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Review

Toward Sustainable 3D Concrete Printing: A Critical Review of Waste-Derived Materials Across Binder, Geopolymer, and Aggregate Systems

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Abstract

Three-dimensional concrete printing (3DCP) has emerged as a promising digital construction technology that reduces material waste, eliminates formwork, and enables complex geometries. However, its sustainability remains constrained by the extensive use of ordinary Portland cement (OPC) and natural aggregates. This review comprehensively evaluates waste utilization in extrusion-based 3D printed concrete, classifying applications into three pathways: cement replacement in OPC-based systems, waste-derived precursors in alkali-activated/geopolymer binders, and fine aggregate replacement. Industrial, agricultural, and marine wastes are assessed regarding their effects on rheology, printability, mechanical performance, interlayer bonding, and durability. The reviewed literature investigated waste incorporation levels reaching up to 50% for cement replacement, up to 70% for alkali-activated/geopolymer systems, and up to 100% for aggregate replacement, depending on the material type and application pathway. Industrial wastes, particularly fly ash, slag, silica fume, and metakaolin, represent the most mature materials and generally improve printability and long-term performance. Agricultural and marine wastes show promising sustainability potential but remain insufficiently investigated. Despite encouraging laboratory-scale results, challenges related to material variability, early-age performance, standardization, and scalability continue to limit practical implementation. The review identifies critical research gaps and outlines future directions for developing sustainable and field-ready 3DCP technologies.

Keywords: 3D concrete printing; waste materials; sustainable construction; geopolymer binders; cement replacement

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1. Introduction

The construction sector faces mounting pressure to reduce its environmental footprint, largely driven by its heavy reliance on ordinary Portland cement, which accounts for approximately 7–8% of global CO_2 emissions [1]. In response, sustainable digital construction technologies have gained increasing attention, among which extrusion-based three-dimensional concrete printing has emerged as a promising solution. By eliminating the need for formwork, reducing material waste, and enabling complex geometries with

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high dimensional accuracy, 3DCP offers a viable pathway toward low-carbon and resource-efficient construction practices [2,3]. Recent review studies have further highlighted the rapid development of 3DCP technologies, addressing topics such as material design, interlayer performance, durability, and structural reliability [4]. However, its environmental benefits remain limited as long as printable mixtures depend on high cement contents and natural aggregates to meet requirements of pumpability, extrudability, buildability, and early-age structural stability.

To mitigate this limitation, extensive research has focused on incorporating waste materials into 3D printable mixtures as partial for conventional constituents. These materials, derived from industrial, agricultural, and marine sources, have demonstrated the potential to improve both fresh state and hardened properties while simultaneously reducing embodied carbon and promoting circular economy principles [5,6]. Industrial by-products such as fly ash and ground granulated blast furnace slag have been widely investigated and exhibit consistent improvements in rheological behavior, structural build-up, and mechanical performance [7,8]. Agricultural wastes, including rice husk ash (RHA) and sugarcane bagasse ash (SCBA), have also shown promising potential as supplementary cementitious materials, contributing to improved workability and long-term strength, although their application remains relatively limited [9,10]. More recently, emerging studies have begun to explore marine-derived materials, particularly seashell-based particles, highlighting their potential as alternative constituents in printable mixtures. Despite these encouraging findings, the performance of waste-integrated systems remains highly dependent on material variability, preprocessing techniques, dosage levels, and compatibility with extrusion-based printing systems.

From a functional perspective, the incorporation of waste materials in 3D printed concrete can be systematically classified into three main categories, which also form the structural framework of this review. The first category involves the use of waste as a partial replacement for cement in OPC-based systems, where supplementary cementitious materials are incorporated to reduce clinker content. The second category focuses on alkali-activated or geopolymer binders, in which waste-derived precursors act as the primary binding system instead of OPC. The third category includes the use of waste as a replacement for natural fine aggregates, where alternative materials are used to substitute sand. This classification not only clarifies the different roles of waste materials in 3DCP but also provides a consistent basis for comparing their performance in terms of printability, mechanical properties, and sustainability.

Despite the rapid growth of research in this field, the existing literature remains unevenly distributed across different waste streams. Bibliometric findings indicate that the majority of published studies primarily focus on industrial waste materials, whereas agricultural and marine-derived wastes account for only a limited proportion of the available 3DCP literature. Industrial waste materials continue to dominate current research due to their relatively stable properties, established industrial availability, and well-documented performance in cementitious systems. In contrast, agricultural wastes are still largely confined to cement replacement applications and remain very limited in geopolymer and aggregate replacement systems. Marine-derived wastes remain at an early stage of development within extrusion-based 3D concrete printing research, despite their abundance and favorable chemical composition, particularly calcium carbonate-rich seashell materials. Existing studies involving marine wastes remain limited and are mainly restricted to fine aggregate substitution applications. This imbalance highlights a critical research gap and underscores the need to expand investigations toward underutilized waste resources.

In addition, substantial inconsistencies remain across published studies regarding mix design methodologies, rheological characterization procedures, printability assessment, and mechanical performance evaluation [11–14]. Such inconsistencies hinder meaningful comparison between studies and limit the development of standardized design guidelines and reliable field-scale implementation strategies. Consequently, most large-scale 3DCP applications still depend on proprietary cement-rich mixtures, revealing a persistent disconnect between laboratory-scale research and practical construction applications.

Unlike previous review studies that primarily focused on selected industrial waste materials or provided generalized discussions on sustainability in 3D printed concrete, the present review adopts a function-oriented classification framework for waste utilization in extrusion-based 3D concrete printing. The review systematically categorizes waste integration into cement replacement, alkali-activated/geopolymer binders, and fine aggregate replacement pathways while combining bibliometric analysis with critical technical evaluation. In addition, particular emphasis is placed on comparative maturity assessment among industrial, agricultural, and marine-derived waste streams as well as rheological behavior, printability performance, scalability limitations, techno-economic feasibility, and implementation readiness for practical construction applications.

Accordingly, this study aims to provide a comprehensive and structured review of waste materials used in extrusion-based 3D printed concrete, organized according to their functional role within the mixture. Particular emphasis is placed on evaluating industrial, agricultural, and marine wastes, identifying current challenges and research gaps, and assessing their influence on fresh-state rheology, printability, structural build-up, interlayer bonding, and long-term performance. Furthermore, future research directions are outlined to support the transition toward sustainable, scalable, and field-ready 3D printed concrete technologies.

2. Bibliometric Analysis and Methodology

A bibliometric analysis was conducted to map the research landscape and provide a structured overview of waste-modified 3DCP. Scopus and Web of Science (WoS) were selected as the primary databases due to their broad coverage of peer-reviewed engineering, construction materials, and additive manufacturing research, as well as their reliable citation indexing and compatibility with bibliometric analysis tools. These databases are widely adopted in review and bibliometric studies related to sustainable construction materials and 3D concrete printing technologies. Google Scholar was not included due to its indexing of non-peer-reviewed sources, duplicate records, and limited filtering consistency, while PubMed was considered less relevant given the engineering-oriented scope of extrusion-based 3D concrete printing research. The analysis focused on publications published between 2018 and 2025, as 2018 marks the emergence of studies explicitly addressing the incorporation of waste materials in 3D-printed concrete, coinciding with the rapid expansion of sustainability-oriented 3DCP research.

The search strategy employed keywords related to additive manufacturing and waste-integrated cementitious materials. Boolean operators were used to improve search consistency and reproducibility. Representative search strings included: (“3D concrete printing” OR “3DCP” OR “3D printed concrete” OR “additive manufacturing in construction”) AND (“waste materials” OR “industrial waste” OR “agricultural waste” OR “marine waste” OR “fly ash” OR “slag” OR “recycled materials” OR “geopolymer”).

The article selection process followed four sequential stages: identification, screening, eligibility assessment, and inclusion, as illustrated in Figure 1. A total of 186 records were initially identified from the Scopus and Web of Science databases. After removing 87 duplicate records, 99 unique publications remained for screening. Titles and abstracts were subsequently evaluated to assess their relevance to waste utilization in extrusion-based 3DCP. Eight records were excluded because they did not meet the predefined inclusion criteria. The remaining 91 studies met the eligibility criteria following title, abstract, and full-text assessment and were subsequently included in the bibliometric analysis and detailed review. The inclusion criteria considered peer-reviewed journal articles and conference papers published in English between 2018 and 2025 that focused on extrusion-based 3D concrete printing incorporating waste-derived materials. Studies unrelated to printable cementitious materials, non-English publications, and studies lacking direct relevance to waste utilization or printable concrete performance were excluded from the analysis. This procedure ensured that only studies directly relevant to waste-integrated 3DCP systems were considered. The overall workflow adopted for data collection, screening, and analysis is illustrated in Figure 1.

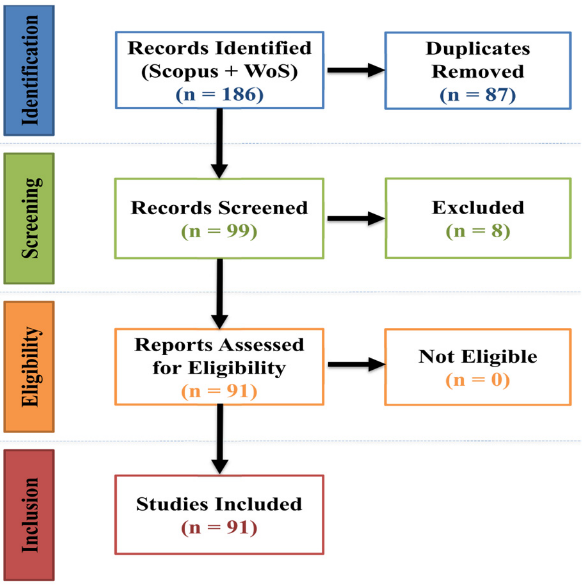

Figure 1. Bibliometric workflow for data collection and analysis.

To identify dominant research themes and conceptual structures within the field, keyword co-occurrence analysis was performed using VOSviewer (version 1.6.20). A minimum occurrence threshold of 3 keywords was applied during the co-occurrence analysis to improve the relevance of the generated network and reduce isolated or weakly connected terms. The resulting network, presented in Figure 2, reveals three major research clusters, which can be further aligned with the functional classification adopted in this review, namely waste as cement replacement, alkali-activated or geopolymer binders, and waste as aggregate replacement. The first cluster is centered on materials and mix design, encompassing cementitious systems, rheological control, pumpability, buildability, and mechanical performance. The second cluster relates to printing process and structural performance, with emphasis on extrusion parameters, interlayer bonding, and mechanical anisotropy. The third cluster reflects the increasing prominence of sustainability and circular-economy concepts, including CO_2 reduction strategies, recycling pathways, and life-cycle assessment considerations.

Beyond providing an overview of publication trends and research hotspots, the bibliometric analysis directly contributed to the development of the review framework adopted in this study. The keyword co-occurrence analysis revealed three dominant thematic clusters corresponding to waste utilization as cement replacement, alkali-activated/geopolymer binders, and aggregate replacement in 3D printed concrete. These bibliometrically identified themes were subsequently used to organize the review sections, enabling a structured evaluation of material performance, printability characteristics, sustainability benefits, and research gaps associated with each waste utilization pathway.

