundary layer formation [93] (Figure 10b), the decomposition of organic compounds in indirect methods [76,159], or insufficient energy density preventing proper consolidation (Figure 10a,c). The nature of the material also influences these defects; high-viscosity glasses such as fused quartz or ZBLAN inhibit bubble formation [93,130], while irregularly shaped powders tend to generate greater porosity than spherical powders [93,130].



**Figure 10.** (a) Microbubbles Generated by Low Laser Energy Density in Parts Designed via SLM (Adapted from [93], under CC BY 4.0 License); (b) Photograph of Surface Bubbles on a Printed Part Obtained via BJT (Adapted from [94], under CC BY 4.0 License); and (c) Micro-Computed Tomography of a Glass Cube Fabricated Using Optimal Processing Limits, Revealing Porosities Obtained during LPBF via Digital Image Processing (Adapted from [37], under CC BY 4.0 License).

Cracking is the most frequently cited defect, reported by nearly 63% of authors. Cracks are produced by high residual stresses derived from abrupt thermal gradients during rapid cooling [21,40,118], thermal shock, or differential shrinkage during the drying and sintering phases of binder-based techniques [8,110]. Brittle materials, such as cobalt-based metallic glasses or soda-lime glass, are particularly prone to this defect [37,93,118].

Elevated surface roughness is frequently associated with extrusion, PBF, and BJT techniques. This defect stems from the inherent nature of layer-by-layer processing, nozzle or particle size constraints [19,21,92,130], deposition system precision limits, and the adhesion of partially fused powder to the part surface [41,93]. Using materials with fine particles or high silica loads can improve resolution; additionally, properly controlling material rheology significantly decreases surface roughness [8,72].

Deformation or warping is common in processes characterized by elevated internal stresses or anisotropic shrinkage, especially when fabricating large structures [8,78,107,118]. Materials with a high thermal expansion coefficient and low thermal conductivity, such as certain silicate glasses, exhibit greater susceptibility to warping [88,106].

Finally, delamination or deficient interlayer adhesion occurs when the temperature of the preceding layer is too low relative to the newly deposited layer [21,82], or when contamination or differential shrinkage is present. The use of materials with low sintering capacity or organic additives that decompose prior to complete fusion exacerbates this problem [101].

Regarding defect mitigation, defect formation in glass additive manufacturing depends not only on the printed geometry but also on the coupled control of thermal history, feedstock behavior, and post-print densification. In direct glass processing, large thermal gradients promote residual stresses and thermal cracking, whereas in powder-based or particle-derived routes, incomplete consolidation and postprocessing shrinkage can further compromise dimensional fidelity and optical quality [39,41]. Accordingly, defect analysis should be complemented by process-oriented mitigation strategies, particularly those targeting thermal management, porosity reduction, and densification control [20,39,160].

In molten-glass or laser-assisted deposition routes, geometric stability and build quality depend strongly on process parameters that govern melt viscosity and deposition behavior. Small temperature adjustments can determine whether the extrudate retains its shape or deforms after deposition, and optimization of laser power, feed speed, travel speed, and defocus improve dimensional uniformity in quartz-glass deposition [21,148]. Advanced thermal control further improves build quality: closed-loop temperature regulation in quartz-glass additive manufacturing produced smoother surfaces, denser structures, and lower porosity than uncontrolled deposition [160].

In indirect routes based on photopolymerization or silica nanocomposites, porosity and transparency losses are addressed through carefully designed post-thermal treatment. These routes require solvent removal, debinding, and sintering to convert the printed precursor into dense glass [161]. For fused silica, both stereolithographic and nanocomposite-based fabrication strategies have been shown to yield transparent amorphous components following thermal conversion. However, dimensional shrinkage, residual stress, cracking, and interfacial delamination persist as significant limitations, necessitating careful optimization of the chemical formulation of the materials and the associated processing parameters [5,41].

Mitigation strategies cannot be generalized across all glass AM routes. In stereolithographic borosilicate glass, the relatively low softening temperature can interfere with thermal post-processing and cause poor fidelity or structural instability if the heat-treatment program is not carefully tuned [34]. Likewise, in powder-based glass processing, preheating

is a direct lever for suppressing cracking and reducing residual porosity by promoting viscous-flow consolidation [39].

#### 4.3.3. Testing and Analysis

The most common tests used to characterize printed parts evaluate microstructure, optical quality, structural integrity, and mechanical properties. Scanning electron microscopy (SEM) is frequently employed to analyze morphologies, surface defects, porosity, and inter-layer bonding, while X-ray diffraction (XRD) is utilized to confirm the amorphous structure of the glass and detect unwanted crystallization. Optical properties are typically analyzed using UV–Visible spectroscopy to measure transmittance, alongside white light microscopy and interferometry to assess surface roughness and form deviation. Mechanical properties are evaluated via three- or four-point bending tests, nanoindentation for hardness and elastic modulus [18,118], and compression tests. Additionally, micro-computed tomography (micro-CT) is widely used to quantify internal porosity and volumetric defects [41].

Specialized tests are also employed to characterize glass AM components. These include photoluminescence spectroscopy to study laser-induced optical defects [18]; micro-Raman spectroscopy to quantify monomer conversion and residual carbon content [18,76]; solid-state nuclear magnetic resonance (NMR) spectroscopy to identify chemical structures and organic residues [76]; flow-induced birefringence analysis to study polymeric orientation in microfluidic devices [90]; and thermal shock resistance measurements via direct flame exposure [77]. Less common analyses include long-term thermal stability tests at elevated temperatures (1000 °C) [88] and evaluations of the temperature response in doped fiber lasers [113].

Numerical analyses are frequently integrated into the characterization process. Finite element analysis (FEA) models simulate stress distribution, crack propagation, and the overall mechanical behavior of structures. Computational fluid dynamics (CFD) simulations are utilized to study heat transfer and viscoelastic deformation during deposition [21]. Similarly, thermal models are implemented to predict temperature gradients and consolidation behavior in laser fusion processes [40]. Furthermore, some investigations apply Weibull theory to analyze the reliability and consistency of mechanical properties [29,97], and employ micromechanical scale models (e.g., Halpin–Tsai, Mori–Tanaka) to predict the properties of fiber-reinforced composites [162].

## 5. Discussion

### 5.1. The Overall Picture and Design

Advances in glass AM reveal a complex design challenge, where the desired functional properties clash directly with the technical feasibility of the process, dimensional stability, and manufacturing throughput [1,163]. The glass AM landscape demands a careful balancing act between geometric resolution, optical transparency, and process scalability, as different manufacturing routes offer partial advantages coupled with diverse limitations [18,163,164].

In this context, VPP technologies—including SLA and DLP—represent the state of the art in terms of precision and microstructural control for silica and silica-derived glasses [165–167]. These routes enable the fabrication of high-resolution complex structures and, upon subsequent heat treatment, yield transparent glasses with optical properties comparable to commercial fused silica. Indeed, transmittances exceeding 80% in the 400–1200 nm range, optical quality comparable to fused silica, and up to 97% transmittance in the visible spectrum for recent low-temperature formulations have been reported [166,168,169]. However, this pathway remains heavily dependent on debinding and sintering stages, and conventional formulations with high organic loading exhibit

significant linear shrinkage—frequently exceeding 20%—which compromises geometric fidelity and limits integration onto temperature-sensitive substrates [18,168].

Conversely, approaches such as BJT and MEX/FDM emerge as more production-oriented alternatives due to their shaping simplicity, lower relative equipment costs, and excellent compatibility with formulations based on powders, pastes, or thermoplastic compounds [5]. In both cases, part shaping occurs without the need to directly melt the glass during layer-by-layer deposition, allowing processing at or near room temperature prior to thermal post-treatment. This broadens the diversity of processable compositions and facilitates the fabrication of complex geometries at a larger scale [163]. In indirect fused silica extrusion, the fabrication of high-aspect-ratio vessels, wall thicknesses down to 250  $\mu\text{m}$ , microchannels, and multi-material or multi-color components has already been demonstrated, confirming its potential for macroscale structures and functionally integrated designs [5]. Nonetheless, these routes systematically sacrifice optical clarity and, in the case of BJT, ultimate density. This is because interlayer interfaces, residual porosity, and defects associated with binder removal increase light scattering and degrade mechanical properties unless additional treatments—such as infiltration, polishing, or optimized sintering—are implemented [5,163,169].

Unlike micro-scale optical applications, large-scale glass AM prioritizes structural integrity and technical aesthetics over absolute optical clarity. Consequently, in architectural and artistic domains, glass AM has attracted considerable attention by enabling the exploration of architectural tectonics—the integration of skin, structure, jointing, and material—which historically evolves alongside available construction processes. Emerging glass fabrication techniques unlock novel architectural and structural design possibilities that reduce component counts and trade dependencies, enhance building performance, and generate new design potential [21]. Ultimately, three-dimensional printing allows the creation of complex geometries that promote material efficiency through structural optimization and achieve levels of detail unattainable through standardized construction methods.

## 5.2. Physical Mechanisms and Thermomechanical Behavior

When evaluating failure modes in direct additive manufacturing processes that employ localized energy sources—specifically LPBF applied to glass—the scientific literature demonstrates that structural defects should not be classified merely as coincidental surface cracks. Instead, they are direct manifestations of an inherent thermomechanical problem within the process [37,39,40]. Cracking represents a physical bottleneck associated with low thermal shock tolerance, highly temperature-dependent viscosity, and the brittle nature of glass during localized laser heating [39,120]. Due to the combination of highly localized heating, low absorption efficiency in certain glass systems, and rapid cooling rates, the laser–glass interaction induces pronounced thermal gradients that drive the accumulation of both thermal and residual stresses [170–172].

