

Sweet Science: How Biotechnology is Shaping the Future of Edible 3D Printing

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Abstract

Biotechnology plays an important role in developing sugars and sugar substitutes used in 3D printing edible decorations. Traditional sugar, derived from cane or beet, is being increasingly supplemented with biotechnologically engineered alternatives that offer improved functionality, sustainability, and customization for 3D food printing. Through microbial fermentation, biotechnology enables the production of sugar substitutes like erythritol, xylitol, and isomalt, which are ideal for printing due to their unique properties such as lower melting points, enhanced stability, and resistance to crystallization. Enzymatic modifications further refine sugars' texture, viscosity, and crystallization behaviour, optimizing them for precise printing and creating smoother, more intricate edible designs. Additionally, biotechnology facilitates the development of biodegradable and eco-friendly sugar-based materials, addressing concerns about food waste and environmental sustainability. Fortified sugars and biopolymers are also engineered and transformed to incorporate health benefits, such as added fibre, vitamins, and probiotics, opening new possibilities for functional, personalized food prints. Overall, biotechnology is not only improving the quality and versatility of sugar in 3D food printing, but also enabling the creation of more sustainable, customized, and health-conscious edible decorations that push the boundaries of culinary artistry.

Keywords: sweet, 3D printing edible decoration

1. Introduction

Three-dimensional food printing (3DFP) represents one of the most promising innovations in food technology, integrating additive manufacturing principles with culinary and nutritional sciences. Beyond aesthetics, 3DFP enables precise control of texture, flavor, and nutrient distribution, offering applications ranging from customized nutrition and medical foods to artistic confectionery. However, one of the primary challenges in 3DFP lies in developing printable materials with appropriate rheology, stability, and functional properties. Biotechnology has emerged as a key enabler in overcoming these challenges. Through microbial

fermentation, enzymatic modification, and the synthesis of bio-based polymers, biotechnology provides novel food-grade materials that are printable, nutritious, and sustainable. This review explores the mechanisms by which biotechnology shapes the future of edible 3D printing, with a focus on sugar substitutes, fermentation-driven functional foods, enzymatic tailoring, and sustainable material innovation.

2. Biotechnology and functional 3D food printing

Biotechnology has emerged as a transformative driver in the evolution of 3D food printing (3DFP) – an interdisciplinary field combining digital design, food science, and material engineering to create customizable, functional, and sustainable edible products. This convergence aligns with the fourth industrial revolution's goals of

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personalization, automation, and circular bioeconomy integration. At its core, biotechnology provides bioengineered ingredients, enzymatically enhanced compounds, and microbial-derived materials that optimize printability, nutrition, and structure.

In recent years, research has shown that biotechnology expands 3DFP's functional range from novelty confectionery to nutritionally enriched foods with targeted health benefits [1]. Peptide-based hydrogels (PHs) represent a breakthrough class of bioengineered food materials—capable of acting as rheologically stable inks, improving textural fidelity and enabling nutrient encapsulation. Similarly, the combination of 3D printing and microbial biofilm engineering allows for the design of probiotic-embedded foods that deliver live cultures and bioactive molecules [2].

Traditional 3D food inks, such as starch, gelatin, or sucrose, face major rheological and physicochemical limitations that restrict their structural accuracy and print fidelity. The crystallization behavior of sucrose, in particular, leads to irregular surface textures and nozzle blockages, while gelatin-based inks exhibit thermosensitivity, resulting in deformation or collapse under fluctuating printing temperatures. Starch matrices, though cost-effective, often demonstrate inconsistent viscosity and retrogradation tendencies that hinder continuous extrusion and post-print stabilization.

Biotechnology provides solutions to these challenges through enzymatic modification and molecular design. Enzymes such as invertase, amylase, and transglucosidase can hydrolyze or reconfigure carbohydrate linkages, transforming high-crystallinity sugars into amorphous or semi-crystalline forms with more desirable viscoelastic profiles. This modification controls gelation kinetics, melting behavior, and flow consistency, ensuring smooth extrusion during printing. Additionally, enzymatic treatments can alter the ratio of glucose and fructose components, effectively reducing crystallization potential and enhancing moisture retention.