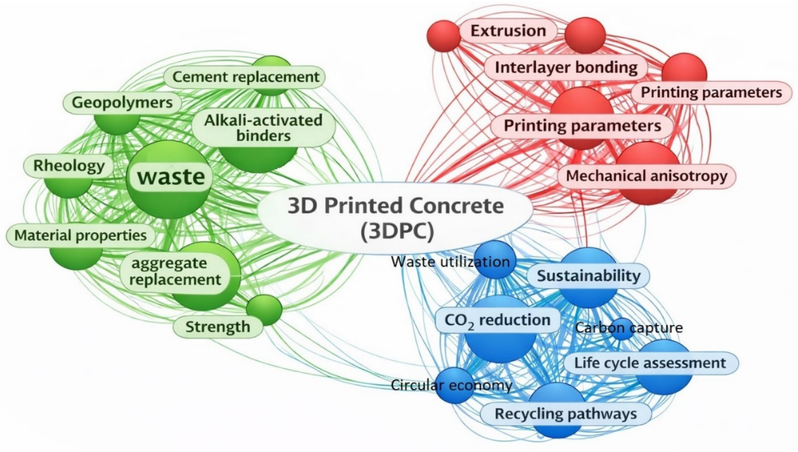

Figure 2. Keyword clusters used in this review process (Different colors represent distinct thematic clusters identified through keyword co-occurrence analysis).

Together, these clusters indicate a clear transition from early hardware-driven investigations toward material-centered and sustainability-oriented research agendas, while also supporting the structured categorization of waste utilization in 3D printed concrete proposed in this study.

Publication trend analysis further highlights the rapid growth of the field. As shown in Figures 3 and 4, the number of publications related to 3D-printed concrete, particularly those incorporating waste materials, has increased steadily since 2020, with a pronounced acceleration between 2022 and 2025. This growth reflects a shift from proof-of-concept printing demonstrations toward more advanced studies addressing mix-design optimization, rheological tailoring, and performance-driven engineering. The geographical distribution of research output as shown in Figure 5 reveals a highly concentrated global landscape, with China leading at approximately 32% of total publications, followed by Australia (≈6.5%), the United States and India (≈5% each), and several European countries contributing between 3% and 4%. Overall, Asia accounts for nearly half of global research activity, while Europe contributes approximately 32%, highlighting strong regional engagement driven by sustainability policies and industrial investment.

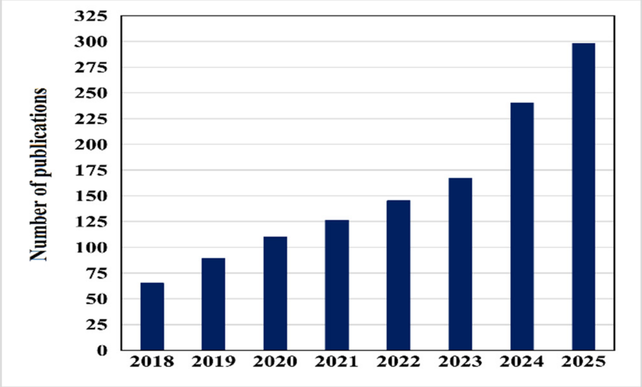

Figure 3. Bar graph for previous publications related to 3DPC based on Scopus and Web of Science.

A synthesis of the bibliometric findings indicates that early studies primarily focused on fly ash and ground granulated blast furnace slag (GGBFS) due to their established pozzolanic activity and favorable printability characteristics [5]. Subsequent research expanded toward a broader range of industrial and agricultural waste materials, including ceramic waste, recycled glass, construction and demolition waste (CDW) fines, and RHA, in alignment with strengthening circular-economy objectives [15,16]. However, the literature remains strongly dominated by industrial waste streams, while agricultural wastes are comparatively less explored and marine-derived wastes are only beginning to emerge, with very limited studies investigating their role in 3D printed concrete, particularly as aggregate replacements. More recent studies increasingly emphasize application-oriented investigations involving architectural and structural elements, yet the incorporation of diverse waste streams, especially underutilized agricultural and marine materials, remains limited [17,18].

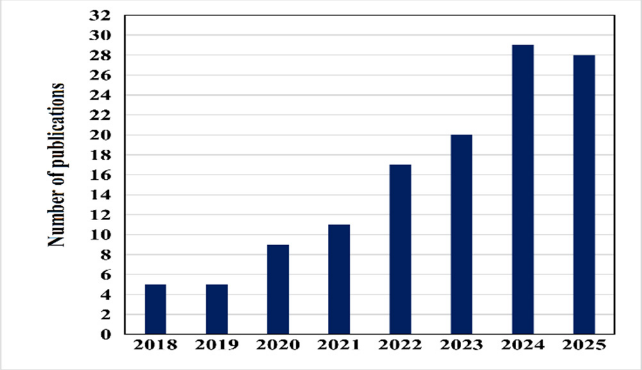

Figure 4. Relevant articles published in the area of 3D concrete printing with waste materials.

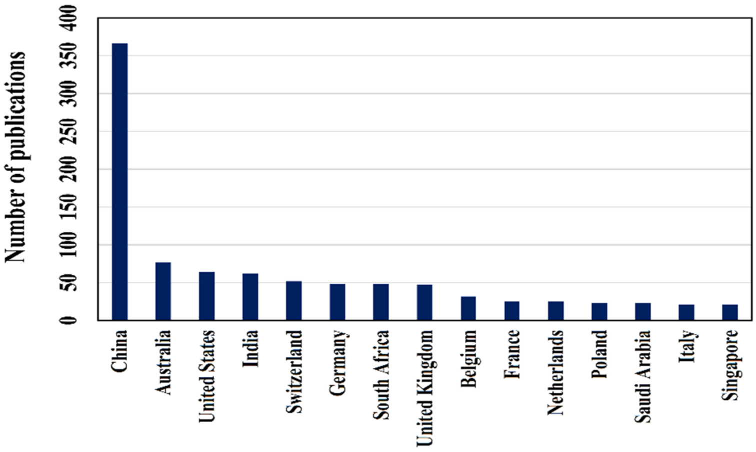

Figure 5. Bar chart of the top 15 countries by number of publications.

Despite this progress, waste-modified mixtures still represent a relatively small fraction of the overall 3DCP literature, while real-scale validation and durability-focused studies remain scarce. Furthermore, inconsistencies in mix design strategies, material preprocessing, and performance evaluation hinder the comparability of results and the transition from laboratory-scale investigations to practical implementation. These observations confirm that although waste-based 3DCP research is expanding rapidly, significant gaps persist in terms of material diversity, standardization, and field-scale validation, thereby justifying the need for a comprehensive, structured, and application-oriented review based on the functional classification of waste utilization proposed in this study.

3. Overview of 3D Concrete Printing Technology

3.1. Principles and Process of Extrusion-Based 3D Printing

Extrusion-based 3DCP operates on the principle of layer-by-layer deposition of a cementitious material along a predefined toolpath derived from a digital CAD model and translated into machine-readable G-code. The process typically involves sequential stages including material mixing, pumping, extrusion through a nozzle, and continuous deposition without the need for formwork or mechanical vibration, as illustrated in Figure 6. In contrast to conventional concrete casting, extrusion-based 3DCP introduces a strong interdependence between material rheology, process parameters, and early-age structural behavior. The extruded filament must maintain its geometric stability immediately after deposition while simultaneously supporting the load of subsequently printed layers prior to setting and hardening [19,20]. These requirements impose stringent constraints on fresh-state material behavior, clearly distinguishing printable mixtures from conventional or self-compacting concrete systems. Such unique processing conditions have driven increasing research efforts toward modifying cementitious mixtures to meet the demanding rheological and structural requirements of 3DCP. In this context, the incorporation of waste-derived materials has emerged as a promising approach to tailor fresh-state performance while enhancing sustainability. Different waste streams can significantly influence flowability, thixotropic rebuilding, and structural build-up, thereby playing a critical role in achieving the balance between printability and mechanical performance required for successful extrusion-based 3D printing.

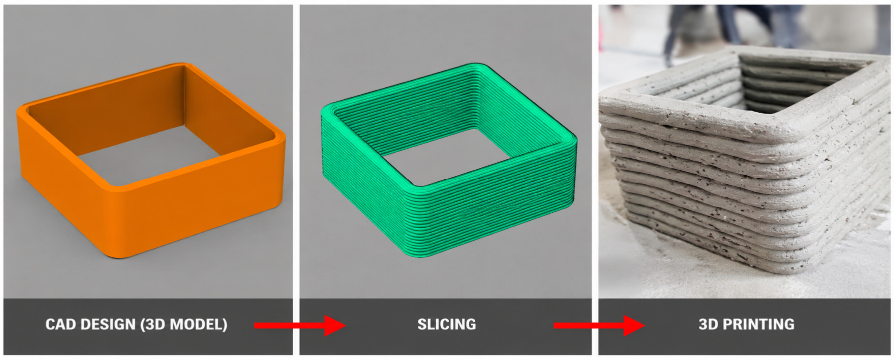

Figure 6. Process flow of 3DCP (CAD design, slicing, and 3D printing). Colors are used for visual differentiation only.

3.2. Key Material Requirements

The successful implementation of extrusion-based 3DCP is primarily governed by the fresh-state behavior of the cementitious mixture. Adequate flowability is essential to ensure continuous pumping and stable extrusion, whereas excessive fluidity may result in filament deformation, loss of dimensional accuracy, or structural collapse during multilayer deposition. Following extrusion, the rapid development of static yield stress combined with pronounced thixotropic rebuilding is critical to maintain filament geometry and support the weight of subsequent layers without instability [21]. In addition, setting behavior must be carefully controlled, as premature stiffening can interrupt the extrusion process, while excessive retardation may adversely affect buildability and surface quality. Accordingly, key rheological parameters, including dynamic and static yield stress, structuration rate, and thixotropic index, play a central role in defining the printability window of 3DCP mixtures [22]. These requirements clearly distinguish printable concrete from conventional cast or self-compacting systems and necessitate a precise balance between pumpability, extrudability, and early-age structural build-up [23]. In this context, the incorporation of waste-derived materials provides a versatile approach for tailoring fresh-state properties. Different types of waste materials can significantly influence rheological behavior, either enhancing flowability or promoting structural build-up, depending on their physical and chemical characteristics. Therefore, understanding the role of waste materials in controlling printability is essential for optimizing mixture design in sustainable 3D printed concrete.