In soda-lime glass, modeling and experimental evidence show that, above the relaxation region, the material can flow or relax locally; however, during cooling, this deformation is “frozen in,” developing tensile radial stresses between the relaxed zone and the surrounding unrelaxed glass [171]. In crack-prone compositions such as soda-lime and borosilicate glasses, the rapid thermal evolution of the process can prevent sufficiently gradual stress relaxation within the useful viscous-forming window. Consequently, the material enters regimes where incomplete consolidation, residual porosity, and cracking susceptibility coexist [39,40,170]. During solidification and subsequent cooling, residual stress profiles are induced that can exceed the tensile fracture threshold of the glass, triggering microfissures, crack propagation into the substrate, and the failure of multi-layer

builds [37,171]. In borosilicate glass, crack-free tracks have been successfully fabricated with preheating up to 510 °C; for soda-lime glass, 350 °C proved sufficient to prevent cracking; and in quartz glass, even higher temperatures reduced porosity by accelerating viscous coalescence [39,40,170].

### 5.3. Dimensional Stability

A critical evaluation of the literature reveals unresolved discrepancies regarding dimensional retention when using indirect glass additive manufacturing technologies, particularly those dependent on post-print debinding and sintering stages. In these systems, thermal post-processing not only governs the ultimate densification but also introduces significant linear shrinkage, geometric distortion, and, in numerous cases, anisotropic shrinkage. This behavior forces the incorporation of scaling factors, support redesign, or predictive modeling to compensate for deviations between the nominal CAD geometry and the final part [99,168,173]. This loss of fidelity is not driven by a single factor, but rather by the complex interaction among viscous flow during sintering, non-ideal interlayer packing, anisotropic pore distribution, build orientation, and mechanical constraints imposed by either the substrate or the consolidation environment itself [99,130,174].

Concurrently, a more recent line of research demonstrates that these effects are not entirely intractable and can be partially mitigated by controlling powder and sintering variables. Key factors include PSD, particle morphology, crystallization state, initial packing density, and material confinement during consolidation. For instance, in BJT-printed glass, spherical particles exhibited a shrinkage behavior closer to isotropy compared to milled or frit powders. In other glass or glass–ceramic systems, adjusting particle size and coalescence kinetics facilitated a reduction in distortion or improved densification at lower temperatures [94,130,175].

Nonetheless, the literature does not yet offer sufficient consensus to generally assert that an optimized PSD simultaneously guarantees near-full densification and uncompromised geometric fidelity. Trade-offs persist among powder flowability, packing homogeneity, densification kinetics, and dimensional stability. Furthermore, recent critical reviews underscore that the thermal post-processing of glass AM parts remains scarcely explored in open literature [21,130,176].

### 5.4. Glass AM Technologies Versus Conventional Processing

Based on the analysis conducted in this review, comparing glass AM with conventionally manufactured glass reveals a heterogeneity that is intrinsically linked to both the nature of the selected AM technology and the family of the processed material. Conventionally manufactured glass (via traditional molding or float processing) establishes a homogeneous and robust baseline characterized by full density, optimal optical transmittance, and high structural mechanical strength. Within the glass AM field, however, the replication of these standard properties remains significantly fragmented and varied.

Micro- and nanoscale VPP technologies, such as TPP and DLP, successfully match the conventional attributes of fused silica glass to an outstanding degree [6,7]. Nonetheless, the primary source of this heterogeneity lies in the fact that these levels of strength and transparency are achieved at the expense of limited build volumes and critical linear shrinkage rates, which pose a risk of part cracking.

On the other hand, DED methods—such as LGD or filament-fed soda-lime and borosilicate systems—achieve competitive transmittances alongside macrostructural densities comparable to conventional glass. These properties are attained directly during the printing process, bypassing the need for prolonged downstream thermal treatments. However,

heterogeneity in these processes manifests as a highly anisotropic mechanical behavior and the entrapment of microbubbles caused by viscosity fluctuations within the molten pool.

At the opposite end of the optical performance spectrum, LPBF/SLM and FDM/MEX yield the poorest transparency values and considerable levels of internal porosity. This is primarily attributed to balling (spheroidization) effects, the incomplete melting of irregular particles, and rapid cooling rates that induce structural opacity. Despite these optical limitations, these technologies exhibit remarkable mechanical and industrial maturity for the fabrication of low-pressure catalytic reactors, non-optical structural components, or large-scale architectural elements that prioritize chemical stability and cost-effectiveness.

### 5.5. Future Perspectives

A distinct trend emerging from the literature indicates a strategic shift toward the convergence of complementary processes, as individual glass AM technologies present disparate capabilities and inherent limitations [17,19,20]. To overcome these processing bottlenecks more effectively, hybrid approaches propose the integration of additive shaping methodologies with thermal conditioning, machining, or precision subtractive stages [17,20,141].

Following this approach, it is feasible to employ paste extrusion systems based on MEX or VPP of particle-loaded resins to define the base geometric morphology or the green body of the component. Subsequently or concurrently, this architecture can be subjected to precision machining, subtractive laser engraving, or in-situ CO<sub>2</sub> laser-assisted remelting [16]. Such integration enables the immediate mitigation of surface roughness inherited from layer-by-layer deposition, the dissolution of microbubbles trapped at print-track interfaces, and the elimination of residual porosity that degrades optical performance. Ultimately, the viability of these hybrid platforms—such as combining embedded extrusion with VAM—enables high-efficiency fabrication of macroscale components featuring internal microfluidic networks and nanometer-scale, optical-grade surface finishes [141,142,173].

The remarkable surge in research surrounding glass AM underscores its transformative potential across diverse technological domains. In particular, the ability of AM techniques to rapidly and cost-effectively fabricate optical lenses with complex geometries and sub-nanometric surface roughness promises to revolutionize optical manufacturing, opening new avenues in laser processing, machine vision, and optical communications. Beyond single-material capabilities, a key advantage of glass AM over conventional lens fabrication lies in multi-material integration, which enables the design and production of custom-engineered lenses with enhanced optical performance and expanded functionality. Leveraging multi-material feedstocks alongside multi-scale architectures provides a viable pathway toward next-generation optics tailored to specific operational demands. Furthermore, the advent of 4D printing—defined as an advanced additive manufacturing approach utilizing smart materials that alter their shape or functional properties over time in response to external environmental stimuli, where the fourth dimension represents time—will allow fabricated structures to dynamically adapt and self-adjust, unlocking programmable devices with superior operational capabilities [177,178].

### 5.6. Sustainability and Glass AM

To date, literature directly addressing sustainability within the domain of glass AM remains notably sparse, presenting a compelling research opportunity as these various additive manufacturing platforms rapidly transition toward maturity. AM facilitates a transition toward a circular and resource-efficient manufacturing paradigm by directly addressing the energy and material inefficiencies inherent to traditional glass production [179–181].

The transition toward next-generation sustainable glass AM will increasingly rely on green chemistry and consolidation techniques to eliminate carbon emissions and toxic byproducts during processing. Future efforts should focus on replacing traditional petroleum-derived binders with bio-derived, water-soluble biopolymers [62,182]. Additional studies should prioritize standardized life cycle assessment frameworks to compare glass AM with conventional glass manufacturing routes, including tooling, mold use, transportation, and material waste, using metrics such as cumulative carbon emissions, water consumption, and energy demand [179,183,184].

The implementation of recycled glass in additive manufacturing represents a sustainable alternative, but it faces multiple challenges regarding its technical and productive viability. These challenges are primarily related to compositional variability and the presence of impurities, which introduce uncertainty into the material's optical, thermal, and mechanical properties, thereby hindering the identification of optimal extrusion or fusion conditions.

## 6. Conclusions

This review reveals that glass additive manufacturing is undergoing sustained growth, predominantly driven by photopolymerization and extrusion-based technologies, which offer the highest resolution and microstructural control for silica-based components. Furthermore, process viability and the mitigation of intrinsic defects—such as porosity and cracking—are shown to rely critically on the coupled optimization of chemical formulation, material rheology, and thermal history control.

The evidence indicates that, to date, no single dominant technology is capable of entirely and simultaneously replicating all the properties of conventionally manufactured glass. Instead, diverse developments in glass AM are tailored to address distinct challenges within specific applications, balancing the trade-offs between geometric resolution, optical transparency, and process scalability. Nevertheless, the emergence of hybrid technologies that integrate multiple manufacturing steps represents a promising frontier for producing finished components with properties comparable to those obtained through conventional manufacturing routes.

The principal limitation of this review arises from the substantial heterogeneity of reported outcomes and the absence of standardized methodologies across the existing literature, coupled with a scarcity of quantitative research on the sustainability and life cycle analysis of printed glass. In this context, methodologies based on computational modeling and data analysis are beginning to be employed to optimize process parameters and improve final component quality. These developing techniques facilitate the modeling of non-linear relationships and reduce the need for physical experimentation. The integration of these technologies with advanced simulation and real-time control constitutes a promising line of research.