Furthermore, engineered oligosaccharides and functional sugar derivatives produced via biotechnology, such as isomaltulose or maltitol, offer superior stability and lower hygroscopicity, preventing unwanted phase separation. These biotechnologically optimized sugars not only enhance print resolution and layer adhesion but

also extend shelf life, taste uniformity, and aesthetic appeal in edible constructs, particularly in confectionery and decorative applications, where structural precision and smoothness are paramount [3].

Moreover, biotechnology's integration in food printing extends to functionalization, where ingredients are modified to include probiotics, vitamins, or prebiotic fibers. Probiotic encapsulation within 3D-printed matrices has demonstrated improved survival under gastric conditions [4], aligning with precision nutrition and enabling foods tailored to specific dietary needs or medical requirements.

3DFP's application in functional food design fosters sustainability through waste valorization and ingredient optimization. Biotechnologically derived sugars and polysaccharides can be sourced from lignocellulosic biomass or microbial cultures, transforming byproducts into high-value food materials [5]. The outcome is a paradigm shift from traditional, resource-intensive food manufacturing to a bio-based, data-driven production model emphasizing both nutritional and environmental performance.

3. Microbial fermentation for sugar substitutes and biopolymers

Microbial fermentation represents a cornerstone of biotechnological advancement in edible 3D printing, offering sustainable and functional solutions for the development of sugar substitutes and biopolymers. Through controlled microbial processes, organisms such as *Moniliella pollinis*, *Lactobacillus plantarum*, and *Candida magnoliae* can synthesize compounds like erythritol, mannitol, and xylitol, which replicate sweetness without the metabolic drawbacks of sucrose [6].

These bioengineered sweeteners possess advantageous physical properties lower melting points, reduced hygroscopicity, and improved thermal stability making them ideal for additive manufacturing. Lactic acid bacteria (LAB) produce sugar alcohols and organic acids that not only replace sugar but also serve as texturizing and preservative agents in printed matrices [7]. LAB-based fermentation further yields biopolymers such as exopolysaccharides (EPS) that enhance the rheology and mechanical stability of food inks [8].

EPS such as dextran, gellan gum, xanthan, and pullulan demonstrate tunable viscoelastic properties and biocompatibility [9]. Their use allows for controlled extrusion, shape retention, and moisture regulation during printing and storage. EPS produced from extremophilic bacteria exhibit resistance to crystallization, allowing their deployment in multi-material 3D food systems that integrate flavor gradients or color layers [10].

Microbial fermentation contributes to nutritional and metabolic improvements in 3D-printed foods. Many microbial polysaccharides act as prebiotic fibers, selectively stimulating beneficial gut bacteria and enhancing digestibility [11]. Microbial biotechnology can tailor the nutritional profile of plant-based printed foods, enriching them with natural antioxidants, vitamins, and peptides [12]. This aligns 3D food printing with functional and health-oriented goals.

Fermentation utilizes renewable feedstocks—such as molasses, glycerol, or fruit waste to generate high-purity biopolymers and sweeteners, thereby minimizing chemical synthesis and carbon footprint. Integrating fermentation with 3D printing contributes to closed-loop food production, where waste materials are converted into printing-grade ingredients [13]. This model exemplifies the circular bioeconomy, reducing dependence on agricultural monocultures and synthetic additives.

Figure 1 presents an integrated model demonstrating how biotechnological processes (microbial fermentation, enzymatic modification, and bio-based material synthesis) interact to enhance the

production of functional and sustainable edible 3D-printed foods.

- Microbial fermentation enables the generation of sugar substitutes (e.g., erythritol, isomalt) and microbial exopolysaccharides (EPS) that serve as natural biopolymers with tunable rheological properties [7, 13].

