

Review

Engineering Starch for Non-Food Additive Manufacturing: Properties, Printability, and Emerging Uses

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Abstract

The development of sustainable materials for additive manufacturing (AM) has positioned starch as a compelling alternative to conventional thermoplastics. However, the successful implementation of starch in 3D printing (3DP) relies on precise control of its supramolecular organization, rheological behavior, and processing conditions. This article analyzes starch-based hydrogels for extrusion-driven AM, establishing explicit links between molecular architecture, gelatinization, and viscoelastic performance. The influence of key rheological parameters on extrudability and shape fidelity is examined in parallel with critical processing conditions. Chemical and physical modification routes of starch are compared in terms of their structural impact and printability enhancement. The integration of additives such as polysaccharides, proteins, and inorganic salts is discussed as a strategy to overcome intrinsic mechanical limitation. Emerging non-food application in drug delivery, tissue engineering, or conductive/intelligent hydrogels demonstrates the expanding technological relevance of starch-based formulation. Remaining challenges include predictive, rheology-based design, and the development of multifunctional 4D-printing capabilities. Progress in this field is crucial for positioning starch as a robust platform for sustainable AM, but, despite this progress, a systematic and quantitative framework linking starch molecular architecture and rheological behavior to printing-process parameters and outcomes is still lacking, thus constituting the central gap addressed in this review.

Keywords: starch; additive manufacturing; hydrogels; 3D printing; biopolymers; drug delivery; biosensors; conductive hydrogel



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1. Introduction

Additive manufacturing (AM), commonly referred to as 3D printing, enables the fabrication of three-dimensional objects from 3D computer-aided design (CAD) by depositing and layering structural materials or biological components, such as thermoplastics, metals, ceramics, or biological cells. Having emerged several decades ago with the advent of stereolithography (SLA), AM has undergone noticeable technological evolution, giving rise to a large range of new tools capable of producing diverse classes of single or composite materials. Currently, AM encompasses a wide array of technologies, including extrusion, (binder-)jetting, sheet lamination, powder bed fusion, and vat photopolymerization [1]. Its innovative potential has garnered significant attention, as AM emerges as a transformative

technology revolutionizing product manufacturing across various industries, including healthcare, aerospace, automotive, and architecture/construction [2–5].

A critical analysis of the State of the Art reveals that a significant proportion of AM studies relies on thermoplastic systems, including polyolefins, (meth)acrylates, and poly(vinyl alcohol). Formulations based on acrylonitrile butadiene styrene (ABS) resins have likewise been extensively reported. The chemical identity and formulation of the thermoplastic matrix, whether employed as a single component or within multicomponent blends, provide a versatile framework for tailoring the mechanical properties of the resulting materials. Such adaptability is critical for fulfilling the stringent and application specific requirements of advanced sectors, particularly in the biomedical and aeronautical fields.

Following current research trends, and driven by ambitions for sustainability and circularity, the scientific community is increasingly exploring bio-based alternatives to substitute conventional thermoplastics in additive manufacturing. In this context, numerous studies have examined the potential of polysaccharides and their derivatives, including hemicelluloses and starch, as well as chitosan, alginates, and other renewable polymeric materials, such as polylactic acid (PLA), which offer tunable properties for mechanical performance, printability, and biodegradability (Table 1).

Table 1. Selected examples of bio-based polymers explored as alternatives to conventional thermoplastics in additive manufacturing.

Conventional Thermoplastics	Alternative Bio-Based Polymers	Applications	References
ABS (acrylonitrile–butadiene–styrene)	PLA (polylactic acid)	Filaments, rapid prototyping	[6,7]
PE (polyethylene), PP (polypropylene)	PHA (polyhydroxyalkanoate)	Film, packaging	[8,9]
PHEMA (poly-2-hydroxyethyl methacrylate), PVA (polyvinyl alcohol)	Starch, alginate, chitosan, gelatin	Hydrogels, biomedical	[10–12]
PEG (polyethylene glycol), PVP (polyvinyl pyrrolidone)	HPC (hydroxypropyl cellulose)	Drug delivery systems	[13]
PEDOT: PSS (poly(3,4-ethylenedioxythiophene) (PEDOT) and sodium poly(styrene sulfonate) (PSS))	Sodium alginate and functionalized agar	Sensors/electronic Interfaces	[14,15]

More specifically, starch has progressively gained significant attention as a potential inflow in AM. Widely available, low-cost, and biocompatible, starch also exhibits tunable physicochemical properties, making it a particularly attractive candidate for extrusion-based additive manufacturing, including pneumatic extrusion, screw-assisted extrusion, fused deposition modeling (FDM), and solid freeform fabrication (SFF) techniques (Table 2).

Beyond material selection, precise control of process parameters is increasingly recognized as essential to achieving structural fidelity in extrusion-based additive manufacturing. Recent work has demonstrated that finite-element simulation frameworks, built directly from printer G-code and calibrated against key process parameters, can predict the true, physically deformed filament cross-section with a thickness error of 1% and a width error of 8% relative to experimental measurements, and reproduce the resulting mechanical tensile response with correlations exceeding 95% in the elastic regime and 90% in the elastoplastic regime across multiple raster orientations [16]. Such predictive, simulation-based approaches illustrate the broader shift toward digitally optimized extrusion processes and provide useful foundational context for the rheology-based formulation and process design strategies for starch-based inks.

Table 2. Representative examples of starch-derived formulation in extrusion-based AM and some selected applications.

Material Composition	Starch Concentration/Amylose Content	AM Type and Parameters	Rheological Values	Applications	Ref.
Starch (waxy maize) + oat protein + cellulose nano-fiber	10–15 wt%/0%	Pneumatic extrusion: room temp.; air pressure: 22–114 kPa; speed: 2 mm/s; nozzle diam.: 0.41 mm; nozzle height: 0.3 mm	$G' = 261\text{--}280$ Pa; yield point = 5.34–8.52 Pa	Food design (design of healthy novel food)	[17]
Starch (normal (NW and waxy (WM) maize; potato (P)) + ibuprofen	30 wt%/27% (NM), 0% (WM), 25% (P)	Direct ink writing (DIW): speed: 6 mm/s; nozzle diam.: 0.8 mm; nozzle height: 5–7.2 mm; 100% infill	$G' = 261\text{--}280$ Pa; yield point = 5.34–8.52 Pa	Encapsulation, drug delivery (tailored administration of hydrophobic drugs)	[18]
Starch (corn) + glycerol + montmorillonite + magnesium stearate + citric acid + methylsulfonylmethane	70 wt%/26%	Fused Depositing Modeling (FDM): temp.: 205–220 °C; speed: 12–300 mm/s; nozzle diam.: 0.8 mm; 40–50% infill	N.D.	Encapsulation, drug delivery (scaffold for deep wound treatment)	[19]
Starch (corn (C), potato (P), cassava (CS)) + hydroxyapatite (HA)	1.63–5.46 wt%/25% (C), 20% (P); 15% (CS)	Solid freeform fabricator (SFF): speed: 40 mm/s; nozzle diam.: 0.7–0.9 mm; nozzle height: 1.5 mm; 40% infill	N.D.	Biomedical scaffold, tissue engineering (mimic of natural bone)	[20]
Starch (corn) + gelatin	10 wt%/N.D.	Bioprinting: speed: 2–14 mm/s; nozzle diam.: 0.3 mm; 30% infill	$G' = \sim 380\text{--}5000$ Pa; yield point = $\sim 130\text{--}1100$ Pa	Biomedical scaffold, tissue engineering (bioactive compounds)	[21]
Starch (potato) + anthocyanin + phycocyanin + chondroitin sulfate	12–18 wt%/30%	Direct ink writing (DIW): speed: 18–30 mm/s; nozzle diam.: 0.2–0.6 mm	$G' = \sim 160\text{--}1350$ Pa	Smart or intelligent packaging (colorimetric indicator of packaged food freshness)	[22]
Starch (potato) + gold nanoparticles	4 (w/v)/N.D.	Inkjet printing: temp.: 50 °C; 500 Hz jetting frequency	N.D.	Flexible electronics (substitute to organic solvent-based formulations)	[23]

Despite this progress, a systematic and quantitative framework linking starch molecular architecture and rheological behavior to printing-process parameters and outcomes is still lacking, and it thereby constitutes the central gap addressed in this review.

2. Materials and Methods

This review was compiled through a structured, though not formally systematic, literature search covering the scientific literature on starch-based materials for extrusion-based additive manufacturing. Relevant records were identified using SciFinder, Scopus, and Google Scholar, selected as complementary sources covering the chemistry, engineering, and materials-science literature relevant to this topic. Google Scholar searches were additionally used to capture recent publications and grey literature not yet indexed in the two bibliographic databases, and to cross-check the completeness of the Scopus and SciFinder results.

The search followed a two-tier strategy. First, broad searches combining the core terms “starch” and “3D printing”/“additive manufacturing” were used to identify the general body of literature and existing reviews on starch-based additive manufacturing, providing an overview of the field and its main sub-topics. Second, once the structure of the review had been established, targeted searches were performed for each specific technical section, combining “starch” and/or “3D printing” with terms specific to the topic under discussion. The specific search terms used for each section are summarized in Table 3 below. In addition to database searching, the reference lists of key review articles identified during the search were manually screened to identify additional relevant primary research articles (snowball sampling).

Table 3. Search terms and Boolean combinations used for each section of the review.

Topic/Section	Keywords and Boolean Combinations
General/broad search	(“starch” OR “starch-based”) AND (“3D print*” OR “additive manufactur*”)
Narrowed to material behavior	“starch” AND “3D printing” AND (“rheolog*” OR “printability” OR “extrusion”)
Gelatinization/rheology	“starch” AND “gelatinization” AND (“rheolog*” OR “viscoelastic*” OR “storage modulus” OR “shear-thinning”)
Process parameters	“starch” AND “3D printing” AND (“nozzle” OR “printing speed” OR “extrusion pressure” OR “printing temperature”)
Chemical modification	“starch” AND (“oxidation” OR “cross-link*” OR “esterification” OR “etherification”) AND (“3D printing” OR “printability”)
Physical modification	“starch” AND (“high pressure processing” OR “ultrasound” OR “microwave” OR “radio frequency” OR “pulsed electric field” OR “dry heat treatment”) AND “3D printing”
Biological modification	“starch” AND (“enzymatic modification” OR “debranching enzyme” OR “genetic modification” OR “CRISPR” OR “waxy starch” OR “high amylose”) AND (“printability” OR “3D printing”)
Additives	“starch” AND (“xanthan gum” OR “carrageenan” OR “gelatin” OR “protein” OR “inorganic salt”) AND (“3D printing” OR “hydrogel”)
Non-food applications	“starch” AND “3D printing” AND (“drug delivery” OR “controlled release”) OR (“tissue engineering” OR “scaffold” OR “bioprinting”) OR (“conductive” OR “biosensor” OR “electronic”) OR (“smart packaging” OR “intelligent packaging” OR “freshness indicator”)

Both review articles and original research articles were considered eligible, with a preference for research articles reporting direct experimental evidence on starch rheology, modification, or printing performance, and reviews used primarily to provide overview/context and to identify further primary sources. Searches were not restricted to a fixed start date in order to capture the foundational literature on starch gelatinization and rheology, but the search and article selection prioritized publications from the last decade, reflecting the relatively recent emergence of starch-based additive manufacturing as an active research area. Only articles published in English were considered. Conference abstracts and patents were not included as primary evidence, although patent literature was consulted informally during background reading.

Records identified via database searching were first screened by title and abstract to exclude studies unrelated to starch and/or additive manufacturing/3D printing. Full texts of the remaining records were then assessed for eligibility, excluding non-English-language articles, conference-abstract-only or patent-only records, and studies whose content was judged insufficiently relevant to the scope of this review. Studies addressing food-related 3D-printing applications of starch were included only where their formulation, rheological, or processing findings were judged directly transferable to the non-food applications discussed in this review, consistent with the non-food scope stated in the manuscript title.

3. Starch-Based Materials for 3D Printing

From a (supra)molecular perspective, starch is a natural biopolymer composed primarily of amylose and amylopectin, two homopolymers of D-glucopyranose. These monomers are linked mainly through α -(1,4) glycosidic bonds with α -(1,6) linkages occurring mostly at the branch points of amylopectin. During the thermal process, which occurs either at the stage of starch extraction from its raw material or immediately prior to 3D printing, starch undergoes gelatinization, and the semicrystalline organization of the biopolymer is disrupted. From a phenomenological point of view, amylose chains leach into the aqueous phase and reorganize through intermolecular hydrogen bonding, forming a continuous gel network. The branched architecture of amylopectin interpenetrates this network, reinforcing its supramolecular structure and contributing to the mechanical stability of the resulting starch gel. This process imparts viscoelastic properties to the gelatinized starch, allowing it to respond to applied shear forces and exhibit shear-thinning behavior. Additionally, retrogradation of both homopolymers after gelatinization further enhances the mechanical strength of the starch gel, enabling it to effectively retain its shape after printing. Owing to these unique gel characteristics, starch demonstrates significant potential as an extrusion material for AM [24].

Practically speaking, extrusion-based AM relies on different mechanisms that govern how the material is deposited. Pneumatic extrusion is particularly suited for low-viscosity starch formulations and can drive multiple extrusion heads with variable flow rates. In screw-based extrusion, the material is loaded into a cartridge and transported by a motor-driven auger, with the starch paste extruded through a nozzle [25]. Piston-based extrusion, by contrast, offers precise control over the extrusion rate by adjusting motor speed, making it especially effective for highly viscous starch gels [26]. All of these mechanisms fall under the umbrella of direct ink writing (DIW), a room-temperature extrusion technique distinct from thermoplastic-based fused deposition modeling (FDM).

Table 4. Comparison of the main starch sources reported for extrusion-based deposition.