3.3. Mechanical and Durability Considerations

After hardening, 3D-printed concrete elements typically exhibit anisotropic mechanical behavior as a direct consequence of the layer-by-layer deposition process. Variations in compressive, tensile, and flexural strength are commonly observed depending on the orientation of applied loads relative to the printing direction, with weak interlayer bonding representing a primary source of mechanical vulnerability [24,25]. From a durability perspective, the absence of vibration and conventional formwork can increase susceptibility to micro cracking, elevated permeability, and shrinkage-related defects, particularly at interlayer interfaces. Environmental exposure conditions, such as drying, freeze-thaw cycles, and chloride ingress, may further accelerate degradation if interlayer cohesion and microstructural continuity are not adequately achieved [26,27]. Although many printable mixtures can attain compressive strength levels comparable to those of conventionally cast concrete, interlayer integrity and long-term durability remain critical challenges that must be addressed to enable large-scale structural applications of 3DCP. In this context, the incorporation of waste-derived materials can play a significant role in influencing hardened performance. Depending on their composition and morphology, waste materials may enhance or impair interlayer bonding, modify microstructural densification, and affect long-term durability characteristics. Therefore, a comprehensive understanding of how different waste streams impact mechanical anisotropy and durability is essential for the development of reliable and sustainable 3D printed concrete systems.

3.4. Challenges and Limitations of Conventional 3DCP Mixes

Despite significant advances in printing hardware and process control, several material-related limitations continue to hinder the widespread adoption of extrusion-based 3DCP. Most printable mixtures rely on high Portland cement contents to achieve early-age strength and buildability, which directly conflicts with sustainability objectives due to the associated environmental impact [28]. Conventional concrete formulations, particularly those containing coarse aggregates or elevated water contents, often exhibit segregation, nozzle blockage, or insufficient filament stability, making them unsuitable for extrusion-based processes [29]. In addition, the layer-by-layer deposition inherent to 3DCP increases susceptibility to cold joints (weak interfaces formed between successive printed layers due to insufficient bonding), especially when prolonged interlayer intervals or surface drying occur during printing [30]. Early-age shrinkage, settlement, and deformation in the absence of external confinement can further lead to geometric inaccuracies and cracking [31]. These challenges are compounded by the lack of standardized testing methods for evaluating rheological behavior, buildability, and interlayer mechanical performance, which limits the comparability of results across studies and slows down technological advancement [32]. Furthermore, the integration of reinforcement remains a critical challenge, as embedding steel bars, fiber meshes, or continuous reinforcement along the printing path introduces geometric and process-related constraints that current 3DCP systems struggle to accommodate effectively [33]. In response to these limitations, considerable research efforts have been directed toward modifying printable mixtures through the incorporation of alternative materials, particularly waste-derived constituents. Such approaches aim to reduce cement consumption, improve sustainability, and enhance both fresh state and hardened performance. However, the effectiveness of these strategies varies significantly depending on the type, processing, and functional role of the waste material, thereby highlighting the importance of a structured classification of waste utilization, such as cement replacement, geopolymer binders, and aggregate replacement, as adopted in this study.

4. Waste as Cement Replacement in 3D Printed Concrete

The incorporation of supplementary cementitious materials (SCMs) as partial replacements for OPC has emerged as a key strategy to enhance the sustainability of extrusion-based 3DCP. Given the high cement demand of printable mixtures required to achieve adequate pumpability, extrudability, and early-age buildability, reducing OPC content without compromising performance remains a critical challenge [34,35]. In this context, waste-derived materials have been widely explored as alternative binders due to their pozzolanic or latent hydraulic properties, enabling partial substitution of cement while maintaining or improving fresh state and hardened characteristics [36]. The integration of such materials can significantly influence rheological behavior, including flowability, yield stress, and thixotropic rebuilding, which are essential for defining the printability window of 3DCP mixtures. Beyond fresh-state performance, SCMs also contribute to microstructural refinement, interlayer bonding, and long-term mechanical and durability properties [37]. However, the effectiveness of cement replacement strategies is highly dependent on material type, replacement level, and interaction with the printing process. While industrial by-products dominate current research in this area, agricultural wastes are comparatively less explored, and marine-derived materials remain largely under-investigated. Accordingly, this section critically reviews the use of waste materials as cement replacements in OPC-based 3D printed concrete, with a focus on industrial, agricultural, and marine waste streams, highlighting their influence on printability, mechanical performance, and sustainability.

4.1. Industrial Waste Materials as Cement Replacement in 3D Printed Concrete

Industrial by-products have been extensively investigated as supplementary SCMs in extrusion-based 3DPC, owing to their availability, pozzolanic reactivity, and potential to enhance both fresh state and hardened performance. These materials play a critical role in reducing Portland cement consumption while enabling the tuning of rheological behavior required for printability. However, their effectiveness depends strongly on particle characteristics, replacement levels, and compatibility with the printing process.

Fly ash (FA), a by-product of coal combustion, is among the most widely studied SCMs in 3DPC. It is typically incorporated at replacement levels of 10–30% of OPC. Due to its spherical particle morphology, FA improves flowability and reduces plastic viscosity, thereby enhancing extrudability and pumpability. However, higher replacement levels 30% may delay early hydration and reduce green strength, adversely affecting buildability unless compensated through mix optimization or blending with other SCMs. In hardened state, FA-based printable mixtures generally exhibit slightly reduced early-age strength but achieve comparable or improved long-term mechanical performance, confirming its suitability for sustainable 3DPC applications [38–41].

Ground granulated blast furnace slag (GGBFS) is an amorphous industrial by-product commonly used in combination with FA to enhance both fresh and hardened properties [42–44]. Typical replacement levels range from 20% to 50% [42,43]. GGBFS contributes to improved particle packing and microstructural densification, resulting in enhanced compressive and flexural strength as well as improved durability [42–44]. From a rheological perspective, it increases yield stress and structural build-up, which can enhance buildability but may reduce flowability at higher contents [42,43]. Optimized FA and GGBFS blends are widely reported to provide a balanced combination of workability and mechanical performance in 3D printing applications [42–44].

Silica fume (SF), an ultra-fine by-product of silicon alloy production, is typically used at low replacement levels of 5–10%. Its high amorphous silica content and extremely fine particle size significantly enhance particle packing and reduce porosity, leading to improved strength and interlayer bonding. In fresh state, SF increases yield stress and water demand, often requiring the use of superplasticizers to maintain workability. When properly dosed, SF contributes to improved rheological stability and mechanical performance in 3D printable mixtures [45–47].

Red mud (RM), a residue from alumina production, has recently attracted attention as a potential cement replacement in 3DPC, typically at levels of 10–20%. Preliminary studies indicate that RM can be incorporated into printable mixtures while maintaining structural integrity and reducing cement consumption. However, its high alkalinity and variable particle characteristics require careful mix design to ensure adequate rheological performance and early strength development. Current research remains limited, highlighting the need for further systematic investigations to establish its suitability across different printing conditions [48–51].

Steel slag (SS), a by-product of steelmaking, is increasingly explored as an SCM due to its chemical similarity to cementitious materials. It is generally used at replacement levels of 5–20% in 3DPC. While it is intrinsic reactivity is lower than that of GGBFS, pre-treatment methods such as fine grinding or carbonation can enhance its hydration behavior. In fresh state, SS may increase yield stress and viscosity, potentially reducing extrudability at high contents. In hardened state, it contributes to microstructural refinement and durability improvement. Initial studies suggest that moderate replacement levels 10% can improve buildability and sustainability, although higher contents may negatively affect rheological performance [52–55].

Metakaolin (MK) is a highly reactive pozzolanic material produced through the calcination of kaolinite clay. It has been extensively studied as a partial replacement for OPC in extrusion-based three-dimensional concrete printing. It is typically incorporated at replacement levels ranging from 5% to 20%. The inclusion of MK significantly influences fresh-state behavior by increasing thixotropic and accelerating structural build-up, which enhances buildability and shape retention during layer deposition. Lower replacement levels 5–10% primarily improve rheological stability and extrusion control, while higher contents 15–20% contribute to enhanced early-age strength and improved interlayer bonding, provided that mix design is carefully optimized to maintain adequate flowability. In hardened state, MK improves microstructural densification through its high pozzolanic reactivity, resulting in increased compressive strength and reduced porosity. These combined effects make MK a highly effective SCM for enhancing both fresh and hardened performance in OPC-based 3D printed concrete systems [56–58].

Other industrial by-products, including waste glass powder (WGP) and ceramic waste powder (CWP) have also been explored as partial cement replacements. WGP, typically used at 5–15%, contains high levels of amorphous silica and can act as both a filler and a pozzolanic material, improving microstructural densification, interlayer bonding, and long-term strength. Similarly, CWP derived from ceramic products such as tiles and sanitary ware can enhance sustainability and matrix refinement, although it is pozzolanic reactivity is generally lower and requires further validation in 3D printing applications [59–61].

4.2. Agricultural Waste Materials as Cement Replacement in 3D Printed Concrete

Compared to industrial by-products, the use of agricultural waste materials as cement replacements in extrusion-based 3DPC remains relatively limited. Existing research has primarily focused on a small number of materials, particularly RHA and SCBA, while other agricultural wastes have received little to no attention in the context of 3D printing. This limited research scope highlights a significant gap in the literature, especially considering the wide availability and sustainability potential of agricultural residues.

Rice husk ash (RHA), produced from the controlled combustion of rice husks, and has been investigated as a partial replacement for OPC in extrusion-based 3D printed concrete. In printable mixtures, replacement levels of approximately 15–20% have been reported to improve rheological behavior, particularly in terms of workability and buildability, making the material suitable for layer-by-layer deposition. However, the incorporation of RHA may increase water demand due to its high surface area and porous structure, which can influence early-age compressive strength if not properly addressed through mix optimization. Despite these challenges, RHA contributes to sustainable mixture design by reducing cement consumption and utilizing agricultural waste, making it a promising supplementary material for 3D printed concrete applications [62,63].

Sugarcane bagasse ash (SCBA), a by-product of the sugar industry, has also been explored as a cement replacement in extrusion-based 3D printed concrete. Typical replacement levels range from 10% to 25%, with performance varying depending on dosage. Lower replacement levels (around 10%) improve fresh-state properties; including flowability, shape retention, and overall printability, while maintaining or slightly enhancing early mechanical strength. Moderate levels (around 20%) contribute to improved long-term compressive strength and microstructural densification. However, higher replacement levels (approximately 25%) may reduce early-age strength and require adjustments in water content and admixture dosage to maintain adequate extrusion performance. Overall, SCBA demonstrates strong potential as a sustainable supplementary binder, capable of enhancing both fresh and hardened properties in 3D printed concrete when properly optimized [64,65].

4.3. Marine Waste Materials as Cement Replacement in 3D Printed Concrete

Marine waste materials, particularly discarded seashells from seafood processing, have attracted growing attention as sustainable alternatives to conventional cementitious constituents due to their high calcium carbonate content and widespread availability. Existing studies in conventional concrete systems indicate that finely processed seashell powders, when used at relatively low replacement levels (typically 5–15%), can influence both fresh and hardened properties while contributing to reduced environmental impact. These effects are generally attributed to their filler behavior, particle-packing enhancement, and potential interaction with cement hydration when adequately processed [66]. However, despite these promising characteristics, the application of marine waste materials, as direct cement replacements in extrusion-based 3D printed concrete remains very limited. The limited studies available in the context of 3D printing have predominantly focused on the use of seashell particles as fine aggregate substitutes rather than as reactive binder components. This indicates that, unlike industrial and even agricultural waste materials, marine-derived wastes have not yet been systematically investigated within printable cementitious systems. This gap highlights a significant research opportunity to evaluate the feasibility of marine waste powders as supplementary cementitious materials in 3DCP, particularly in terms of their influence on rheology, printability, and early-age structural performance. Expanding research in this area could contribute to diversifying sustainable material sources and advancing circular economy strategies in digital construction.