**Author Contributions:** Conceptualization, E.F.C.C. and E.A.T.B.; methodology, E.F.C.C. and E.A.T.B.; formal analysis, E.F.C.C., A.D.G.R. and E.A.T.B.; investigation, E.F.C.C., A.D.G.R. and E.A.T.B.; writing—original draft preparation, E.F.C.C.; writing—review and editing, E.F.C.C., A.D.G.R. and E.A.T.B.; visualization, E.F.C.C., and A.D.G.R.; supervision, E.F.C.C., A.D.G.R. and E.A.T.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|                    |                                                                    |
|--------------------|--------------------------------------------------------------------|
| AM                 | Additive Manufacturing                                             |
| PRISMA             | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| SLA                | Stereolithography                                                  |
| DIW                | Direct Ink Writing                                                 |
| SLS                | Selective Laser Sintering                                          |
| SLM                | Selective Laser Melting                                            |
| FDM                | Fused Deposition Modeling                                          |
| DED                | Directed Energy Deposition                                         |
| T <sub>g</sub>     | Glass Transition                                                   |
| DLP                | Digital Light Processing                                           |
| BGs                | Bioactive Glasses                                                  |
| MBG                | Mesoporous Bioactive Glasses                                       |
| BMG                | Bulk Metallic Glass                                                |
| BJT                | Binder Jetting                                                     |
| MEX                | Material Extrusion                                                 |
| PBF                | Powder Bed Fusion                                                  |
| VPP                | Vat Photopolymerization                                            |
| TPP                | Two-Photon Polymerization                                          |
| IASM               | Integrated Additive and Subtractive Manufacturing                  |
| SPD                | Selective Dust Deposition                                          |
| LAP                | Laser-Assisted Printing                                            |
| LPBF               | Laser Powder Bed Fusion                                            |
| LGD                | Direct Glass Laser Deposition                                      |
| LPD                | Laser Powder Deposition                                            |
| CAL                | Computed Axial Lithography                                         |
| LCD                | Liquid Crystal Display                                             |
| LCM                | Lithography-Based Ceramic Manufacturing                            |
| Op <sub>μ</sub> sl | One-Photon Micro-Stereolithography                                 |
| PμSL               | Projection Micro Stereolithography                                 |
| VAM                | Volumetric Additive Manufacturing                                  |
| SEM                | Scanning Electron Microscopy                                       |
| XRD                | X-Ray Diffraction                                                  |
| NMR                | Nuclear Magnetic Resonance Spectroscopy                            |
| FEA                | Finite Element Analysis                                            |
| CFD                | Computational Fluid Dynamics                                       |

## References

1. Zhou, L.; Miller, J.; Vezza, J.; Mayster, M.; Raffay, M.; Justice, Q.; Al Tamimi, Z.; Hansotte, G.; Sunkara, L.D.; Bernat, J. Additive Manufacturing: A Comprehensive Review. *Sensors* **2024**, *24*, 2668. [[CrossRef](#)] [[PubMed](#)]
2. Berman, B. 3-D Printing: The New Industrial Revolution. *Bus. Horiz.* **2012**, *55*, 155–162. [[CrossRef](#)]
3. Liu, X.; Yang, Y.; Qiu, J. Emerging Techniques for Customized Fabrication of Glass. *J. Non-Cryst. Solids X* **2022**, *15*, 100114. [[CrossRef](#)]
4. Luo, J.; Pan, H.; Kinzel, E.C. Additive Manufacturing of Glass. *J. Manuf. Sci. Eng.* **2014**, *136*, 061024. [[CrossRef](#)]
5. Mader, M.; Hambitzer, L.; Schlautmann, P.; Jenne, S.; Greiner, C.; Hirth, F.; Helmer, D.; Kotz-Helmer, F.; Rapp, B.E. Melt-Extrusion-Based Additive Manufacturing of Transparent Fused Silica Glass. *Adv. Sci.* **2021**, *8*, 2103180. [[CrossRef](#)] [[PubMed](#)]
6. Klein, J.; Stern, M.; Franchin, G.; Kayser, M.; Inamura, C.; Dave, S.; Weaver, J.C.; Houk, P.; Colombo, P.; Yang, M.; et al. Additive Manufacturing of Optically Transparent Glass. *3D Print. Addit. Manuf.* **2015**, *2*, 92–105. [[CrossRef](#)]
7. Inamura, C.; Stern, M.; Lizardo, D.; Houk, P.; Oxman, N. Additive Manufacturing of Transparent Glass Structures. *3D Print. Addit. Manuf.* **2018**, *5*, 269–283. [[CrossRef](#)]

8. Walton, B.L.; Dudukovic, N.A.; Johnson, J.; Yee, T.D.; Nguyen, D.T.; Ellis, M.E.; Porcincula, D.H.; Krikorian, C.C.; Duoss, E.B.; Dylla-Spears, R.J. Unlocking Larger Scales and Aspect Ratios in 3D Printed Glass: Coupling Active Mixing and UV Curing for Advanced Printability and Crack Resistance. *Adv. Mater. Technol.* **2025**, *10*, 2401284. [[CrossRef](#)]
9. Fu, Q.; Saiz, E.; Tomsia, A.P. Direct Ink Writing of Highly Porous and Strong Glass Scaffolds for Load-Bearing Bone Defects Repair and Regeneration. *Acta Biomater.* **2011**, *7*, 3547–3554. [[CrossRef](#)] [[PubMed](#)]
10. Kolan, K.C.R.; Leu, M.C.; Hilmas, G.E.; Brown, R.F.; Velez, M. Fabrication of 13–93 Bioactive Glass Scaffolds for Bone Tissue Engineering Using Indirect Selective Laser Sintering. *Biofabrication* **2011**, *3*, 025004. [[CrossRef](#)] [[PubMed](#)]
11. Eqtesadi, S.; Motealleh, A.; Miranda, P.; Pajares, A.; Lemos, A.; Ferreira, J.M.F. Robocasting of 45S5 Bioactive Glass Scaffolds for Bone Tissue Engineering. *J. Eur. Ceram. Soc.* **2014**, *34*, 107–118. [[CrossRef](#)]
12. Eqtesadi, S.; Motealleh, A.; Pajares, A.; Miranda, P. Effect of Milling Media on Processing and Performance of 13-93 Bioactive Glass Scaffolds Fabricated by Robocasting. *Ceram. Int.* **2015**, *41*, 1379–1389. [[CrossRef](#)]
13. Gmeiner, R.; Mitteramskogler, G.; Stampfl, J.; Boccaccini, A.R. Stereolithographic Ceramic Manufacturing of High Strength Bioactive Glass. *Int. J. Appl. Ceram. Technol.* **2015**, *12*, 38–45. [[CrossRef](#)]
14. Avallé, M.; Frascio, M. Mechanical Characterization and Modeling of Glass Fiber-Reinforced Polyamide Built by Additive Manufacturing. *Materials* **2025**, *18*, 745. [[CrossRef](#)] [[PubMed](#)]
15. Guerra Silva, R.; Gonzalez, E.; Inostroza, A.; Morales Pavez, G. Flexural Analysis of Additively Manufactured Continuous Fiber-Reinforced Honeycomb Sandwich Structures. *J. Manuf. Mater. Process.* **2024**, *8*, 226. [[CrossRef](#)]
16. Zhang, H.; Zhang, Q.; Xiang, P.; Wang, Y.; Lei, J. Direct Additive Manufacturing of Transparent Fused Silica Glasses Using an Integrated Paste Printing and Laser In-Situ Melting Technology. *Addit. Manuf.* **2024**, *84*, 104135. [[CrossRef](#)]
17. Luo, H.; Zhang, Y.; Yu, J.; Dong, X.; Zhou, T. Additive, Subtractive and Formative Manufacturing of Glass-Based Functional Micro/Nanostructures: A Comprehensive Review. *Mater. Des.* **2023**, *233*, 112285. [[CrossRef](#)]
18. Huang, P.-H.; Laakso, M.; Edinger, P.; Hartwig, O.; Duesberg, G.S.; Lai, L.-L.; Mayer, J.; Nyman, J.; Errando-Herranz, C.; Stemme, G.; et al. Three-Dimensional Printing of Silica Glass with Sub-Micrometer Resolution. *Nat. Commun.* **2023**, *14*, 3305. [[CrossRef](#)] [[PubMed](#)]
19. Zhang, D.; Liu, X.; Qiu, J. 3D Printing of Glass by Additive Manufacturing Techniques: A Review. *Front. Optoelectron.* **2021**, *14*, 263–277. [[CrossRef](#)] [[PubMed](#)]
20. Xin, C.; Li, Z.; Hao, L.; Li, Y. A Comprehensive Review on Additive Manufacturing of Glass: Recent Progress and Future Outlook. *Mater. Des.* **2023**, *227*, 111736. [[CrossRef](#)]
21. Shaw, M.; Vlahopoulos, D.; Usma-Mansfield, C.; Sarmiento, J.; Snooks, R.; Koutsonikolas, T.; Birbilis, N. The Additive Manufacturing of Glass: A Critical Review. *Appl. Sci.* **2025**, *15*, 3414. [[CrossRef](#)]
22. Moore, L.A.; Smith, C.M. Fused Silica as an Optical Material [Invited]. *Opt. Mater. Express* **2022**, *12*, 3043–3059. [[CrossRef](#)]
23. Kitamura, R.; Pilon, L.; Jonasz, M. Optical Constants of Silica Glass from Extreme Ultraviolet to Far Infrared at near Room Temperature. *Appl. Opt.* **2007**, *46*, 8118–8133. [[CrossRef](#)] [[PubMed](#)]
24. Brückner, R. Properties and Structure of Vitreous Silica. I. *J. Non Cryst. Solids* **1970**, *5*, 123–175. [[CrossRef](#)]
25. Jiang, X.; Chen, D.; Quan, Y.; Long, X.; Wu, S.; Tan, Z. The Densification Characteristics of Polished Fused Silica Glass and Its Scattering Characteristics. *Photonics* **2023**, *10*, 447. [[CrossRef](#)]
26. Turner, B.N.; Strong, R.; Gold, S.A. A Review of Melt Extrusion Additive Manufacturing Processes: I. Process Design and Modeling. *Rapid Prototyp. J.* **2014**, *20*, 192–204. [[CrossRef](#)]
27. Song, S.; Hou, Y.; Sun, M.; Wang, B.; Bao, C.; Liu, R.; Dong, W.; Lu, B.; Ma, E. Incorporating Boron Carbide into Fused Silica Imparts Multiple Mechanisms to Facilitate Vat Photopolymerization. *Addit. Manuf.* **2024**, *85*, 104159. [[CrossRef](#)]
28. Lyu, P.; Pan, J.; Liu, Z.; Fang, F. Polishing of Fused Silica by Laser-Enhanced Plasma at the Atomic and Close-to-Atomic Scale. *CIRP Ann.* **2025**, *74*, 281–285. [[CrossRef](#)]
29. Li, Z.; Jia, Y.; Xiao, R.; Chen, J.; Wu, H.; Wen, X.; Lu, Y. 3D-Printed Fused Silica Glass Microlattice as Mechanical Metamaterial. *Cell Rep. Phys. Sci.* **2024**, *5*, 102172. [[CrossRef](#)]
30. Shelby, J.E. *Introduction to Glass Science and Technology*; Royal Society of Chemistry: London, UK, 2005.
31. Cheng, S. Viscosity-Temperature Relation Based on the Evolution of Medium-Range Structures of Silica. *J. Non Cryst. Solids* **2021**, *557*, 120582. [[CrossRef](#)]
32. Lima, M.M.; Monteiro, R. Characterisation and Thermal Behaviour of a Borosilicate Glass. *Thermochim. Acta* **2001**, *373*, 69–74. [[CrossRef](#)]
33. Layher, A.M.; Tewes, L.; Thumann, F.; Boeckh, T.; Koppka, S.; Enke, D.; Rädlein, E.; Bliedtner, J. Laser-Based Additive Manufacturing of Alkali Borosilicate Glass Powder: Influence of Laser-Beam Properties on Component Quality. *J. Manuf. Mater. Process.* **2025**, *9*, 305. [[CrossRef](#)]
34. Okpowe, O.; Drozd, V.; Ares-Muzio, O.; Pala, N.; Wang, C. Additive Manufacturing of Borosilicate Glass via Stereolithography. *Ceram. Int.* **2022**, *48*, 12721–12728. [[CrossRef](#)]