Starch Source	Typical Amylose Content	Gelatinization Temperature Range	Typical Rheological Behavior for Extrusion-Based 3DP	References
Maize or corn	25–28% (waxy variants < 5%; high-amylose cultivars up to 55–72%)	64–75 °C	Moderate viscosity and G' at conventional amylose levels. Strongly amylose-dependent.	[27]
Potato	0–25%	58–68 °C	Low gelatinization temperature and high native viscosity. Shear-thinning with good self-supporting behavior at 15–25% w/w concentration, giving G' in the order of 600–1050 Pa.	[24]
Cassava/tapioca	17–20%	64–74 °C	High native viscosity that can hinder smooth extrusion.	[28]
Rice	15–30%	70–80 °C	Generally, the best hot-extrusion printability among the common cereal starches, combining adequate flow stress with strong self-supporting behavior and smooth, continuous filament deposition.	[24]
Wheat	25–28%	57–66 °C	Printability strongly depends on the parent flour's gluten level. Starch from medium-gluten flour gives the most accurate, unbroken printed lines, indicating an intermediate, well-balanced viscosity/setback profile.	[29]
Pea/bean	30–40%	60–71 °C	Higher native amylose content than cereal starches gives stronger gel networks in principle, but native pea starch has low water-holding capacity, narrowing its printable formulation window relative to pre-gelled forms.	[30]

Beyond these conventional botanical sources (shown in Table 4), waste-derived starches recovered from agro-industrial by-products have recently attracted interest as low-cost, sustainable feedstocks for non-food 3D printing. Their valorization reduces the environmental burden and disposal cost associated with agro-industrial and food-processing residues, and contributes to a circular-economy approach to biomaterial sourcing. However, these starches typically present greater compositional variability than purified commercial starches, owing to residual protein, fiber, and ash content inherited from the source material, and generally require additional purification and/or plasticization steps to reach mechanical and rheological properties comparable to those of virgin starch before they can be reliably used in printable formulations [31,32].

For starch-based hydrogels, which typically exhibit high viscosity, piston-driven DIW is the preferred method, as it ensures consistent extrusion without substantial heating while preserving the shape fidelity of the deposited layer [33,34]. The effectiveness of piston-driven extrusion for starch gels is governed not only by the extrusion mechanisms themselves but also by the intrinsic physicochemical and rheological properties of the starch–water system. In particular, the amylose-to-amylopectin ratio critically influences viscosity, elasticity, and structural stability during and after extrusion [35]. Combined with the shear-thinning behavior of gelatinized starch, these properties make piston-driven DIW highly suitable for fabricating well-defined starch-based 3D structures (Figure 1).

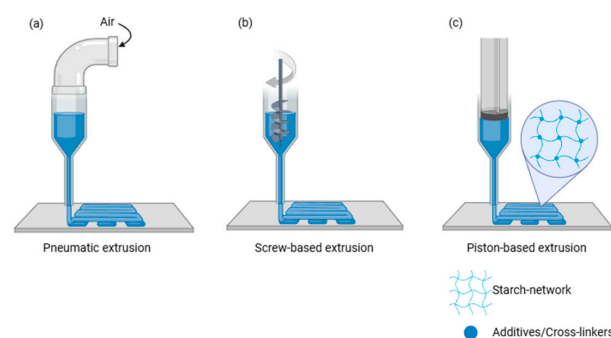


Figure 1. Pneumatic (a), screw-driven (b), and piston (c) mechanisms for extrusion of starch-based hydrogels in DIW printing (adapted from [36]).

For efficient extrusion, starch-based printable hydrogels must have a sufficiently low viscosity, while a high storage modulus (G') ensures the structural stability of the printed product. The rheological behavior of starch is largely dependent on the molecular structure of amylopectin. Longer amylopectin chains and higher molecular weights are generally correlated with increased viscosity and gel hardness, whereas shorter chains reduce viscosity and the consistency index (K value) [37,38]. Amylose content also plays a critical role, with amylose chains positively correlated with the flow behavior index (n value) of starch gels [38]. Starches with a higher amylose content exhibit greater viscosity and K value than those with lower amylose levels, which can complicate extrusion due to the increased viscosity [39]. Furthermore, amylose retrogradation during short-term storage enhances the elasticity of starch gels, which is crucial for shaping and hardening printed products by promoting stronger and more compact structures [40]. Globally, if $\tan \delta$, which is the ratio of G'' (loss modulus) to G' (storage modulus), also known as the damping factor, is lower than 1 ($G'' < G'$), the gel exhibits more solid-like behavior; if it is higher than 1 ($G'' > G'$), the gel behaves more like a viscous liquid [41].

The concentration of starch in the hydrogel also plays a crucial role. Higher starch concentrations primarily lead to an increase in solid content, which directly impacts the flow properties of the gel. Higher solid content facilitates shear-induced structural changes, which aids in the formation of 3D-printed products [42]. As solid content rises, viscosity

also increases due to intensified molecular interaction, mainly from the physical entanglement of polysaccharide chains [43]. Water mobility in the system is influenced by the starch concentration, highlighting the role of starch content in regulating water movement, as well as gel density, via larger H-bond interaction between water molecules and polymer. The concentration of starch also affects the mechanical strength of products. A higher biopolymer concentration promotes the formation of a compact gel network, resulting in increased elasticity. However, excessive mechanical strength and solid-like behavior can lead to fractured deposited lines, making extrusion difficult. For example, starch slurries with higher concentrations exhibit more solid-like behavior and poor fluidity, whereas lower concentration slurries display more liquid-like behavior and better fluidity, thus making extrusion easier but compromising shape stability during printing [44]. Starch-based products made from high-concentration starch form dense gel networks with thicker pore walls and smaller pore sizes, which enhance their structural integrity and extrudability [34]. It has also been observed that printed potato starch materials exhibited a dense network due to the high storage modulus and yield stress provided by high starch concentrations, ensuring greater printing precision and strength. Thus, high starch concentrations improve both the mechanical strength and viscosity of the gel, leading to more accurate and durable printed products. However, starch gel with high concentrations must be properly matched to the extrusion capacity, or they risk becoming too difficult to extrude through the nozzle [45].

During gelatinization, starch granules begin to swell upon reaching their gelling point, leading to a rapid increase in viscosity until the peak is reached (Figure 2). As heating continues, the granules break down, causing the viscosity to drop to what is known as the trough viscosity. When the starch gel cools, the rearrangement of amylose and amylopectin, also known as retrogradation, increases the viscosity once again, reaching the final viscosity [46,47]. Each stage of gelatinization is associated with distinct rheological properties, particularly regarding viscosity [48]. By controlling the degree of gelatinization, it is possible to enhance and regulate the 3D-printability of starch. Moreover, a higher degree of gelatinization improves starch degradation, as the process disrupts the starch structure and increases its proneness to enzymatic hydrolysis. Since degradation is an important quality metric for starch products, pre-gelatinization plays a key role in the quality of starch-based 3D-printed materials [49].

The breakdown efficiency of starch-based printed products depends largely on the extent of the ordered structure that remains intact in the 3D-printer barrel and the rearrangement during extrusion and deposition. As pre-gelatinization increases, most ordered structures, such as crystal domain and α -helices, are destroyed, leading to greater molecular mobility and hydrolytic decomposition [50]. Conversely, lower pre-gelatinization during printing results in more resistant starches with slower degradation that preserve the ordered structure [45]. In summary, the degree of pre-gelatinization significantly influences both printability and degradability by modulating the rheological properties and maintaining the ordered structure in starch-based 3D-printed products.

Beyond the qualitative description of shear-thinning and gel-like behavior, the literature provides several directly quantified benchmarks that separate successful from unsuccessful hot-extrusion 3D-printing outcomes. Perhaps the clearest quantitative threshold reported to date is that of Cui et al., who found that potato starch composite gels (with added sodium alginate and/or xanthan gum) achieving a geometric printing accuracy of $\geq 95\%$ corresponded to an apparent viscosity of 574–1120 Pa·s at a shear rate of 1 s^{-1} ; gels with an apparent viscosity below 574 Pa·s or above 1120 Pa·s at this shear rate were unsuccessfully printed, either collapsing under their own weight or failing to extrude as a continuous filament [43]. A comparable optimal apparent viscosity of approxi-

mately 620 Pa·s at 1 s^{-1} was independently reported for mashed potato gels. Zeng et al., working with corn and rice starch gels, similarly identified a preferable combination of storage modulus (G'), yield stress (τ_y), and flow stress (τ_f) of 1150–6909 Pa, 32–455 Pa, and 140–722 Pa, respectively, for successful hot-extrusion printing, corresponding to a starch concentration of 20% at 70–75 °C for corn starch and 15–20% at 75–85 °C for rice starch. Outside these concentration/temperature windows, gels were either too weak to self-support or too viscous to extrude smoothly [34]. Yang et al. reported that a potato starch-thickened lemon juice gel at 15 wt% starch, with an apparent viscosity of 8079.3 Pa·s (at a shear rate of 0.1 s^{-1}), G' of 4924.2 Pa, G'' of 760.8 Pa, and $\tan \delta$ of 0.155, produced the smoothest surface texture and the best geometric match to the target model; increasing the starch content to 17.5–20 wt% produced excessively viscous gels with a lower $\tan \delta$ that were difficult to extrude and prone to broken, discontinuous deposited lines, while decreasing it to 10–12.5 wt% produced gels with a higher $\tan \delta$ that over-extruded and failed to retain their printed shape [44]. Complementary structure–property data support these thresholds: Ji et al. reported K -index and n -index values, obtained by fitting the power-law model, of $K = 159.7\text{--}283.8 \text{ Pa}\cdot\text{s}^n$ for the best-performing wheat and corn starch gels, compared with $K = 122.2 \text{ Pa}\cdot\text{s}^n$ for the poorly performing sweet potato starch gel, whose printed center height collapsed [38]. Ahmadzadeh and Ubeyitogullari similarly showed that corn starch inks with a linear-region elastic modulus (G'_0) of 950–1500 Pa produced well-defined, near-spherical 3D-printed beads, whereas a lower-amylose starch ink with a G'_0 of only 120 Pa failed to retain a spherical shape after printing, consistent with the general benchmark proposed elsewhere that an elastic, gel-like material suitable for extrusion-based printing should exhibit $G' > 500 \text{ Pa}$, together with $\tan \delta < 0.2$ [39].

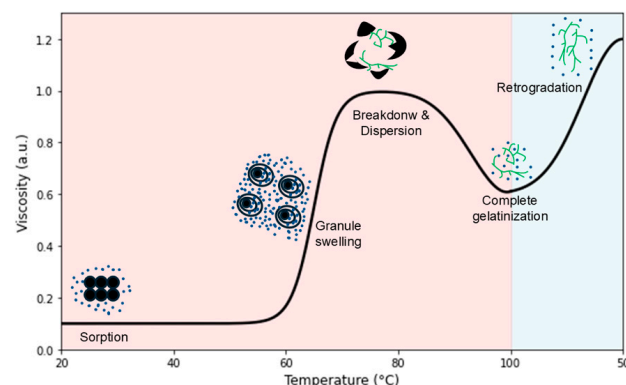


Figure 2. Evolution of the viscosity (and evidence of microstructural transitions) of starch systems as a function of the temperature.

4. Critical Technical Parameters and Their Optimization for 3D Printing Starch

The final performance of a 3D-printed starch-based construct is governed not only by the physicochemical, mechanical, rheological, and microstructural properties of the starch–gel formulation, but also by the careful optimization of processing parameters, including printing speed, extrusion flow rate, nozzle diameter, and printing temperature. These parameters are critical for enhancing the accuracy, resolution, and overall efficiency of the 3D-printing process [51].

The dimensional accuracy of starch-based 3D-printed objects depends strongly on printing speed, generally between 5 and 50 mm/s for DIW-compatible materials (Figure 3). Yang et al. proposed an equation (Equation (1)) to estimate the optimal speed, considering the extruded volume (V_{ex}), nozzle diameter (D_n), nozzle height (h_n), and nozzle movement speed (v_n) [44,52]. Printing speed must be balanced with material characteristics. Indeed,

excessive speed or pressure leads to filament overlap and deformation, while too low speed or pressure causes discontinuous extrusion and collapse.

$$V_{ex} = \frac{\pi}{4} v_n D_n^2 = \frac{\pi}{4} v_n h_n^2 \quad (1)$$

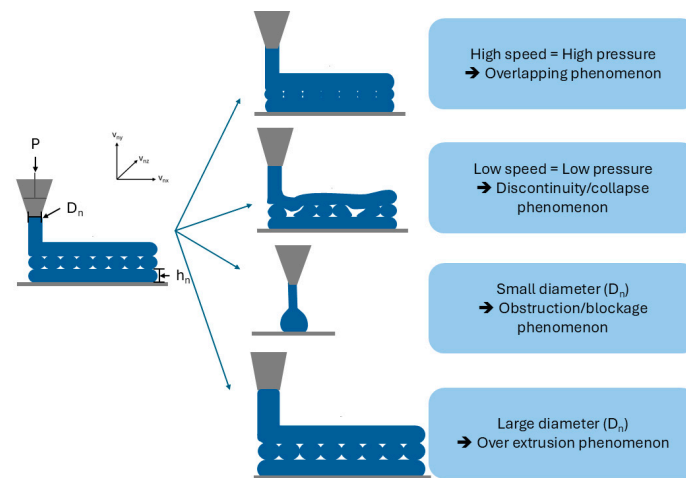


Figure 3. Key technical parameters influencing starch-based 3D-printing performance.

This equation expresses the nozzle movement speed (v_n , in mm/s) required to deposit a given extruded volume (V_{ex} , in mm³/s) uniformly, as a function of the nozzle diameter (D_n , in mm) and nozzle height (h_n , in mm), and it is the balance between these variables, together with the extrusion flow rate and pressure, that ultimately determines filament thickness, internal pore structure, and overall print quality. For a fixed extruded volume and nozzle diameter, a nozzle movement speed that is too low relative to the material output causes more material to accumulate per unit length than the nozzle geometry and layer height can accommodate. The excess material then spreads laterally and vertically, producing filament overlap, flattened or fused strands, and loss of shape fidelity in the deposited layer, consistent with the curling, stacking, and poor resolution reported under excessive extrusion pressure [53]. Conversely, when the nozzle movement speed is too high, or the material flow rate too low, relative to the extruded volume, insufficient material is delivered per unit length, and the deposited filament becomes discontinuous, thinner than the nozzle diameter, and highly porous, failing to bond adequately with the preceding layer, which compromises the mechanical integrity of the printed structure and, in the most severe cases, leads to structural collapse under the weight of subsequently deposited layers [54]. Nozzle geometry further constrains this balance: nozzle diameter directly affects shape, surface roughness, and extrusion uniformity, with too small a diameter risking clogging of the starch gel and too large a diameter causing over-extrusion and poor resolution [55], while a larger diameter also increases the volume delivered per unit time at a given speed, requiring a proportionally higher nozzle movement speed to avoid over-deposition; nozzle height, in turn, governs the vertical space available for the extrudate to settle without being compressed against the previous layer or, if excessive, without losing contact and continuity with it. In practice, this means that any change in nozzle geometry (diameter or height) or in extrusion pressure requires a corresponding adjustment of the nozzle movement speed, for a given extrusion flow rate, in order to remain within the printable window that avoids both overlapping/deformation and discontinuity/porosity/collapse.