4.4. Comparative Discussion of Waste Materials as Cement Replacement in 3D Printed Concrete

The incorporation of waste materials as partial replacements for OPC in extrusion-based 3DCP exhibits substantial variability in performance, governed by the physicochemical characteristics, reactivity, and processing of the selected waste materials. Based on the reviewed literature, a clear distinction emerges among industrial, agricultural, and marine waste streams in terms of research maturity, functional performance, and applicability in printable systems. Industrial waste materials, including FA, GGBFS, SF, MK, RM, SS, WGP, and CWP, represent the most extensively investigated category. Highly reactive materials such as FA, GGBFS, SF, and MK exhibit well-established pozzolanic or latent hydraulic behavior, enabling effective cement replacement while maintaining or enhancing both fresh state and hardened properties. FA is widely recognized for improving flowability and extrusion stability, whereas GGBFS and MK contribute to increased structural build-up and early-age strength, which are critical for layer wise deposition. In contrast, materials such as RM and SS demonstrate comparatively lower reactivity, require careful preprocessing, and mix optimization to ensure compatibility with extrusion-based systems. Meanwhile, WGP and CWP primarily act as filler-type supplementary materials, contributing to particle packing, microstructural refinement, and long-term performance enhancement rather than significant early-age reactivity. The broad availability, diverse functionality, and relatively consistent performance of industrial waste materials have led to their dominant role in 3DCP research, with extensive studies addressing both material design and structural performance.

Agricultural waste materials, primarily RHA and SCBA, remain very limited despite their promising sustainability potential. These materials have demonstrated the ability to improve rheological behavior, including flowability and buildability, while contributing to long-term strength development. However, their application is often constrained by higher water demand, variability in chemical composition, and dependence on controlled combustion and processing conditions. Consequently, their use in 3D printing remains largely limited to laboratory-scale investigations, with relatively few studies addressing durability performance or large-scale implementation.

Marine waste materials, particularly seashell-derived powders, represent the least developed category within this field. Although their high calcium carbonate content and abundance suggest potential as sustainable cementitious resources, their application as direct cement replacements in extrusion-based 3D printed concrete has not yet been systematically explored. Existing studies are largely confined to conventional concrete systems or to their use as fine aggregate substitutes in 3D printing. As a result, their effects on rheology, printability, and early-age structural performance in 3DCP remain largely unknown.

A comparative summary of the different waste categories used as cement replacements in 3D printed concrete is presented in Table 1.

Overall, this comparative analysis highlights a clear imbalance in current research efforts, with a strong concentration on industrial waste materials, limited but growing interest in agricultural residues, and a notable absence of marine waste applications as cement replacements in 3D printed concrete. However, the reviewed studies also reveal that no single waste material can simultaneously optimize printability, mechanical performance, and sustainability. Highly reactive materials such as GGBFS, SF, and MK generally enhance buildability and strength development but may increase viscosity and reduce workability, requiring careful rheological control. Conversely, FA improves flowability and extrusion performance but may compromise early-age strength at higher replacement levels. Agricultural wastes such as RHA and SCBA offer significant environmental benefits; however, their performance is often constrained by high water demand, variability in chemical composition, and dependence on processing conditions. Furthermore, the lack of systematic investigations on marine-derived cement replacements represents a major research gap for 3D printing applications. These findings indicate that future research should focus not only on increasing waste utilization but also on balancing material performance, printability requirements, and sustainability objectives through optimized mix design and standardized testing methodologies.

Table 1. Comparative Summary of Waste Materials as Cement Replacement in 3DPC.

Waste Category	Material	Typical Replacement (%)	Fresh-State Performance	Hardened Performance	Key Limitations/Challenges	Research Level
Industrial	FA	10–30	Improved flowability and extrudability.	Reduced early strength, improved long-term strength.	Delayed hydration and reduced early-age strength at high replacement levels (>30%).	High
	GGBFS	20–50	Increased yield stress, improved buildability.	Enhanced strength and durability.	Excessive contents may reduce flowability and complicate extrusion.	High
	SF	5–10	Increased viscosity, yield stress, thixotropy, and improved cohesion	Enhanced strength and bonding.	High water demand and increased viscosity require superplasticizer optimization.	High
	MK	5–20	Improved thixotropy and buildability.	Enhanced early strength and bonding.	May reduce workability and increase water demand at high dosages.	High
	RM	10–20	Requires controlled rheology.	Maintains strength; potential densification.	High alkalinity, compositional variability, and limited validation in 3DCP.	Low
	SS	5–20	Increased viscosity at high content.	Improved durability; limited early strength.	Relatively low reactivity and adverse rheological effects at high replacement levels.	Low
	WGP	5–15	Improved flowability and cohesion.	Enhanced long-term strength.	Limited early-age reactivity; performance depends on particle fineness.	Medium
	CWP	5–15	Moderate effect on flowability.	Improved microstructure; limited reactivity.	Lower pozzolanic activity and insufficient large-scale validation.	Medium
Agricultural	RHA	15–20	Improved rheology and buildability.	Increased water demand; may reduce early strength.	High water demand and variability associated with combustion and processing conditions.	Low
	SCBA	10–25	Improved printability; requires adjustment.	Improved long-term strength.	Variable chemical composition and reduced early-age strength at high replacement levels.	Low
Marine	-	-	Not investigated as a cement replacement in 3D printed concrete.	Not evaluated as a cement replacement in 3D printed concrete.	Lack of experimental studies addressing rheology, printability, and structural performance in 3DCP.	Very Low

5. Waste as Alkali-Activated/Geopolymer Binders in 3D Printed Concrete

Alkali-activated binders (AABs), commonly referred to as geopolymer binders, are inorganic binding systems produced through the alkali activation of aluminosilicate-rich precursors. These binders have gained increasing attention as sustainable alternatives to OPC in extrusion-based 3DCP. This interest is primarily driven by their significantly lower carbon footprint, ability to utilize industrial by-products, and potential to deliver superior long-term performance. This geopolymerization process enables enhanced durability, chemical resistance, and microstructural stability. In the context of 3D printing, alkali-activated systems offer additional advantages, including tunable rheological behavior, rapid structural build-up, and improved interlayer bonding. However, their performance is highly dependent on precursor type, activator composition, and mix design optimization [67–69]. Accordingly, this section reviews the use of waste-derived materials in geopolymer 3D printed concrete, with a primary focus on industrial waste precursors, followed by emerging agricultural and marine-based materials.

5.1. Industrial Waste Materials as Alkali-Activated or Geopolymer Binders in 3D Printed Concrete

Industrial by-products represent the backbone of alkali-activated (geopolymer) systems in extrusion-based 3D printed concrete due to their high aluminosilicate content and well-established reactivity. These materials can function either as primary precursors forming the geopolymer matrix or as supplementary modifiers that tailor rheological behavior, reaction kinetics, and long-term performance. Their role in 3D printing is particularly critical, as they directly influence both printability (flowability, yield stress, thixotropy) and hardened properties (strength, durability, and interlayer bonding).

Fly ash (FA) is one of the most widely utilized industrial by-products as a primary precursor in alkali-activated 3D printed concrete. Its high aluminosilicate content and predominantly amorphous structure enable effective participation in geopolymerization reactions under alkaline activation. In extrusion-based printable systems, FA is typically incorporated at relatively high proportions, ranging from 30% to 70% of the total binder. Its spherical particle morphology significantly enhances fresh-state behavior by improving flowability and extrudability, reducing internal friction, and extending pumpability windows. Additionally, FA contributes to controlled yield stress and thixotropic rebuilding, which are essential for maintaining filament stability during layer-by-layer deposition. In the hardened state, FA-based systems form a three-dimensional N-A-S-H (sodium aluminosilicate hydrate) gel network, which governs the mechanical performance and durability of the geopolymer matrix. Experimental studies have reported compressive strength values in the range of 40–50 MPa at 28 days, while maintaining adequate extrusion performance. These characteristics make FA a reliable and widely adopted primary precursor for sustainable geopolymer-based 3D printing systems [70–72].

Ground granulated blast furnace slag (GGBFS) is frequently incorporated alongside FA in geopolymer 3D printed concrete to enhance early-age reactivity and mechanical performance. It is typically used at replacement levels of 20–50% of the precursor system. The addition of GGBFS introduces calcium into the geopolymer matrix, leading to the formation of C-A-S-H (calcium aluminosilicate hydrate) gel, which accelerates setting and significantly improves early strength development. This is particularly beneficial in extrusion-based systems where early structural stability is critical for buildability. From a rheological perspective, GGBFS increases yield stress and enhances structural build-up, contributing to improved shape retention and layer stability. However, excessive slag content may reduce flowability and complicate extrusion, necessitating careful optimization of mix proportions and activator composition. The synergistic combination of FA and GGBFS is widely recognized as the most effective and commonly used geopolymer formulation for 3D printing applications [73–75].

Silica fume (SF), an ultra-fine industrial by-product rich in amorphous silica, has been investigated as a supplementary precursor and rheology modifier in alkali-activated 3D printed concrete. It is typically incorporated at low dosages of approximately 5–10%. Due to its extremely fine particle size and high reactivity, SF enhances geopolymer gel formation by increasing the availability of reactive silica. In fresh-state systems, it improves cohesion, reduces segregation, and enhances interlayer bonding, which are critical for maintaining structural integrity during printing. However, SF also increases viscosity and water demand, which may reduce flowability if used in excessive amounts. In hardened state, it contributes to significant microstructural densification, reduced porosity, and improved compressive and flexural strength, making it a valuable additive for optimizing geopolymer 3D printing systems [76–78].

Metakaolin (MK) is a highly reactive aluminosilicate material widely used as a modifier in alkali-activated 3D printed concrete systems. It is typically incorporated at low to moderate dosages (10–20% of the binder). MK plays a critical role in enhancing geopolymerization kinetics by promoting the formation of both C-A-S-H and N-A-S-H gels. In fresh-state behavior, it significantly improves thixotropy and structural build-up, leading to enhanced shape stability and reduced deformation during layer deposition. Additionally, MK improves rheological control, enabling smoother extrusion and better filament definition. In hardened systems, it contributes to increased early-age strength and improved interlayer bonding, making it particularly effective for optimizing both printability and structural performance [79,80].