35. Zhao, X.; Zhai, D.; Jell, G.; Wu, C.; Gao, H.; Jones, J.R. Borosilicate Bioactive Glass 3D Fibrous Matrices with Increased Borate Content Stimulate Healing Cascades in Chronic Wounds. *Acta Biomater.* **2025**, *202*, 605–621. [[CrossRef](#)] [[PubMed](#)]
36. Luo, J.; Goldstein, J.T.; Urbas, A.M.; Bristow, D.A.; Landers, R.G.; Kinzel, E.C. Additive Manufacturing of Borosilicate Glass (Conference Presentation). In Proceedings of the Laser 3D Manufacturing IV, San Francisco, CA, USA, 30 January–2 February 2017.
37. Datsiou, K.C.; Spirrett, F.; Ashcroft, I.; Magallanes, M.; Christie, S.; Goodridge, R. Laser Powder Bed Fusion of Soda Lime Silica Glass: Optimisation of Processing Parameters and Evaluation of Part Properties. *Addit. Manuf.* **2021**, *39*, 101880. [[CrossRef](#)]
38. Kasch, S.; Schmidt, T.; Eichler, F.; Thurn, L.K.; Jahn, S.; Bremen, S. Solution Approaches and Process Concepts for Powder Bed-Based Melting of Glass. In *Industrializing Additive Manufacturing*; Springer: Berlin/Heidelberg, Germany, 2021.
39. Grigoriev, S.N.; Khmyrov, R.S.; Gridnev, M.A.; Tarasova, T.V.; Gusarov, A.V. Optimizing the Process Parameters for Additive Manufacturing of Glass Components by Selective Laser Melting: Soda-Lime Glass Versus Quartz Glass. *J. Manuf. Sci. Eng. Trans. ASME* **2022**, *144*, 064503. [[CrossRef](#)]
40. Datsiou, K.C.; Ashcroft, I. Numerical Investigation of Laser Powder Bed Fusion of Glass. *Glass Struct. Eng.* **2024**, *9*, 185–200. [[CrossRef](#)]
41. Datsiou, K.C.; Saleh, E.; Spirrett, F.; Goodridge, R.; Ashcroft, I.; Eustice, D. Additive Manufacturing of Glass with Laser Powder Bed Fusion. *J. Am. Ceram. Soc.* **2019**, *102*, 4410–4414. [[CrossRef](#)]
42. Luo, J.; Gilbert, L.J.; Qu, C.; Landers, R.G.; Bristow, D.A.; Kinzel, E.C. Additive Manufacturing of Transparent Soda-Lime Glass Using a Filament-Fed Process. *J. Manuf. Sci. Eng. Trans. ASME* **2017**, *139*, 061006. [[CrossRef](#)]
43. Soldera, M.; Alamri, S.; Sürmann, P.A.; Kunze, T.; Lasagni, A.F. Microfabrication and Surface Functionalization of Soda Lime Glass through Direct Laser Interference Patterning. *Nanomaterials* **2021**, *11*, 129. [[CrossRef](#)] [[PubMed](#)]
44. Seel, M.; Akerboom, R.; Knaack, U.; Oechsner, M.; Hof, P.; Schneider, J. Fused Glass Deposition Modelling for Applications in the Built Environment | Schmelzschichten Aus Glas Für Anwendungen Im Bauwesen. *Mater. Werkst.* **2018**, *49*, 870–880. [[CrossRef](#)]
45. Deng, W.; Spathi, C.; Coulbeck, T.; Erhan, K.; Backhouse, D.; Marshall, M.; Ireson, R.; Bingham, P.A. Exploratory Research in Alternative Raw Material Sources and Reformulation for Industrial Soda-Lime-Silica Glass Batches. *Int. J. Appl. Glass Sci.* **2020**, *11*, 340–356. [[CrossRef](#)]
46. Zaki, R.M.; Strutyński, C.; Kaser, S.; Bernard, D.; Hauss, G.; Faessel, M.; Sabatier, J.; Canioni, L.; Messaddeq, Y.; Danto, S.; et al. Direct 3D-Printing of Phosphate Glass by Fused Deposition Modeling. *Mater. Des.* **2020**, *194*, 108957. [[CrossRef](#)]
47. Maturi, F.E.; Gaddam, A.; Brites, C.D.S.; Souza, J.M.M.; Eckert, H.; Ribeiro, S.J.L.; Carlos, L.D.; Manzani, D. Extending the Palette of Luminescent Primary Thermometers: Yb<sup>3+</sup>/Pr<sup>3+</sup> Co-Doped Fluoride Phosphate Glasses. *Chem. Mater.* **2023**, *35*, 7229–7238. [[CrossRef](#)] [[PubMed](#)]
48. Sasan, K.; Lange, A.; Yee, T.D.; Dudukovic, N.; Nguyen, D.T.; Johnson, M.A.; Herrera, O.D.; Yoo, J.H.; Sawvel, A.M.; Ellis, M.E.; et al. Additive Manufacturing of Optical Quality Germania-Silica Glasses. *ACS Appl. Mater. Interfaces* **2020**, *12*, 6736–6741. [[CrossRef](#)] [[PubMed](#)]
49. Hong, Z.; Luo, T.; Jiang, S.; Liang, R. Fiber-Fed 3D Printing of Germanate Glass Optics. *Photonics* **2023**, *10*, 378. [[CrossRef](#)]
50. Varshneya, A.K.; Mauro, J.C. *Fundamentals of Inorganic Glasses*; Elsevier: Amsterdam, The Netherlands, 2019.
51. Calvez, L. Chalcogenide Glasses and Glass-Ceramics: Transparent Materials in the Infrared for Dual Applications. *Comptes Rendus Phys.* **2017**, *18*, 314–322. [[CrossRef](#)]
52. Zhou, T.; Zhu, Z.; Liu, X.; Liang, Z.; Wang, X. A Review of the Precision Glass Molding of Chalcogenide Glass (ChG) for Infrared Optics. *Micromachines* **2018**, *9*, 337. [[CrossRef](#)] [[PubMed](#)]
53. Wang, Y.; Dai, S. Mid-Infrared Supercontinuum Generation in Chalcogenide Glass Fibers: A Brief Review. *Photonix* **2021**, *2*, 9. [[CrossRef](#)]
54. Adam, J.L.; Calvez, L.; Trolès, J.; Nazabal, V. Chalcogenide Glasses for Infrared Photonics. *Int. J. Appl. Glass Sci.* **2015**, *6*, 287–294. [[CrossRef](#)]
55. Carcreff, J.; Cheviré, F.; Lebullenger, R.; Gautier, A.; Chahal, R.; Adam, J.L.; Calvez, L.; Brilland, L.; Galdo, E.; Le Coq, D.; et al. Investigation on Chalcogenide Glass Additive Manufacturing for Shaping Mid-Infrared Optical Components and Microstructured Optical Fibers. *Crystals* **2021**, *11*, 228. [[CrossRef](#)]
56. Ahmed Simon, A.; Badamchi, B.; Subbaraman, H.; Sakaguchi, Y.; Jones, L.; Kunold, H.; van Rooyen, I.J.; Mitkova, M. Introduction of Chalcogenide Glasses to Additive Manufacturing: Nanoparticle Ink Formulation, Inkjet Printing, and Phase Change Devices Fabrication. *Sci. Rep.* **2021**, *11*, 14311. [[CrossRef](#)] [[PubMed](#)]
57. Wang, J.; Wu, G.; Feng, Z.; Wang, J.; Wang, Y.; Jiao, K.; Wang, X.; Bai, S.; Zhang, P.; Zhao, Z.; et al. Se-H-Free As<sub>2</sub>Se<sub>3</sub> Fiber and Its Spectral Applications in the Mid-Infrared. *Opt. Express* **2022**, *30*, 24072–24083. [[CrossRef](#)] [[PubMed](#)]
58. Casamenti, E.; Torun, G.; Borasi, L.; Lautenbacher, M.; Bertrand, M.; Faist, J.; Mortensen, A.; Bellouard, Y. Glass-in-Glass Infiltration for 3D Micro-Optical Composite Components. *Opt. Express* **2022**, *30*, 13603–13615. [[CrossRef](#)] [[PubMed](#)]
59. Baines, F.; Fiume, E. 3D Printing of Hierarchical Scaffolds Based on Mesoporous Bioactive Glasses (MBGs)-Fundamentals and Applications. *Materials* **2020**, *13*, 1688. [[CrossRef](#)] [[PubMed](#)]