Temperature was also assessed on the properties and printability of 3D-printed starch gels. Some analyses evidence that there is no correlation between printing temperature and gel viscosity during printing. However, an increase in temperature enhances material flowability and reduces the force required for extrusion. Additionally, higher temperatures

improve structural fidelity post-printing. Likewise, Zeng et al. examined the correlation between temperature, properties and structures, via experimental data comparisons, on a starch pre-gel that undergoes final gelation during printing [34]. Their findings indicate that gel elasticity increases up to a certain temperature threshold before decreasing. Higher temperatures lead to a more compact and homogeneous network structure. Finally, optimal printability is achieved at a temperature close to the gelatinization point.

5. Improvement of the Stability of Starch-Based Materials

5.1. Chemical Modification

The modification of starch, through the introduction of specific functional groups (including carboxyl, acetyl, and hydroxypropyl) onto the hydroxyl moieties, is known as a strategy to modulate its printability. The scientific literature on this topic remains limited, with few precise correlations established between the molecular structure of these modified starches and their printability, highlighting a clear knowledge gap that warrants further investigation. Among all the modification options, which also include esterification, etherification, and even hydrolysis, only the oxidation and the cross-linking have been more documented.

Oxidation, most commonly achieved through O₃ (ozone) treatment but also reported using sodium hypochlorite, hydrogen peroxide, and periodate oxidation [56], has been found to greatly enhance the rheological properties and functionality of starch and alter its structure by cleaving glycosidic bonds within amylopectin and amylose molecules and replacing hydroxyl groups with carbonyl and carboxyl groups. These structural changes enhance the rheological properties and functional performance of starch, as reported by Maniglia et al. [28]. Their findings revealed that starch formulation prepared using starch ozonated for 30 min exhibited superior printability and produced high-resolution products compared to native cassava starch. The improved printability is attributed to oxidation, which encourages the development of an organized network through molecular charge rearrangement and modifications in size distribution. Zheng et al. reported a unique strategy integrating the use of a printable oxidized starch-based hydrogel cross-linked with calcium ions to make microporous hemostatic wound dressings [10]. Although O₃ processing remains the most extensively documented route, a hypochlorite-oxidized starch system has also been successfully applied to DIW of hydrogel with exceptional printability properties [57].

It was found that cross-linking also improves the printability of gels by modifying the viscoelastic properties. On the one hand, an example of ionic cross-linking is proposed by Yang et al. They produced hydrogels through a straightforward process involving gelatinization and cross-linking in a calcium chloride solution, showing a positive dependence between rheological properties and the amount of Ca²⁺ ions as a cross-linker [58]. On the other hand, an example of covalent cross-linking is proposed by Zhu et al. They produced hydrogels by mixing chitosan and oxidized starch, whose oxidation was controlled to produce active carbonyls, to perform a Schiff-base reaction as a cross-linking point, thus improving their mechanical properties and printability [59].

5.2. Physical Modification

Physical modification techniques, such as dry-heating treatment (DHT), high-pressure processing (HPP), ultrasound-assisted (UA), microwave-assisted (μW), radio frequency (RF), and pulsed electric fields (PEFs), have emerged as innovative methods for tailoring starch properties. These advanced approaches, combined with the ability to modify starch's microstructure without chemical alteration, offer promising results for achieving specific functional characteristics [53,60].

Dry-heat treatment (DHT) is a versatile, straightforward, safe, and environmentally friendly physical method for modifying the structural and physicochemical properties of starch without by-products. This method effectively reduces the swelling capacity of starch while significantly altering its gelatinization, viscoelasticity, and gel properties [61]. Hydrogels produced with starch having undergone a DHT demonstrated shear-thinning behavior and rheological parameters suitable for additive manufacturing. Indeed, Sponchiado et al. showed that the increase in storage modulus indicated that DHT enhances gel formation, resulting in greater rigidity and improved recovery ability under stress [62]. Additionally, the consistently low $\tan \delta$ value (less than 1) highlights the predominantly solid-like behavior of the system.

High-pressure processing (HPP) is a non-thermal method that applies pressures between 100 and 600 MPa to starches for a few minutes at relatively low temperature (typically between 25 and 50 °C). This technique effectively inactivates microorganisms while inducing structural changes in starch granules, including alterations in crystallinity, swelling behavior, and hydration properties [63,64]. These structural changes then affect the functional properties of starch, increasing its resistance to heat and shear while improving its gelling capabilities. The research of Larrea-Wachtendorff revealed that potato starch hydrogels produced through HPP exhibit gel-like characteristics, represented by high viscosity, pronounced shear-thinning and elastic behavior, and robust mechanical properties [65]. These attributes can be tailored to meet the requirements of various applications in direct ink writing.

Ultrasound-assisted (UA) modification is another method to modify starch, utilizing high-frequency mechanical waves (from 16 kHz to 10 MHz) to reorganize polymers. This technique is typically applied to starch suspensions, where the cavitation effect plays a key role in inducing structural changes on the granule through a partial depolymerization, which can seriously impact the viscosity depending on the conditions used [66]. However, this enhances the flexural strength and dynamic mechanical properties of the sample [67]. According to Xu et al., the application of UA as a pretreatment method notably enhanced the 3D-printing quality of a wheat starch–papaya system [68].

Radio frequency (RF) electromagnetic wave treatments utilize dielectric heating to generate volumetric heating through dipole rotation and ionic conduction mechanisms, typically operating at frequencies between 10 and 300 MHz. Compared with microwave heating (300 MHz–300 GHz), RF treatment operates at lower frequencies, resulting in greater penetration depth and more uniform heating within the treated material. The process involves dipole rotation and ion migration within the starch material, which ultimately modifies its physicochemical, rheological, and gelling properties [69]. A group of researchers illustrated that applying moderate RF treatment to a starch–water system enhanced its extrudability during printing, while maintaining adequate viscosity and structural integrity after deposition, ensuring the printed product retained its desired shape [70].

Microwave-assisted (μ W) modification consists of exposing starch to electromagnetic wave energy for a defined duration. The starch soaks up the microwave radiation, aligning with the electric field and initiating heat through molecular dipole rotation and collision with other molecules. This mechanism increases water loss, leading to elevated internal pressure within the granules, causing their structural collapse [71]. μ W treatment effectively enhances the functional properties of starch, increasing its resistance to heat and shear while upgrading its thickening and gelling capabilities [60]. Guo et al. reported that microwave-assisted heating of buckwheat starch led to weakened hydrogen bonding and enhanced plasticity within the starch–pectin gel system [72]. The resulting Ca^{2+} -cross-linked gel

demonstrated improved printability, facilitating smoother extrusion and higher precision during 3D printing.

Pulsed electric field (PEF) alteration of starch utilizes electric pulses with elevated voltage (1–80 kV/cm) applied to starch suspensions for tiny periods. This treatment induces both physical and chemical modification in starch molecules, including cross-link formation, the fragmentation of starch granules into smaller ones, and a relative reduction in the crystallinity rate, and stabilizes starch emulsions more effectively. Starch modified through PEF demonstrates enhanced functional properties, such as increased viscosity, improved stability, and greater resistance to enzymatic degradation [60]. Research carried out by the team of Maniglia et al. focused on the effects of PEF treatment on wheat and cassava starches under different electric field forces and energy supplies [73]. Their findings revealed that PEF-treated wheat starch demonstrated superior 3D-printing performance, such as increased hardness, reduced adhesiveness, and a smoother surface, compared to native wheat starch. Conversely, PEF treatment had no notable impact on the properties of cassava starch, showing results comparable to its native form. Therefore, modifications by PEF can be of interest but dependent on the botanical source.

Table 5 presents the different physical modification strategies, their respective benefits, and their major identified drawbacks.

Table 5. Advantages and limitations of starch physical-modification technologies.

Technology Type	Advantages	Disadvantages	Applications	References
Dry-heating treatment	High safety, improved flow and viscosity, functional enhancement	Time-consuming, browning risk, limited modification	High-viscosity, heat-stable starch	[74]
High-pressure processing	Non-thermal modification, gelatinization without swelling, uniformity	Extremely high equipment cost, batch processing limitations, starch type sensitivity	High-value product, unique texture gels	[75]
Ultrasound-assisted modification	Molecular weight reduction, increased reactivity, flexibility	Not purely physical, scale-up difficulties, low impact on crystalline regions	Porous starch preparation, enzymatic pretreatment	[76]
Radio frequency	Deep penetration, selective heating, energy efficient	Expensive and bulky equipment, risk arcing, less research	Bulk powder processing, drying/sterilization	[77]
Microwave-assisted modification	Extremely fast heating, penetrative heating, relatively low cost	Non-uniform heating, hard to control, moisture sensitivity	Rapid drying, lab-scale modification	[78]
Pulsed electric field	Structural rearrangement, low energy consumption	Only fluids/slurries, conductivity limits, industrial bottlenecks	Starch milk modification, functional fluid formulation	[79]

While DHT, HPP, UA modification, RF treatment, μ W modification, and PEF treatment each confer measurable improvements in starch rheological performance and printability (Table 5), their industrial adoption should be weighed against the intrinsic economic advantage of native starch, which is abundant, inexpensive, and already produced at very large scales using simple, continuous processing lines. By contrast, several of these physical-modification routes remain constrained by high capital cost; batch-wise processing, rather than continuous processing; and elevated energy demand. For instance, non-thermal high-pressure and pulsed-field technologies require specialized, application-specific equipment and technical expertise that are not yet fully integrated into conventional starch-processing lines, thus limiting their uptake beyond pilot- or laboratory-scale demonstration [80]. This is particularly evident for PEF, for which industrial uptake remains low primarily because of the shortage of robust, cost-effective, continuously operating electrical systems capable of the field-strength consistency required for reliable, short-payback-period operation [81]. Similar equipment-cost and batch-processing limitations apply to HPP and RF treatments, as already summarized in Table 5, whereas UA and μ W modifications,

although comparatively low-cost at the laboratory scale, face their own scale-up difficulties (UA) or heating-uniformity control issues (μW). These constraints contrast with the well-established, high-throughput, comparatively low-cost manufacturing base of conventional AM thermoplastics such as ABS and PLA (Table 1), whose life-cycle energy and cost profile benefit from decades of process optimization and infrastructure investment, even though ABS and PLA production and printing themselves carry a non-negligible environmental footprint, driven largely by the electrical energy consumed during filament fabrication, the printing process itself, and post-processing/testing steps [82]. Altogether, this suggests that, at present, the energy- and capital-intensive physical modification routes for starch are unlikely to be economically competitive with conventional thermoplastics for commodity-scale, non-food additive manufacturing, and are more realistically positioned for high-value, lower-volume applications where the functional gains in printability, mechanical performance, or biocompatibility can offset the additional processing cost. Continued progress in continuous-flow reactor design, modular/scalable pulse-power and pressure systems, and process intensification will be needed before these modification routes can be considered for larger-scale, cost-sensitive non-food AM applications.

5.3. Biological Modification

Starch printability can also be tailored through biological approaches, encompassing both the enzymatic modification of extracted starch and the genetic modification or selective breeding of the starch-producing plant itself. These two routes act at different stages of the value chain but both ultimately act on the same structural determinants of printability, as discussed before: the amylose-to-amylopectin ratio, chain length distribution, and granule/molecular order.

Enzymatic modification exploits the specificity of starch-active enzymes to selectively cleave or form glycosidic bonds within the starch molecule, thereby reshaping its molecular weight distribution and fine structure without recourse to chemical reagents [83]. Endo-acting enzymes, such as α -amylase, cleave internal α -(1,4) glycosidic bonds within amylose and amylopectin chains, while debranching enzymes such as isoamylase and pullulanase specifically hydrolyze the α -(1,6) branch-point linkages of amylopectin, releasing linear, short-chain glucans [84]. This debranching reduces the degree of branching and typically increases the propensity of the resulting linear chains to re-associate upon cooling, producing thermoreversible gels of markedly higher gel strength than their native, fully branched counterparts [84]. Conversely, transglucosylating enzymes can introduce new glycosidic linkages, generating branched or cyclic structures with reduced viscosity and altered gelation behavior. The degree of enzymatic treatment provides a further tuning parameter: Park et al. demonstrated that progressively increasing the extent of enzymatic modification of rice starch produced graded changes in molecular weight, crystallinity, and pasting behavior, indicating that reaction time and enzyme loading can be used as a practical lever to target a specific rheological window [85]. For 3D-printing applications, this enzymatic tunability is particularly relevant where a native starch's viscosity or gelation temperature falls outside the printable window: partial debranching can be used to lower viscosity and improve extrudability, while controlled retrogradation of the resulting short linear chains can be exploited to enhance post-printing shape retention.

Genetic modification and selective breeding act further upstream, altering the activity of the enzymes of the starch biosynthetic pathway itself, so as to obtain cultivars whose native starch already possesses a molecular architecture favorable for a target application, without requiring further post-extraction processing. Conventional selective breeding has long been used to generate high-amylose or waxy cultivars, and more recent work has extended this principle using targeted gene editing. Jayarathna et al. used CRISPR/Cas9 to

stack mutations in the genes of potato, showing that combining these mutations restored an ordered granule morphology while producing amylopectin chain-length distributions and gelatinization temperatures distinct from both the wild-type and single-gene-edited lines, illustrating the fine control that multi-gene editing can offer over starch molecular architecture [86]. In a related study, the same starch synthesis gene mutations were shown to alter the morphological, compositional, and functional properties of the resulting potato starch sufficiently to affect its performance in film-forming applications, with selected mutant lines retaining oxygen-barrier properties comparable to the wild-type despite substantial differences in amylose content [87]. The relevance of this genetic route to printability specifically was directly demonstrated by Shahbazi et al., who compared eight starch varieties of normal and waxy genotype under extrusion-based 3D printing: normal-type starches consistently produced well-defined, dimensionally stable printed structures, whereas waxy starches failed to maintain their shape after printing, providing direct evidence that genotype-driven amylose content is a first-order determinant of printing outcome, independent of any post-extraction modification [88].