Recycled construction and demolition waste (CDW), including crushed concrete, brick powder, and masonry residues, has been investigated as a supplementary precursor in geopolymer 3D printed concrete. When finely ground, CDW contains reactive silica and alumina phases, although its reactivity is generally lower than that of FA or GGBFS. In extrusion-based systems, CDW is typically incorporated at 10–40% of the binder in combination with highly reactive precursors. Its inclusion improves particle packing and increases yield stress, enhancing buildability and shape stability of printed layers. However, excessive content may reduce flowability and extrusion continuity. In hardened state, CDW contributes to geopolymer gel formation and microstructural densification, resulting in moderate compressive strength and acceptable durability when properly processed [81,82].

Waste glass powder (WGP) has been explored as a supplementary geopolymer precursor due to its high content of amorphous silica. It is typically incorporated at 5–20% of the total binder. In alkali-activated systems, WGP contributes to geopolymerization by supplying reactive silica, which enhances gel formation and improves reaction kinetics. In fresh-state behavior, WGP plays a key role in improving cohesion, extrusion smoothness, and interlayer adhesion, thereby enhancing printability and reducing the risk of segregation or filament instability. In the hardened state, WGP contributes to microstructural refinement by reducing porosity and enhancing matrix densification. It improves interlayer bonding and long-term mechanical performance without significantly compromising compressive strength. These characteristics make WGP a practical and sustainable additive in geopolymer 3D printed systems [83].

Red mud (RM), a by-product of alumina production, has been investigated as a supplementary precursor in geopolymer systems, particularly in ternary blends with FA and GGBFS. Typical formulations include 25–50% FA, up to 25% GGBFS, and RM as the remaining fraction (approximately 10–25%). RM contributes alumina and silica to the geopolymerization process, participating in gel formation and influencing mechanical performance. However, due to its high alkalinity, variable composition, and relatively lower reactivity compared to FA and GGBFS, its incorporation requires careful control of activator dosage and mix design parameters. In fresh state, RM may increase stiffness and yield stress, affecting workability and extrusion behavior. In hardened systems, it has been shown to enhance chemical resistance and support sustainable binder design. Despite these advantages, direct applications in extrusion-based 3D printing remain limited, indicating the need for further investigation [84,85].

Mine tailings, including residues from copper and gold mining, have recently emerged as alternative aluminosilicate precursors in geopolymer 3D printed concrete. These materials typically contain significant amounts of silica and alumina, allowing partial participation in geopolymerization when finely ground. In extrusion-based systems, mine tailings are generally incorporated at relatively high levels (approximately 20–60%) in combination with more reactive precursors such as FA or GGBFS. Their inclusion increases yield stress and enhances structural build-up, improving shape stability and buildability during printing. However, high contents may reduce flowability and extrudability, requiring careful optimization. In hardened systems, mine tailings contribute to geopolymer gel formation and can provide moderate to good compressive strength and durability depending on their composition and fineness [86,87].

5.2. Agricultural Waste Materials as Alkali-Activated or Geopolymer Binders in 3D Printed Concrete

Agricultural waste materials, including RHA, POFA, and other biomass-derived ashes, have been widely investigated as sustainable precursors or supplementary materials in alkali-activated (geopolymer) concrete due to their high silica and alumina content, as well as their environmental benefits. These materials have demonstrated promising performance in conventional geopolymer systems, contributing to geopolymer gel formation, microstructural densification, and long-term mechanical strength [88,89]. However, despite this well-established potential, their application in extrusion-based 3D printed geopolymer concrete remains notably limited. The majority of existing studies are confined to conventional casting methods, with only indirect implications for 3D printing. The incorporation of these materials into extrusion-based printable systems is not straightforward, as it requires precise control of rheological properties, such as flowability, yield stress, and thixotropic rebuilding, along with adequate early-age strength to ensure buildability. Furthermore, the variability in chemical composition, combustion conditions, and particle characteristics of agricultural ashes introduces additional challenges for their consistent use in geopolymer 3D printing. As a result, systematic investigations addressing their direct implementation in extrusion-based systems are still lacking. Overall, this highlights a clear research gap and a significant opportunity to explore agricultural waste-derived geopolymer binders tailored for 3D printing applications, particularly through mix design optimization and rheological tuning.

5.3. Marine Waste Materials as Alkali-Activated or Geopolymer Binders in 3D Printed Concrete

Alkali-activated and geopolymer binders have gained increasing attention in extrusion-based 3DCP due to their lower carbon footprint and their ability to valorize industrial by-products. Within this context, marine-derived waste materials, particularly seashell ash, have been identified as potentially viable supplementary precursors owing to their chemical composition, which is typically rich in calcium oxide (CaO) with minor silica content. Such characteristics suggest a possible contribution to geopolymer gel formation, particularly in calcium-rich systems. In conventional alkali-activated and geopolymer concretes, limited studies have demonstrated that seashell-derived powders can influence microstructural development and mechanical performance when incorporated in blended systems. These effects are generally associated with filler behavior, calcium contribution, and potential interaction with geopolymer reaction products. However, these investigations remain confined to cast systems and do not directly address the specific requirements of extrusion-based fabrication [90,91]. In contrast, the application of marine waste materials as precursors in extrusion-based geopolymer 3D printing remains very limited in the current literature. To date, no systematic studies have been identified that evaluate their direct impact on critical printing parameters such as rheology, extrudability, buildability, or early-age structural stability. Given that these parameters are fundamentally different from those governing conventional casting processes, the transferability of existing findings is inherently limited. This gap indicates that, despite their theoretical potential, marine-derived wastes remain very limited within geopolymer 3D printing research frameworks. Accordingly, future investigations are needed to assess their feasibility as binder components, particularly through controlled processing, mix design optimization, and evaluation of fresh-state behavior under extrusion conditions. Such efforts could expand the range of sustainable precursors and support the development of circular-economy-driven materials in additive construction.

5.4. Comparative Discussion of Waste Materials as Alkali-Activated or Geopolymer Binders in 3D Printed Concrete

The use of waste-derived materials in alkali-activated and geopolymer binders for extrusion-based 3DPC demonstrates a clear hierarchy in terms of research maturity, material performance, and practical applicability. Based on the reviewed literature, industrial, agricultural, and marine waste streams exhibit markedly different levels of development and integration within printable geopolymer systems.

Industrial waste materials represent the most mature and extensively studied category. Precursors such as FA and GGBFS form the backbone of geopolymer 3D printing due to their high reactivity and well-established geopolymerization mechanisms. These materials provide a balanced combination of fresh-state workability and hardened performance, enabling adequate pumpability, extrudability, buildability, and early-age strength. Supplementary materials such as SF, MK, and WGP are frequently incorporated to refine rheological behavior, enhance interlayer bonding, and improve microstructural densification. Emerging industrial wastes, including red mud, mine tailings, and recycled CDW powders, have also demonstrated potential as partial precursors. However, their variability in composition and relatively lower reactivity require careful mix design optimization and, in some cases, pre-treatment or blending with highly reactive materials.

In contrast, agricultural waste materials have received comparatively limited attention in geopolymer 3D printing research. Although ashes such as RHA, POFA, and other biomass-derived residues exhibit suitable chemical compositions for geopolymerization, their application has been largely limited to conventional geopolymer concrete. The absence of systematic studies in extrusion-based systems suggests that challenges related to rheological control, particle variability, and early strength development remain insufficiently addressed. Consequently, their integration into 3D printing remains at an early exploratory stage.

Marine waste materials remain at the earliest stage of development among the waste streams discussed in this review. Despite their availability and potential chemical contribution, particularly from calcium-rich seashell-derived powders, their application as geopolymer precursors in 3D printed concrete remains very limited. Existing studies are confined to conventional geopolymer systems, with no direct evaluation of their performance under extrusion conditions. This lack of research is particularly significant given the distinct rheological and buildability requirements of 3D printing, which cannot be directly inferred from traditional casting behavior.

A comparative summary of the different waste categories used as alkali-activated or geopolymer binders in 3D printed concrete is presented in Table 2.

Overall, the comparative analysis reveals that while industrial waste-derived geopolymer systems are well established and increasingly optimized for 3D printing applications, agricultural and marine waste-derived precursors remain very limited. Although industrial waste-derived geopolymer systems have demonstrated considerable potential for extrusion-based 3D printing, several challenges remain. The performance of these systems is highly dependent on precursor reactivity, activator composition, and rheological optimization. While FA-GGBFS blends provide a favorable balance between printability and strength development, excessive slag contents may accelerate setting and reduce extrusion consistency. Similarly, supplementary materials such as SF and MK improve structural build-up but often increase viscosity and activator demand. Emerging materials including red mud, mine tailings, and recycled CDW exhibit promising sustainability benefits; however, their compositional variability and lower reactivity continue to limit widespread implementation. In addition, the near absence of agricultural and marine waste-derived geopolymer systems highlights important research opportunities for future development.

Table 2. Comparative Summary of Waste Materials as Alkali-Activated or Geopolymer Binders in 3D Printed Concrete.

Waste Category	Material	Typical Content (%)	Fresh-State Performance	Hardened Performance	Key Limitations/Challenges	Research Level
Industrial	FA	30–70	High flowability, good extrudability, controlled yield stress.	Strong N-A-S-H gel formation, good long-term strength.	Slow geopolymerization kinetics and limited early-age strength unless combined with calcium-rich precursors.	High
	GGBFS	20–50	Increased yield stress, improved buildability, reduced flow at high content.	Improved early strength, dense C-A-S-H structure.	Excessive contents may accelerate setting and reduce extrusion consistency.	High
	SF	5–10	Increased cohesion, reduced flowability, and improved interlayer bonding.	Enhanced densification and strength.	Increased viscosity and activator demand may negatively affect workability.	High
	MK	10–20	Improved thixotropy and shape stability.	Enhanced early strength and bonding.	High water/activator demand and potential loss of flowability at elevated contents.	High
	WGP	5–20	Improved cohesion and extrusion stability.	Reduced porosity, improved long-term strength.	Reactivity strongly depends on particle fineness and glass composition.	Medium
	CDW	10–40	Improved packing and buildability, reduced flowability at high content.	Moderate strength, acceptable durability.	Variable composition and increased water demand may adversely affect rheology and require blending with highly reactive precursors.	Medium
	RM	10–25	Increased stiffness requires optimization.	Improved chemical resistance, moderate strength.	High alkalinity, compositional variability, and limited validation in extrusion-based systems.	Low
	Mine Tailings	20–60	Increased yield stress, improved buildability, reduced flowability.	Moderate strength depending on composition.	Low intrinsic reactivity and dependence on intensive processing or activation.	Low
Agricultural	-	-	Not investigated as geopolymer precursors in 3D printed concrete.	Not evaluated as geopolymer precursors in 3D printed concrete.	Lack of direct studies addressing rheological control, printability, and geopolymerization behavior in 3DCP.	Very Low
Marine	-	-	Not investigated as geopolymer precursors in 3D printed concrete.	Not evaluated as geopolymer precursors in 3D printed concrete.	Absence of experimental evidence regarding extrusion performance, buildability, and geopolymer binder development.	Very Low