60. Zhang, M.; Zhai, X.; Ma, T.; Huang, Y.; Jin, M.; Yang, H.; Fu, H.; Zhang, S.; Sun, T.; Jin, X.; et al. Sequential Therapy for Bone Regeneration by Cerium Oxide-Reinforced 3D-Printed Bioactive Glass Scaffolds. *ACS Nano* **2023**, *17*, 4433–4444. [[CrossRef](#)] [[PubMed](#)]
61. Zhu, Y.; Zhang, X.; Chang, G.; Deng, S.; Chan, H.F. Bioactive Glass in Tissue Regeneration: Unveiling Recent Advances in Regenerative Strategies and Applications. *Adv. Mater.* **2025**, *37*, e2312964. [[PubMed](#)]
62. Mahmoud, M.; Kraxner, J.; Mehta, A.; Elsayed, H.; Galusek, D.; Bernardo, E. Alkali Activation-Induced Cold Consolidation of Waste Glass: Application in Organic-Free Direct Ink Writing of Photocatalytic Dye Destructors. *J. Eur. Ceram. Soc.* **2024**, *44*, 5449–5459. [[CrossRef](#)]
63. He, L.; Yin, J.; Gao, X. Additive Manufacturing of Bioactive Glass and Its Polymer Composites as Bone Tissue Engineering Scaffolds: A Review. *Bioengineering* **2023**, *10*, 672. [[CrossRef](#)]
64. Zheng, K.; Chen, Q. 3D Printing of Bioactive Glasses and Glass-Ceramics for Bone Tissue Regeneration. In *Additive Manufacturing of Glass: From Science to Applications*; Elsevier: Amsterdam, The Netherlands, 2024.
65. Carnieri, M.V.; Garcia, D.d.F.; Voltolini, R.; Volpato, N.; Mafra, M.; Bernardelli, E.A.; Stimamiglio, M.A.; Rebelatto, C.K.; Correa, A.; Berti, L.F.; et al. Cytocompatible and Osteoconductive Silicon Oxycarbide Glass Scaffolds 3D Printed by DLP: A Potential Material for Bone Tissue Regeneration. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1297327. [[CrossRef](#)] [[PubMed](#)]
66. Pacheco-Vergara, M.J.; Ricci, J.L.; Mijares, D.; Bromage, T.G.; Rabieh, S.; Coelho, P.G.; Witek, L. 3D Printed Mesoporous Bioactive Glass, Bioglass 45S5, and  $\beta$ -TCP Scaffolds for Regenerative Medicine: A Comparative in Vitro Study. *Biomed. Mater. Eng.* **2023**, *34*, 439–458. [[CrossRef](#)] [[PubMed](#)]
67. Martelli, A.; Bellucci, D.; Cannillo, V. Additive Manufacturing of Polymer/Bioactive Glass Scaffolds for Regenerative Medicine: A Review. *Polymers* **2023**, *15*, 2473. [[CrossRef](#)] [[PubMed](#)]
68. Nommeots-Nomm, A.; Lee, P.D.; Jones, J.R. Direct Ink Writing of Highly Bioactive Glasses. *J. Eur. Ceram. Soc.* **2018**, *38*, 837–844. [[CrossRef](#)]
69. Gao, W.; Chang, L.; Ma, H.; You, L.; Yin, J.; Liu, J.; Liu, Z.; Wang, J.; Yuan, G. Flexible Organic Ferroelectric Films with a Large Piezoelectric Response. *NPG Asia Mater.* **2015**, *7*, e189. [[CrossRef](#)]
70. Kruzic, J.J. Bulk Metallic Glasses as Structural Materials: A Review. *Adv. Eng. Mater.* **2016**, *18*, 1308–1331. [[CrossRef](#)]
71. Zhang, L.; Xu, F.; Zhang, J.; Bian, B.; Hu, Y.; Xue, F.; Du, J. Large-Scale Area of Magnetically Anisotropic Nanoparticle Monolayer Films Deposited by MAPLE. *J. Mater. Sci. Technol.* **2022**, *106*, 28–32. [[CrossRef](#)]
72. Li, Z.; Jia, Y.; Duan, K.; Xiao, R.; Qiao, J.; Liang, S.; Wang, S.; Chen, J.; Wu, H.; Lu, Y.; et al. One-Photon Three-Dimensional Printed Fused Silica Glass with Sub-Micron Features. *Nat. Commun.* **2024**, *15*, 2689. [[CrossRef](#)] [[PubMed](#)]
73. Li, Z.; Jia, Y.; Su, F.; Chen, J.; Wen, X.; Liang, W.; Wu, H.; Lu, Y. 3D-Printed Silica Glass Micro-Mechanical Device (MMD) for in Situ Mechanical Testing. *Extrem. Mech. Lett.* **2025**, *78*, 102384. [[CrossRef](#)]
74. Kluck, S.; Schiffmann, L.; Riehl, L.; Prediger, R.; Hambitzer, L.; Rapp, B.E.; Kotz-Helmer, F. Ultra Sonic Spray Coating of Silica Nanocomposites for Smoothing 3D-Printed Fused Silica Glass and Metal Casted Injection Molding Tools. *Virtual Phys. Prototyp.* **2025**, *20*, e2516666. [[CrossRef](#)]
75. Zhang, W.; Wang, H.; Wang, H.; Ha, S.T.; Chen, L.; Li, X.L.; Pan, C.-F.; Wu, B.; Rahman, M.A.; Ke, Y.; et al. Nanoscale 3D Printing of Glass Photonic Crystals with Near-Unity Reflectance in the Visible Spectrum. *Sci. Adv.* **2025**, *11*, eadv0267. [[CrossRef](#)] [[PubMed](#)]
76. Hong, Z.; Ye, P.; Loy, D.A.; Liang, R. Integrated 3D Printing of Transparency-on-Demand Glass Microstructure. *Adv. Opt. Mater.* **2025**, *13*, 2500390. [[CrossRef](#)]
77. You, R.; Hong, Z.; Chen, J.; Zhang, Z.; Wang, Y.; Sun, Y.; Song, B.; Loy, D.A.; Ji, Z.; Liang, R. Extremely Compact 3D Printed Glass Ternary Diffractive Optical Element for Holographic Images. *Adv. Opt. Mater.* **2025**, *13*, 2501074. [[CrossRef](#)] [[PubMed](#)]
78. Li, B.; Li, Z.; Cooperstein, I.; Shan, W.; Wang, S.; Jiang, B.; Zhang, L.; Magdassi, S.; He, J. Additive Manufacturing of Transparent Multi-Component Nanoporous Glasses. *Adv. Sci.* **2023**, *10*, e2305775. [[CrossRef](#)] [[PubMed](#)]
79. Hong, Z.; Sun, Y.; Ye, P.; Loy, D.A.; Liang, R. Bio-Inspired Compact, High-Resolution Snapshot Hyperspectral Imaging System with 3D Printed Glass Lightguide Array. *Adv. Opt. Mater.* **2023**, *11*, 2300156. [[CrossRef](#)] [[PubMed](#)]
80. Hong, Z.; Ye, P.; Loy, D.A.; Liang, R. High-Precision Printing of Complex Glass Imaging Optics with Precondensed Liquid Silica Resin. *Adv. Sci.* **2022**, *9*, e2105595. [[CrossRef](#)] [[PubMed](#)]
81. Guzi de Moraes, E.; Ferreira, I.M.; Teixeira, L.B.; Cartapati, L.H.; Souza, M.T.; Novaes de Oliveira, A.P. Additive Manufacturing of Cellular Structures from Recycled Soda-Lime Glass Printing Inks by Robocasting. *Ceram. Int.* **2023**, *49*, 6554–6562. [[CrossRef](#)]
82. Demchyna, B.; Tkach, R.; Kotselko, R. Analysis of Additive Manufacturing of Glass Domes: Challenges and Prospects for Use on Mars. *Arch. Mater. Sci. Eng.* **2024**, *129*, 31–41. [[CrossRef](#)]
83. Liu, C.; Oriekhov, T.; Lee, C.; Harvey, C.M.; Fokine, M. Rapid Fabrication of Silica Microlens Arrays via Glass 3D Printing. *3D Print. Addit. Manuf.* **2024**, *11*, 460–466. [[CrossRef](#)] [[PubMed](#)]
84. Zhang, Q.; Lei, J.; Chen, Y.; Wu, Y.; Xiao, H. Glass 3D Printing of Microfluidic Pressure Sensor Interrogated by Fiber-Optic Refractometry. *IEEE Photonics Technol. Lett.* **2020**, *32*, 414–417. [[CrossRef](#)] [[PubMed](#)]