- Enzymatic modification processes (using invertase, inulinase, α -galactosidase, etc.) optimize texture, crystallization behavior, and viscosity, leading to smoother and more stable printable sugars [9]

- Bio-based materials from microalgae and fungi provide sustainable, biodegradable matrices compatible with 3D printing and food safety requirements [10].

These pathways collectively yield functional foods (e.g., probiotic or fortified snacks) and sustainable edible structures with enhanced nutritional and aesthetic qualities, aligning with the broader goal of personalized, health-conscious, and eco-friendly 3D food systems [4, 14].

Co-culture fermentation systems – Involving yeast and bacteria – enable synergistic production of sweeteners, EPS, and flavor compounds. These systems can be engineered to express recombinant enzymes like glucose isomerase or fructosyl-transferase, further improving the yield and specificity of sugar substitute synthesis. When coupled with metabolic engineering and CRISPR-based genetic optimization, fermentation becomes a programmable process, precisely tailored to produce custom ingredients for 3DFP applications.

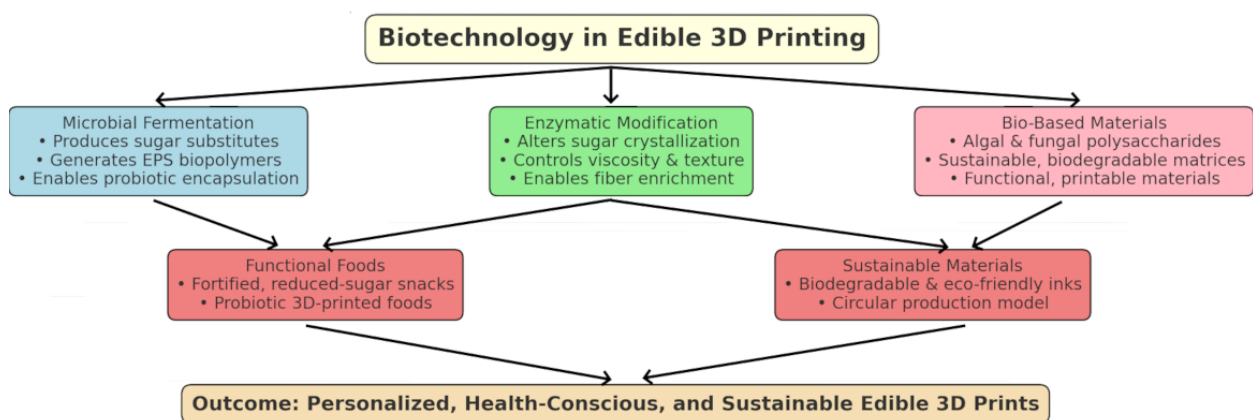


Figure 1. The role of biotechnology in edible 3D printing

4. Enzymatic modification for printability and functionality

Enzymatic modification bridges the molecular characteristics of carbohydrates and the mechanical requirements of 3D printing. Enzymes serve as biocatalysts that modify sugar structures, influencing their crystallization kinetics, viscosity, and melting behavior – critical factors for extrusion-based additive manufacturing.

Enzymatic processing using α -galactosidase, inulinase, and invertase reduces fructan content in bran-based food materials, improving both health outcomes and printability [14]. Such enzymatic hydrolysis decreases polymerization, yielding smaller, more soluble oligosaccharides that can flow smoothly through printer nozzles without clogging or crystallizing prematurely.

Enzymatic treatment enhances interlayer adhesion and surface finish by modulating the rheological profile of sugar-based inks. Amylases and transglucosidases convert starch-based substrates into maltodextrins and dextrins with optimal viscosity ranges for extrusion [15]. Controlled hydrolysis allows fine-tuning of gelation time and structural integrity post-printing, ensuring high-resolution edible constructs.