6. Waste as Aggregate Replacement in 3D Printed Concrete

The replacement of natural aggregates, particularly river sand, with waste-derived materials has emerged as a critical strategy for enhancing the sustainability of extrusion-based 3DCP. Unlike cement replacement, which primarily targets the reduction of embodied carbon associated with binder production, aggregate substitution focuses on conserving natural resources, reducing environmental degradation linked to sand extraction, and promoting circular utilization of solid wastes [92]. In extrusion-based 3D printing, the role of fine aggregates extends beyond simple volumetric filling, as they significantly influence fresh-state rheology, particle packing, and interparticle friction. These factors directly affect pumpability, extrudability, and buildability of the printed material. The incorporation of waste-derived aggregates can therefore alter yield stress, viscosity, and thixotropic behavior, which are critical for maintaining filament stability and dimensional accuracy during layer-by-layer deposition [93]. However, replacing natural sand with waste materials presents unique challenges. Variations in particle shape, grading, surface texture, and water absorption of waste aggregates can significantly affect flow behavior and extrusion stability. In some cases, irregular or angular particles may increase internal friction, reducing flowability, while highly absorptive materials may require additional water or admixture adjustments to maintain printability. Furthermore, the influence of waste aggregates on interlayer bonding and anisotropic mechanical performance remains an important consideration in printed structures [94]. Existing studies on waste as aggregate replacement in 3D printed concrete are relatively limited compared to binder-level modifications, and are primarily concentrated on industrial waste streams such as recycled plastics, steel slag, and construction and demolition waste [95]. In contrast, agricultural and marine waste aggregates remain very limited, with only a few emerging studies investigating their feasibility. This uneven distribution highlights the need for systematic evaluation of waste aggregates across different categories, particularly under realistic extrusion conditions. Accordingly, this section critically reviews the use of industrial, agricultural, and marine waste materials as partial replacements for natural sand in extrusion-based 3D printed concrete, with emphasis on their influence on fresh-state behavior, printability, and hardened performance.

6.1. Industrial Waste Materials as Aggregate Replacement in 3D Printed Concrete

Industrial waste materials have been the primary focus of research on aggregate replacement in extrusion-based 3DPC, owing to their availability, controlled processing, and relatively consistent properties compared to other waste streams. These materials are typically used as partial replacements for natural fine aggregates (sand), directly influencing fresh-state rheology, printability, and hardened mechanical performance.

Recycled plastic waste, particularly in the form of mixed post-consumer plastics (e.g., commercially processed products such as Resin8), has recently been investigated as a sustainable alternative to natural fine aggregates in extrusion-based 3D printed concrete. In experimental studies, recycled plastic particles have been used to replace approximately 5%, 10%, and 15% of natural sand by volume in printable mixtures. The investigated particle sizes typically range from sub-5 mm to sub-1 mm, including blended gradations to evaluate their influence on material behavior. In the fresh state, the incorporation of recycled plastic waste generally improves flowability due to the low density and smooth surface texture of plastic particles, which reduce interparticle friction. However, this is accompanied by a reduction in thixotropic rebuilding, which can negatively affect buildability and shape stability during layer-by-layer deposition. In the hardened state, increasing plastic content leads to reductions in compressive and flexural strength, primarily due to the weak interfacial bonding between plastic particles and the cementitious matrix, as well as the lower elastic modulus of plastic compared to natural aggregates. Despite this, the inclusion of even small replacement levels demonstrates the feasibility of integrating plastic waste into 3D printable systems without completely compromising extrusion continuity. This highlights its potential as a circular economy solution for diverting plastic waste into sustainable construction applications [96,97].

Steel slag aggregate, a by-product of the steelmaking industry, has been explored as a sustainable replacement for natural sand in extrusion-based 3D printed concrete due to its high availability, rough surface texture, and favorable mechanical characteristics. Experimental studies have investigated steel slag as a partial fine aggregate replacement in the range of approximately 5% to 30% by volume. Among these, replacement levels of around 10–20% are generally reported to provide an optimal balance between printability and mechanical performance. In fresh-state behavior, the angular and rough texture of steel slag particles increases interparticle friction, leading to higher yield stress and enhanced structural build-up. This effect is beneficial for buildability and shape retention during printing. However, at higher replacement levels (>20%), the mixture tends to exhibit reduced flowability, requiring adjustments in water content and superplasticizer dosage to maintain extrusion stability. In the hardened state, 3D printed elements incorporating steel slag within the optimal range exhibit compressive and flexural strengths comparable to conventional mixtures with natural sand. These findings confirm that steel slag can serve as a viable recycled industrial aggregate in 3D printed concrete, provided that mix design is carefully optimized [98].

Recycled construction and demolition waste, including fine aggregates derived from crushed concrete, masonry, bricks, tiles, and glass, and has attracted increasing attention as a sustainable alternative to natural sand in extrusion-based 3D printed concrete. In existing studies, recycled CDW aggregates with maximum particle sizes ranging from approximately 0.9 mm to 2.36 mm have been investigated as direct replacements for natural sand. Replacement levels vary widely, with some studies exploring substitution ratios up to 100% by volume in printable mixtures. In the fresh state, the incorporation of recycled CDW typically leads to increased static yield stress and plastic viscosity, along with reduced flowability. These effects are primarily attributed to the higher water absorption capacity and irregular surface texture of recycled particles. The impact becomes more pronounced at higher replacement levels but can be partially mitigated through adjustments in superplasticizer dosage and water content. In terms of hardened performance, compressive and flexural strengths of 3D printed elements containing CDW aggregates generally decrease compared to control mixtures. Reported reductions range from negligible at low replacement levels to significant losses (up to approximately 60%) at very high substitution ratios. Nevertheless, acceptable buildability and extrusion performance can be attained through proper mix design optimization. Overall, these findings demonstrate that recycled CDW aggregates are a viable and sustainable alternative to natural fine aggregates in 3D printed concrete, although careful control of particle grading, water demand and admixture dosage is essential to balance fresh and hardened properties [99].

6.2. Agricultural Waste Materials as Aggregate Replacement in 3D Printed Concrete

Despite the growing body of research on the utilization of waste materials in extrusion-based 3DCP, the application of agricultural wastes as direct replacements for natural fine aggregates remains very limited [94]. Existing studies in 3D printed concrete have predominantly focused on industrial by-products, recycled construction and demolition waste, and other alternative mineral aggregates, with limited attention given to agricultural residues [100]. Materials such as rice husk ash, sugarcane bagasse ash, palm oil fuel ash, and other crop-derived by-products have been widely studied in conventional concrete and geopolymer systems due to their pozzolanic properties and environmental benefits [101]. However, their use as fine aggregate (sand) replacements in extrusion-based 3D printing systems remains very limited in the current literature. This absence can be attributed to several technical challenges. Agricultural wastes are typically characterized by low particle density, irregular morphology, and high water absorption, which can significantly affect rheological behavior, including flowability, yield stress, and extrusion stability. In addition, their influence on buildability and interlayer bonding in printed structures remains unclear [5]. Overall, the lack of experimental studies addressing agricultural waste as aggregate replacement in 3D printed concrete highlights a clear research gap. Future investigations should focus on particle processing, grading optimization, and rheological tailoring to enable their integration into printable mixtures, thereby expanding the scope of sustainable materials in additive construction.

6.3. Marine Waste Materials as Aggregate Replacement in 3D Printed Concrete

Research on the use of marine-derived waste materials as fine aggregate replacements in extrusion-based three-dimensional printed cementitious composites remains extremely limited. Existing studies on marine wastes are predominantly focused on conventional concrete applications or on their use as supplementary fillers, with very limited direct investigation within extrusion-based 3D printing systems. This indicates that, compared to industrial waste aggregates, marine-derived materials remain very limited under the specific rheological and buildability requirements of 3D printing.

Among the limited available studies, seashell particles, produced by crushing and milling discarded shells from seafood industries, have been directly studied as a partial replacement for natural river sand in extrusion-based printable mortars. In this study, seashell particles were used to replace natural sand at 15% and 30% by weight of the fine aggregate. The results showed that increasing the seashell content led to a reduction in compressive and tensile strength, which was primarily attributed to increased void content and the lower elastic modulus of seashell particles compared to natural sand. However, it was also observed that fine seashell powders partially participated in cement hydration, contributing to localized microstructural densification. This dual behavior highlights that seashell particles can act both as inert aggregates and as reactive fillers, depending on particle size distribution [102].

Despite this initial investigation, the application of marine waste materials as fine aggregate replacements in 3D printed concrete remains largely underdeveloped. Critical aspects such as rheological behavior, extrusion stability, buildability, and interlayer bonding remain largely unassessed. Furthermore, the variability in marine waste composition, particle morphology, and processing methods introduces additional challenges that have yet to be addressed in the context of extrusion-based systems. Overall, the scarcity of experimental studies highlights a significant research gap and underscores the need for future work focused on optimizing particle processing, mix design strategies, and rheological performance to enable the effective integration of marine waste aggregates into sustainable 3D printed concrete.

6.4. Comparative Discussion of Waste Materials as Aggregate Replacement in 3D Printed Concrete

The use of waste materials as partial replacements for natural fine aggregates in extrusion-based 3DCP reveals a clear disparity in research development, material performance, and practical applicability across different waste categories. Based on the reviewed literature, industrial, agricultural, and marine waste streams exhibit significantly different levels of investigation and technological readiness.

Industrial waste materials represent the most extensively investigated category for aggregate replacement in 3D printed concrete. Materials such as recycled plastic waste, steel slag, and construction and demolition waste have been systematically studied across a wide range of replacement levels and particle characteristics. These materials demonstrate varying but generally manageable effects on fresh-state behavior, including changes in flowability, yield stress, and thixotropic response. In particular, steel slag and CDW tend to increase yield stress and structural build-up, enhancing buildability, while recycled plastic particles improve flowability but may reduce structural stability. Despite some reductions in mechanical performance, especially at higher replacement levels, industrial waste aggregates have been successfully incorporated into printable mixtures, confirming their feasibility as sustainable alternatives to natural sand.

In contrast, agricultural waste materials remain very limited as fine aggregate replacements in extrusion-based 3D printed concrete. Although these materials have been widely studied in conventional concrete and geopolymer systems, no direct experimental studies have been identified that evaluate their performance as sand substitutes in 3D printing. This absence suggests that challenges related to particle morphology, water absorption, and rheological instability have limited their application in printable systems. Consequently, their influence on extrusion behavior, buildability, and interlayer bonding remains unknown.

Marine waste materials represent the least developed yet most promising category. Current research is extremely limited, with only isolated studies investigating seashell particles as partial sand replacements. These studies demonstrate that marine-derived aggregates can influence both fresh and hardened properties, although reductions in mechanical strength have been observed due to increased porosity and lower stiffness of the particles. At the same time, fine seashell powders show potential for microstructural densification, indicating that particle size plays a critical role in performance. However, fundamental aspects such as rheological control, extrusion stability, and layer adhesion remain largely unaddressed.

A comparative summary of the different waste categories used as aggregate replacement in 3D printed concrete is presented in Table 3.