Taken together, enzymatic and genetic modification represent complementary biological levers for tailoring starch printability: the former offers rapid, post-extraction fine-tuning of an existing starch batch, while the latter offers a means of obtaining starches with intrinsically favorable properties “at the source”, potentially reducing the need for downstream chemical or physical modification. Both routes act on the same underlying structural determinants as the other additive-based strategies.

5.4. Integration of Specific Additives

In starch-based gel systems, achieving optimal 3D-printing performance typically requires more than the native polymer alone. Functional additives are frequently employed to modulate rheological properties and address challenges inherent to hydrogel formulation, thereby enabling precise extrusion and structural fidelity during printing (Figure 4). Most 3D-printing materials exhibit shear-thinning behavior for effective extrusion, but natural starch gels lack sufficient shape retention, hindering the production of complex tridimensional structures and compromising printing performance. To overcome these limitations, additives are introduced to enhance the printability and overall quality of the printed products. Commonly used additives include polysaccharides and/or carbohydrates (such as xanthan gum, cellulose, κ -carrageenan, agar, pectin, alginate, and chitosan), proteins (including gelatin, collagen, and gluten), and inorganic salts [53,89].

Polysaccharides, a group of biologically active natural compounds with high molecular weight, have been extensively studied for their ability to enhance/modify the gel properties and microstructure of native starch. For example, Liu et al. proved that incorporating xanthan gum and κ -carrageenan in starch-based formulations optimized their gelation temperature, increased viscosity and yield stress, upgraded thixotropic properties, and minimized the time-dependent modulus [90]. Another study investigated the influence of various biopolymers, including guar gum, sodium carboxymethyl cellulose, and gum arabic, on the rheological properties, microstructure, and printability of rice starch gels. The findings revealed that incorporating these carbohydrates notably improved the printing performance of the hydrogels by increasing the viscosity and storage modulus, while promoting the formation of more compact structures [91]. Arabinoxylans and chitosan have also been studied as additives in starch-based gel systems for 3D printing [92,93].

Proteins play a crucial role in shaping the structure and viscoelastic properties of gel components. Integrating proteins is an effective approach for modifying starch. Through non-covalent interactions, such as electrostatic forces and hydrogen bonding, proteins interact with starch to enhance the functional attributes of hydrogels, including their

thickening and gelation abilities [94]. It was demonstrated that incorporating pea proteins facilitates cross-linking among starch granules, thereby enhancing the overall degree of cross-linking in potato starch-based materials used for 3D printing [95]. Moreover, hybrid systems containing proteins enhance gel viscoelasticity by leveraging potential hydrophobic interactions and sulfhydryl–disulfide-bond switches [96].

In addition to the aforementioned carbohydrates and proteins, mineral salts may play a role in the formation of printable gels. Indeed, salts such as NaF, NaCl, K₂SO₄, KNO₃, KSCN, and LiCl have been studied by Wang et al. on the rheological properties and strength of gels [97]. Salting-out ions (e.g., F[−] and SO₄^{2−}) strengthened the three-dimensional network of potato starch gel through two distinct, complementary mechanisms rather than by fully preventing gelatinization. During the initial heating phase, these ions protect starch–starch hydrogen bonding within the granule, which raises the gelatinization temperature and reduces swelling power and solubility. This only partially restricts granule disruption, leaving more intact granular remnants that reinforce the paste network, much like filler particles, while still permitting sufficient amylose leaching to form a continuous printable gel. Separately, during subsequent cooling and storage, the same protective effect on starch–starch hydrogen bonding also promotes a stronger retrogradation tendency, further increasing gel strength. In contrast, salting-in ions had the opposite effects, weakening gel structure and rheological properties [97].

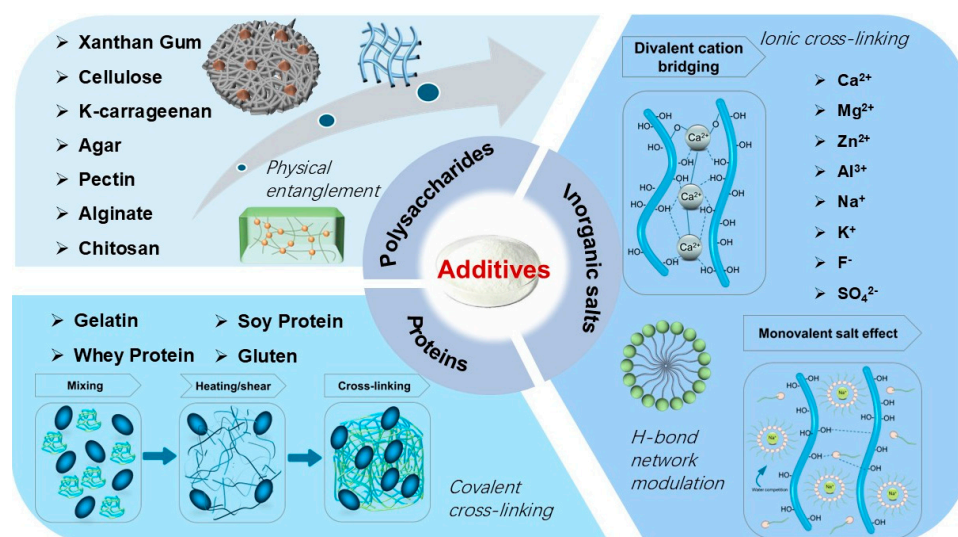


Figure 4. Schematic illustration of the principal interaction and cross-linking mechanisms between starch and functional additives in printable hydrogel systems. These four mechanisms differ substantially in chemical nature, bond strength, and reversibility and should not be interpreted as equivalent. Polysaccharide additives reinforce the gel network primarily through physical entanglement, further stabilized by hydrogen bonding between hydroxyl groups. Protein additives undergo a sequential mixing, heat/shear-induced unfolding, and cross-linking process that can involve genuine covalent bond formation. Divalent and trivalent cations act through ionic cross-linking. Monovalent ions do not bridge chains directly but instead modulate the existing hydrogen-bonding network.

6. Beyond Food: Emerging Non-Food Applications of 3D-Printed Starch-Based Materials

Table 6 summarizes selected applications of starch-based materials in 3D printing. Beyond the food sector, particularly for the design of personalized foods and edible formulations, starch has also demonstrated significant potential in non-food applications, including biomedical devices and sustainable packaging solutions.

Table 6. Overview of non-food applications of starch-based materials in 3D printing.

Applications	Starch Type	Specific Applications	References
Biomedical	Bio-ink	Wheat starch Bio-ink contained 5.0 <i>w/v</i> % gelatin–Ph and 10 U/mL horseradish peroxidase (HRP), with 16.7 <i>w/w</i> % starch and 10 mM H ₂ O ₂ as the support material. After printing, cell viability reached >80%, exhibiting an elongated morphology and proliferative capacity.	[98]
	Tissue scaffold	Normal corn starch (the amylose content of this starch is 27%, and its weight-average molecular weight (Mw) is 7.03×10^7 kDa) Cell scaffolds were prepared by double methacrylation of common corn starch and chitosan. The UV-cured scaffolds exhibited tunable compressive strength (150–200 kPa) and deformability (50–60%), achieving a balance between mechanical properties and tissue safety.	[99]
	Soft-tissue repair	Corn starch (high-amylose cornstarch, practical grade, S4180) with an average molecular mass of 692.7 g/mol and 27% amylose A novel shear-thinning and self-healing hydrogel based on gelatin, starch, and halloysite nanotubes (G-S-H) has been developed for 3D printing of soft tissues. This hydrogel exhibited excellent mechanical properties, degradation rate, and biocompatibility.	[100]
	Wound dressing	Corn starch (Ph. Eur. grade, amylopectin/amylose ratio 74/26) High-starch-content thermoplastic filaments (TPS) were prepared for FDM 3D printing of scaffolds. These scaffolds exhibited the following characteristics: ability to absorb simulated exudate (achieving 35% hydration within 7 days).	[19]
Drug delivery	Targeted delivery	Pregel corn starch (Anova) A novel pH-sensitive delivery system based on starch and alginate/pectin matrix was developed. Probiotics were encapsulated in a starch gel core, and the encapsulated bacteria exhibited a high survival rate of 93.2%.	[101]
	Atopic dermatitis	Aldehyde-modified rice starch A 3D-printed hydrogel composed of gelatin and dialdehyde starch (DAS) has been developed, which can encapsulate and release hydrocortisone (HC).	[102]
Green packaging	Plastic wrap	Rice starch (RS, moisture 9.5%, <i>w/w</i> ; protein $\leq 1\%$, and ash $\leq 1\%$, db) The preparation of modified starch–ferulic acid composite materials can inhibit the growth of microorganisms, thereby extending the shelf life of products.	[103]
	Intelligent labels	Cassava starch A green 3D-printing technology for smart labels has been developed, which involves adding gallic acid (GA) to a blueberry anthocyanin (BA) solution to enhance the color development of the pigment. The printing formulation exhibits shear-thinning properties and a yield strength in the range of 500–600 Pa.	[104]

6.1. Biomedical Applications

The most popular application combining starch and additive manufacturing is the establishment of controlled release systems (Figure 5). 3D printing addresses the limitations of conventional systems, such as low encapsulation performance, poor stability, and short half-life [105]. Chatzitaki et al. described the engineering of starch-based soft delivery forms of isoniazid employing pressure-assisted micro-syringe 3DP. The printed tablets had a considerably porous microstructure that enhanced water absorption and isoniazid diffusion in simulated gastric fluid, resulting in complete drug release within 45 min [106]. The versatile nature of starch gels and three-dimensional printers was demonstrated by Ahmadzadeh et al. by increasing the stability of lutein, a bioactive molecule that is poorly soluble in water, via encapsulation in gel composed of starch and ethyl cellulose, using a 3D printer whose nozzles are in a coaxial position [107]. This 3D-printed dual-layer system (starch/ethyl-cellulose) offers a novel technological platform for encapsulating bioactive compounds.

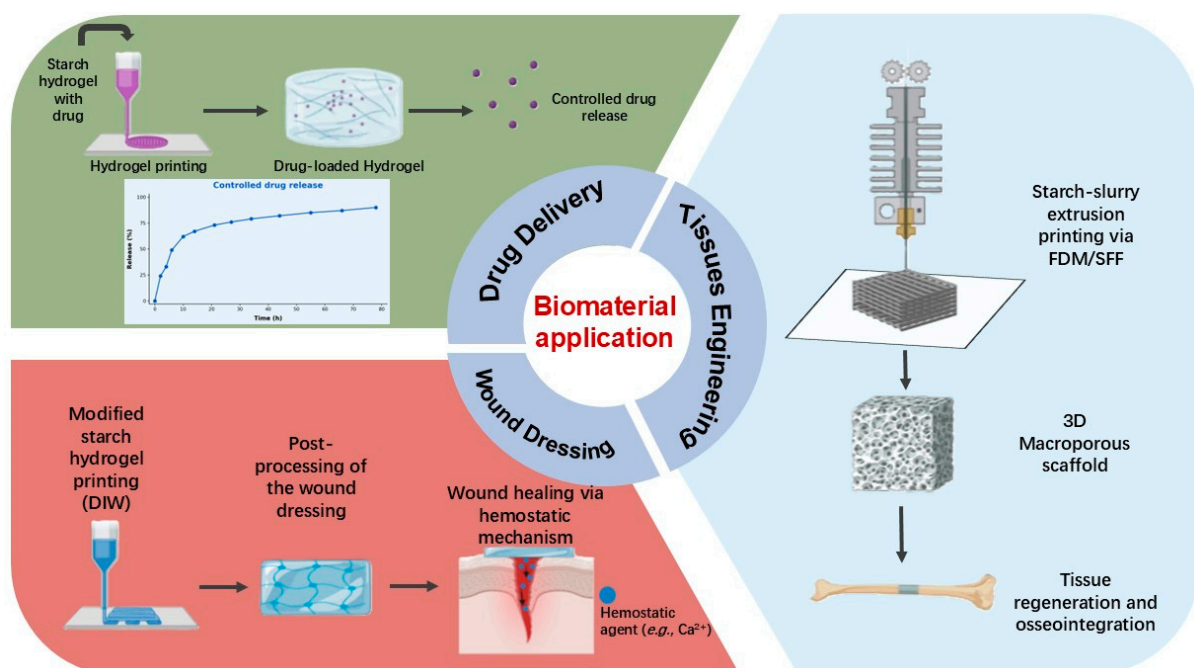


Figure 5. Schematic overview of three core biomedical applications of starch-based 3D printing. Drug-loaded starch hydrogels can be printed into porous structures, enabling controlled drug release. Modified starch hydrogels printed via DIW can be post-processed into wound dressings that promote hemostasis through the release of a cross-linking agent (e.g., Ca^{2+}) at the wound site. Starch slurry extruded via FDM/SFF yields 3D macroporous scaffolds whose interconnected pore architecture supports tissue regeneration and osseointegration. Together, these routes illustrate the versatility of starch-based inks across extrusion and micro-dispensing 3D-printing modalities for biomedical applications.

