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3-D Printing Technology Used in Extrusion: Emerging Applications in Food Processing

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ABSTRACT

Additive manufacturing, popularly known as 3-D printing, has moved from prototyping plastics and metals into the food sector, where extrusion is the dominant deposition route. Extrusion-based 3D food printing builds an edible object layer by layer by forcing a semi-solid or paste-like food material, called a food ink, through a nozzle under controlled pressure. The process borrows its material-transport logic from conventional food extrusion cooking, but replaces continuous shaping through a fixed die with computer-controlled, point-by-point deposition that can generate almost any geometry. This article reviews the principle of extrusion-based 3D food printing, its relationship with conventional single- and twin-screw extrusion cooking, the rheological requirements that decide whether a food material can be printed, the raw materials currently used as food inks, and the applications of this technology in personalized nutrition, dysphagia and geriatric care, confectionery, meat analogue design, and space food systems. The challenges that still limit large-scale adoption, namely printing speed, food safety, regulatory clarity, and cost, are also discussed.

Keywords: 3-D printing, Food processing, Extrusion, Emerging technology and novel technology

INTRODUCTION

Extrusion is one of the oldest and most versatile unit operations in food processing. In its conventional form, raw material is fed into a barrel, conveyed by one or two rotating screws, subjected to heat, pressure, and shear, and finally forced through a shaped die to produce a continuous, uniformly shaped product such as pasta, breakfast cereal, snack pellets, or textured vegetable protein (Hussain *et al.,* 2022). The technology is valued because a single machine can mix, cook, sterilize, shape, and texturize a formulation in one continuous step (Frame, 1994).

Three-dimensional printing applies a very different logic to the same underlying transport phenomenon. Instead of pushing material continuously through a fixed die to make a long, uniform strand, a 3D printer moves the nozzle (or the build platform) in three axes while depositing material only where the digital model requires it, building the object one thin layer at a time (3D food printing (n.d.). When the deposition itself is achieved by extruding a food paste through a nozzle, the technique is called extrusion-based 3D food printing (3DFP), and it is by far the most widely used and most extensively researched of the four broad 3D food printing categories, the others being inkjet printing, binder jetting, and selective sintering (Ehsan *et al.,* 2025).

For a food technologist, extrusion-based 3DFP is best understood as extrusion re-purposed for shape freedom rather than for shape uniformity. The same questions that matter in a twin-screw extrusion line, material flow behaviour, moisture content, particle size, and thermal history, decide whether a formulation can be printed, but the target is now a bespoke three-dimensional structure rather than a continuous extrudate (Hussain *et al.,* 2022). This convergence has opened a distinct branch of food process engineering, with applications ranging from personalised therapeutic diets

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to novelty confectionery and even food systems for long-duration space missions (Enfield *et al.,* 2022; Shabir *et al.,* 2024).

Conventional Extrusion Technology in Food Processing

Principle of Extrusion Cooking

Extrusion cooking is a high-temperature, short-time thermo-mechanical process in which heat transfer, mass transfer, pressure build-up, and shear act together inside the barrel to cook, sterilize, dry, texturize, and shape a food material in a single pass (Extrusion Cooking (n.d.). Raw material entering the feed zone is conveyed forward by the screw; as the flight depth decreases toward the transition and metering zones, the material is compressed, and resistance to flow builds up because of the restriction imposed by the die at the exit (Extrusion Cooking (n.d.). This combination of thermal and mechanical energy gelatinizes starch, denatures and texturizes protein, and inactivates microorganisms and anti-nutritional factors, while the die imposes the final cross-sectional shape.

Single-Screw and Twin-Screw Extruders

Single-screw extruders have a simple feed, transition, and metering zone arrangement and are still used for straightforward shaping duties, but twin-screw extruders, particularly the co-rotating, self-wiping type, dominate modern food processing because of their superior mixing, venting, and handling of high-moisture and high-fat formulations (Pein, 2025a; Pein, 2025b). A twin-screw machine consists of two intermeshing screws rotating inside a figure-of-eight barrel, a feeding system, multiple independently controlled heating and cooling zones, and a die block instrumented with pressure and temperature sensors (MT Food Machine Technical Resource, 2026). Modular screw elements allow the intensity of mixing, shear, and residence time to be tuned for a given raw material, which is why twin-screw extrusion is used for products as different as expanded snacks, textured vegetable protein, pet food kibble, and instant noodles (Pein, 2025b; MT Food Machine Technical Resource, 2026).