Enzymatic modification extends to proteins and polysaccharides functioning as matrix stabilizers. Enzyme-assisted crosslinking using transglutaminase or laccase increases elasticity and water-binding capacity of edible inks, crucial for maintaining texture during post-processing. Multi-enzyme cascades integrate several catalytic steps to achieve simultaneous texture, sweetness, and functionality optimization. Enzymatic synthesis of isomaltooligosaccharides (IMOs) from starch via transglycosylation not only enhances prebiotic potential but also reduces crystallization – a dual benefit for 3D printing applications.

5. Sustainable bio-based and algal materials

The sustainability imperative in modern food biotechnology strongly promotes the adoption of bio-based, renewable materials for edible 3D printing applications. Microalgae and fungi are increasingly recognized as efficient, low-impact sources of polysaccharides, cellulose derivatives, and functional biopolymers that can replace traditional, non-biodegradable components in food inks. Enzymatically modified algal cellulose—

particularly methacrylate-functionalized carboxymethyl cellulose (CMC) exhibits excellent print fidelity, rheological stability, and biodegradability [16]. These bioinks provide both structural precision and environmental compatibility, reducing the industry's reliance on petroleum-based plastics for edible decorations and packaging.

Similarly, fungal-derived chitin-glucan complexes and β -glucans serve as sustainable thickening, stabilizing, and gelling agents, compatible with natural colorants, flavor compounds, and nutrient additives. Their incorporation reduces energy consumption during molding and drying, while maintaining desirable texture and integrity. By valorizing waste biomass from algal and fungal sources, biotechnology supports a circular bioeconomy, turning organic residues into functional 3D printing substrates and fostering a greener, more resilient food production system.

6. Fermentation-driven probiotic and functional foods

A major frontier in biotechnology-enhanced 3D food printing lies in developing fermented probiotic systems, combining microbiology, materials science, and digital fabrication. The concept of probiotic 3D printing integrates viable microorganisms within edible matrices, offering personalized health benefits such as gut microbiome modulation and immune regulation [17].

Functional foods leverage controlled fermentation to stabilize probiotics before printing. Strains like *Lactobacillus rhamnosus* or *Bifidobacterium breve* are encapsulated in hydrocolloid matrices to preserve cell viability during thermal extrusion [18]. Chen et al. (2023) demonstrated 3D printing, where probiotics induce color changes in starch-protein gels during growth, offering real-time indicators of microbial activity and freshness [19]. Biotechnological co-processing enhances synergy between 3D printing and fermentation, allowing co-cultures to develop within printed structures. This in situ fermentation transforms the printed matrix into a living food system that continues to mature post-printing. Such microbial interactions facilitate biosynthesis of organic acids, vitamins, and bioactive peptides – creating next-generation functional foods [20]

7. Future perspectives: personalized and functional edible prints

The next decade will witness a convergence between synthetic biology, AI-driven design, and 3D food printing, leading to personalized, health-conscious, and sustainable edible products. Future research should focus on programmable microbial systems, enabling on-demand production of sweeteners, nutrients, and textures through embedded biological circuits.

Personalization will define the trajectory of 3DFP. By integrating biosensing and adaptive control, foods may dynamically respond to consumer nutritional profiles, creating individualized diets powered by real-time biotechnology [21]. Sustainable biomanufacturing pipelines leveraging waste substrates, enzymatic catalysis, and microbial fermentation will further align the edible 3D printing industry with global carbon reduction goals.

Conclusions

Biotechnology is reshaping the landscape of edible 3D printing by introducing sustainable, functional, and health-oriented ingredients that bridge the gap between food innovation and environmental responsibility. Microbial fermentation, enzymatic modification, and biopolymer synthesis collectively enable the creation of novel printable materials with improved rheological properties, reduced waste, and enhanced nutritional profiles. These advancements not only elevate food aesthetics and personalization but also align with global sustainability goals through circular bioeconomy principles. Looking forward, the integration of synthetic biology, AI-driven design, and smart biosensing materials promises to revolutionize 3D food printing, enabling precision nutrition, adaptive food customization, and real-time quality control, transforming the future of food manufacturing into a more intelligent and eco-conscious process.

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