Table 3. Comparative summary of waste materials as aggregate replacement in 3D printed concrete.

Waste Category	Material	Typical Replacement (%)	Fresh-State Performance	Hardened Performance	Key Limitations/Challenges	Research Level
Industrial	Recycled Plastic Waste	5–15	Increased flowability and reduced thixotropy, which may lower buildability.	Reduction in compressive and flexural strength with increasing content.	Weak interfacial bonding with the cement matrix and progressive loss of mechanical performance at higher replacement levels.	High
	Steel Slag Aggregate	5–30 (optimum 10–20)	Increased yield stress and structural build-up; reduced flowability at higher content.	Comparable compressive and flexural strength at optimal replacement levels.	Excessive replacement levels may adversely affect workability and require additional water or admixture optimization.	High
	Recycled CDW	up to 100	Increased viscosity and yield stress; reduced flowability; higher water demand.	Reduction in mechanical strength, significant at high replacement levels.	High water absorption, variable particle quality, and strength loss at elevated replacement ratios.	Medium
Agricultural	-	-	Not investigated as aggregate replacement in 3D printed concrete.	Not evaluated as aggregate replacement in 3D printed concrete.	Absence of experimental studies; effects on rheology, buildability, interlayer bonding, and durability remain unknown.	Very Low
Marine	Seashell Particles	15–30	Influence on rheology and printability not fully established [102].	Reduction in strength with partial microstructural densification from fine particles [102].	Limited experimental evidence and insufficient understanding of extrusion behavior, layer adhesion, and long-term performance [102].	Low

Overall, this comparative analysis highlights a clear research hierarchy: industrial waste aggregates are well established and experimentally validated, whereas agricultural and marine wastes remain very limited or nearly absent in extrusion-based 3D printing research. The reviewed studies indicate that aggregate replacement generally involves a trade-off between sustainability and material performance. Industrial waste aggregates such as steel slag can improve buildability through increased structural build-up, whereas recycled plastic particles may enhance flowability but often reduce mechanical strength due to weak matrix–particle interactions. Recycled CDW aggregates offer substantial resource conservation benefits; however, their high water absorption and variable quality can adversely affect both fresh-state behavior and hardened performance. Marine-derived aggregates, particularly seashell particles, show preliminary promise but remain insufficiently investigated with respect to rheology, extrusion stability, and interlayer bonding. Therefore, future research should focus not only on replacement feasibility but also on optimizing particle characteristics and mix design to achieve consistent printing performance.

7. Application-Oriented Review of 3D Concrete Printing

Three-dimensional concrete printing has rapidly evolved from a laboratory-scale concept into a viable construction technology applied across multiple sectors, including residential housing, infrastructure, public facilities, commercial buildings, architectural installations, and marine environments. Its key advantages, such as design flexibility, elimination of formwork, rapid construction, reduced labor demand, and improved material efficiency, have driven increasing global adoption. However, despite these advancements, most real-scale applications continue to rely on proprietary, cement-rich mixtures optimized primarily for printability and early-age stability. The incorporation of waste-derived materials, whether as cement replacements, alkali-activated (geopolymer) binders, or fine aggregate substitutes, remains largely confined to experimental and pilot-scale studies. Table 4 summarizes representative global 3DCP projects and highlights the limited integration of waste-based materials in full-scale construction practice.

Analysis of global 3DCP deployments reveals a clear relationship between application domain and material selection strategy. Structural and infrastructural applications, such as multi-story buildings and load-bearing bridges, continue to rely predominantly on cement-rich mixtures due to stringent requirements related to early-age strength, dimensional accuracy, durability, and compliance with design codes. Although laboratory studies demonstrate the feasibility of incorporating industrial by-products and recycled materials across different functional roles, concerns related to material variability, buildability control, and quality assurance limit their adoption in risk-sensitive structural applications. In contrast, non-structural and semi-structural applications, including public facilities, urban furniture, and architectural elements, offer greater flexibility, allowing the incorporation of ceramic waste, recycled fines, and other alternative materials due to lower structural performance demands.

Marine and coastal applications represent a particularly promising domain for the integration of circular materials. In these environments, ceramic waste, calcium carbonate-based by-products, and slag-rich binders have been successfully utilized in reef structures and coastal protection elements, providing both environmental and functional benefits such as bio-receptivity and ecological enhancement. However, marine-derived wastes, particularly seashell-based materials, remain very limited and are currently limited to niche applications, indicating a clear opportunity for further research and development.

Despite encouraging laboratory-scale findings, several interrelated challenges continue to hinder large-scale adoption of waste-based mixtures in 3DCP. These include limitations in early-age performance, such as delayed reaction kinetics and reduced structural build-up, as well as significant variability in material properties, particularly in agricultural and recycled wastes such as construction and demolition waste (CDW) and red mud. Additionally, compatibility issues with existing printing systems and the lack of standardized testing methods and certification frameworks further restrict practical implementation. As a result, non-structural applications and marine infrastructure currently offer the most viable pathways for integrating waste-derived materials under real construction conditions. Overall, advancing field-scale adoption will require coordinated progress in mix design optimization, printability standardization, hardware adaptability, and regulatory development, supported by large-scale demonstration projects that bridge the gap between laboratory research and practical construction.

Table 4. Global applications of 3D concrete printing.

Domain	Project	Structural/Functional Complexity	Waste	Ref.
Residential Housing	5-Storey Printed Apartment (Shanghai, China).	High—Multi-story structural system.	Not reported	[103]
	298.5 m^2 Printed House (Yaroslavl, Russia).	Medium—Single-family structural shell.	Not reported	[103]
	24-h Printed House (Moscow, Russia).	Medium—Rapid construction housing.	Not reported	[103]
	Dubai Municipality Building (Dubai, UAE).	High—Structural wall system.	Not reported	[104]
Infrastructure	3D-Printed Pedestrian Bridge (Madrid, Spain).	High—Structural load bearing.	Not reported	[103]
	3D-Printed Concrete Bridge (Eindhoven, The Netherlands).	High—Segmental structural bridge.	Not reported	[104]
	Storm water Chambers (Wigan, UK).	Medium—Functional components.	Not reported	[105]
	Heritage Fountain Restoration (Palekh, Russia).	Low—Non-structural element.	Not reported	[103]
Public Facilities	3D-Printed Bus Stop (Fengjing, China).	Medium—Shelter structure.	Ceramic waste	[103]
	3D printed seats in public park (Dubai, UAE).	Low—Utility building.	Not reported	[106]
	3D printed park (Shenzhen, China).	Low—Urban components.	Recycled fines/aggregates	[107]
Commercial Buildings	3D-Printed Commercial Building (Hamilton, New Zealand).	Medium—Commercial shell.	Not reported	[103]
	3D-Printed Office Building (Dubai, UAE).	Medium—Office facility.	Not reported	[103]
Architectural & Cultural Installations	ETH Origen Festival Columns (Riom, Switzerland).	High—Free-form architecture.	Not reported	[103]
	Bloom Pavilion (Los Angeles, CA, USA).	High—Large free-form shell.	Not reported	[104]
Marine & Coastal	Reef Modules (Summer Island, Maldives).	Medium—Ecological units.	Ceramic waste	[108]
	3D-Printed Reef Tiles (Singapore).	Medium—Ecological enhancement.	$CaCO_3$ by-products + ceramic powders	[109]
	Construction Reef Units (Rotterdam, The Netherlands).	High—Coastal engineering elements.	Blast furnace slag	[110]
	3D-Printed Mega Reef (Brescou Island, France).	High—Bio-enhancing reef structure.	Not reported	[111]

8. Research Gaps, Challenges, and Future Directions

Figure 7 presents a schematic summary of the major research gaps, challenges, and future research directions identified in this review. The key themes highlighted in the framework, including material-related challenges, standardization and scale-up barriers, durability concerns, advanced mix design strategies, and techno-economic considerations, are discussed in detail in the following subsections.

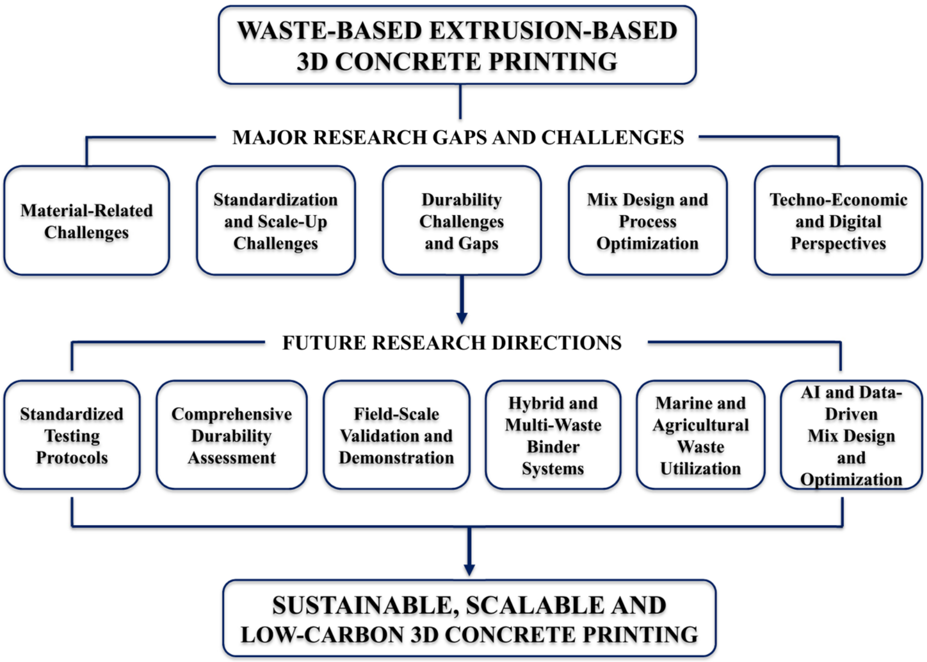

Figure 7. Schematic overview of the major research gaps, challenges, and future research directions for waste-based extrusion 3D concrete printing.

8.1. Material-Related Challenges and Research Gaps

Despite the rapid advancement of extrusion-based 3DCP and the growing body of research on waste-integrated materials, the transition from laboratory-scale studies to reliable field-scale implementation remains limited. This gap is largely attributed to challenges in achieving consistent fresh-state performance, particularly in terms of rheology, printability, and buildability. Waste-derived materials, whether used as cement replacements, geopolymer precursors, or fine aggregate substitutes, often exhibit significant variability in particle size distribution, chemical composition, and reactivity, which directly influences yield stress, viscosity, and thixotropic rebuilding. In OPC-based systems, high replacement levels of supplementary cementitious materials, including fly ash and agricultural ashes such as RHA and SCBA, may delay hydration and reduce early-age strength, thereby compromising buildability. Similarly, in alkali-activated systems, controlling reaction kinetics and setting behavior remains challenging, particularly when incorporating less reactive or heterogeneous precursors such as red mud, mine tailings, and construction and demolition waste. While industrial by-products generally exhibit stable and well-characterized properties, agricultural and recycled wastes introduce additional variability due to differences in source and processing conditions, complicating mix design optimization and limiting reproducibility. Moreover, marine-derived wastes, such as seashell powders, remain very limited, particularly as cement replacements or geopolymer precursors, with existing studies largely restricted to aggregate substitution, highlighting a clear imbalance in current research efforts.