Applications of Conventional Extrusion in the Food Industry

Beyond snack and cereal manufacture, extrusion cooking is central to the production of pasta, ready-to-eat breakfast cereals, pet foods and aquafeeds, processed cheese, confectionery, and increasingly, plant-based meat analogues, where high-moisture extrusion aligns and cross-links plant proteins into anisotropic, fibrous structures that mimic muscle tissue [Extruders (n.d.); Sui *et al.*, 2024]. It is this last application area, structuring proteins through controlled shear and thermal history, that links most directly to the extrusion-based 3D printing systems discussed in the following sections.

Three-Dimensional Printing: Concept and Classification

3D printing, or additive manufacturing, builds an object by adding material layer by layer according to a digital computer-aided design file, in contrast to subtractive manufacturing, which removes material from a bulk block [3D food printing (n.d.)]. When the printed material is an edible formulation, the process is termed 3D food printing. Four principal technologies have been adapted for food: extrusion-based printing, inkjet printing, binder jetting, and selective laser sintering, each differing in how material is deposited and solidified, and each suited to a different category of food material (Ehsan *et al.,* 2025; Arshad *et al.*, 2025).

An Inkjet printing deposit fine droplets of low-viscosity liquid ink and is best suited to decorating surfaces or depositing small amounts of flavour, colour, or functional ingredients rather than building large three-dimensional structures. Binder jetting selectively binds a

Table 1 : Comparison of the major 3D food printing technologies

Technology	Material form required	Deposition principle	Typical food application
Extrusion-based printing	Semi-solid paste, gel, or dough	Material forced through a nozzle by piston, screw, or pneumatic pressure	Purees, starch/protein gels, chocolate, dough
Inkjet printing	Low-viscosity liquid	Fine droplets ejected onto a surface	Surface decoration, flavour/ colour deposition
Binder jetting	Powder bed	Liquid binder selectively deposited on powder layers	Sugar-based confectionery
Selective sintering	Powder bed	Laser or hot air locally fuses powder particles	Sugar and fat-based systems

Source: Compiled from references (Hussain *et al.,* 2022; 3D food printing (n.d.); Ehsan *et al.,* 2025; Arshad *et al.*, 2025)