85. Hu, D.; Wang, C.; Li, D.; Xu, W.; Zhang, X. Vibration Deformation Measurement and Defect Identification Based on Time-Averaged Digital Holography. *Photonics* **2025**, *12*, 373. [\[CrossRef\]](#)
86. Sleiman, K.; Sleiman, O.; Rettschlag, K.; Jäschke, P.; Kaierle, S. Experimental Investigations on the Formation of Boundary Layers in Glass-Based Additive Manufacturing of Fused Silica Fibers by Laser Glass Deposition. *Int. J. Adv. Manuf. Technol.* **2024**, *135*, 1753–1766. [\[CrossRef\]](#)
87. Denkena, B.; Dittrich, M.-A.; Malek, T.; Sleiman, K.; Rettschlag, K.; Jäschke, P.; Kaierle, S. Numerical Investigation of the Influence of Process Parameters and Tool Path on the Temperature in the Laser Glass Deposition (LGD) Process. *Prod. Eng.* **2023**, *17*, 381–390. [\[CrossRef\]](#)
88. Zhang, Q.; Lei, J.; Chen, Y.; Tang, J.; Wu, Y.; Hua, L.; Xiao, H. Information Integrated Glass Module Fabricated by Integrated Additive and Subtractive Manufacturing. *Opt. Lett.* **2020**, *45*, 1663–1666. [\[CrossRef\]](#) [\[PubMed\]](#)
89. Lin, Z.; Xu, J.; Song, Y.; Li, X.; Wang, P.; Chu, W.; Wang, Z.; Cheng, Y. Freeform Microfluidic Networks Encapsulated in Laser-Printed 3D Macroscale Glass Objects. *Adv. Mater. Technol.* **2020**, *5*, 1900989. [\[CrossRef\]](#)
90. Burshtein, N.; Chan, S.T.; Toda-Peters, K.; Shen, A.Q.; Haward, S.J. 3D-Printed Glass Microfluidics for Fluid Dynamics and Rheology. *Curr. Opin. Colloid Interface Sci.* **2019**, *43*, 1–14. [\[CrossRef\]](#)
91. Wang, P.; Chu, W.; Li, W.; Tan, Y.; Liu, F.; Wang, M.; Qi, J.; Lin, J.; Zhang, F.; Wang, Z.; et al. Three-Dimensional Laser Printing of Macro-Scale Glass Objects at a Micro-Scale Resolution. *Micromachines* **2019**, *10*, 565. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Fadlelmula, M.M.; Mazinani, B.; Subramanian, V. Towards Personalized Microfluidics: 3D Printing of High-Performance Micropumps by Control and Optimization of Fabrication-Induced Surface Roughness. *Addit. Manuf.* **2024**, *94*, 104468. [\[CrossRef\]](#)
93. Yang, T.; Feng, Z.; Qiu, Y.; Han, W.; Kong, L. Selective Laser Melting of Glass with Irregular Shaped Powder. *J. Mater. Res. Technol.* **2023**, *26*, 7259–7272. [\[CrossRef\]](#)
94. Vasconcelos, J.; Sardinha, M.; Vicente, C.M.S.; Reis, L. Additive Manufacturing of Glass-Ceramic Parts from Recycled Glass Using a Novel Selective Powder Deposition Process. *Appl. Sci.* **2022**, *12*, 13022. [\[CrossRef\]](#)
95. Gal-Or, E.; Gershoni, Y.; Scotti, G.; Nilsson, S.M.E.; Saarinen, J.; Jokinen, V.; Strachan, C.J.; Boije Af Gennäs, G.; Yli-Kauhaluoma, J.; Kotiaho, T. Chemical Analysis Using 3D Printed Glass Microfluidics. *Anal. Methods* **2019**, *11*, 1802–1810. [\[CrossRef\]](#)
96. Shi, Y.; Chai, Y.; Hu, S. Preparation and Characterization of Printed LTCC Substrates for Microwave Devices. *Act. Passiv. Electron. Compon.* **2019**, *2019*, 6473587. [\[CrossRef\]](#)
97. Wang, S.; Peng, L.; Song, C.; Wang, C. Digital Light Processing Additive Manufacturing of Thin Dental Porcelain Veneers. *J. Eur. Ceram. Soc.* **2023**, *43*, 1161–1167. [\[CrossRef\]](#)
98. Yao, Y.; Zhou, X.; Hao, J.; Wang, W.; Xing, B.; Zhu, L.; Zhao, Z. Effect of a UV Absorber on Lithium Disilicate Glass-Ceramics Fabricated by Vat Photopolymerization. *Ceram. Int.* **2025**, *51*, 28260–28266. [\[CrossRef\]](#)
99. Schönherr, J.A.; Baumgartner, S.; Hartmann, M.; Stampfl, J. Stereolithographic Additive Manufacturing of High Precision Glass Ceramic Parts. *Materials* **2020**, *13*, 1492. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Elsayed, H.; Zocca, A.; Schmidt, J.; Günster, J.; Colombo, P.; Bernardo, E. Bioactive Glass-Ceramic Scaffolds by Additive Manufacturing and Sinter-Crystallization of Fine Glass Powders. *J. Mater. Res.* **2018**, *33*, 1960–1971. [\[CrossRef\]](#)
101. Sun, C.; Tian, X.; Wang, L.; Liu, Y.; Wirth, C.M.; Günster, J.; Li, D.; Jin, Z. Effect of Particle Size Gradation on the Performance of Glass-Ceramic 3D Printing Process. *Ceram. Int.* **2017**, *43*, 578–584. [\[CrossRef\]](#)
102. Carcreff, J.; Chevire, F.; Galdo, E.; Lebullenger, R.; Gautier, A.; Adam, J.L.; Coq, D.L.; Briland, L.; Chahal, R.; Renversez, G.; et al. Mid-Infrared Hollow Core Fiber Drawn from a 3D Printed Chalcogenide Glass Preform. *Opt. Mater. Express* **2020**, *11*, 198–209. [\[CrossRef\]](#)
103. Baudet, E.; Ledemi, Y.; Larochelle, P.; Morency, S.; Messaddeq, Y. 3D-Printing of Arsenic Sulfide Chalcogenide Glasses. *Opt. Mater. Express* **2019**, *9*, 2307–2317. [\[CrossRef\]](#)
104. Yashdeep; Subbiah, S. Use of Magnetic Fields to Impact Glass-Transition and Crystallization during Manufacturing of ZBLAN Optical Fibers. *Manuf. Lett.* **2024**, *41*, 442–450. [\[CrossRef\]](#)
105. Galdo, E.; Cozic, S.; Szymczyk, L.; Chevire, F.; Lebullenger, R.; Gautier, A.; Calvez, L.; Poulain, S.; Poulain, M.; Troles, J. ZBLAN Glass 3D Printing: The First Steps. *Opt. Mater. Express* **2025**, *15*, 1189–1195. [\[CrossRef\]](#)
106. de Lima, C.J.; Veer, F.; Zhang, H.; Filho, F.F.M.; Copuroglu, O.; Nijse, R. Thermal, Optical and Mechanical Properties of New Glass Compositions Containing Fly Ash. *Glass Technol. Eur. J. Glass Sci. Technol. Part A* **2021**, *62*, 96–108. [\[CrossRef\]](#)
107. Moore, D.G.; Barbera, L.; Masania, K.; Studart, A.R. Three-Dimensional Printing of Multicomponent Glasses Using Phase-Separating Resins. *Nat. Mater.* **2020**, *19*, 212–217. [\[CrossRef\]](#) [\[PubMed\]](#)
108. Mazinani, B.; Fadlelmula, M.M.; Subramanian, V. Highly Stable Low-Temperature Phosphate Glass as a Platform for Multimaterial 3D Printing of Integrated Functional Microfluidic Devices. *Adv. Eng. Mater.* **2025**, *27*, 2501603. [\[CrossRef\]](#)
109. Kondarage, A.I.; Poologasundarampillai, G.; Nommeots-Nomm, A.; Lee, P.D.; Lalitharatne, T.D.; Nanayakkara, N.D.; Jones, J.R.; Karunaratne, A. In Situ 4D Tomography Image Analysis Framework to Follow Sintering within 3D-Printed Glass Scaffolds. *J. Am. Ceram. Soc.* **2022**, *105*, 1671–1684. [\[CrossRef\]](#) [\[PubMed\]](#)