Another well-known application is wound dressing and matrix scaffolding (e.g., for cell growth or mimicking human tissues) thanks to the high biocompatibility of starch-based hydrogels. A green hot-extrusion method was used by Zheng et al. to create a 3D-printed oxidized starch hydrogel infused with calcium ions. The hydrogel demonstrated strong water absorption, enhanced gel strength, and controlled Ca^{2+} release, effectively promoting hemostasis *in vitro* [10]. *In vivo* studies verified its rapid blood-clotting capability and improved wound healing. This affordable and versatile formulation presents a promising option for wound care, ensuring quick hemostasis and recovery. Recently, a group of researchers developed a bio-ink based on arrowroot starch and gellan gum that can hold

animal cells [108]. The physicochemical properties of the printed matrix were evaluated to assess cell adhesion and growth. The results confirmed that the starch/gellan gum system effectively supports cell attachment and proliferation, as well as high viability. Similarly, Shyam et al. conducted a study on developing a starch and gelatin composite as a potential biomaterial for cardiac tissue engineering. Their findings revealed that gelatin concentration significantly influenced the rheological properties and printability of the biomaterial. Moreover, the scaffold demonstrated excellent biological activity, supporting cell adhesion and enhancing cell proliferation [21].

Starch has also been used as a functional excipient across other 3D-printing modalities for oral dosage forms. In powder-bed-based printing, partially pregelatinized starch has been used, together with lactose, as the primary binder for developing flexible tablet platforms suitable for early-phase clinical trials, where both hydrophilic and hydrophobic active pharmaceutical ingredients needed to be accommodated across a wide range of drug loadings and tablet masses [109]. A related study further showed that the particle size distribution of the lactose–starch blend critically governs powder wettability and printing-ink penetration and, hence, the resulting tablet hardness and dissolution behavior [110]. More recently, Bashetty et al. demonstrated that starch alone can serve as the sole matrix former in selective laser-sintering (SLS) 3D printing, yielding mechanically robust, amorphized indomethacin tablets with markedly faster and more complete drug release than the crystalline drug, illustrating an excipient-minimal, sustainable route to SLS-printed oral dosage forms [111]. Taken together, these studies show that starch's binding, gelling, and thermal behavior can be exploited across both extrusion-based and powder-bed 3D-printing platforms for pharmaceutical manufacturing.

6.2. Industrial Biodegradable Applications

In the chemical industry, starch is increasingly explored as a functional component and non-biomedical composite filaments for FDM, directly addressing the chemical and material industry's search for bio-based alternatives to petroleum-derived thermoplastics. Haryńska et al. developed a fully bio-based FDM filament combining PLA with potato-derived thermoplastic starch (TPS), demonstrating remarkable printability, enhanced hydrolytic degradability, and substantially greater compostability compared to conventional PLA filament [112]. Building on similar TPS/PLA blending strategies, Ju et al. incorporated poly(butylene adipate-co-terephthalate) (PBAT) and an epoxide-based chain extender into a TPS/PLA/PBAT ternary filament, achieving a 113% increase in elongation at break and a 190% increase in impact strength relative to the unmodified blend, while retaining full biodegradability [113]. Beyond PLA-based systems, Esper et al. showed that blending starch with polyhydroxybutyrate (PHB) markedly improved the flexibility and homogeneity of FDM filaments, mitigating the intrinsic brittleness and poor processability of pure PHB [114]. Collectively, these studies demonstrate that starch can serve as a versatile, low-cost bio-based modifier across multiple thermoplastic matrices (PLA, PBAT, and PHB) for chemical industry applications like FDM filament production.

6.3. Emerging Non-Food Applications (Electronic Devices, Intelligent Materials, and Responsive Materials)

Significant advancements have recently been achieved in developing hydrogels with enhanced mechanical strength and flexibility. Additionally, new functionalities, such as electrical conductivity and multi-stimuli responsiveness, have been incorporated into hydrogel designs. These improvements have broadened the scope of functional hydrogels, enabling their use in diverse fields, including bioelectronics, intelligent materials, and sensor technology (Figure 6) [115].

One of the emerging applications in the use of 3D printers and starch is the development of electronic devices. Bacalzo et al. developed a starch-based aqueous gold nanoparticle (AuNP) formulation for inkjet printing. This formulation enables the formation of conductive films at low temperatures ($<200\text{ }^{\circ}\text{C}$) with a low resistance [23]. The synthesis process involved heating a starch solution in NaOH to induce hydrolysis, which subsequently activated the reduction of Au^{3+} to Au^0 . Some hydrolyzed starch molecules acted as stabilizers, regulating nanoparticle growth. This eco-friendly, water-based formulation offers a versatile solution for printing conductive patterns on various substrates. Another hydrogel tailored for printed electronic technology was developed by Willfahrt et al. They developed a novel hydrogel by modifying corn starch with citric acid through melt-blending [116]. The optimal formulation, containing 10% citric acid by weight, exhibited an ionic conductivity of $2.30 \pm 0.07\text{ mS}\cdot\text{cm}^{-1}$, along with suitable rheological properties, making it well suited for supercapacitor printing. Similarly, fully bio-based hydrogels with excellent printability, high toughness, and self-healing capabilities were developed using starch and natural rubber latex through a straightforward heating process, during which an in situ silver mirror reaction resulted in the formation of conductive hydrogel suitable for durable wearable sensors [115]. Starch-based inks have also been directly 3D-printed into functional devices for bioelectricity generation and bioelectronics. Wang et al. developed a 3D-printed bioelectrode for a starch-fed microbial fuel cell (MFC), in which a synthetic microbial consortium was directly embedded in a conductive bioink and extruded through a 3D printer into a microporous bioelectrode; the resulting 3D-printed starch MFC showed markedly lower charge-transfer resistance and higher power output than conventionally assembled electrodes, directly converting starch into bioelectricity [117].

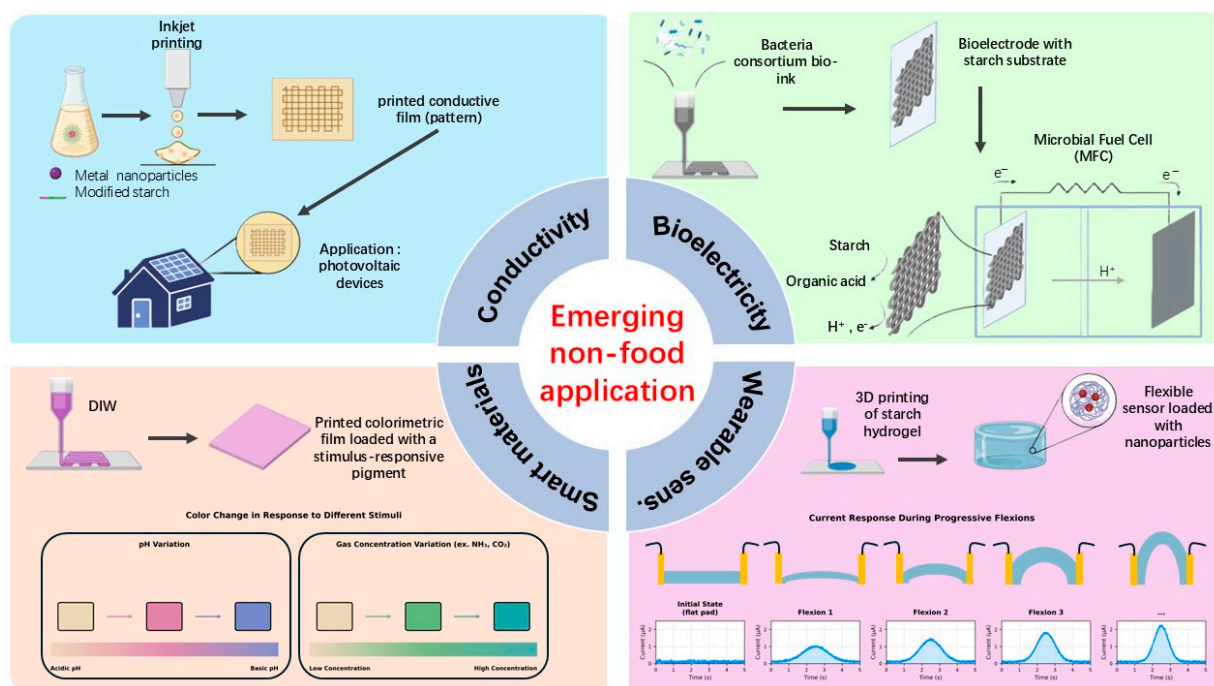


Figure 6. Schematic overview of four emerging non-food application domains for 3D-printed starch-based materials. Modified starch combined with metal nanoparticles can be inkjet-printed into conductive film patterns for photovoltaic devices. Starch substrates printed with a bacterial-consortium bio-ink form bioelectrodes for microbial fuel cells, generating bioelectricity (adapted from [117]). Starch hydrogels printed via DIW and loaded with stimulus-responsive pigments yield colorimetric films that change color in response to stimuli. Finally, 3D-printed starch hydrogels loaded with nanoparticles can be fabricated into flexible sensors capable of generating a current response under mechanical flexion.

In parallel with the development of electronic devices and artificial intelligence, so-called intelligent or smart packaging is gaining popularity and interest [118]. As an example, a 3D-printed smart colorimetric film with high sensitivity was developed by embedding anthocyanin and phycocyanin as a color indicator and using chondroitin sulfate as both co-pigment and carrier within a potato matrix to visualize food freshness [22]. The printed film accurately detected food freshness by simulating nitrogen compound release with ammonia and was paired with a smartphone app for digital monitoring of color changes through RGB value analysis. Su et al. designed a hydrogel based on starch and alginate that is capable of, in addition to being conductive, remolding itself to complex external conditions thanks to physical interactions between the polymers and Ca^{2+} ions present [119]. Due to the properties of this hydrogel, they have engineered a sensor adapted for monitoring different movements and vibrations of vocal cords. However, hydrogel can freeze when temperatures drop below 0 °C. To counter this problem, a group of researchers have developed a new type of hydrogel that is 3D-printable and has anti-freeze properties, while also retaining its mechanical properties. Yang et al. synthesized that hydrogel via gelation after gelatinization of starch in 3M CaCl_2 solution at subzero temperatures [58].

7. Future Perspectives

The rapid evolution of starch-based hydrogels is fueled by their unique properties and diverse applications, as advances in synthesis increasingly combine physical or chemical modifications with cross-linking strategies to enhance their functionality. Research has delved into smart or tunable hydrogels and those designed for 3D encapsulation. Ongoing studies and further exploration are crucial for the continued advancement of hydrogel technology, especially since there is a strong correlation between the design and the compounds used and their final characteristics. For the future, the development of a new hydrogel with a focus on rheological properties is needed to match with 3D-printing technology [120].

Starch-based hydrogels have shown great potential for application in 3D-printing food manufacturing and biomedical engineering due to their excellent biocompatibility, biodegradability, and cost-effectiveness. Although existing physical and chemical modification and cross-linking strategies have significantly improved the mechanical strength and molding accuracy of starch-based materials, further exploration is needed in the following key areas to achieve their widespread application in complex environments.

7.1. Rheology-Based Formulation Design and Precision Printing

The preparation of starch-based formulations lacks systematic research on the quantitative relationship between the material's microstructure and printing behavior. There is a close correlation between the design and modification of starch hydrogels and their final properties. Therefore, future research needs to develop formulations that can precisely match the extrudability, shear-thinning behavior, and shape fidelity of materials in 3D printing technology. Precise design can be achieved by establishing predictive models between rheological parameters (such as storage modulus and yield stress) and printing-process parameters (such as nozzle diameter and extrusion pressure).

Starch set aside, concrete examples from other bio-based additive manufacturing polymers illustrate how digital and predictive processing-parameter optimization can be used to maximize structural integrity, offering a template that could be transposed to starch-based formulations. Rilling et al. combined topological optimization with a tailored infill density fraction to predict and maximize the ultimate strength and Young's modulus of additively manufactured porous PLA parts, demonstrating that a computationally guided, density-graded infill design can substantially increase load-carrying capacity without a proportional increase in material use [121]. A directly analogous data-driven strategy

has recently been demonstrated for hydrogel DIW, the printing modality most relevant to starch-based inks discussed throughout this review. Jeong et al. built a rheology-printability database of 150 3D-printed hydrogels, incorporating nonlinear viscoelastic descriptors, such as large-amplitude oscillatory shear measurements, and trained a machine-learning model that predicts printability from rheological inputs with a reported error margin under 10%, thereby reducing the trial-and-error burden traditionally associated with DIW ink formulation [122]. With these two examples, at the level of solid thermoplastics (PLA) and of hydrogel inks (DIW), respectively, we can see how coupling rheological/mechanical databases with predictive or topology-optimization algorithms can move formulation design from empirical trial-and-error toward a quantitatively guided process. We argue that a similar predictive, data-driven framework linking starch-formulation variables (amylose/amylopectin ratio, solid content, and degree of pre-gelatinization) and rheological descriptors (storage modulus and yield stress) to printing outcomes (shape fidelity and mechanical strength) represents a promising and currently underexploited direction for starch-based additive manufacturing.

7.2. In-Depth Development of Intelligent and 4D-Printing Functions

Currently, single-structure molding is insufficient to meet the needs of personalized applications. Future research will focus on the development of “smart” hydrogels, which involve introducing responsive groups or nanofillers to endow starch-based scaffolds with dynamic responsiveness to environmental stimuli such as pH, temperature, enzymes, or light. This property can be used not only to construct 4D-printed scaffolds with shape-memory effects but also to develop smart sensor tags that can monitor food freshness or wound-healing status. Furthermore, for 3D encapsulation applications, how to achieve targeted and sustained release of cells/active factors at specific physiological sites (such as the intestines or wounds) while maintaining high cell/active factor viability through material design remains a critical challenge.

In addition to introducing stimulus-responsive chemistries, the geometry of the printed structure itself is increasingly recognized as a design variable that governs mechanical performance, deformation behavior, and energy absorption, and is therefore directly relevant to the development of multi-functional, next-generation starch-based constructs. Tuninetti et al. provide a comprehensive review of biomimetic lattice structures, showing how bio-inspired unit-cell topologies can be systematically designed and manufactured to achieve tailored combinations of high stress resistance, controlled deformation, and energy-absorption capacity, well beyond what single, non-optimized bulk geometries can offer [123]. Although this review focuses primarily on metallic and polymeric lattice structures produced by conventional additive manufacturing routes, the underlying design principle, namely that structural geometry can be engineered in parallel with material chemistry to achieve multi-functional performance, is directly transferable to starch-based smart hydrogels and 4D-printable scaffolds. Coupling stimulus-responsive starch formulations with biomimetic, load-optimized, or deformation-optimized lattice geometries could, in principle, allow future starch-based constructs to combine environmental responsiveness with tailored mechanical and energy-absorption behavior, an avenue that remains, to our knowledge, unexplored for starch-based materials and represents a promising direction for future multi-functional, bio-inspired 4D-printing research.