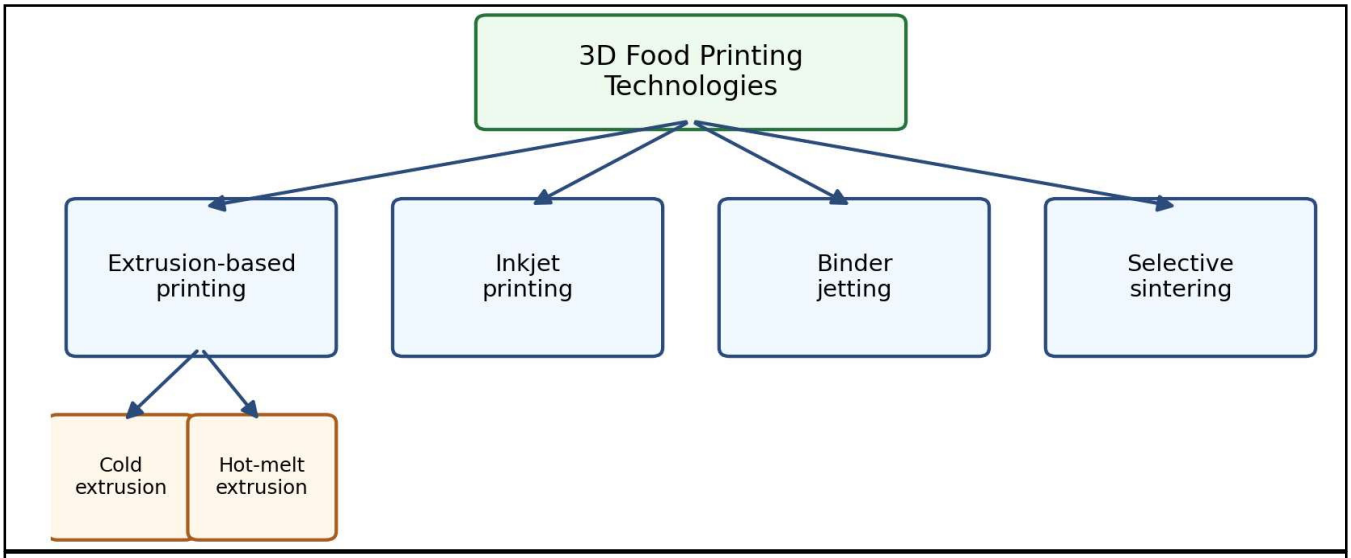

Fig. 1 : Classification of major 3D food printing technologies

powder bed with a liquid binder, layer by layer, and has been explored for sugar-based confectionery. Selective sintering uses a laser or hot air to fuse powder particles locally, a route demonstrated for sugar and fat-based systems (Ehsan *et al.,* 2025; Arshad *et al.*, 2025). Extrusion-based printing, by contrast, can process semi-solid pastes, gels, and doughs directly, which matches the physical form of the great majority of real food materials; this is the principal reason it has become the dominant platform for 3D food printing research and commercial development [Hussain *et al.,* 2022; 3D food printing (n.d.)].

Extrusion-Based 3D Food Printing: Principle and Mechanism

In extrusion-based 3DFP, a food paste held in a syringe- or cartridge-type reservoir is forced through a small nozzle by a piston, screw, or pneumatic pressure, while the nozzle or the build platform traces the x, y, and z coordinates generated by slicing a digital model into thin horizontal layers (Hussain *et al.,* 2022). The deposited material must flow readily under the applied shear so that it can pass through the nozzle, yet it must stop flowing and hold its shape as soon as it is deposited, so that the next layer can be built on top of it without collapse (Qin *et al.*, 2025). This dual requirement, easy flow under shear and rapid structural recovery at rest, is the central engineering problem of extrusion-based 3D food printing, and it is normally solved by formulation rather than by hardware. Three extrusion mechanisms are generally recognised for food materials (Tan *et al.*, 2018; Teng *et al.*, 2022).

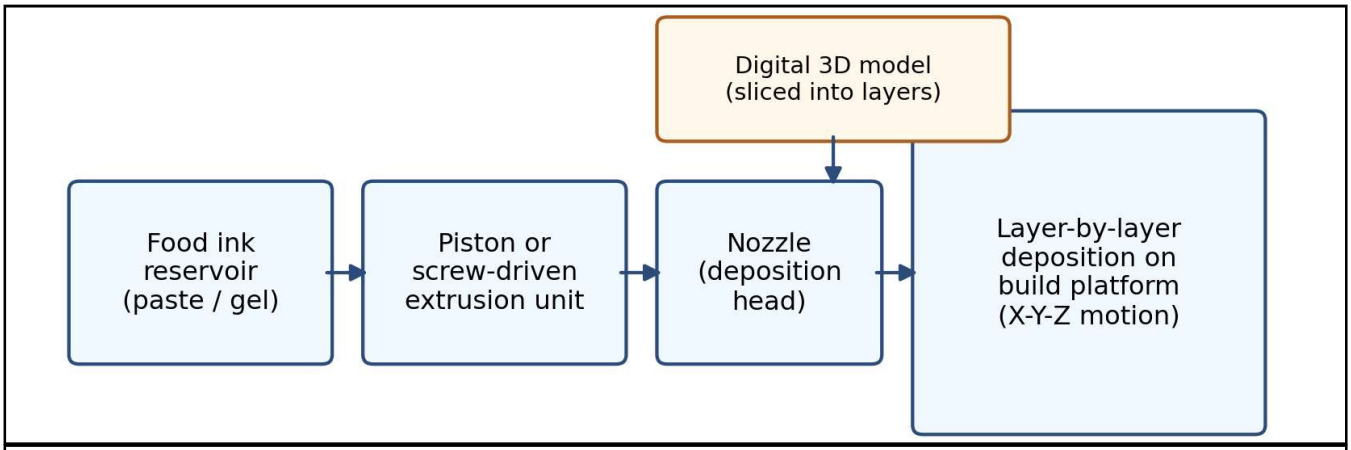

Fig. 2 : Schematic of the extrusion-based 3D food printing process

Table 2 : Extrusion mechanisms used in 3D food printing

Extrusion type	Temperature condition	Setting mechanism	Representative materials
Cold extrusion	Ambient / refrigerated, no phase change	Inherent yield stress of the paste	Mashed potato, purees, hydrocolloid gels, soft cheese
Hot-melt extrusion	Heated to just above melting point (e.g., 31-36 degC for chocolate)	Solidification on cooling after deposition	Chocolate, fats, sugar-fat blends
Extrusion with post-deposition gel-setting	Ambient during printing	Ionic cross-linking, thermal setting, or enzymatic bridging after deposition	Alginate gels, enzyme-set protein systems