110. Hmood, F.J.; Wilbig, J.; Nicolaides, D.; Zocca, A.; Günster, J. An Approach to Monitor the Real-Time Deformation during Heat Treatment of 3D-Printed Glass. *Ceram. Int.* **2021**, *47*, 20045–20050. [[CrossRef](#)]
111. Farina, E.; Gastaldi, D.; Bairo, F.; Vernè, E.; Massera, J.; Orlygsson, G.; Vena, P. Micro Computed Tomography Based Finite Element Models for Elastic and Strength Properties of 3D Printed Glass Scaffolds. *Acta Mech. Sin.* **2021**, *37*, 292–306. [[CrossRef](#)]
112. Chinn, A.C.; Marsh, E.L.; Nguyen, T.; Alhejaj, Z.B.; Butler, M.J.; Nguyen, B.T.; Sasan, K.; Dylla-Spears, R.J.; Destino, J.F. Silica-Encapsulated Germania Colloids as 3D-Printable Glass Precursors. *ACS Omega* **2022**, *7*, 17492–17500. [[CrossRef](#)] [[PubMed](#)]
113. Maniewski, P.; Flint, A.I.; Bannerman, R.H.S.; Lee, T.; Beresna, M. Tunable KHz Distributed Feedback Fiber Laser Fabricated in 3D-Printed Glass. *APL Photonics* **2024**, *9*, e00935. [[CrossRef](#)]
114. Ouyang, M.; Zhang, H.; Li, M.; Zhang, J.; Gong, Y.; Huang, X.; Liu, X.; Qiu, J.; Yang, Z.; Dong, G. 3D Printing of Luminescent Glass with Controlled Distribution of Emission Colors for Multi-Dimensional Optical Anti-Counterfeiting. *Laser Photon. Rev.* **2023**, *17*, 2300068. [[CrossRef](#)]
115. Begum, S.R.; Vasumathi, M.; Karupaiah, V.; Narayanan, V. Effect of Process Parameters on Mechanical and Tribological Characteristics of FDM Printed Glass Fiber Reinforced PLA Composites. *Rapid Prototyp. J.* **2024**, *30*, 1859–1875. [[CrossRef](#)]
116. Chu, Y.; Fu, X.; Luo, Y.; Canning, J.; Tian, Y.; Cook, K.; Zhang, J.; Peng, G.-D. Silica Optical Fiber Drawn from 3D Printed Preforms. *Opt. Lett.* **2019**, *44*, 5358–5361. [[CrossRef](#)] [[PubMed](#)]
117. Morampudi, P.; Namala, K.K.; Gajjala, Y.K.; Barath, M.; Prudhvi, G. Review on Glass Fiber Reinforced Polymer Composites. *Proc. Mater. Today Proc.* **2020**, *43*, 314–319. [[CrossRef](#)]
118. Kuš, A.; Rajt'uková, V.; Pilarczyk, W.; Hudák, R.; Mehner, T.; Maj, L.; Lampke, T.; Małachowska, A. First Co-Based Bulk Metallic Glass Printed by Selective Laser Melting. *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.* **2025**, *56*, 2989–3005. [[CrossRef](#)]
119. Hofmann, D.C.; Bordeenithikasem, P.; Pate, A.; Roberts, S.N.; Vogli, E. Developing Processing Parameters and Characterizing Microstructure and Properties of an Additively Manufactured FeCrMoBC Metallic Glass Forming Alloy. *Adv. Eng. Mater.* **2018**, *20*, 1800433. [[CrossRef](#)]
120. Zheng, Q.; Mauro, J.C. Viscosity of Glass-Forming Systems. *J. Am. Ceram. Soc.* **2017**, *100*, 6–25. [[CrossRef](#)]
121. Nascimento, M.L.F.; Aparicio, C. Data Classification with the Vogel-Fulcher-Tammann-Hesse Viscosity Equation Using Correspondence Analysis. *Phys. B Condens. Matter* **2007**, *398*, 71–77. [[CrossRef](#)]
122. Luis Ferreira Nascimento, M.; Aparicio, C. Viscosity of Strong and Fragile Glass-Forming Liquids Investigated by Means of Principal Component Analysis. *J. Phys. Chem. Solids* **2007**, *68*, 104–110. [[CrossRef](#)]
123. Martendal, C.P.; de Oliveira, A.P.N. Glass Viscosity at Crystallization Temperature: An Approach. *J. Therm. Anal. Calorim.* **2017**, *130*, 1903–1912. [[CrossRef](#)]
124. Vu, A.T.; Vu, A.N.; Grunwald, T.; Bergs, T. Modeling of Thermo-Viscoelastic Material Behavior of Glass over a Wide Temperature Range in Glass Compression Molding. *J. Am. Ceram. Soc.* **2020**, *103*, 2791–2807. [[CrossRef](#)]
125. Gao, Q.; Jian, Z. Fragility and Vogel-Fulcher-Tammann Parameters near Glass Transition Temperature. *Mater. Chem. Phys.* **2020**, *252*, 123252. [[CrossRef](#)]
126. Siacor, F.D.C.; Chen, Q.; Zhao, J.Y.; Han, L.; Valino, A.D.; Taboada, E.B.; Caldon, E.B.; Advincula, R.C. On the Additive Manufacturing (3D Printing) of Viscoelastic Materials and Flow Behavior: From Composites to Food Manufacturing. *Addit. Manuf.* **2021**, *45*, 102043. [[CrossRef](#)]
127. Gedeon, O. Origin of Glass Fragility and Vogel Temperature Emerging from Molecular Dynamics Simulations. *J. Non. Cryst. Solids* **2018**, *498*, 109–117. [[CrossRef](#)]
128. ISO/ASTM 52900:2021; Additive Manufacturing—General Principles—Fundamentals and Vocabulary. International Organization for Standardization: Geneva, Switzerland, 2021.
129. Pires, L.S.O.; Fernandes, M.H.F.V.; de Oliveira, J.M.M. Biofabrication of Glass Scaffolds by 3D Printing for Tissue Engineering. *Int. J. Adv. Manuf. Technol.* **2018**, *98*, 2665–2676. [[CrossRef](#)]
130. Cho, S.; Jeong, D.; Kim, H. Influence of Powder Characteristics on Shrinkage Behavior of 3D-Printed Glass Structures. *Ceram. Int.* **2020**, *46*, 16827–16832. [[CrossRef](#)]
131. Nan, B.; Gołebiewski, P.; Buczyński, R.; Galindo-Rosales, F.J.; Ferreira, J.M.F. Direct Ink Writing Glass: A Preliminary Step for Optical Application. *Materials* **2020**, *13*, 1636. [[CrossRef](#)] [[PubMed](#)]
132. Singh, R.; Gupta, A.; Tripathi, O.; Srivastava, S.; Singh, B.; Awasthi, A.; Rajput, S.K.; Sonia, P.; Singhal, P.; Saxena, K.K. Powder Bed Fusion Process in Additive Manufacturing: An Overview. *Proc. Mater. Today Proc.* **2019**, *26*, 3058–3070. [[CrossRef](#)]
133. Tarak, F.; Okoruwa, L.; Ozkan, B.; Sameni, F.; Schaefer, G.; Sabet, E. AI for AM: Machine Learning Approach to Design the Base Binder Formulation for Vat-Photopolymerisation 3D Printing of Zirconia Ceramics. *Virtual Phys. Prototyp.* **2025**, *20*, e2469822. [[CrossRef](#)]
134. Paral, S.K.; Lin, D.Z.; Cheng, Y.L.; Lin, S.C.; Jeng, J.Y. A Review of Critical Issues in High-Speed Vat Photopolymerization. *Polymers* **2023**, *15*, 2716. [[CrossRef](#)] [[PubMed](#)]

135. Lipkowitz, G.; Saccone, M.A.; Panzer, M.A.; Coates, I.A.; Hsiao, K.; Ilyn, D.; Kronenfeld, J.M.; Tumbleston, J.R.; Shaqfeh, E.S.G.; DeSimone, J.M. Growing Three-Dimensional Objects with Light. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2303648121. [[CrossRef](#)] [[PubMed](#)]
136. Zhang, F.; Zhu, L.; Li, Z.; Wang, S.; Shi, J.; Tang, W.; Li, N.; Yang, J. The Recent Development of Vat Photopolymerization: A Review. *Addit. Manuf.* **2021**, *48*, 102423. [[CrossRef](#)]
137. Elsayed, H.; Gobbin, F.; Barci, A.; Bernardo, E.; Colombo, P. Cold Consolidation of Pharmaceutical Waste Glass Powders Through Alkali Activation and Binder Jet 3D Printing. *Materials* **2024**, *17*, 5164. [[CrossRef](#)] [[PubMed](#)]
138. Liu, C.; Oriekhov, T.; Fokine, M. Investigation of Glass Bonding and Multi-Layer Deposition during Filament-Based Glass 3D Printing. *Front. Mater.* **2022**, *9*, 978861. [[CrossRef](#)]
139. Bakhtiari, H.; Bidgoli, M.O.; Hosseini, M. Advances, Limitations, and Future Perspectives in 3D Printing of Porous Glasses: A Technical Note. *J. Comput. Appl. Mech.* **2025**, *56*, 69–75. [[CrossRef](#)]
140. Massimino, D.; Townsend, E.; Folinus, C.; Stern, M.; Becker, K. Additive Manufacturing of Interlocking Glass Masonry Units. *Glass Struct. Eng.* **2024**, *9*, 397–417. [[CrossRef](#)]
141. De Marzi, A.; Giometti, G.; Erler, J.; Colombo, P.; Franchin, G. Hybrid Additive Manufacturing for the Fabrication of Freeform Transparent Silica Glass Components. *Addit. Manuf.* **2022**, *54*, 102727. [[CrossRef](#)]
142. Tisato, S.; Vera, G.; Song, Q.; Nekoonam, N.; Helmer, D. Additive Manufacturing of Multi-Material and Hollow Structures by Embedded Extrusion-Volumetric Printing. *Nat. Commun.* **2025**, *16*, 6730. [[CrossRef](#)] [[PubMed](#)]
143. Barbera, L.; Madrid-Wolff, J.; Emma, R.; Masania, K.; Boniface, A.; Loterie, D.; Delrot, P.; Moser, C.; Studart, A.R. Multimaterial Volumetric Printing of Silica-Based Glasses. *Adv. Mater. Technol.* **2024**, *9*, 2202117. [[CrossRef](#)]
144. Schadte, P.; Krohne, K.; Felis, A.; Kleinow, L.; Stock, L.; Schockemöhle, L.; Offermann, J.; Groneberg, O.; Carstensen, J.; Kienle, L.; et al. LAMP: Laser-Assisted Melt Printing for Direct Silica Glass 3D Printing with in Situ Nanoparticle Synthesis. *Mater. Des.* **2025**, *260*, 114972. [[CrossRef](#)]
145. Hong, Z.; Ye, P.; Loy, D.A.; Liang, R. Three-Dimensional Printing of Glass Micro-Optics. *Optica* **2021**, *8*, 904–910. [[CrossRef](#)]
146. Hari, A.S.; Patadiya, J.; Kandasubramanian, B. Recent Advancements in 3D Printing Methods of Optical Glass Fabrication: A Technical Perspective. *Hybrid. Adv.* **2024**, *7*, 100289. [[CrossRef](#)]
147. Xu, H.; Chen, S.; Hu, R.; Hu, M.; Xu, Y.; Yoon, Y.; Chen, Y. Continuous Vat Photopolymerization for Optical Lens Fabrication. *Small* **2023**, *19*, e2300517. [[CrossRef](#)] [[PubMed](#)]
148. Lv, Z.; Zhang, X.; Chen, J.; Lang, M.; Liu, H.; Cheng, Y. Additive Manufacturing of Quartz Glass Using Coaxial Wire Feeding Technology. *Opt. Laser Technol.* **2025**, *181*, 111671. [[CrossRef](#)]
149. Spirrett, F.; Datsiou, K.C.; Magallanes, M.; Ashcroft, I.; Goodridge, R. Powder-Fed Directed Energy Deposition of Soda Lime Silica Glass on Glass Substrates. *J. Am. Ceram. Soc.* **2023**, *106*, 227–240. [[CrossRef](#)]
150. Lang, M.; Ruan, X.L.; He, C.; Chen, Z.Q.; Xu, T.; Zhang, H.B.; Cheng, Y.T. Efficient Fabrication of Quartz Glass Using Laser Coaxial Powder-Fed Additive Manufacturing Approach. *3D Print. Addit. Manuf.* **2024**, *11*, 655–665. [[CrossRef](#)] [[PubMed](#)]
151. Wang, F.; Cooper, N.; He, Y.; Hopton, B.; Johnson, D.; Zhao, P.; Tuck, C.J.; Hague, R.; Fromhold, T.M.; Wildman, R.D.; et al. Additive Manufacturing of Functionalised Atomic Vapour Cells for Next-Generation Quantum Technologies. *Quantum Sci. Technol.* **2025**, *10*, 015019. [[CrossRef](#)]
152. De Beer, M.P.; Van Der Laan, H.L.; Cole, M.A.; Whelan, R.J.; Burns, M.A.; Scott, T.F. Rapid, Continuous Additive Manufacturing by Volumetric Polymerization Inhibition Patterning. *Sci. Adv.* **2019**, *5*, eaau8723. [[CrossRef](#)] [[PubMed](#)]
153. Chen, D.; Murakami, K.; Abe, H.; Li, Z.; Sekimura, N. Investigation of Interactions between Defect Clusters in Stainless Steels by in Situ Irradiation at Elevated Temperatures. *Acta Mater.* **2019**, *163*, 78–90. [[CrossRef](#)]
154. Ziaee, M.; Crane, N.B. Binder Jetting: A Review of Process, Materials, and Methods. *Addit. Manuf.* **2019**, *28*, 781–801. [[CrossRef](#)]
155. Vendrell, X.; Yadav, D.; Raj, R.; West, A.R. Influence of Flash Sintering on the Ionic Conductivity of 8 Mol% Yttria Stabilized Zirconia. *J. Eur. Ceram. Soc.* **2019**, *39*, 1352–1358. [[CrossRef](#)]
156. Gharehpapagh, B.; Aliyev, R.; Gupta, N.K.; Milek, M.; Zeidler, H. Multi-Material Glass Additive Manufacturing: A Review of Materials, Techniques, and Integration Challenges. *Prog. Addit. Manuf.* **2026**, *11*, 3655–3675. [[CrossRef](#)]
157. Liu, C.; Qian, B.; Ni, R.; Liu, X.; Qiu, J. 3D Printing of Multicolor Luminescent Glass. *RSC Adv.* **2018**, *8*, 31564–31567. [[CrossRef](#)] [[PubMed](#)]
158. Saetova, N.S.; Shirokova, E.S.; Krainova, D.A.; Chebykin, N.S.; Ananchenko, B.A.; Tolstobrov, I.V.; Belozarov, K.S.; Kuzmin, A.V. The Development of 3D Technology for the Creation of Glass Sealants for Tubular Oxide Fuel Cells. *Int. J. Appl. Glass Sci.* **2022**, *13*, 684–694. [[CrossRef](#)]
159. Myers, L.A.; Schwartz, J.J.; De Beer, M.P.; Walton, R.L.; Porcincula, D.H. Development of Transparent, Particle-Loaded Photoresins for Volumetric Additive Manufacturing of Silica Glass. *J. Polym. Sci.* **2024**, *62*, 2683–2691. [[CrossRef](#)]
160. Chen, J.; Lv, Z.; Zhang, X.; Xu, T.; Cheng, Y. Temperature Control of Quartz-Glass Melting Areas in Laser Additive Manufacturing. *Micromachines* **2025**, *16*, 29. [[CrossRef](#)] [[PubMed](#)]