7.3. Multi-Component Synergistic Systems and Clinical/Industrial Translation

The limitations of natural starch in terms of mechanical properties and bioactivity restrict its application in hard tissue repair or large-scale industrial production. Future research should focus on exploring the properties of nanocomposite formulations made

from starch and synthetic polymers using multi-component interpenetrating networks (IPNs). Simultaneously, to promote the translation of laboratory results into practical applications, a standardized post-printing evaluation system must be established.

8. Conclusions

Starch has emerged as a highly promising bio-based material for extrusion-based additive manufacturing, owing to its abundance, biodegradability, biocompatibility, and tunable physicochemical properties. Its intrinsic ability to undergo gelatinization, retrogradation, and shear-thinning behavior enables the formation of viscoelastic hydrogels compatible with direct ink-writing technologies. However, successful implementation of starch in 3D printing requires precise control over formulation parameters, including amylose-to-amylopectin ratio; solid content; degree of pre-gelatinization; and rheological properties, such as storage modulus, yield stress, and viscosity.

Beyond native starch, chemical, physical, and biological modification strategies have demonstrated significant potential for tailoring microstructure, mechanical strength, and print fidelity. The integration of polysaccharides, proteins, and mineral salts further expands the functional design, enabling improved extrudability, structural stability, and performance for specific application. Importantly, these advances position starch-based 3D-printed materials as a versatile platform for non-food additive manufacturing, with growing relevance in controlled drug delivery, tissue engineering scaffolds, pharmaceutical formulations, chemical-industry applications, and conductive or bioelectronic hydrogels.

Despite these advances, key challenges remain, particularly in establishing predictive structure–property–process relationships, enhancing mechanical robustness in demanding environments, and achieving reliable scale-up for industrial translation. Future research should therefore prioritize rheology-guided formulation design, development of multi-responsive and 4D-printable systems, and standardized protocols.

Overall, starch-based hydrogels represent a sustainable and adaptable platform for next-generation additive manufacturing, with strong potential to contribute to circular material strategies and advanced functional applications.

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References

1. Bhatia, S.K.; Ramadurai, K.W. *3D Printing and Bio-Based Materials in Global Health*; SpringerBriefs in Materials; Springer: Cham, Switzerland, 2017.
2. Valino, A.D.; Dizon, J.R.C.; Espera, A.H.; Chen, Q.; Messman, J.; Advincula, R.C. Advances in 3D Printing of Thermoplastic Polymer Composites and Nanocomposites. *Prog. Polym. Sci.* **2019**, *98*, 101162. [[CrossRef](#)]
3. Palmara, G.; Frascella, F.; Roppolo, I.; Chiappone, A.; Chiadò, A. Functional 3D Printing: Approaches and Bioapplications. *Biosens. Bioelectron.* **2021**, *175*, 112849. [[CrossRef](#)]

4. Long, W.J.; Tao, J.L.; Lin, C.; Gu, Y.C.; Mei, L.; Duan, H.B.; Xing, F. Rheology and Buildability of Sustainable Cement-Based Composites Containing Micro-Crystalline Cellulose for 3D-Printing. *J. Clean. Prod.* **2019**, *239*, 118054. [\[CrossRef\]](#)
5. Raina, A.; Haq, M.I.U.; Javaid, M.; Rab, S.; Haleem, A. 4D Printing for Automotive Industry Applications. *J. Inst. Eng. India Ser. D* **2021**, *102*, 521–529. [\[CrossRef\]](#)
6. Skoczinski, P.; Carus, M.; Tweddle, G.; Ruiz, P.; de Guzman, D.; Ravenstijn, J.; K  b, H.; Hark, N.; Dammer, L.; Raschka, A. Bio-Based Building Blocks and Polymers: Global Capacities, Production and Trends 2022–2027. *Indus. Biotech.* **2023**, *19*, 185–194. [\[CrossRef\]](#)
7. Ji, A.; Zhang, S.; Bhagia, S.; Yoo, C.G.; Ragauskas, A.J. 3D Printing of Biomass-Derived Composites: Application and Characterization Approaches. *RSC Adv.* **2020**, *10*, 21698–21723. [\[CrossRef\]](#)
8. D  hler, N.; Wellenreuther, C.; Wolf, A. Market Dynamics of Biodegradable Bio-Based Plastics: Projections and Linkages to European Policies. *EFB Bioecon. J.* **2022**, *2*, 100028. [\[CrossRef\]](#)
9. Mehrpouya, M.; Vahabi, H.; Barletta, M.; Laheurte, P.; Langlois, V. Additive Manufacturing of Polyhydroxyalkanoates (PHAs) Biopolymers: Materials, Printing Techniques, and Applications. *Mater. Sci. Eng. C* **2021**, *127*, 112216. [\[CrossRef\]](#)
10. Zheng, B.; Qiu, Z.; Xu, J.; Zeng, X.; Liu, K.; Chen, L. 3D Printing-Mediated Microporous Starch Hydrogels for Wound Hemostasis. *J. Mater. Chem. B* **2023**, *11*, 8411–8421. [\[CrossRef\]](#)
11. Barcena, A.J.R.; Dhal, K.; Patel, P.; Ravi, P.; Kundu, S.; Tappa, K. Current Biomedical Applications of 3D-Printed Hydrogels. *Gels* **2024**, *10*, 8. [\[CrossRef\]](#)
12. Zhuang, P.; Greenberg, Z.; He, M. Biologically Enhanced Starch Bio-Ink for Promoting 3D Cell Growth. *Adv. Mater. Technol.* **2021**, *6*, 2100551. [\[CrossRef\]](#)
13. Beg, S.; Almalki, W.H.; Malik, A.; Farhan, M.; Aatif, M.; Rahman, Z.; Alruwaili, N.K.; Alrobaian, M.; Tarique, M.; Rahman, M. 3D Printing for Drug Delivery and Biomedical Applications. *Drug Discov. Today* **2020**, *25*, 1668–1681. [\[CrossRef\]](#)
14. Distler, T.; Boccaccini, A.R. 3D Printing of Electrically Conductive Hydrogels for Tissue Engineering and Biosensors—A Review. *Acta Biomater.* **2020**, *101*, 1–13. [\[CrossRef\]](#)
15. Wang, J.; Liu, Y.; Su, S.; Wei, J.; Rahman, S.E.; Ning, F.; Christopher, G.; Cong, W.; Qiu, J. Ultrasensitive Wearable Strain Sensors of 3D Printing Tough and Conductive Hydrogels. *Polymers* **2019**, *11*, 1873. [\[CrossRef\]](#)
16. Hachimi, T.; Ait Hmazi, F.; Arhouni, F.E.; Rejdali, H.; Riyad, Y.; Majid, F. Advancing FDM 3D Printing Simulations: From G-Code Conversion to Precision Modelling in Abaqus. *J. Manuf. Mater. Process.* **2025**, *9*, 338. [\[CrossRef\]](#)
17. Lille, M.; Nurmela, A.; Nordlund, E.; Mets  -Kortelainen, S.; Sozer, N. Applicability of Protein and Fiber-Rich Food Materials in Extrusion-Based 3D Printing. *J. Food Eng.* **2018**, *220*, 20–27. [\[CrossRef\]](#)
18. Gonz  lez, K.; Larraza, I.; Berra, G.; Eceiza, A.; Gabilondo, N. 3D Printing of Customized All-Starch Tablets with Combined Release Kinetics. *Int. J. Pharm.* **2022**, *622*, 121872. [\[CrossRef\]](#)
19. Dominici, F.; Imbriano, A.; Puglia, D.; Pagano, C.; Luzi, F.; Rafanelli, A.; Di Michele, A.; Bonacci, F.; Ceccarini, M.R.; Primavilla, S.; et al. Starch-Based Scaffold Produced by FDM 3D Printing Technique as Innovative and Biosustainable Wound Dressing. *Eur. J. Pharm. Biopharm.* **2025**, *210*, 114698. [\[CrossRef\]](#)
20. Koski, C.; Bose, S. Effects of Amylose Content on the Mechanical Properties of Starch-Hydroxyapatite 3D Printed Bone Scaffolds. *Addit. Manuf.* **2019**, *30*, 100817. [\[CrossRef\]](#)
21. Shyam, R.; Palaniappan, A. Development and Optimization of Starch-Based Biomaterial Inks and the Effect of Infill Patterns on the Mechanical, Physicochemical, and Biological Properties of 3D Printed Scaffolds for Tissue Engineering. *Int. J. Biol. Macromol.* **2024**, *258*, 128986. [\[CrossRef\]](#)
22. Bao, Y.; Wang, M.; Li, J.; Yang, X.; Wen, B.; Wang, L.; He, Y.; Si, X.; Li, B. A Starch-Based 3D Printed Intelligent Colorimetric Film Co-Loaded Natural Pigments for Visualizing Food Freshness: Effect of Nozzle Size on Gel Structure Formation. *Food Hydrocoll.* **2024**, *155*, 110218. [\[CrossRef\]](#)
23. Bacalzo, N.P.; Go, L.P.; Querebillo, C.J.; Hildebrandt, P.; Limpoco, F.T.; Enriquez, E.P. Controlled Microwave-Hydrolyzed Starch as a Stabilizer for Green Formulation of Aqueous Gold Nanoparticle Ink for Flexible Printed Electronics. *ACS Appl. Nano Mater.* **2018**, *1*, 1247–1256. [\[CrossRef\]](#)
24. Chen, H.; Xie, F.; Chen, L.; Zheng, B. Effect of Rheological Properties of Potato, Rice and Corn Starches on Their Hot-Extrusion 3D Printing Behaviors. *J. Food Eng.* **2019**, *244*, 150–158. [\[CrossRef\]](#)
25. Sun, J.; Zhou, W.; Yan, L.; Huang, D.; Lin, L.-y. Extrusion-Based Food Printing for Digitalized Food Design and Nutrition Control. *J. Food Eng.* **2018**, *220*, 1–11. [\[CrossRef\]](#)
26. Goel, A.; Meher, M.K.; Gulati, K.; Poluri, K.M. Fabrication of Biopolymer-Based Organs and Tissues Using 3D Bioprinting. In *3D Printing Technology in Nanomedicine*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 43–62.
27. Cheng, Y.; Yuqing, H.; Xiao, L.; Gao, W.; Kang, X.; Sui, J.; Cui, B. Impact of Starch Amylose and Amylopectin on the Rheological and 3D Printing Properties of Corn Starch. *Int. J. Biol. Macromol.* **2024**, *278*, 134403. [\[CrossRef\]](#)