Source: Compiled from references (Qin *et al.*, 2025; Teng *et al.*, 2022; Karyappa and Hashimoto, 2019; Singapore University of Technology and Design, 2019)

Room-Temperature (Cold) Extrusion

Cold extrusion deposits a paste, gel, or purée at ambient or refrigerated temperature without any phase change during printing. Materials such as mashed potato, hydrocolloid gels, fruit and vegetable purées, and soft cheese are typically printed this way, and printability depends entirely on the rheology of the formulation as prepared, rather than on temperature control during printing (Teng *et al.*, 2022).

Hot-Melt Extrusion

Hot-melt extrusion heats the food material slightly above its melting point immediately before or during extrusion so that it flows through the nozzle and then resolidifies on cooling. Chocolate is the archetypal example: conventional hot-melt 3D printing of chocolate requires the ink to be held within a narrow band of about 31 to 36 degrees Celsius so that it remains fluid enough to extrude but sets quickly enough after deposition to hold its shape, a constraint that closely mirrors fused deposition modelling used for thermoplastics (Karyappa and Hashimoto, 2019; Singapore University of Technology and Design, 2019). Because this temperature window is narrow and easily disturbed, researchers have explored alternative cold-extrusion chocolate inks, formulated by blending chocolate syrup or paste with cocoa powder to obtain shear-thinning, yield-stress behaviour without any need for temperature control during printing (Karyappa and Hashimoto, 2019; 3D printing of chocolate, a new approach, 2019).

Extrusion Followed by Gel-Setting

A third route relies on a chemical or enzymatic setting reaction after deposition rather than on cooling. The ink is extruded at room temperature in a fluid or weakly structured state and is then set into a stable gel through ionic cross-linking, such as calcium-induced gelation of alginate, thermal setting, or enzymatic bridging, allowing complex internal structures to be built from materials that would otherwise be too soft to self-support (Qin *et al.*, 2025).

Process Parameters Governing Print Quality

Even with a printable formulation, the geometric accuracy, surface finish, and structural stability of the final object depend strongly on machine settings. The nozzle diameter fixes the minimum feature size and the cross-section of each deposited strand; a narrower nozzle gives finer resolution but raises the risk of clogging with particulate or fibrous ingredients, while a wider nozzle

Table 3 : Key process parameters influencing extrusion-based 3D food printing quality

Parameter	Effect of increasing the parameter	Practical consequence
Nozzle diameter	Wider strand per pass; lower resolution	Faster printing but coarser detail; narrow nozzles risk clogging with fibrous or particulate inks
Layer height	Fewer layers needed for a given object height	Faster build but weaker interlayer bonding; very thin layers can over-compress the strand
Printing (path) speed	Less time for material relaxation at the nozzle	Too fast for the ink's yield behaviour can starve flow or tear the deposited strand
Print/ink temperature	Alters viscosity and setting behaviour	Must stay within a narrow window for hot-melt or gel-setting inks to remain flowable yet set correctly

Source: Compiled from references (Thangalakshmi *et al.*, 2022; Bugday *et al.*, 2024)

allows faster deposition at the cost of detail (Thangalakshmi *et al.*, 2022). Layer height, generally set as a fraction of the nozzle diameter, controls vertical resolution and interlayer bonding; excessively thick layers reduce bonding strength between layers, while excessively thin layers may over-compress the deposited strand (Thangalakshmi *et al.*, 2022). Printing speed and the print head's path width must be matched to the material's yield behaviour, since printing too fast for a given ink can starve the nozzle or tear the deposited strand, and print temperature (for hot-melt and gel systems) must be held within the narrow window that keeps the ink flowable without triggering premature setting (Thangalakshmi *et al.*, 2022; Bugday *et al.*, 2024). In a systematic optimisation of a rice flour and jaggery paste ink, nozzle diameter, layer height, path width, and print speed were all found to significantly influence print time, weight, and dimensional accuracy, with layer height and path width identified as the most influential parameters (Thangalakshmi *et al.*, 2022).