161. Murthi, M.; Destino, J.F. Sol-Gel Technologies for Additive Manufacturing Glass Materials. *J. Solgel Sci. Technol.* **2025**, *116*, 2257–2271. [\[CrossRef\]](#)
162. Sano, Y.; Matsuzaki, R.; Ueda, M.; Todoroki, A.; Hirano, Y. 3D Printing of Discontinuous and Continuous Fibre Composites Using Stereolithography. *Addit. Manuf.* **2018**, *24*, 521–527. [\[CrossRef\]](#)
163. Hotař, V.; Stará, M.; Máková, V.; Nikendey Holubová, B. Present State of 3D Printing from Glass. *Pure Appl. Chem.* **2022**, *94*, 169–179. [\[CrossRef\]](#)
164. Zakeri, S.; Vippola, M.; Levänen, E. A Comprehensive Review of the Photopolymerization of Ceramic Resins Used in Stereolithography. *Addit. Manuf.* **2020**, *35*, 101177. [\[CrossRef\]](#)
165. Pagac, M.; Hajnys, J.; Ma, Q.P.; Jancar, L.; Jansa, J.; Stefek, P.; Mesicek, J. A Review of Vat Photopolymerization Technology: Materials, Applications, Challenges, and Future Trends of 3d Printing. *Polymers* **2021**, *13*, 598. [\[CrossRef\]](#) [\[PubMed\]](#)
166. Liu, C.; Qian, B.; Liu, X.; Tong, L.; Qiu, J. Additive Manufacturing of Silica Glass Using Laser Stereolithography with a Top-down Approach and Fast Debinding. *RSC Adv.* **2018**, *8*, 16344–16348. [\[CrossRef\]](#) [\[PubMed\]](#)
167. Chen, L.; Mukai, M.; Hatta, Y.; Miura, S.; Maruo, S. Low-Temperature Glass 3D Printing via Two-Photon and Single-Photon Polymerization of Oligo-Silsesquioxanes. *Polymers* **2025**, *17*, 3204. [\[CrossRef\]](#) [\[PubMed\]](#)
168. Tao, Y.; Gu, X.; Wu, H.; Ni, J.; Hu, Y.; Wu, D.; Chu, J.; Li, J. Ultralow Shrinkage 3D Transparent Nanoporous Glass Printing through Low-Temperature Sintering for Micro-Optical Applications. *ACS Nano* **2025**, *19*, 31643–31655. [\[CrossRef\]](#) [\[PubMed\]](#)
169. Bauer, J.; Crook, C.; Baldacchini, T. A Sinterless, Low-Temperature Route to 3D Print Nanoscale Optical-Grade Glass. *Science* **2023**, *380*, 960–966. [\[CrossRef\]](#) [\[PubMed\]](#)
170. Gridnev, M.A.; Korotkov, A.D.; Khmyrov, R.S. Preheating Regimes for Selective Laser Melting of Borosilicate Glass. *High Temp. Mater. Process.* **2022**, *26*, 63–74. [\[CrossRef\]](#)
171. Capelle, A.; Aspe, B.; Shavdina, O.; Diallo, B.; Pellerin, N.; Depardieu, M.; Thomann, A.L.; Semmar, N. Study of CO<sub>2</sub> Laser-Induced Thermal Stress Mechanisms on Decorative Soda-Lime Glass. *J. Laser Micro Nanoeng.* **2023**, *18*, 161–169. [\[CrossRef\]](#)
172. Kumar, V.P.; Jebaraj, A.V. Comprehensive Review on Residual Stress Control Strategies in Laser-Based Powder Bed Fusion Process—Challenges and Opportunities. *Lasers Manuf. Mater. Process.* **2023**, *10*, 400–442. [\[CrossRef\]](#)
173. Toombs, J.T.; Luitz, M.; Cook, C.C.; Jenne, S.; Li, C.C.; Rapp, B.E.; Kotz-Helmer, F.; Taylor, H.K. Volumetric Additive Manufacturing of Silica Glass with Microscale Computed Axial Lithography. *Science* **2022**, *376*, 308–312. [\[CrossRef\]](#) [\[PubMed\]](#)
174. Manière, C.; Kerbart, G.; Harnois, C.; Marinell, S. Modeling Sintering Anisotropy in Ceramic Stereolithography of Silica. *Acta Mater.* **2020**, *182*, 163–171. [\[CrossRef\]](#)
175. Rodrigues Pais Alves, M.F.; Santos, C.; Olhero, S.M.; Vaz Fernandes, M.H.F. Pressureless Sintered Lithium Disilicate Glass-Ceramics: Influence of Particle Size and Crystallization State. *J. Eur. Ceram. Soc.* **2024**, *44*, 6135–6146. [\[CrossRef\]](#)
176. Chai, N.; Yue, Y.; Chen, X.; Zeng, Z.; Li, S.; Wang, X. Isotropic Sintering Shrinkage of 3D Glass-Ceramic Nanolattices: Backbone Preforming and Mechanical Enhancement. *Int. J. Extrem. Manuf.* **2024**, *6*, 025003. [\[CrossRef\]](#)
177. Korrayi, R.R.; Jena, A.; Marupalli, B.C.G.; Samal, B.B.; Varshney, S.K.; Kumar, C.S. Four-Dimensional (4D) Microprinting. In *Additive Manufacturing with Novel Materials: Processes, Properties and Applications*; Scrivener: Austin, TX, USA, 2024.
178. Jian, B.; Li, H.; He, X.; Wang, R.; Yang, H.Y.; Ge, Q. Two-Photon Polymerization-Based 4D Printing and Its Applications. *Int. J. Extrem. Manuf.* **2024**, *6*, 012001. [\[CrossRef\]](#)
179. Ribeiro, I.; Matos, F.; Jacinto, C.; Salman, H.; Cardeal, G.; Carvalho, H.; Godina, R.; Peças, P. Framework for Life Cycle Sustainability Assessment of Additive Manufacturing. *Sustainability* **2020**, *12*, 929. [\[CrossRef\]](#)
180. Su, J.; Ng, W.L.; An, J.; Yeong, W.Y.; Chua, C.K.; Sing, S.L. Achieving Sustainability by Additive Manufacturing: A State-of-the-Art Review and Perspectives. *Virtual Phys. Prototyp.* **2024**, *19*, e2438899. [\[CrossRef\]](#)
181. Hegab, H.; Khanna, N.; Monib, N.; Salem, A. Design for Sustainable Additive Manufacturing: A Review. *Sustain. Mater. Technol.* **2023**, *35*, e00576. [\[CrossRef\]](#)
182. Colangelo, S. Reducing the Environmental Footprint of Glass Manufacturing. *Int. J. Appl. Glass Sci.* **2024**, *15*, 350–366. [\[CrossRef\]](#)
183. Naser, A.Z.; Defersha, F.; Pei, E.; Zhao, Y.F.; Yang, S. Toward Automated Life Cycle Assessment for Additive Manufacturing: A Systematic Review of Influential Parameters and Framework Design. *Sustain. Prod. Consum.* **2023**, *41*, 253–274. [\[CrossRef\]](#)
184. Huang, R.; Riddle, M.E.; Graziano, D.; Das, S.; Nimbalkar, S.; Cresko, J.; Masanet, E. Environmental and Economic Implications of Distributed Additive Manufacturing: The Case of Injection Mold Tooling. *J. Ind. Ecol.* **2017**, *21*, S130–S143. [\[CrossRef\]](#)

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.