28. Maniglia, B.C.; Lima, D.C.; Matta Junior, M.D.; Le-Bail, P.; Le-Bail, A.; Augusto, P.E.D. Hydrogels Based on Ozonated Cassava Starch: Effect of Ozone Processing and Gelatinization Conditions on Enhancing 3D-Printing Applications. *Int. J. Biol. Macromol.* **2019**, *138*, 1087–1097. [\[CrossRef\]](#)
29. Shi, S.; Wen, J.; Geng, H.; Zhan, X.; Liu, Y. Physicochemical Properties, Structural Properties and Gels 3D Printing Properties of Wheat Starch. *Int. J. Biol. Macromol.* **2024**, *261*, 129885. [\[CrossRef\]](#)
30. Venkatachalam, A.; Wilms, P.F.C.; Patón Baeza, J.; Schutyser, M.A.I.; Zhang, L. Formulation of Pea-Based Inks with Different Starches to Produce Customized 3D Printed and Baked Snacks. *Curr. Res. Food Sci.* **2026**, *12*, 101320. [\[CrossRef\]](#)
31. Saha, D.; Padhiary, M.; Hoque, A.; Prasad, G. 3D Printing Technology for Valorization of Food Processing Wastes and Byproducts: A Systematic Review. *Waste Manag. Bull.* **2025**, *3*, 100192. [\[CrossRef\]](#)
32. Rahman, A.M.; Rahman, T.T.; Pei, Z.; Ufodike, C.O.; Lee, J.; Elwany, A. Additive Manufacturing Using Agriculturally Derived Biowastes: A Systematic Literature Review. *Bioengineering* **2023**, *10*, 845. [\[CrossRef\]](#)
33. Tan, L.J.; Zhu, W.; Zhou, K. Recent Progress on Polymer Materials for Additive Manufacturing. *Adv. Funct. Mater.* **2020**, *30*, 2003062. [\[CrossRef\]](#)
34. Zeng, X.; Chen, H.; Chen, L.; Zheng, B. Insights into the Relationship between Structure and Rheological Properties of Starch Gels in Hot-Extrusion 3D Printing. *Food Chem.* **2021**, *342*, 128362. [\[CrossRef\]](#)
35. Lin, S.; Liu, X.; Cao, Y.; Liu, S.; Deng, D.; Zhang, J.; Huang, G. Effects of Xanthan and Konjac Gums on Pasting, Rheology, Microstructure, Crystallinity and in Vitro Digestibility of Mung Bean Resistant Starch. *Food Chem.* **2021**, *339*, 128001. [\[CrossRef\]](#)
36. Murphy, S.V.; Atala, A. 3D Bioprinting of Tissues and Organs. *Nat. Biotechnol.* **2014**, *32*, 773–785. [\[CrossRef\]](#)
37. Hu, W.X.; Chen, J.; Xu, F.; Chen, L.; Zhao, J.W. Study on Crystalline, Gelatinization and Rheological Properties of Japonica Rice Flour as Affected by Starch Fine Structure. *Int. J. Biol. Macromol.* **2020**, *148*, 1232–1241. [\[CrossRef\]](#)
38. Ji, S.; Xu, T.; Li, Y.; Li, H.; Zhong, Y.; Lu, B. Effect of Starch Molecular Structure on Precision and Texture Properties of 3D Printed Products. *Food Hydrocoll.* **2022**, *125*, 107387. [\[CrossRef\]](#)
39. Ahmadzadeh, S.; Ubeyitogullari, A. Generation of Porous Starch Beads via a 3D Food Printer: The Effects of Amylose Content and Drying Technique. *Carbohydr. Polym.* **2023**, *301*, 120296. [\[CrossRef\]](#)
40. Xiao, W.; Shen, M.; Ren, Y.; Rong, L.; Liu, W.; Chen, X.; Yang, J.; Li, J.; Xie, J. Mesona Chinensis Polysaccharides Promote Molecular Crosslinking and Gel Formation of Debranched Waxy Maize Starch. *LWT* **2021**, *148*, 111773. [\[CrossRef\]](#)
41. Phuhongsung, P.; Zhang, M.; Bhandari, B. 4D Printing of Products Based on Soy Protein Isolate via Microwave Heating for Flavor Development. *Food Res. Int.* **2020**, *137*, 109605. [\[CrossRef\]](#)
42. Fang, F. Shear-Induced Synergistic Effects of Konjac Glucomannan and Waxy Potato Starch on Viscosity and Gel Strength. *Food Hydrocoll.* **2021**, *114*, 106540. [\[CrossRef\]](#)
43. Cui, Y.; Li, C.; Guo, Y.; Liu, X.; Zhu, F.; Liu, Z.; Liu, X.; Yang, F. Rheological & 3D Printing Properties of Potato Starch Composite Gels. *J. Food Eng.* **2022**, *313*, 110756. [\[CrossRef\]](#)
44. Yang, F.; Zhang, M.; Bhandari, B.; Liu, Y. Investigation on Lemon Juice Gel as Food Material for 3D Printing and Optimization of Printing Parameters. *LWT* **2018**, *87*, 67–76. [\[CrossRef\]](#)
45. Liu, S.; Shen, M.; Xiao, Y.; Luo, Y.; Xie, J. Effect of Maize, Potato, and Pea Starches with Mesona Chinensis Polysaccharide on Pasting, Gelatinization Properties, Granular Morphology and Digestion. *Food Hydrocoll.* **2020**, *108*, 106047. [\[CrossRef\]](#)
46. Chang, Q.; Zheng, B.; Zhang, Y.; Zeng, H. A Comprehensive Review of the Factors Influencing the Formation of Retrograded Starch. *Int. J. Biol. Macromol.* **2021**, *186*, 163–173. [\[CrossRef\]](#)
47. Xiao, Y.; Liu, S.; Shen, M.; Jiang, L.; Ren, Y.; Luo, Y.; Xie, J. Effect of Different Mesona Chinensis Polysaccharides on Pasting, Gelation, Structural Properties and in Vitro Digestibility of Tapioca Starch-Mesona Chinensis Polysaccharides Gels. *Food Hydrocoll.* **2020**, *99*, 105327. [\[CrossRef\]](#)
48. Ai, Y.; Jane, J.L. Gelatinization and Rheological Properties of Starch. *Starch/Staerke* **2015**, *67*, 213–224. [\[CrossRef\]](#)
49. Zeng, L.; Zhang, L.; Li, K.; He, J.; Xin, H.; Wang, Q. Effect of Gelatinization Processing on the Antioxidant, Digestion, and Physicochemical Properties of Wheat Starch Enhanced with Tannic Acid. *LWT* **2020**, *125*, 109228. [\[CrossRef\]](#)
50. Parada, J.; Aguilera, J.M. Effect of Native Crystalline Structure of Isolated Potato Starch on Gelatinization Behavior and Consequently on Glycemic Response. *Food Res. Int.* **2012**, *45*, 238–243. [\[CrossRef\]](#)
51. Bulut, E.G.; Candoğan, K. Development and Characterization of a 3D Printed Functional Chicken Meat Based Snack: Optimization of Process Parameters and Gelatin Level. *LWT* **2022**, *154*, 112768. [\[CrossRef\]](#)
52. Saadi, M.A.S.R.; Maguire, A.; Pottackal, N.T.; Thakur, M.S.H.; Ikram, M.M.; Hart, A.J.; Ajayan, P.M.; Rahman, M.M. Direct Ink Writing: A 3D Printing Technology for Diverse Materials. *Adv. Mat.* **2022**, *34*, e2108855. [\[CrossRef\]](#)
53. Rong, L.; Chen, X.; Shen, M.; Yang, J.; Qi, X.; Li, Y.; Xie, J. The Application of 3D Printing Technology on Starch-Based Product: A Review. *Trends Food Sci. Technol.* **2023**, *134*, 149–161. [\[CrossRef\]](#)
54. Derossi, A.; Caporizzi, R.; Azzollini, D.; Severini, C. Application of 3D Printing for Customized Food. A Case on the Development of a Fruit-Based Snack for Children. *J. Food Eng.* **2018**, *220*, 65–75. [\[CrossRef\]](#)

55. Liu, Y.; Liang, X.; Saeed, A.; Lan, W.; Qin, W. Properties of 3D Printed Dough and Optimization of Printing Parameters. *Innov. Food Sci. Emerg. Technol.* **2019**, *54*, 9–18. [\[CrossRef\]](#)
56. Vanier, N.L.; El Halal, S.L.M.; Dias, A.R.G.; da Rosa Zavareze, E. Molecular Structure, Functionality and Applications of Oxidized Starches: A Review. *Food Chem.* **2017**, *221*, 1546–1559. [\[CrossRef\]](#)
57. Zhang, Y.; Lv, J.; Qiu, Z.; Chen, L. Influence of Carboxyl Content on the Rheological Properties and Printability of Oxidized Starch for 3D Printing Applications. *Int. J. Biol. Macromol.* **2025**, *289*, 138794. [\[CrossRef\]](#)
58. Yang, Z.; Chen, X.; Xu, Z.; Ji, N.; Xiong, L.; Sun, Q. Anti-Freezing Starch Hydrogels with Superior Mechanical Properties and Water Retention Ability for 3D Printing. *Int. J. Biol. Macromol.* **2021**, *190*, 382–389. [\[CrossRef\]](#)
59. Zhu, J.; Xie, F.; Qiu, Z.; Chen, L. Effect of Active Carbonyl-Carboxyl Ratio on Dynamic Schiff Base Crosslinking and Its Modulation of High-Performance Oxidized Starch-Chitosan Hydrogel by Hot Extrusion 3D Printing. *Carbohydr. Polym.* **2024**, *343*, 122438. [\[CrossRef\]](#)
60. Gulzar, S.; Narciso, J.O.; Elez-Martínez, P.; Martín-Belloso, O.; Soliva-Fortuny, R. Recent Developments in the Application of Novel Technologies for the Modification of Starch in Light of 3D Food Printing. *Curr. Opin. Food Sci.* **2023**, *52*, 101067. [\[CrossRef\]](#)
61. Liu, W.; Pan, W.; Li, J.; Chen, Y.; Yu, Q.; Rong, L.; Xiao, W.; Wen, H.; Xie, J. Dry Heat Treatment Induced the Gelatinization, Rheology and Gel Properties Changes of Chestnut Starch. *Curr. Res. Food Sci.* **2022**, *5*, 28–33. [\[CrossRef\]](#)
62. Sponchiado, P.A.I.; de Melo, M.T.; Bitencourt, B.S.; Guedes, J.S.; Tapia-Blácido, D.R.; Augusto, P.E.D.; Ramos, A.P.; Maniglia, B.C. Clean Modification of Potato Starch to Improve 3D Printing of Potential Bone Bio-Scaffolds. *Emergent Mater.* **2024**, *8*, 2695–2708. [\[CrossRef\]](#)
63. Balakrishna, A.K.; Abdul Wazed, M.; Farid, M. A Review on the Effect of High Pressure Processing (HPP) on Gelatinization and Infusion of Nutrients. *Molecules* **2020**, *25*, 2369. [\[CrossRef\]](#)
64. Koshenaj, K.; Ferrari, G. A Comprehensive Review on Starch-Based Hydrogels: From Tradition to Innovation, Opportunities, and Drawbacks. *Polymers* **2024**, *16*, 1991. [\[CrossRef\]](#)
65. Larrea-Wachtendorff, D.; Tabilo-Munizaga, G.; Ferrari, G. Potato Starch Hydrogels Produced by High Hydrostatic Pressure (HHP): A First Approach. *Polymers* **2019**, *11*, 1673. [\[CrossRef\]](#)
66. Maleki, S.; Aarabi, A.; Far, F.A.; Dizaji, H.Z. Heat Moisture Treatment and Ultrasound-Induced Hydrothermal Wheat Starch Modification: Techno-Functional, Microstructural and Quality 3D Printed Characteristics. *Int. J. Biol. Macromol.* **2024**, *276*, 133992. [\[CrossRef\]](#)
67. Sun, X.; Mazur, M.; Cheng, C.T. A Review of Void Reduction Strategies in Material Extrusion-Based Additive Manufacturing. *Addit. Manuf.* **2023**, *67*, 103463. [\[CrossRef\]](#)
68. Xu, K.; Zhang, M.; Bhandari, B. Effect of Novel Ultrasonic-Microwave Combined Pretreatment on the Quality of 3D Printed Wheat Starch-Papaya System. *Food Biophys.* **2020**, *15*, 249–260. [\[CrossRef\]](#)
69. Ma, S.; Zhang, Q.; Lin, Q.; Pan, L.; Yu, X.; Jiang, H. Performance of 3D-Printed Samples Based on Starch Treated by Radio Frequency Energy. *Innov. Food Sci. Emerg. Technol.* **2023**, *85*, 103337. [\[CrossRef\]](#)
70. Ma, S.; Liu, J.; Zhang, Q.; Lin, Q.; Liu, R.; Xing, Y.; Jiang, H. 3D Printing Performance Using Radio Frequency Electromagnetic Wave Modified Potato Starch. *Innov. Food Sci. Emerg. Technol.* **2022**, *80*, 103064. [\[CrossRef\]](#)
71. Oyeyinka, S.A.; Akintayo, O.A.; Adebo, O.A.; Kayitesi, E.; Njobeh, P.B. A Review on the Physicochemical Properties of Starches Modified by Microwave Alone and in Combination with Other Methods. *Int. J. Biol. Macromol.* **2021**, *176*, 87–95. [\[CrossRef\]](#)
72. Guo, C.; Zhang, M.; Devahastin, S. Improvement of 3D Printability of Buckwheat Starch-Pectin System via Synergistic Ca²⁺-Microwave Pretreatment. *Food Hydrocoll.* **2021**, *113*, 106483. [\[CrossRef\]](#)
73. Maniglia, B.C.; Pataro, G.; Ferrari, G.; Augusto, P.E.D.; Le-Bail, P.; Le-Bail, A. Pulsed Electric Fields (PEF) Treatment to Enhance Starch 3D Printing Application: Effect on Structure, Properties, and Functionality of Wheat and Cassava Starches. *Innov. Food Sci. Emerg. Technol.* **2021**, *68*, 102602. [\[CrossRef\]](#)
74. Pawase, P.A.; Pathare, A.M.; Bashir, O.; Saleem, F.; Shrama, E.; Mudgal, S.; Ahmad, M. Physical, Chemical, and Nano-Enabled Modifications of Starch for Sustainable Food Packaging Films: Recent Trends, Challenges, and Prospects. *Carbohydr. Polym. Technol. Appl.* **2025**, *11*, 100986. [\[CrossRef\]](#)
75. Tarahi, M.; Ahmadi Partovi, G.; Hedayati, S. Mung Bean as an Emerging Source of Starch: A Review on Its Isolation, Structure, Functionality, Modification, and Application. *Food Chem.* **2025**, *497*, 147033. [\[CrossRef\]](#)
76. Amobonye, A.; Bendoraitiene, J.; Peciulyte, L.; Rutkaite, R. Review of Recent Advancements in Starch Modification: Improving the Functionality of Starch-Based Films. *Int. J. Biol. Macromol.* **2025**, *315*, 144354. [\[CrossRef\]](#)
77. Allai, F.M.; Nissar, J.; Shafi, A.; Bashir, M.; Mehreen; Zahoor, I.; Ganaie, T.A.; Gul, K.; Ahad, T. Horse Chestnut Starch: Structure, Properties, Modification and Its Applications—A Review. *Carbohydr. Polym. Technol. Appl.* **2025**, *10*, 100755. [\[CrossRef\]](#)
78. Vicente, A.; Caballero, P.A.; Villanueva, M.; Ronda, F. Advances in Microwave-Induced Physical Modification of Flours: From Structural Changes to Product Development. *Food Hydrocoll.* **2026**, *172*, 112026. [\[CrossRef\]](#)