Rheology and Printability of Food Inks

Printability is fundamentally a rheological property. A food ink suitable for extrusion-based 3DFP must show pronounced shear-thinning behaviour, so that its apparent viscosity drops sharply under the shear imposed inside the nozzle, and it must possess a measurable yield stress, the minimum stress required to initiate flow, so that the deposited strand does not slump or spread once the nozzle has moved on (Bugday *et al.*, 2024; Maldonado-Rosas *et al.*, 2022). Oscillatory rheological measurements are commonly used to quantify the storage modulus, loss modulus, and their ratio, tan delta, as indicators of gel strength and viscoelastic solid-like behaviour after deposition (Kaveti, 2022). A strong correlation has been reported between yield stress and the force required to extrude a paste, while printing accuracy correlates more moderately with yield stress and the strain-thinning exponent, reflecting the practical difficulty of achieving perfectly homogeneous, well-hydrated food pastes at laboratory and pilot scale (Maldonado-Rosas *et al.*, 2022).

Hydrocolloids are the principal tool used to engineer this rheological window into an otherwise unprintable food material. Xanthan gum, kappa-carrageenan, gellan gum, pectin, alginate, gelatin, and carboxymethyl cellulose are all commonly incorporated, individually or in combination, to raise viscosity, impart yield stress, and improve shape retention after printing (Kaveti, 2022; Nikolaou *et al.*, 2025). In one study, xanthan gum's high water-hydration capacity was shown to suppress swelling of dispersed vegetable powder particles, keeping the rheological properties more consistent across different vegetable sources and giving smoother extrusion with less printing force (Nikolaou *et al.*, 2025). In composite starch-protein-hydrocolloid systems, kappa-carrageenan produced the strongest gels and the highest dimensional accuracy, in the range of ninety-three to ninety-six percent, among the hydrocolloids tested (Kaveti, 2022). These findings illustrate that printability is not an intrinsic property of a raw ingredient but an outcome of formulation design guided by rheological testing.

Raw Materials Used in Extrusion-Based 3D Food Printing

Starch-Based Materials

Gelatinized starch is one of the most widely studied 3D food printing inks because the swelling, partial melting, and amylose leaching that occur on heating in the presence of water create a viscoelastic gel with the shear-thinning and rapid shear-recovery behaviour that printing requires (Kim *et al.*, 2018; Rong *et al.*, 2023). The degree of pre-printing gelatinization strongly affects both printability and starch digestibility; for rice and wheat starch pastes, optimal printability and resistance to digestion were reported at gelatinization degrees of about fifty and forty percent, respectively, since partial rather than complete gelatinization preserves enough ordered structure to support the printed object while still allowing sufficient flow (Xian *et al.*, 2024). Extrusion-based 3D printing itself, because it applies high shear at comparatively low moisture content, can mechanically break down starch granules in a manner distinct from conventional aqueous gelatinization, offering a further route to tune structure and, potentially, nutritional digestibility (Zheng *et al.*, 2022). Blending native starch with pre-gelatinized high-amylose starch or with proteins such as soy, pea, or whey protein isolate has also been used to reinforce weak native-starch gels and widen the printable window (Shahbazi *et al.*, 2023).

Protein-Based Materials

Dairy proteins, egg white, soy protein, pea protein, and other plant proteins are all used as functional 3D printing inks, generally in combination with hydrocolloids or starch to achieve adequate self-supporting strength (Cheng *et al.*, 2024). In systems built from pea protein

isolate and chickpea protein concentrate stabilised with gellan and xanthan gum, both formulations showed the yield stress, shear-thinning flow, and weak-gel viscoelasticity associated with good printability, though the chickpea-based ink achieved a substantially higher yield stress than the pea-based one, showing that protein source, not just protein content, governs printing performance (Guo *et al.*, 2022).

Chocolate and Confectionery

Chocolate remains the most commercially visible food ink, printed mainly by hot-melt extrusion within its narrow molten-temperature range, and used to create intricate decorative and novelty confectionery shapes that would be difficult to mould conventionally (Karyappa and Hashimoto, 2019; Singapore University of Technology and Design, 2019). Sugar-based systems are also printed by binder jetting and selective sintering for similar decorative purposes (Ehsan *et al.,* 2025).