Another important research gap is the limited availability of predictive rheological and mechanical performance models capable of correlating waste material characteristics with printability and hardened properties in extrusion-based 3D concrete printing. Current studies are predominantly based on experimental trial-and-error approaches, while robust predictive frameworks linking particle characteristics, chemical composition, and replacement levels to yield stress, buildability, interlayer bonding, and mechanical performance remain scarce. The development of such models would facilitate mix design optimization, improve prediction accuracy, and accelerate the practical implementation of waste-based printable materials.

8.2. Standardization and Scale-Up Challenges

Another major limitation lies in the lack of standardized testing methods and performance criteria for 3D printable materials, as current studies employ diverse approaches to evaluate rheology, printability, interlayer bonding, and mechanical performance. This inconsistency hinders meaningful comparison across studies and delays the development of reliable design guidelines and certification frameworks. At the application level, a substantial gap persists between material development and real-scale implementation, as most full-scale 3DCP projects continue to rely on proprietary, cement-rich mixtures due to strict requirements related to early-age strength, durability, and quality control. In addition, waste-modified mixtures often require adjustments in pumping systems, nozzle configurations, and deposition parameters, limiting compatibility with existing printing technologies. Across the three main utilization pathways, industrial waste materials can be considered relatively mature, particularly in cement replacement and geopolymer systems, while agricultural wastes remain moderately explored and marine wastes represent the least developed category. This disparity underscores the need for a more balanced research approach that extends beyond conventional industrial materials toward underutilized waste streams.

8.3. Durability Challenges and Research Gaps

From a porosity and durability perspective, the influence of waste materials in extrusion-based 3D printed concrete varies considerably according to the waste type and its role within the mixture. Industrial waste materials such as FA, GGBFS, SF, and MK generally exhibit the most favorable durability performance due to pore refinement, reduced permeability, and improved resistance to chloride ingress. Several studies also report enhanced dimensional stability and lower susceptibility to durability-related deterioration mechanisms as a result of matrix densification and reduced pore connectivity. Agricultural waste materials, particularly RHA and SCBA, demonstrate similar potential through pozzolanic reactions and microstructural refinement, although the available evidence remains considerably more limited. In contrast, recycled aggregate systems, especially those incorporating construction and demolition waste, often exhibit higher water absorption and porosity, which may increase susceptibility to shrinkage-related deterioration and environmental ingress at elevated replacement levels. Marine-derived wastes remain the least investigated category, with existing studies very limited to seashell aggregate incorporation and providing insufficient evidence regarding chloride resistance, freeze–thaw durability, shrinkage behavior, long-term mechanical reliability, and environmental exposure performance. Overall, industrial waste materials currently demonstrate the most consistent improvements in porosity characteristics and durability performance, whereas agricultural, recycled, and marine-derived wastes require further validation under long-term service conditions.

Despite these encouraging findings, important durability-related knowledge gaps remain for agricultural, recycled, and particularly marine-derived waste materials used in extrusion-based 3D concrete printing. Comprehensive evaluation of shrinkage behavior, permeability, freeze–thaw resistance, chloride penetration, and long-term interlayer durability under environmental exposure conditions is required to establish the structural reliability of these materials. In particular, comparative durability assessments across different waste categories remain scarce, limiting the ability to identify the most suitable waste streams for specific environmental and structural applications. Greater attention should also be directed toward field-scale validation and large-scale demonstration projects, particularly for agricultural and marine-derived waste materials, to evaluate their performance under realistic construction and environmental conditions. Addressing these challenges is essential for supporting the widespread adoption of sustainable waste-based materials in extrusion-based 3D concrete printing.

8.4. Advanced Mix Design and Process Optimization

Future research should therefore focus on developing robust and application-oriented mix design strategies capable of accommodating material variability while maintaining consistent printability and mechanical performance. Particular emphasis should be placed on agricultural and marine waste materials, which require dedicated mix design methodologies due to their high water absorption, irregular particle morphology, and compositional variability. For agricultural wastes such as RHA and SCBA, future studies should focus on optimizing particle fineness, pretreatment methods, and replacement strategies to balance printability, mechanical performance, and durability.

Given the limited research on marine-derived wastes in 3D concrete printing, a dedicated research roadmap for seashell-based materials is needed. Future investigations should focus on:

- Optimizing particle size distribution and grinding procedures to improve packing density, rheological behavior, and printability.
- Comparing the performance of raw and calcined seashell materials as supplementary cementitious materials, geopolymer precursors, or fine aggregate replacements.
- Evaluating the compatibility of seashell-derived materials with alkaline activators and hybrid binder systems used in extrusion-based 3D concrete printing.
- Investigating the influence of seashell-based materials on interlayer bonding, durability, and long-term structural performance under realistic environmental conditions.

In addition, systematic approaches involving particle preprocessing, grading optimization, controlled replacement strategies, and hybrid binder systems are needed to improve compatibility with extrusion-based printing processes. Advanced rheological characterization techniques should also be adopted to evaluate dynamic and static yield stress evolution, thixotropic rebuilding, pumpability, extrusion stability, and interlayer behavior under realistic printing conditions. In parallel, standardized protocols for printability and buildability assessment are essential to improve reproducibility and enable meaningful comparison across studies.

8.5. Techno-Economic and Digital Perspectives

From a techno-economic perspective, the large-scale implementation of agricultural and marine waste materials in extrusion-based 3D concrete printing still faces several practical challenges. Although many of these waste streams are locally abundant and potentially low-cost, additional processing requirements such as drying, grinding, calcination, sieving, and chemical activation may significantly increase production costs and energy demand. Furthermore, variability in waste availability, seasonal generation, transportation logistics, and quality consistency may limit reliable industrial-scale utilization and supply chain standardization. Consequently, the economic feasibility of agricultural and marine waste-based printable mixtures depends not only on reducing raw material costs, but also on achieving stable processing performance, compatibility with existing printing systems, and simplified large-scale integration. Future research should therefore incorporate techno-economic analysis, life-cycle cost assessment, and scalability evaluation to better determine the practical viability and commercialization potential of sustainable waste-based 3D printing materials.

Furthermore, advances in material processing techniques, including thermal activation, chemical activation, and particle size refinement, may significantly enhance the reactivity and performance of low-reactivity waste streams. Finally, the integration of digital tools, including machine learning, optimization algorithms, and data-driven mix design approaches, offers substantial potential for accelerating material development and improving prediction accuracy for printable concrete behavior. Addressing these challenges through coordinated interdisciplinary research will be essential for advancing 3D concrete printing toward a scalable, low-carbon, and circular construction technology.

8.6. Key Recommendations for Future Research

Based on the current state of knowledge, the following key recommendations are proposed to advance the development and practical implementation of waste-based 3D concrete printing technologies:

- Establish standardized rheological testing methods and printability assessment protocols for waste-modified printable mixtures.
- Conduct comprehensive durability investigations focusing on chloride ingress, freeze–thaw resistance, shrinkage behavior, permeability, and long-term interlayer performance.
- Expand life-cycle assessment (LCA), environmental impact, and techno-economic studies to compare different waste streams and quantify sustainability benefits.
- Increase field-scale validation and demonstration projects, particularly for agricultural and marine waste-based printable mixtures.
- Develop hybrid binder and precursor systems combining industrial, agricultural, recycled, and marine-derived wastes to improve printability and mechanical performance.
- Integrate machine learning, optimization algorithms, and data-driven mix design approaches to accelerate material development and enhance process control.

9. Conclusions

This review systematically evaluated the incorporation of waste-derived materials in extrusion-based 3DCP through three principal application pathways: cement replacement in OPC-based systems, alkali-activated/geopolymer binders, and fine aggregate substitution. The findings indicate that waste integration offers a viable route toward reducing the environmental impact of 3DCP while maintaining acceptable fresh state and hardened performance, provided that material selection and mix design are carefully optimized. Industrial by-products such as fly ash, ground granulated blast furnace slag, silica fume, and metakaolin demonstrate the highest level of technical maturity, showing consistent improvements in rheology, buildability, and long-term mechanical performance across both OPC-based and geopolymer systems. In contrast, agricultural wastes such as rice husk ash and sugarcane bagasse ash exhibit promising but less consistent behavior, primarily due to higher water demand and variability in physicochemical properties. Marine-derived wastes remain one of the least investigated waste categories in 3D concrete printing. Existing studies are very limited to seashell-based aggregate applications and remain insufficient to establish comprehensive understanding of their rheological behavior, long-term durability, compatibility with binder systems, and large-scale implementation potential.

Across the three utilization pathways, the performance of waste-integrated 3D printable mixtures is strongly governed by fresh-state rheological behavior, early-age structural build-up, and interlayer bonding. While many waste materials contribute to improved sustainability and, in some cases, enhanced long-term properties, challenges related to delayed hydration, reduced early strength, and variability in material characteristics continue to limit their widespread adoption. In geopolymer systems, the combination of aluminosilicate-rich precursors, particularly FA and GGBFS, has demonstrated strong potential for developing low-carbon printable binders with satisfactory mechanical performance, although control of reaction kinetics and printability remains critical. In the context of aggregate replacement, recycled materials such as construction and demolition waste, steel slag, and recycled plastics have shown feasibility as partial substitutes for natural sand, but often require careful optimization to balance flowability, buildability, and mechanical strength.

Despite significant progress at the material level, the transition of waste-based 3D printed concrete from laboratory research to real-scale construction remains limited. This is primarily due to the lack of standardized testing methods, uncertainties in long-term performance, and compatibility challenges with existing printing systems and construction practices. Current large-scale applications continue to rely predominantly on cement-rich mixtures, highlighting a disconnect between research developments and field implementation. Bridging this gap requires a shift toward application-oriented research, including large-scale validation, standardized evaluation frameworks, and improved integration between material development and printing technology.

Overall, the review highlights that while industrial waste materials are relatively well established in 3DCP, agricultural and marine wastes represent significant untapped resources for advancing sustainability in digital construction. Future research should prioritize the standardization of key rheological parameters; particularly yield stress, thixotropic rebuilding, and printability assessment methods, to improve comparability across studies. In addition, comprehensive durability investigations addressing shrinkage behavior, chloride ingress, freeze–thaw resistance, permeability, and long-term interlayer performance are required to support practical implementation. Particular attention should be directed toward agricultural and marine-derived waste streams through optimized preprocessing strategies, particle-size control, and compatibility assessment with both cementitious and alkali-activated systems. For seashell-based materials, future studies should further evaluate raw versus calcined forms, their interaction with binder systems, and their influence on long-term durability. These efforts, combined with field-scale validation, techno-economic assessment, and data-driven mix design approaches, will be essential for accelerating the transition of waste-based 3D concrete printing from laboratory research to sustainable construction practice.

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