79. Chen, X.; Liu, Y.; Duan, R.; Haran, Y.; Li, S.; Liu, Z.; Zeng, X.; Liu, Z.; Li, J.; Yan, S. Recent Advances in Green Modification of Lotus Rhizome Starch: Physicochemical Properties, Techno-Functional Characteristics and Challenges. *Food Chem.* **2025**, *496*, 146724. [\[CrossRef\]](#)
80. Ubaid, M.; Ahmed, M.; Sheikh, M.A.; Jan, T.; Sheikh, I.; Ahmed, N.; Kumar, K.; Kumar, A.; Vashisht, A. Potato Starch as a Next-Generation Biopolymer: Functionality, Modification, Sustainability, and Industrial Perspectives. *Food Phys.* **2026**, *3*, 100082. [\[CrossRef\]](#)
81. Arshad, R.N.; Abdul-Malek, Z.; Munir, A.; Buntat, Z.; Ahmad, M.H.; Jusoh, Y.M.M.; Bekhit, A.E.D.; Roobab, U.; Manzoor, M.F.; Aadil, R.M. Electrical Systems for Pulsed Electric Field Applications in the Food Industry: An Engineering Perspective. *Trends Food Sci. Technol.* **2020**, *104*, 1–13. [\[CrossRef\]](#)
82. Al Rashid, A.; Khan, S.A.; Koç, M. Life Cycle Assessment on Fabrication and Characterization Techniques for Additively Manufactured Polymers and Polymer Composites. *Clean. Environ. Syst.* **2024**, *12*, 100159. [\[CrossRef\]](#)
83. Punia Bangar, S.; Ashogbon, A.O.; Singh, A.; Chaudhary, V.; Whiteside, W.S. Enzymatic Modification of Starch: A Green Approach for Starch Applications. *Carbohydr. Polym.* **2022**, *287*, 119265. [\[CrossRef\]](#)
84. Xia, W.; Zhang, K.; Su, L.; Wu, J. Microbial Starch Debranching Enzymes: Developments and Applications. *Biotechnol. Adv.* **2021**, *50*, 107786. [\[CrossRef\]](#)
85. Park, H.R.; Kang, J.; Rho, S.J.; Kim, Y.R. Structural and Physicochemical Properties of Enzymatically Modified Rice Starch as Influenced by the Degree of Enzyme Treatment. *J. Carbohydr. Chem.* **2020**, *39*, 250–266. [\[CrossRef\]](#)
86. Jayarathna, S.; Hofvander, P.; Péter-Szabó, Z.; Andersson, M.; Andersson, R. GBSS Mutations in an SBE Mutated Background Restore the Potato Starch Granule Morphology and Produce Ordered Granules despite Differences to Native Molecular Structure. *Carbohydr. Polym.* **2024**, *331*, 121860. [\[CrossRef\]](#)
87. Jayarathna, S.; Péter-Szabó, Z.; Nestor, G.; Andersson, M.; Vilaplana, F.; Andersson, R. Impact of Mutations in Starch Synthesis Genes on Morphological, Compositional, Molecular Structure, and Functional Properties of Potato Starch. *PLoS ONE* **2024**, *19*, e0310990. [\[CrossRef\]](#)
88. Shahbazi, M.; Jäger, H.; Ettelaie, R.; Ulbrich, M. Insights into the Supramolecular Structure and Degradation Mechanisms of Starch from Different Botanical Sources as Affected by Extrusion-Based 3D Printing. *Biomacromolecules* **2023**, *24*, 69–85. [\[CrossRef\]](#)
89. Zhang, J.; Li, Y.; Cai, Y.; Ahmad, I.; Zhang, A.; Ding, Y.; Qiu, Y.; Zhang, G.; Tang, W.; Lyu, F. Hot Extrusion 3D Printing Technologies Based on Starchy Food: A Review. *Carbohydr. Polym.* **2022**, *294*, 119763. [\[CrossRef\]](#)
90. Liu, Z.; Bhandari, B.; Prakash, S.; Mantihal, S.; Zhang, M. Linking Rheology and Printability of a Multicomponent Gel System of Carrageenan-Xanthan-Starch in Extrusion Based Additive Manufacturing. *Food Hydrocoll.* **2019**, *87*, 413–424. [\[CrossRef\]](#)
91. Huang, M.; Zhang, M.; Guo, C. 3D Printability of Brown Rice Gel Modified by Some Food Hydrocolloids. *J. Food Process. Preserv.* **2020**, *44*, e14502. [\[CrossRef\]](#)
92. Montoya, J.; Medina, J.; Molina, A.; Gutiérrez, J.; Rodríguez, B.; Marín, R. Impact of Viscoelastic and Structural Properties from Starch-Mango and Starch-Arabinoxylans Hydrocolloids in 3D Food Printing. *Addit. Manuf.* **2021**, *39*, 101891. [\[CrossRef\]](#)
93. Feng, L.; Wu, J.; Cai, L.; Li, M.; Dai, Z.; Li, D.; Liu, C.; Zhang, M. Effects of Different Hydrocolloids on the Water Migration, Rheological and 3D Printing Characteristics of β -Carotene Loaded Yam Starch-Based Hydrogel. *Food Chem.* **2022**, *393*, 133422. [\[CrossRef\]](#)
94. Kong, Y.; Chen, J.; Guo, R.; Huang, Q. Regulation of Tapioca Starch 3D Printability by Yeast Protein: Rheological, Textural Evaluation, and Machine Learning Prediction. *J. Food Eng.* **2025**, *387*, 112341. [\[CrossRef\]](#)
95. Chuanxing, F.; Qi, W.; Hui, L.; Quancheng, Z.; Wang, M. Effects of Pea Protein on the Properties of Potato Starch-Based 3D Printing Materials. *Int. J. Food Eng.* **2018**, *14*, 20170297. [\[CrossRef\]](#)
96. Feng, M.; Zhang, M.; Mujumdar, A.S.; Guo, Z. Influence of Components Interaction in Recombined Food Gels on 3D Printing: A Comprehensive Review. *Food Hydrocoll.* **2024**, *151*, 109782. [\[CrossRef\]](#)
97. Wang, W.; Zhou, H.; Yang, H.; Cui, M. Effects of Salts on the Freeze–Thaw Stability, Gel Strength and Rheological Properties of Potato Starch. *J. Food Sci. Technol.* **2016**, *53*, 3624–3631. [\[CrossRef\]](#)
98. Prasetyaningrum, P.W.; Mubarak, W.; Kotani, T.; Sakai, S. Development of Starch-Based Support Material Alternately Extruded with Gelatin-Based Bioinks for 3D Bioprinting Application. *Bioprinting* **2025**, *51*, e00439. [\[CrossRef\]](#)
99. Zhou, X.; Wu, S.; Liu, P.; Wang, L.; Xie, F. Hybrid Bioink of Methacrylated Starch with Minimal Methacrylated Chitosan Enables High-Precision 3D Printing for Complex Tissue Scaffolds. *Carbohydr. Polym.* **2025**, *367*, 124023. [\[CrossRef\]](#)
100. Mollaheydaralimoazzen, M.; Sheikholeslam, M.; Poursamar, S.A.; Farzan, M.; Farzan, M.; Rafienia, M. 3D-Printing of Shear-Thinning and Self-Healing Gelatin/Starch/Halloysite-Nanotube Hydrogels for Soft Tissue Engineering: An in Vitro and in Vivo Assessment. *Int. J. Biol. Macromol.* **2025**, *315*, 144502. [\[CrossRef\]](#)
101. Truong-Le, Q.A.; Lee, S.O.; Ubeyitogullari, A. Encapsulation of Bifidobacterium Bifidum into a PH-Sensitive Alginate-Pectin Gel System Using 3D Food Printing: Enhanced Viability and Targeted Release. *Int. J. Biol. Macromol.* **2025**, *318*, 145134. [\[CrossRef\]](#)

102. Nörnberg, A.B.; Gularte, M.S.; da Fonseca, C.A.R.; San José, D.E.J.M.; Wilhelm, E.A.; Fajardo, A.R. 3D-Printed Gelatin/Dialdehyde Starch Hydrogels for Hydrocortisone Topical Administration and in Vivo Treatment of Atopic Dermatitis. *Colloids Surf. B Biointerfaces* **2025**, *251*, 114613. [\[CrossRef\]](#)
103. Li, Y.; Li, N.; Yao, S.; Hu, H.; Wan, B.; Wu, Z.; Cheng, H.; Li, D.; Liu, D.; Xu, E. Dual Effects of Exogenous Ferulic Acid Bound in Rice Starch as 3D Printable Food Ink: Structural Fluidity and Antimicrobial Activity. *Int. J. Biol. Macromol.* **2025**, *300*, 140262. [\[CrossRef\]](#)
104. Tan, G.; Hou, J.; Meng, D.; Zhang, H.; Han, X.; Li, H.; Wang, Z.; Ghamry, M.; Rayan, A.M. 3D Printing Cassava Starch-Ovalbumin Intelligent Labels: Co-Pigmentation Effects of Gallic Acid on Anthocyanins. *Int. J. Biol. Macromol.* **2024**, *281*, 135684. [\[CrossRef\]](#)
105. Liu, W.; Chen, L.; McClements, D.J.; Peng, X.; Jin, Z. Recent Trends of 3D Printing Based on Starch-Hydrocolloid in Food, Biomedicine and Environment. *Crit. Rev. Food Sci. Nutr.* **2023**, *64*, 8948–8962. [\[CrossRef\]](#)
106. Chatzitaki, A.T.; Mystiridou, E.; Bouropoulos, N.; Ritzoulis, C.; Karavasili, C.; Fatouros, D.G. Semi-Solid Extrusion 3D Printing of Starch-Based Soft Dosage Forms for the Treatment of Paediatric Latent Tuberculosis Infection. *J. Pharm. Pharmacol.* **2022**, *74*, 1498–1506. [\[CrossRef\]](#)
107. Ahmadzadeh, S.; Ubeyitogullari, A. Enhancing the Stability of Lutein by Loading into Dual-Layered Starch-Ethyl Cellulose Gels Using 3D Food Printing. *Addit. Manuf.* **2023**, *69*, 103549. [\[CrossRef\]](#)
108. Joseph, A.; Muhammad, L.F.; Vijayan, A.S.; Xavier, J.; Megha, K.B.; Karthikeyan, A.; Gopinath, N.; Mohanan, P.V.; Nair, B.G. 3D Printed Arrowroot Starch-Gellan Scaffolds for Wound Healing Applications. *Int. J. Biol. Macromol.* **2024**, *264*, 130604. [\[CrossRef\]](#)
109. van den Heuvel, K.A.; Berardi, A.; Buijvoets, L.B.; Dickhoff, B.H.J. 3D-Powder-Bed-Printed Pharmaceutical Drug Product Tablets for Use in Clinical Studies. *Pharmaceutics* **2022**, *14*, 2320. [\[CrossRef\]](#)
110. van den Heuvel, K.A.; de Wit, M.T.W.; Dickhoff, B.H.J. Evaluation of Lactose Based 3D Powder Bed Printed Pharmaceutical Drug Product Tablets. *Powder Technol.* **2021**, *390*, 97–102. [\[CrossRef\]](#)
111. Bashetty, S.R.; Zhang, Y.; Nalajala, N.; Anekalla, T.R.; Gudipati, L.P.; Narala, N.; Alluri, R.; Maniruzzaman, M. Eco-Friendly Selective Laser Sintered (SLS) 3D Printing of Tablets Using Starch 1500® as a Standalone Green Excipient. *Carbohydr. Polym. Technol. Appl.* **2026**, *15*, 101153. [\[CrossRef\]](#)
112. Haryńska, A.; Janik, H.; Sienkiewicz, M.; Mikolaszek, B.; Kucińska-Lipka, J. PLA-Potato Thermoplastic Starch Filament as a Sustainable Alternative to the Conventional PLA Filament: Processing, Characterization, and FFF 3D Printing. *ACS Sustain. Chem. Eng.* **2021**, *9*, 6923–6938. [\[CrossRef\]](#)
113. Ju, Q.; Tang, Z.; Shi, H.; Zhu, Y.; Shen, Y.; Wang, T. Thermoplastic Starch Based Blends as a Highly Renewable Filament for Fused Deposition Modeling 3D Printing. *Int. J. Biol. Macromol.* **2022**, *219*, 175–184. [\[CrossRef\]](#)
114. Esper, L.B.; Batista, I.T.S.; dos Santos, M.V.; Ribeiro, C.A.; Finocchio, H.; Amaral, A.C.; da Silva Barud, H. Compatible Composites Filaments Based on PHB/Starch for 3d Printing via Fused Deposition Modeling. *Biotechnol. Sustain. Mater.* **2025**, *2*, 5. [\[CrossRef\]](#)
115. Zhao, W.; Huang, B.; Zhu, L.; Feng, X.; Xu, J.; Zhang, H.; Yan, S. Printable Hydrogels Based on Starch and Natural Rubber Latex with High Toughness and Self-Healing Capability. *Int. J. Biol. Macromol.* **2022**, *218*, 580–587. [\[CrossRef\]](#)
116. Willfahrt, A.; Steiner, E.; Hötzel, J.; Crispin, X. Printable Acid-Modified Corn Starch as Non-Toxic, Disposable Hydrogel-Polymer Electrolyte in Supercapacitors. *Appl. Phys. A Mater. Sci. Process.* **2019**, *125*, 474. [\[CrossRef\]](#)
117. Wang, X.J.; Wang, J.; Yang, Z.; Zhang, Y.; Cheng, K.; Han, J.Y.; Chang, F.X.; Yong, Y.C. 3D Printing of Synthetic Microbial Consortium for Boosting Bioelectricity Generation from Starch. *Chem. Eng. J.* **2025**, *512*, 162519. [\[CrossRef\]](#)
118. Oliveira, J.; Correia, V.; Castro, H.; Martins, P.; Lanceros-Mendez, S. Polymer-Based Smart Materials by Printing Technologies: Improving Application and Integration. *Addit. Manuf.* **2018**, *21*, 269–283. [\[CrossRef\]](#)
119. Su, C.-Y.; Li, D.; Wang, L.-J.; Wang, Y. Green Double Crosslinked Starch-Alginate Hydrogel Regulated by Sustained Calcium Ion-Gluconolactone Release for Human Motion Monitoring. *Chem. Eng. J.* **2023**, *455*, 140653. [\[CrossRef\]](#)
120. Qamruzzaman, M.; Ahmed, F.; Mondal, M.I.H. An Overview on Starch-Based Sustainable Hydrogels: Potential Applications and Aspects. *J. Polym. Environ.* **2022**, *30*, 19–50. [\[CrossRef\]](#)
121. Rilling, S.; Ríos, I.; Gómez, Á.; Valenzuela, M.; Oñate, A.; Tuninetti, V. Optimized Infill Density through Topological Optimization Increases Strength of Additively Manufactured Porous Polylactic Acid. *Int. J. Adv. Manuf. Technol.* **2023**, *129*, 3739–3750. [\[CrossRef\]](#)
122. Jeong, E.H.; Choi, J.; Park, H.B.; Lee, J.W.; Bae, S.Y.; Kim, B.S.; Yoon, C.K.; Park, J.D. Data-Driven Printability Modeling of Hydrogels for Precise Direct Ink Writing Based on Rheological Properties. *Adv. Sci.* **2026**, *13*, e07639. [\[CrossRef\]](#)
123. Tuninetti, V.; Narayan, S.; Ríos, I.; Menacer, B.; Valle, R.; Al-lehaibi, M.; Kaisan, M.U.; Samuel, J.; Oñate, A.; Pincheira, G.; et al. Biomimetic Lattice Structures Design and Manufacturing for High Stress, Deformation, and Energy Absorption Performance. *Biomimetics* **2025**, *10*, 458. [\[CrossRef\]](#)

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