Fruits, Vegetables, and Meat Analogues

Fruit and vegetable purées, typically dominated by water, require added hydrocolloids to build sufficient structure for printing, and the choice of hydrocolloid strongly affects how consistently different fruit and vegetable sources behave once printed (Menegon and Piazza, 2026; Nikolaou *et al.*, 2025). In parallel, extrusion-based 3D printing is being explored for plant-based and hybrid meat analogues, where pea protein and pea protein-chicken blends have been formulated and printed to evaluate their physico-chemical and textural resemblance to conventional soft meat products (Wang *et al.*, 2023). Because conventional high-moisture extrusion is already the principal industrial route for creating fibrous, meat-like texture from plant protein, its material science overlaps directly with the formulation science needed to print meat analogue inks with realistic texture (Sui *et al.*, 2024; Maxy *et al.*, 2024).

Convergence of Conventional Extrusion Cooking and 3D Printing

The relationship between conventional extrusion cooking and extrusion-based 3D printing is best described as a shared toolbox rather than two unconnected fields. High-moisture extrusion cooking is currently the dominant industrial method for texturizing plant protein into anisotropic, fibrous structures that resemble meat, through phase orientation of the protein melt as it develops in the screw section and is amplified through the cooling die (Sui *et al.*, 2024; Maxy *et al.*, 2024). Several research groups have begun combining this texturizing step with 3D printing, either by using extrudate as a feed material for a subsequent printing stage or by studying 3D printing directly as an alternative structuring technique alongside extrusion, shear-cell processing, and electrospinning for meat analogue manufacture (Högg and Rauh, 2023; Wang *et al.*, 2023). Pre-gelatinization of starch by extrusion cooking before printing is a further point of convergence, since the same degree-of-gelatinization control that determines conventional extruded product quality also determines whether the resulting paste can be printed with dimensional accuracy (Xian *et al.*, 2024; Zheng *et al.*, 2022). In effect, twin-screw extrusion cooking increasingly functions as a pre-processing or ingredient-structuring step that prepares the food matrix, while the 3D printer performs the final, geometry-defining deposition step; the two technologies are complementary parts of the same processing chain rather than substitutes for each other.

Applications of Extrusion-Based 3D Food Printing

Personalized and Precision Nutrition

Because a 3D printer can vary the composition, shape, and internal structure of each individual object under digital control, it is well suited to producing food matched to an individual's calorie, macronutrient, or micronutrient requirements, an application area frequently described as personalized or precision nutrition (Enfield *et al.,* 2022). Nutrient release can, in principle, also be engineered by controlling internal porosity and layer architecture, opening possibilities for functional foods with tailored digestion kinetics (Enfield *et al.,* 2022).

Dysphagia Management and Geriatric Nutrition

Among the most clinically motivated applications is the design of food for people with dysphagia, a swallowing impairment common in the elderly, which forces many patients onto texture-modified, pureed diets that are nutritionally adequate but visually and sensorially unappealing, contributing to reduced intake and malnutrition (Shabir *et al.,* 2024; Chao *et al.*, 2024). 3D printing can reconstruct a purée into the recognisable shape of the original food, such as a pork leg cut or a vegetable, while hydrocolloids and proteins are used to hold the required soft, cohesive texture and to meet standardized swallowing-safety texture levels, for

instance those defined by the International Dysphagia Diet Standardisation Initiative (Shabir *et al.,* 2024; Liu *et al.*, 2021; Xie *et al.*, 2023). Shiitake mushroom pastes reinforced with gum arabic, xanthan gum, and kappa-carrageenan gum have been printed into dysphagia-appropriate, minced-and-moist textures with good self-supporting strength, illustrating how a naturally hard-textured ingredient can be reformulated into a safe, appealing product for this population (Liu *et al.*, 2021).

Space Food Systems

Long-duration space missions face food constraints that conventional processing cannot easily solve: shelf-stable, prepackaged meals struggle to provide five years of nutrient stability, and refrigeration is costly in terms of spacecraft resources (Gannon, 2013). NASA-funded early work explored a printer that could combine shelf-stable macronutrient powders, such as protein and starch, with oil or water at the print head and deliver micronutrients and flavour by inkjet, aiming to counter the gradual degradation of nutrients in stored food and to widen the variety of meals available to a crew (Gannon, 2013; NASA Spinoff, 2019). The same underlying engineering, later applied in more consumer-oriented projects, showed how extrusion-based food printing concepts developed for space applications could be transferred to terrestrial food-service settings (NASA Spinoff, 2019).

Confectionery, Culinary Design, and Novel Food Textures

Restaurants, bakeries, and confectionery manufacturers have used extrusion-based and hot-melt 3D printing to create intricate, customer-specific decorative shapes in chocolate and sugar work that would be laborious to achieve by hand, and companies such as Barilla have collaborated on 3D pasta printers capable of producing unconventional pasta geometries from durum wheat semolina dough (Zhu *et al.*, 2023; Karyappa and Hashimoto, 2019).

Sustainable and Alternative Protein Products

3D printing is also positioned as a tool for reducing food waste, by using imperfect produce or processing by-products as printable ink components, and for accelerating the development of plant-based and hybrid meat analogues with tailored fibrous texture, supporting a broader shift toward more sustainable protein sources (Alami *et al.*, 2024; Wang *et al.*, 2023).

Challenges and Limitations

Despite two decades of research progress, extrusion-based 3D food printing has not achieved large-scale industrial adoption, and several recurring barriers explain why. Printing speed remains far below that of conventional extrusion or moulding lines, which limits throughput and restricts current use to niche, high-value, or personalised products rather than mass production (Tay, 2025; Prithviraj *et al.*, 2025). Food safety and hygienic design are a persistent concern, since nozzles, tubes, and internal contact surfaces are difficult to clean thoroughly and create opportunities for microbial growth and cross-contamination, particularly when a printer is used with multiple different food inks in sequence (Kamble, 2022). The regulatory landscape is still fragmented: in the European Union, 3D-printed foods fall under the Novel Food Regulation and require a safety assessment before market entry, while in the United States the Food and Drug Administration has no dedicated category for printed food and currently references frameworks developed for other 3D-printed products, such as medical devices (Kamble, 2022). Shelf life of printed products, the cost of both printers and consumable food inks, a shortage of workers skilled in both food science and additive manufacturing, and unresolved questions about intellectual property and recipe copyright have also been identified as significant adoption barriers, with food structure and formulation design identified as root-cause challenges that, if solved, would ease many of the downstream difficulties (Neamah and Tandio, 2024). Consumer acceptance is a further open question, since printed foods must overcome both the practical hurdle of matching the taste and texture of conventionally processed equivalents and the psychological hurdle of consumer unfamiliarity with a manufacturing process still associated in the public mind with industrial plastics and machine parts (Shabir *et al.,* 2024; Neamah and Tandio, 2024).

Future Prospects

Ongoing research is addressing these barriers from several directions at once. Multi-material and multi-nozzle printers are being developed to allow different inks, for example a structural base paste and a flavour or nutrient-rich filling, to be deposited within the same object, widening the design space for personalised and functional foods (Neamah and Tandio, 2024). Computational tools,

including computational fluid dynamics simulation of ink flow through the nozzle and artificial-intelligence-assisted formulation and print-parameter optimisation, are being used to reduce the current reliance on trial-and-error formulation (Kaveti, 2022; Neamah and Tandio, 2024). On the materials side, closer integration between conventional twin-screw extrusion cooking, used to pre-structure starch and protein, and the printing step itself is likely to expand the practical library of printable food inks beyond the model hydrocolloid systems that dominate the current literature, bringing the technology closer to real, everyday food matrices (Zheng *et al.*, 2022; Högg and Rauh, 2023). As regulatory frameworks mature and hygienic printer design improves, extrusion-based 3D food printing is expected to move from research demonstrations toward defined, high-value niches, particularly clinical nutrition, dysphagia management, and specialised food service, before any broader consumer adoption becomes realistic (Kamble, 2022; Neamah and Tandio, 2024).

Conclusion

Extrusion-based 3D food printing extends the well-established science of food extrusion into the domain of digitally controlled, geometry-specific manufacturing. The technology depends on the same fundamental transport and structuring principles that govern conventional single- and twin-screw extrusion cooking, but adds a layer of rheological precision, since a printable food ink must flow under shear inside the nozzle and immediately regain enough structure to support subsequent layers. Starch, protein, chocolate, and hydrocolloid-reinforced purées have all been successfully adapted into printable formulations, enabling applications in personalized nutrition, dysphagia-safe food design, space food systems, and novel confectionery. Printing speed, food safety, regulatory uncertainty, and cost remain the principal obstacles to industrial-scale adoption, but continuing convergence between conventional extrusion cooking, rheology-guided ink design, and digital process control suggests that extrusion-based 3D printing will keep expanding from a research tool into a genuine, if specialised, food manufacturing technology.

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